Academia Journal of Scientific Research 8(8): 000-000, August 2020
DOI: 10.15413/ajsr.2020.0504
ISSN 2315-7712

Research Paper

High-Efficiency and Sustainable Cleaner Production in Paddy Fields

Accepted 3rd August, 2020

ABSTRACT

Humans currently face the problems of environmental pollution, threats to food safety and the increase of grain demand due to population increase. Industrial and agricultural production is the primary controllers of environmental pollution and food safety. However, intensive production is required in order to meet the increasing grain demand, and consequently large amounts of chemical fertilizers and pesticides need to be used in agricultural production, especially in developing countries with large populations where land and water resources are scarce. At present, pollution from agriculture (including livestock and poultry breeding) exceeds that from industry. Most of the population of Asia (around 3 billion) depends on rice as their staple food however conventional rice farming (CRF) or rice monoculture (RM) in paddy fields (PF) cannot easily satisfy the protein needs of humans. However, integrated planting–breeding modes (IPBM) in PF, which include rice–duck (RD) and rice–aquaculture modes, can not only meet people's protein demands but can also reduce environmental pollution and thereby increase food safety. This paper introduces various planting–breeding modes in PF and the ways in which they increase rice yield and improve rice quality, allow the harvesting of animal protein, reduce the input of agrochemicals, facilitate environmental improvement, are beneficial to high-efficiency and environmentally friendly pest management, decrease the loss of agrochemicals and increase use ratio, mitigate greenhouse gas emissions and increase social, economic, and ecological benefits. Additionally, suggestions are proposed to select suitable IPBMs based on the characteristics of particular regions. Finally, the rice–crayfish IPBM was taken as an example to analyze the advantages and inadequacies of implementing IPBM in PF.

Key words: Rice paddy, integrated planting–breeding mode, rice–aquaculture mode, rice–crayfish mode rice–duck, social economic ecological benefits.

ABBREVIATIONS: FAO, United Nations Food and Agriculture Organization; **NPSP,** Nonpoint source pollution; **NUE,** Nitrogen use efficiency; **¥,** Renminbi; **NPK,** Nitrogen, phosphorus, potassium; **IPBM,** Integrated planting–breeding mode; **PF,** Paddy fields; **IRFF,** Integrated rice–fish farming; **IRDF,** Integrated rice–duck farming; **RD,** Rice–duck; **RF,** Rice–fish; **RM,** Rice monoculture, **RT,** Rice–turtle; **TM,** Turtle monoculture; **RFS,** Rice–fish–shrimp; **DDT,** Dichlorodiphenyltrichloroethane; **RFD,** Rice–fish–duck; **CRF,** Conventional rice farming; **NDP,** Non-duck paddy; **GWP,** Global warming potential; **FNL,** Fertilizer with no loach; **FL,** Fertilizer with loach; **NFNL,** No fertilizer no loach; **TN,** Total nitrogen; **TP,** Total phosphorus; **TK,** Total potassium; **OP,** Orthophosphate; **GGE,** Greenhouse gas emissions; **NEEB,** Net ecosystem economic budget; **CFF,** Crab–fish farming; **DOC,** Dissolved organic carbon; **RL,** Rice–loach; **RS,** Rice–shrimp; **RC:** Rice–crayfish.

Kehan Zhao, Lianmeng Liu, Ling Wang, Yuxuan Hou and Shiwen Huang*

China National Rice Research Institute, Hangzhou, Zhejiang, China 310006.

*Corresponding author. E-mail: hswswh666@126.com.

INTRODUCTION

According to the FAO, the global population will reach 9.77 billion in 2050 (FAO, Rome, 2017; Figure 1) .This larger (and probably wealthier) world population will have a higher demand for food and food co-products and will thus exert extra pressure on food supply chains around the word. Global food security and supply is a significant problem (Morone et al., 2019). In order to meet the projected population increase, by 2050 global grain yield will be required to increase by more than 50% relative to 2018 levels. Accordingly, the requirement for agricultural products will also increase in the future. However, agricultural resources are continuously

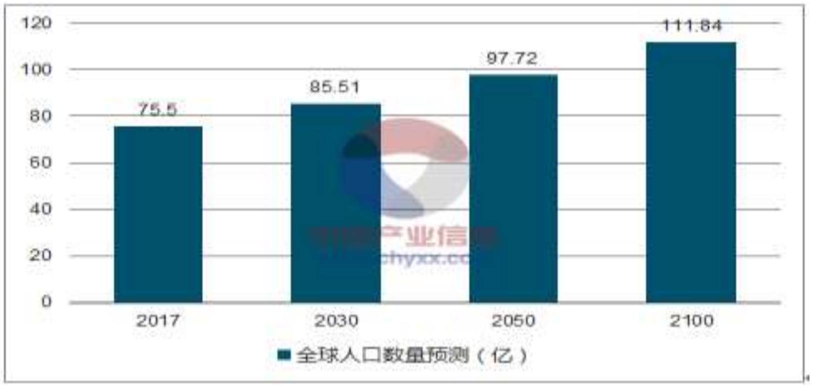

Figure 1: The projected change in global population from 2017 to 2100 (hundred million).

Figure 2: Serious water pollution.

decreasing, as are the per capita cultivated land area, water resources and nutrient resources. This combined with the aging of the population engaged in agriculture, the increasing severity of environmental pollution, the increasing frequency of climatic disasters, the degradation of ecosystems, and the decreasing productivity and stability of cropland, represent serious challenges to global food safety and security, and to the sustainable supply of agricultural products. Environmental pollution caused by agricultural production has become the largest non point source pollution (NPSP) (Min et al., 2016; http://www.360doc.com/content/18/0126/14/40033985_72526 0025.shtml). The sources of agricultural NPSP are mainly the application of fertilizers, pesticides and livestock and poultry breeding. According to an investigation by the United States Environmental Protection Agency (EPA), NPSP is the largest pollution source of rivers and lakes pollution in the USA. Additionally, in the Netherlands, the total N (TN) and total phosphorus (TP) coming from agricultural NPSPs account for 60% and 40–50% of the levels in rivers, respectively. Furthermore, it has been estimated that N and P from agriculture account for 81 and 93% of the levels in water in China, respectively (Figures 2 and 3).

A large amount of the applied N fertilizer escapes to the atmosphere as the greenhouse gas N_2O. In general, fertilizer applied to cropland follows one of three paths: the first is to be absorbed by the current crops, the second is to remain in the soil and be absorbed by next season's crops, and the third is to enter the atmosphere and water environment and thus become a source of pollution. China has only 7% of the world's arable land however it uses 35% of the world's chemical fertilizers. Around 100 million tons of chemical fertilizers are applied in China per year, which corresponds to an average application

Figure 3: Fishes killed by water pollution.

Figure 4a and b: Application amount of chemical fertilizer in unit agricultural acreage of various countries in the world

rate of over 400 kg/ha, far exceeding the average of 225 kg/ha for the developed countries (http://www.fert.cn/news/2017/7/19/201771911244593447.shtml). Rice–growing areas account for 26.2% of the total cultivated area in China and in these areas the unreasonable management of fertilizer and water has caused severe loss of applied fertilizer; for example, in some places the nitrogen loss has reached 30–70%. At present, the nitrogen use efficiency (NUE) of crops is about 50% in the USA and about 65% in the major countries in Europe. However, in China, the average cropland NUE is relatively low; the average NUE of the current crop in China is around 33%, around 15–30% lower than that in developed countries (see Figures 4a and b; https://ourworldindata.org/fertilizer-and-pesticides, http://www.sohu.com/a/285072386_732029). Additionally, in China, around 20 million tons of urea is lost annually through volatilization and eluviation pathways, etc., leading to direct economic loss of 50 billion RMB. A research report showed that in China, the use efficiency of NPK fertilizer was 33,24 and 42% in rice, maize, and wheat, respectively, while for rice the use efficiencies of N, P, and K were 35,25 and 41%, respectively (http://blog.sina.com.cn/s/blog_17a51ced60102xcrb.html). Around 1.3 million tons of agrochemicals are applied in China each year, 2.5 times the global average. However, the adhesion rate is only 10–20%, meaning that 80–90% of the applied agrochemicals escape into the soil, water, and atmosphere, and thus become a source of pollution (Figures 5a and b, https://ourworldindata.org/fertilizer-and-pesticides, http://www.sohu.com/a/285072386_732029).

Although chemical fertilizers and agrochemicals are important for agricultural production, providing a tremendous increase in crop yield and reducing crops loss and thus increasing food security, they also have numerous negative effects on agricultural sustainable development and human health due to unreasonable

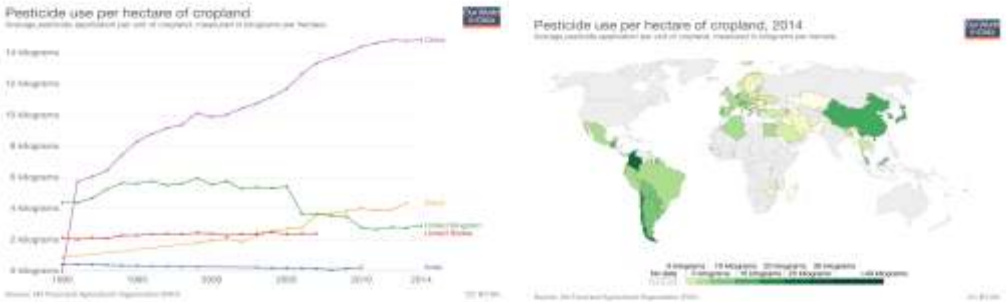

Figure 5a and b: Application amount of pesticides in unit agricultural acreage of various countries in the world

Figure 6: Rice–duck mode (source: Xinhua).

application. This has become a prominent barrier to the sustainable and stable development of agriculture in China (Wang et al., 2017). The excessive use of fertilizers, pesticides, machinery and natural resources required by intensified agriculture has caused significant environmental damage (Zheng et al., 2017; Reddy, 2016). Human beings require not only sufficient botanical starch and protein, but also require adequate amounts of animal protein. Aquatic products (e.g., fish, shrimp, crab, and turtle), livestock, poultry, etc., are excellent sources of high-quality animal protein. Finding ways to use limited agricultural resources (water and land) to produce sufficient amounts of high-quality agricultural products and animal protein to meet increasing alimentary demands has become one of the most important issues in various countries, especially those with a shortage of agricultural resources. Many studies have shown that excessive food production leads to the over-utilization of natural resources, including land, water, and fossil fuels (McLaughlin et al., 2015; Pinstrup-Andersen, 1999). The ever-increasing demand for water in agriculture is one of the key limiting factors for food production. Thus, producing more food per volume of water and per area of land used is vital to addressing food insecurity. Integrated planting–breeding modes(IPBMs) in paddy fields (PF), such as integrated rice–fish farming(IRFF)or integrated rice–duck farming (IRDF) systems, have a great potential to increase both food crop and animal protein productivity and reduce risks associated with water scarcity, land limitation, environmental deterioration and soil infertility (Ahmed et al., 2014). IPBMs provide a wide range of social, economic, and environmental benefits and increase the utilization efficiency of land and water.

The application of IPBMs in PF increases soil fertility, optimizes the use of land and water resources, increases productivity, environmental sustainability, agro-ecosystem biodiversity, the intensity of planting and breeding, farm diversification and improves human nutrition (that is, providing starch and animal protein), and is a sustainable option for producing both rice and animal protein (e.g., aquatic products, duck) while using less land and water, chemical fertilizers, and pesticides. IPBMs in PF therefore represent a possible solution to the continuous increase in the demand for food production and the improvement of nutrition, particularly for small and marginal farmers with limited resources (Korikanthimath et al., 2009).The wider adoption of IPBMs in PF could increase global water and plow land productivity and food security. However, their potential has not been fully explored in many countries.

IPBM in PF could increase grain yield and quality

The presence of ducks in a rice field (rice–duck mode [RD] Figure 6) increases plant height, the number of grains per panicle, the number of filled grains per panicle, thousand grain weight, harvest index, and grain yield. Additionally,

Figure 7: Rice–fish mode (source:Sannong).

studies have shown that using duck in rice fields increases grain yield and consequently increases farmers' income and also reduces the need for agricultural pesticides and environmental protection (Mofidian et al., 2015). IRFF is one of the best options to increase both food and animal protein production with limited land area, and has been practiced in many countries. Rice yield in rice–fish (RF) plots (using crucian carp; Figure 7) has been found to be 20% higher than that in rice-only plots, probably due to the fertilizing effect of the fish excrement (Tsuruta et al., 2011). In RF co-culture, significant negative correlations have been observed between the increased use of pesticides and both fish and rice yields. Rice yields were found to be positively correlated with fish survival, indicating synergistic effects between rice and fish production (Berg et al., 2018). The turtle yield did not significantly differ between rice–turtle (RT) production and turtle monoculture (TM), and rice yield did not significantly differ between RM and RT. The soil N and P were found to increase in TM but not in RT, even though the same quantities of N and P were applied in the two treatments. Rice yields were found to be similar in RT and RM, while turtle yields were found to be similar in RT and TM (Zhang et al., 2016). Moreover, when tiger frog (*Hoplobatrachus rugulosus*), grass carp (*Ctenopharyngodon idellus*), and bullfrog (*Rana catesbiana*) were released in PF in th rice growing season, rice yield increased by 10.1% compared to fields where no animals were released (Wang, 2004).

IRDF has been shown to markedly increase the rice grain yield due to enhanced tiller number and root bleeding rate (Sheng et al., 2018). In rice–fish–shrimp (RFS) systems, rice yield has been shown to increase by 3.04 tons/ha, 16.9% higher than that under RM (Mohanty et al., 2010). The quality of rice produced in IRDF was found to be significantly improved due to the removal of the need for herbicide and the reduced need for pesticide (Yu et al. 2008; Zhang et al. 2009). Moreover, the coarse rice rate, head rice rate, gel consistency and chalkiness rate of rice produced in IRDF have been shown to be superior to those in conventional rice farming (CRF) (Wang et al., 2004). Furthermore under IRDF, the contents of malathion, phosphide, chloride, arsenic, mercury, benzex, and dichlorodiphenyltrichloroethane(DDT) in rice were found to be significantly lower than the Chinese national limits (Li et al. 2003). Additionally, the levels of As, Cd, Cu, Pb, and Zn in crayfish muscle tissue were found to be acceptable for human consumption under all rice–crayfish (RC) rotation practices (Gedik et al., 2017). Moreover, rice produced in IRDF fields was shown to contain almost no pollution from pesticides or fertilizers (Zhang et al., 2002).Over all, research has shown that raising duck or fish in PF can increase grain yield. Consequently, these practices can increase farmers' income, and also reduce the need for agrochemicals, thus protecting the environment (Mofidian et al., 2015).

IPBM in PF could provide a source of animal protein

Rice and fish are important sources of food and nutritional security and income for many people. IRDF and IRFF systems are a potential source of these food sunder scarce land and water resource (Saiful Islam, 2016). In China, aquatic productssupply about 50% of the population's animal protein intake [https://cq.qq.com/a/ 20181024/006024.htm] and rice supplies about 70% of the population's calorie intake. Thus, there is an urgent need for a sustainable means of producing rice and fish [Alam et al., 2001]. IPBMs include IRDF and IRFF (including RF, rice–soft–shelled turtle, rice–shrimp (RS), rice–loach (RL) and rice–crab) modes implemented in PF, which not only maintain rice production but also add additional sources of animal protein. Asia accounts for the vast majority of the world's rice and meat–duck production. In IRDF systems, ducklings are released into rice paddies during the rice vegetative period in order to maximize the use of

Table 1: Average cost–benefit analysis of rice–fish (RF) modes and conventional rice farming (CRF) in different rice growing areas in China in 2014 and 2015 (¥/ha)

Investigate contents/different modes		Rice–fish	Rice–soft-shelled turtle	Rice–shrimp	Rice–loach	Rice–crab	CRF
Inputs	Fingerling cost of aquaculture	2721.45	4702.2	6520.05	22,239.9	3336.45	-
	Aquatic feed cost	3867.75	5490.3	7204.95	12,846.15	3674.55	-
	Aquatic medicine cost	183.3	230.4	167.55	587.25	553.8	-
	Rice seed cost	1191.6	907.8	1324.95	1216.5	1548	1353.15
	Fertilizer cost	1267.95	1024.8	1427.55	866.1	915.45	2260.5
	Organic fertilizer cost	1253.1	235.65	270	874.35	1548	915.45
	Cost of pesticides	282.45	859.35	675	232.2	356.85	1114.5
	Cost of paddy rental	2816.1	5464.35	5250	5130	9366	4565.1
	Reconstruction expense of facilities	1364.85	3310.8	4324.95	3724.35	6242.25	957.6
	Service charge (tractor-ploughing and machine harvesting)	2767.95	2544.75	1575	2213.55	3482.55	3025.05
	Processing charges of product	-	-	-	0.00	510	514.35
	Product marketing cost	520.5	-	-	1155.45	630	-
	Labor costs	5149.5	3846.45	5400	6007.35	3810	2691.6
	Other expenses	675	2507.1	2374.95	811.05	786.6	616.35
	Total input costs (investment)	24,061.65	31,123.65	36,514.95	57,904.2	36,760.5	18,013.5
Earnings	Rice yield (kg/ha)	8676.75	8267.4	7848.75	8473.35	8596.95	8449.35
	Rice price (¥/kg)	3.28	2.74	2.66	3.18	4.78	2.86
	Rice earnings (¥)	28,459.74	22,652.68	20,877.68	26,945.25	41,093.42	24,165.14
	Increase or decrease of RF compared with RM (%)	17.77	−6.26	−13.60	11.51	70.05	0.00
	Output of aquatic products (kg/ha)	906.9	1014	1501.35	1873.35	543.75	-
	Price of aquatic products (¥/kg)	24.42	36.04	33.00	39.54	59.92	-
	Earnings of aquatic products (¥)	22,146.45	36,544.5	49,544.55	74,072.25	32,581.5	-
	Total earnings (¥)	50,606.25	59,197.2	65,897.25	101,017.5	73,674.6	24165
	Net earnings (¥)	26,544.6	28,073.55	29,382.3	43,113.3	36,914.1	6151.5
	Increase or decrease of RF compared withCRF (%)	331.51	356.37	377.64	600.86	500.08	0.00

renewable resources in a closed-cycle flow of nutrients. IRDF used to be widely adopted in tropical and subtropical countries in East Asia but has remained unpopular in the wake of prevailing agricultural productivism characterized by specialization, intensification, mechanization and excessive dependence on agrochemicals. The IRDF mode would further expedite to expand, particularly in low-income parts of Southeast Asia where the rice or duck farming landscape is overwhelmingly dominated by smallholders [Suh, 2014a].

In IRDF, between 300 and 375 ducks/ha are commonly released into PF, and between 600 and 750 kg ducks/ha are harvested after 60 days of co-culture. In the IRFFs of RF, rice–soft-shelled turtle, RS, RL and rice–crab in PF, total animal harvests of about 907, 1014, 1501, 1873, and 544 kg/ha were gained, respectively (Table 1). Additionally, when tiger frog, grass carp and bullfrog were released in PF during the rice growing season, a combined weight of about 1180 kg/ha of fish and frogs were harvested (Wang, 2004; Peng, 2012; Huang et al., 2012). Furthermore, protein yield was found to be significantly higher in RD than in RM, while the output/input, gross income and net income were found to be 15.26, 39.51, and 44.80% higher in RD than in RM, respectively, suggesting that the economic benefits of RD are greater than those of RM [Zheng et al., 2014].

IPBM in PF could reduce the need for agrochemicals and facilitate sustainable development

In modern intensive rice production, the environmental pollution caused by the increased

Table 2: Average input of fertilizers and pesticides for the different RF modes and rice monoculture(RM) in various rice growing areas in China from 2014 to 2015 (¥/ha).

Investigate contents/ Different modes	Rice–fish	Rice–soft–shelled turtle	Rice–shrimp	Rice–loach	Rice–crab	Average		Average increase or decrease of RF compared with CRF (%)
Fertilizer cost	1267.95	1024.8	1427.55	866.1	915.45	1100.4	2260.5	–51.32
Increase or decrease of RF compared with CRF (%)	–43.91	–54.66	–36.85	–61.69	–59.50	–51.32	0.00	
Pesticide cost	207.45	859.35	675	172.2	356.85	436.2	1114.5	–59.52
Increase or decrease of RF compared with CRF (%)	–81.39	–22.89	–39.43	–84.55	–67.98	–60.86	0.00	
Proportion of fertilizer and pesticide input (%)	6.69	4.44	4.58	5.19	3.71	4.83	21.86	–77.56
Increase or decrease of RF compared with CRF (%)	–69.40	–79.69	–79.05	–76.26	–83.03	–77.90	-	

use of agrochemicals and chemical fertilizers poses an enormous threat to rice quality and safety, as well as to ecosystems. IRFF and IRDF have been shown to have numerous benefits for rice farmers (Ahmad et al., 2004), such as increasing the rice yield and improving rice quality, adding a harvest of animal protein and increasing income. Thus, it is of great importance to reduce the amounts of chemical fertilizer and agrochemicals which are used in rice production in order to decrease pollution and guarantee rice quality (Zheng et al., 2014). The RD mode can reduce energy input and increase both energy output and the values of the product safety index based on energy. The product safety indexes of RD and RM production systems were found to be–0.6 and –0.78, respectively, which indicates that the safety potential of products from RD is higher than that of products from RM. Additionally, the RD mode was found to reduce the fertilizer and pesticide requirement by 30.6 and 59.4%, respectively, compared with the CRF system (Table 2) (Deng et al., 2008; Yu et al., 2008). The excessive use of fertilizers and pesticides required by intensified agriculture has caused significant environmental damage. Deploying effective measures to reduce fertilizer and pesticide use without decreasing grain yield and increasing labor intensity has been challenging. However, RD could achieve this goal. RD is a well-tested technique, having been applied for more than 700 years in China (Zheng et al., 2014). The IRDF system is known to have numerous benefits for rice farmers and may be an acceptable solution to the above problems (Ahmad et al., 2004).

In this study, three sustainable rice farming systems were evaluated, namely RM, RF, and RD. The ratios of the economic input to the economic output were 0.41, 0.61, and 0.41 for the RM, RF, and RD systems, respectively. The net profit of the RD system was 3264.2 USD/ha, which was nearly 40% higher than those of the RM and RF systems. Based on the analysis of the economic efficiency and sustainability index, the RD system may be the optimal rice agriculture system from both ecological and economic perspectives (Li et al., 2018). In integrated systems such as RF, RD, and rice–fish–duck (RFD), the physico-chemical parameters of water (dissolved oxygen, nitrate, ammonia, total alkalinity, dissolved organic matter, and total suspended solids) and soil nutrient levels are significantly higher compared to CRF due to the continuous addition of fecal matter and the scooping and churning of soil by fish and ducks in the PF. In integrated rice-based systems, the aquatic biological diversity, including plankton (phytoplankton and zooplankton), soil benthic fauna, and microbial populations, are dynamic, which leads to enhanced soil fertility and sustainable production. In IPBM, higher productivity and profitability in terms of rice equivalent yield and the ratio of the output value and cost of cultivation (OV/CC) were achieved compared to CRF. The adoption of RFD integrated farming systems enhances total farm production and income, and additionally increases water and soil quality indexes through effective nutrient recycling (Nayak et al., 2018). Global food demand is predicted to increase by 50% in 2050, and this expectation is driving agricultural intensification. RF and RD farming systems are a potential way to meet current and future food demand under scarce land and water resources in a sustainable way. These systems make optimal use of scarce land and water resources and increase soil fertility, productivity, environmental sustainability, system biodiversity, the intensity of rice and aquaculture, farm diversification, and additionally improve human nutrition, and can therefore be used to sustainably produce rice and animal protein using less land, water, chemical fertilizers, and pesticides.

IPBM in PF could be beneficial to high-efficiency and environmentally friendly pest management

Raising fish, frog, or duck in PF not only shows potential for controlling weeds and reducing rice pests and diseases but also raises soil fertility, improves soil biodiversity, and increases rice grain yield. Implementing IRFF, IRDF, or rice–frog integrated farming can strongly reduce the amount of pesticides and herbicides that are required, and is therefore beneficial for developing green or organic rice farming. IRDF, in which ducks feed on insects and weeds in PF and fertilize rice plants, has been a flagship technique in Asian sustainable agriculture movements (Suh, 2014b). Teng et al. (2016) compared an IRDF paddy and a non-duck paddy (NDP) and found that the number of weeds and the incidence of stem borers (*Chilo suppressalis, Scirpophaga incertulas*), leaf rollers (*Cnaphalocrocis medinalis*), rice sheath blight (*Rhizoctonia solani*) and plant hoppers (*Nilaparvata lugens, Sogatella furcifera*) were extremely significantly lower in the IRDF field than in the NDP. Additionally, the same study found that the soil contents of NH_4^+-N, alkali-hydrolyzable N, and available P and K, as well as the soil activities of urease, phosphatase, sucrase, and catalase, were higher in the IRDF than the NDP, and furthermore that the rice grain yield in the IRDF was 1.9 times that of the NDP. When reared in PF, ducks control pests and young weeds via their natural feeding behavior, while their feces reduce the required application dosage of agricultural chemicals thereby increasing rice yield, increasing farmers' income and decreasing environmental pollution (Deng et al.,2007; Zhang et al., 2009). Yu et al. (2004b, 2008) investigated the ability of ducks to control rice insect pests, diseases, and weeds in more than 12 provinces (cities) in China. Between 300 and 375 young ducks (20 days old) per ha were released to the PF at the maximal tillering stage and allowed to roam freely for 50–60 days. It was found that at the end of the study period, the total number of insects in the PF had reduced by 87.7% compared with an NDP. One day after the ducks were released, the number of plant hoppers and leaf folders had been reduced by 37.6 and 48.3% respectively, compared with the day before release, while 12 and 42 days after the ducks were released the total number of plant hoppers and leaf hoppers had been reduced by 63.9 and 77.3%, respectively and the number of weeds had been reduced by 50.6 and 94.2%, respectively, compared with an NDP. Moreover, 12 and 42 days after release the incidence of sheath blight disease at the maximal tillering and full heading stages was 67.2 and 52.5% lower than in the NDP respectively, while the quantity of natural enemies of spiders was 1.66–2.61 times higher than that in the NDP. This indicated that pests were effectively controlled in the IRD of PF compared with the NDF. Additionally, in a comparative experimental analysis of 15,100 ha of rice paddies using IRDF and RM over a three-year period, the weighted average output of rice for the IRDF field was 7117.5 kg/ha, which was higher than that of the RM field by 297.0 kg/ha (4.35%). The per ha increase and expenditure saving due to the IRDF mode were found to be 1838.55 and 1565.55 ¥ respectively, compared to the RM mode.

However in previous studies, Yu et al. (2005, 2006) reported that the rice output of an IRDF field was 358.5 kg/ha (4.39%) lower than that of a high-yield CRF field. Nonetheless, the revenue of the IRDF field was higher than that of the CRF field by 1159.5 ¥/ha due to the rice price increase of 0.2 ¥/kg in rice paddies using IRDF. Additionally, the consumption of chemical fertilizers in the IRDF was reduced by 30.24% compared with the RM due to the fertilizing effect of the duck excrement. This process saved 289.5 ¥/ha. Additionally, the ducks' consumption of pests and grass reduced the application of pesticides and herbicides by three times and reduced the dosage of pesticides by 59.5%, saving 694.5 ¥/ha in pesticide expenditure compared with the RM. Thus, the revenue from the IRDF field was larger than that from the RM field by 2562¥/ha, and the overall revenue from the IRDF field was larger than that from the RM field by 4707 ¥/ha. Xu et al. (2014) found that the numbers of natural enemies of spiders were higher in a rice–crab PF than those in a CRF field. They also found that rice–crab integrated farming brings more economic, social, and ecosystem benefits than CRF or RM. Additionally, Ma et al. (2019) found that, although there was no difference in the number or diversity of spider species between rice–crab paddies and CRF, there were more individual spiders in rice–crab paddies than CRF fields.

Moreover, experiments of fish and frog rearing in PF were carried out in Chongqing, Jiangxi, and Zhejiang provinces from 2007 to 2010 (Zhu, 2000;Zhou et al., 2011; Technology Extension Main Station of Aquatic Product of Zhejiang Province, 2012). It was found that these planting modes can effectively control insect pests and weeds and also greatly increase comprehensive benefits such as rice grain yield, animal protein yield, economic income and social and ecological benefits. Tiger frog, grass carp and bullfrog were released in PF during the rice growing season.(Grass carp feed on young weeds, while frogs prey on the larva or nymphs of insects as well as the insects themselves; for example, one adult bullfrog is able to eat more than 100 insects per day). In the field in which the animals were released, the dead heart of rice plants and the white panicle ratio caused by stem borers were reduced by 62.9–83.4% and 58.3–84.8%, respectively, compared with a PF in which no animals were released. Additionally, the amount of plant hoppers per 100 hills and the density of weeds per square meter were reduced by 38.9 and 41.7% respectively, while the number of injured tillers decreased by 21.8% and pesticide application was reduced by two times (Wang, 2004; Peng, 2012). Very large economic, ecological and social benefits were gained from this rice cropping pattern.

IPBM in PF could decrease the loss of agricultural chemicals and increase their use ratio

Li et al. (2008) investigated N losses from N fertilizer via N2O emissions, NH3 volatilization and N leaching in IRDF and IRFF ecosystems in Southern China. Three different treatments were implemented, namely conventional rice fields of RM (CK), IRDF, and IRFF. N2O emissions from N fertilizer were found to be affected by the fertilization way and the drainage of PFs. The analysis of TN losses of application amount via N2O emissions, NH3volatilization, and N leaching indicated that TN losses in the IRDF and IRFF fields were 51.39 and 52.60 kg N/ha, respectively, which were lower than that in the CK field (54.97 kg N/ha), thus suggesting that the presence of duck and fish can decrease N fertilizer loss rates and thus increase N fertilizer use efficiency. Lee et al. (2015) studied the effect of pond loach(Misgurnus anguillicaudatus) on the chemical composition of pond water. Concentrations of NH4+-N and PO43—P were shown to be higher in ponds that received fertilizer, while chlorophyll a (Chl-a)concentrations were found to be two fold higher in ponds with fertilizer and no loach (FNL) and ponds with fertilizer and loach (FL) than in ponds with no fertilizer and no loach (NFNL). Furthermore, Chl-a concentrations in the FL ponds were shown to be 78% lower than those in the FNL ponds, while the density of diatoms and green algae was found to be two fold higher in FNL and FL ponds than in NFNL ponds, with the density of diatoms being lower in the FL ponds than in the FNL ponds.

Zhang et al. (2016) observed that levels of N and P in PF water and PF soil were significantly higher in TM than in RT or RM. They found that only 20.4% of feed-N and 22.8% of feed-P were used by turtles in TM, which caused large quantities of feed-N and feed-P to remaining in the environment. However, in RT, some of the feed-N and-P that was unused by turtles was taken up by the rice plants. These results suggest that integrating intensive turtle aquaculture with rice culture can result in high yields and low environmental impacts. Feng et al. (2016, 2019) found that in the water of an IRFF system, the contents of TN, ammonia-N, nitrate-N, nitrite-N, TP, and orthophosphate (OP) were 70.63, 60.27, 54.86, 71.54, 85.05, and 78.54% lower than those in a fish monoculture pond respectively. Furthermore, they observed that the contents of ammonia-N, TP, and OP in the bottom soil were respectively reduced by 91.14, 36.99, and 58.57% under IRFF compared to fish monoculture. The total cost of the IRFF system was only 2.88% higher than that of the fish monoculture, however the net income was enhanced by 114.48%. These results suggest that IRFF is an efficient means to mitigate eutrophication in intensive-culture ponds and is also a potential new way to increase rice production, thus increasing food security and providing extra income for fish farmers. Additionally, Si et al. (2019) found that N and P sequestration by soil in the RS co-culture mode was higher by 49.2 kg/ha and 9.1 kg/ha ompared to RM respectively and promoted N and P accumulation in the soil. Furthermore, the apparent loss of N and P in RS co-culture mode was shown to be higher by10.2 kg/ha and 1.0 kg/ha compared to RM, respectively. Studies by Dugan et al. (2006), Nhan et al. (2007), Haque et al. (2010) and Ahmed et al. (2011) found that IRFF systems optimally use scarce land and water resources and increase soil fertility, productivity, environmental sustainability, system biodiversity, the intensity of planting and breeding, farm diversification, and improves human nutrition, and are therefore a sustainable option for producing rice, duck, and fish with a lower use of land and water.

IPBM in PF could mitigate greenhouse gas emissions (GGE)

Agriculture has to play a central role for mitigating the unfavorable effects of climate change, by reducing Greenhouse Gases Emission (GGE) to the atmosphere (Fiorini et al., 2020). Agricultural activities are important contributors to GGE. Zhang et al.(2008) found that diurnal variations of N_2O emissions from PF were highly correlated with the activities of ducklings. Specifically, the rates of N_2O emission were normally higher in the early morning and late afternoon due to the frequent movement of ducklings at these times. In general, when ducks were present, the rates of N_2O emission were higher when chemical fertilizer was applied than when organic fertilizer was applied, and more N_2O was emitted from the PF in the tillering stage than in the heading stage. When organic fertilizer was used, the global warming potential (GWP) was about 22% lower than when chemical fertilizer was used. Additionally, Xu et al. (2017) found that IRDF with organic fertilizer decreased the CH_4 emission from PF by 8.80–16.68% and increased the N_2O emission by 4.23–15.20% compared to chemical fertilizer in RM. IRDF and IRFF are important ways to realize the sustainable development of agriculture. In recent decades, many attempts have been made to assess the effects of implementing IRDF or IRFF on GGE, energy use efficiency, soil fertility, and comprehensive economic benefits. Sheng et al. (2018) evaluated the effect of duck raising in PF in Southern China on the CH_4 and N_2O emissions, GWP, rice grain yield, and net ecosystem economic budget (NEEB). The results of integrated GWPs of the IRDF based on CH_4 and N_2O emissions showed that

IRDF reduced the total amount of CH_4 and N_2O emissions from PF compared to CRF. IRDF was also found to increase N_2O emissions compared to CRF, however the decrease of CH_4 emissions was far greater than this increase and therefore overall IRDF greatly reduced GWPs compared to CRF. In 2009 and 2010, IRDF was found to significantly reduce the greenhouse gas intensity by 30.6 and 29.8% respectively, to decrease the GWP by 28.1 and 28.0% respectively and to increase the NEEB by 40.8 and 39.7% respectively, relative to CRF. Taken together, these results suggest that IRDF is an effective strategy to optimize the economic and environmental benefits of PF in Central China (Sheng et al., 2018; Xu et al., 2017). Moreover, Yang et al. (2018) found that IRDF can maintain rice yield and reduce the risks of N and P loss to local environments when utilizing biogas slurry as a substitute for chemical fertilizers. Furthermore, Li et al. (2009) found that IRDF reduced the integrated GWPs based on CH_4 and N_2O in Southern China.

Aquaculture is an important source of atmospheric CH_4 and N_2O. Liu et al. (2016) found that the conversion of PF to crab–fish farming (CFF) significantly reduced CH_4 and N_2O emissions from PF by 48 and 56%, respectively. Over the rice growing season, CH_4 fluxes from PF averaged 1.86 mg m^{-2} h^{-1}, CH_4 fluxes from CFF wetlands with aquatic vegetation present averaged 1.14 mg m^{-2} h^{-1} and CH_4 fluxes from CFF wetlands without aquatic vegetation present averaged 0.50 mg m^{-2} h^{-1}. CH_4 emissions from CFF wetlands were found to be 52% lower than those from PF. The conversion of PF to CFF wetlands is predicted to reduce CH_4emissions by 22–54% in mainland China annually. This suggests that, as well as bringing economic benefits, the conversion of PF to CFF wetlands could also lead to a lower ecosystem CH_4 release rate (Hu et al., 2016). RFS systems could improve PF ecosystems. Mohanty et al. (2010) found that, when supplemental feed was provided, water pH, total alkalinity, total suspended solids, Chl-a content, and plankton content were significantly higher in an RFS system than in an RM system. In the RFS system, when 50% of the area was devoted to fish and shrimp culture, the total net economic returns were 23-fold higher than those in the RM system. Furthermore, Li et al. (2019) found that the growing of rice in fish ponds reduced the water nutrient content (TN, ammonia-N, TP, and total potassium [TK]) and dissolved oxygen content (DOC) in ponds, and also reduced the total amount of oxygen consumption and optimized the oxygen consumption structure in the ponds. By additional rice cultivation, the respiration rates in the water and sediment were respectively significantly reduced by 66.1 and 31.7% in a catfish pond and by 64.4 and 38.7% in a shrimp pond. The IRFF decreased the proportions of respiration in sediment and water, and increased the proportion of fish respiration. These finding suggest that IRFF is an efficient way to reduce hypoxia in intensive-culture ponds. IRFF has received increasing attention as a way to remediate nutrient pollution in aquaculture. Feng et al. (2016, 2019) found that the application of an IRFF system to a pond significantly reduced the nutrient levels in the water and bottom soil compared with fish monoculture.

IPBM in PF could provide social, economic, and ecological benefits

As previously mentioned, the implementation of IPBM in PF (e.g., IRDF, IRFF, RFD, RFS, RS, RT, RL, RC) not only maintains the supply and security of rice but also provides high-quality animal protein, and thus achieves considerable economic returns and environmental improvement. The raising of duck or fish in PF could increase grain yield and consequently increase farmers' income while also reducing the use of agrochemicals and thus protecting the environment. Mofidian et al. (2015) found that, compared with RM, the rice yield was 4.42% higher in an RD system and that rice yield in the RF plots was 20% higher than that in the rice-only plots. Rice grain yield in the RFS system was 3.04 tons/ha (16.9%) higher than that in the RM. Nevertheless, some modes of IPBM show that the rice output of IRDF was 358.5 kg/ha (4.39%) lower than that of high-yield CRF. However, the quality of the rice produced in IRDF was significantly higher due to the lack of need for herbicide and the reduced need for pesticide. Rice produced in RD fields had almost no pollution from pesticides and fertilizer, and the revenue from these fields was 1159.5 ¥/ha higher than that of RM fields due to the price increase of 0.2¥/kg for rice produced in IRDF. Additionally, the consumption of chemical fertilizers in the IRDF was 30.24% lower than that of the RM, while the output/input, gross income and net income of the RD were 15.26, 39.51, and 44.80% higher than that of the RM respectively.

Raising fish, frog, or duck in PF not only shows potential for controlling weed hazards and reducing the prevalence of rice pests and diseases, but can also raise soil fertility, improve soil biodiversity, and increase rice grain yield (Wang, 2004). Implementing IRFF, IRDF or rice–frog integrated farming has been shown to highly reduce the required amount of pesticides and herbicides and to be beneficial to the development of organic rice farming. Specifically, IRDF reduced fertilizer use by 30.6% and pesticide use by 59.4% compared with CRF (Master Station of Whole Country Aquatic Product Technology, 2018; Cao et al., 2017; Yu et al., 2006). Dey et al. (2018) observed that the weighted average output of rice under the IRDF mode was 7117.5 kg/ha, which was higher than that of RM by 297.0 kg/ha (4.35%). Compared to the RM mode, the per ha revenue increase and expenditure saving of the rice and duck in the IRDF mode were 1838.55¥ and 1565.55 ¥, respectively. The overall income from organic IRFF was found to be 72, 210 Indian rupees, around 26%

higher than the income from RM (57,280 rupees).Therefore, it can be concluded that organic RF integration can be a viable technique to achieve comprehensive benefits compared to RM, especially for low-lying areas. Iwai et al. (2018) found that rice growth did not increase the presence of loach or snails in a pond, however observed that rice growth was negatively correlated with weed biomass. They showed that the presence of loach increased turbidity and decreased the concentration of phosphate in the surface water and that the presence of snails decreased the DOC in the surface water, probably due to the animals' high bioturbation rate. Neither total phytoplankton, total weed biomass nor soil density were affected by the animals. These results show that rearing loach in PF can change the aquatic environment but does not increase rice production. However, other studies showed that the rearing of ducks in PF improved rice quality and increased economic benefits by 2000–4500 ¥/ha (Zhang et al., 2002; Deng et al., 2007, 2008).

A total area of 86,400 ha of IRDF was implemented between 2001 and 2003 in Zhejiang Province, China. Compared with RM, in fields with duck rearing, the income was 3404.1¥/ha higher, due to increased revenue and reduced expenditure and the grain yield was 295.5 kg/ha higher. Compared with RM, in fields with duck rearing, the total income was 294 million ¥ higher and the rice grain yield was 25,000 tons higher [Yu et al., 2004a, b].Furthermore, IRFF had a significantly higher income (43.6 million Vietnamese dong $ha^{-1}year^{-1}$) than other farmer groups which implemented CRF. These results suggest that future production systems should not be optimized to provide only one ecosystem service, but should rather be designed to deliver a variety of interlinked ecosystem services, such as rice cultivation, fish aquaculture, pest control, and nutrient recycling (Berg et al., 2012).

IPBM in PF should be able to adjust to local conditions

It is of great importance to rethink current agricultural systems and provide opportunities for more diverse system that maintain and enhance a range of ecosystem services and protect human health as well as maintain food security [Berg et al., 2012]. It is also highly important to select suitable IPBM in PF in order to achieve sustainable development and profitability in the local level. Firstly, it is necessary to select suitable crops and aquatic animal species according to the local environmental and climatic conditions. Secondly, aquatic animal species should be chosen based on the consumption habit of local people. In Eastern China, the price of ducks produced in IRDF is 50–100% higher than that of ducks produced in ordinary duck rearing since consumers in this region (Jiangsu, Zhejiang, and Shanghai) consume large quantities of this meat. Therefore, duck rearing in IRDF in Eastern China could bring the double benefits of increased rice yield and higher economic benefit. On the contrary, citizens in Northeastern China consume far less duck, so the economic benefits of IRDF can be expected to be lower in this region. Moreover, since crayfish is widely consumed in the provinces of Hubei, Jiangsu, Anhui, and Hunan, RC co-culture has achieved considerable economic success in these locations. The combined system of IPBM enhances soil biological activity and nutrient recycling, improves profits, increases crop yields, intensifies land use, prevents soil erosion, helps reduce poverty and malnutrition, and strengthens environmental sustainability. Thus, “win-win” outcomes can be achieved by providing higher investment in research and development, favorable incentive policies, and technologies to enable sustainable and productive integrated farming systems (Reddy et al., 2016).

A case report of an RC coupled mode in PF

The application of IPBM in PF, especially RC co-culture, has developed rapidly in China due to its social, economic and ecological benefits. In 2018, the area of IRFF in China reached 2.13 million ha, and the output of aquatic products from IRFF reached 2.33 million tons. In the same year, the area of IRFF exceeded 66,667 ha in each of the provinces of Hubei, Sichuan, Hunan, Jiangsu, Anhui, Guizhou, Yunnan, and Jiangxi, with the first three of these provinces having IRFF areas of 393,170, 312,230, and 300,150 ha respectively, together, these three provinces accounted for 49.58% of the total area of IRFF in China in 2018. As of 2018, the combined area of RS and RC accounted for 49.67% of the total area of IRFF in China (Figure 8), while rice–crab, RL, RT, and other modes accounted for 4.97, 1.57, 1.00, and 0.69% respectively. In the same year, the output of aquatic products from RS and RC accounted for 62.31% of the total amount of aquatic products produced by IRFF in China, while the output from RF, RL, rice–crab, RT and others accounted for 29.42, 2.96, 1.83, 0.77, and 2.71%, respectively. In China, the RS mode is mainly distributed in the middle and lower reaches of the Yangtze River. Meanwhile, the RC mode has been greatly developed in China in recent years due to its high comprehensive benefits (Master Station of Whole Country Aquatic Product Technology, 2018). The RC mode currently accounts for the highest total output of any IRFF mode in China. The five provinces with the largest areas of RC in China are Hubei (48.96% of the total area of RC in China), Hunan (18.68%), Anhui (13.98%), Jiangsu (7.07%) and Jiangxi (5.57%) together these five provinces make up 94.26% of the total area of RC in China. Additionally, these provinces are also the top five in China in terms of

Figure 8: Rice–crayfish mode.

crayfish production and together account for 96.28% of the total crayfish production in China.

The average cost–benefit and average input of fertilizer and pesticide for different RF and CRF modes in different areas in China in 2014 and 2015 are summarized in Tables 1 and 2. In 2018, the province with the largest area of RC was Hubei with 380,670 ha; in the same year, the province's total production value of crayfish was 32.5 billion ¥, the average output of crayfish from RC was 1800 kg/ha. It has been estimated that in Hubei Province, by implementing the RC planting–breeding mode the comprehensive benefits of PF have been increased by more than 80%, the application amount of chemical fertilizer and pesticide has been reduced by more than 30% and the average economic benefits have increased by 37,500 ¥/ha compared with CRF (Master Station of Whole Country Aquatic Product Technology, 2018). The RC mode can be said to have a "dual character" for the following reasons. This mode can not only stabilize rice production but also increase crayfish breeding in PF. Compared to CRF the rice yield of the RC mode is higher by 4.63–14.01% and the rice quality is improved. Additionally, compared to CRF, the RC mode has higher soil fertility and increased soil contents of readily oxidizable organic carbon, TN, TP, and TK, however it also has higher soil gleization, darker soil color, and tighter soil structure. Furthermore, in some cases the RC mode was found to conserve water, but in other cases it increased water consumption. Meanwhile, although the RC mode decreases the need for fertilizer and pesticide and increases water nutrient concentration, it also increases the risk of water eutrophication. Moreover, while the RC decreases the amount of rice pests, it increases the occurrence of some rice diseases and alters the field biodiversity (Cao et al., 2017).

ACKNOWLEDGEMENTS

The authors are highly thankful to the key R and D project of Zhejiang Province(2019C02018), the national key R & D projects of China (2018YFD0200304, 2016YFD0200801), Innovation project of CAAS (CAAS-ASTIP-2013-CNRRI); China–Norway international cooperation project: "CHN-2152, 14-0039 SINOGRAIN project 2" and Shanghai municipality project "Agriculture through science and technology" (2019-02-08-00-08-F01127) for their kind support.

REFERENCES

Ahmad GJU, Hossain ST, Islam MDR, Rabbi MDF (2004). Rice–duck farming reduces weeding and insecticide requirement and increases grain yield and income of farmers. Int. Rice Res. Notes. 29(1): 74–77.

Ahmed N, Garnett ST (2011). Integrated rice-fish farming in Bangladesh: meeting the challenges of food security. Food Secur. 3(1): 81-92.

Ahmed N, Ward JD, Saint CP (2014). Can integrated aquaculture-agriculture (IAA) produce "more crop per drop"? Food Security. 6: 767-779.

Alam MF, Thomson KJ (2001). Current constraints and future possibilities for Bangladesh fisheries. Food Policy 26(3): 297-313.

Berg H, Berg C, Thanh TN (2012). Integrated rice-fish farming: safeguarding biodiversity and ecosystem services for sustainable food production in the Mekong Delta. J. Sustain. Agric. 36(8): 858-872.

Berg HK, Tam NT (2018). Decreased use of pesticides for increased yields of rice and fish-options for sustainable food production in the Mekong Delta. Sci. Total Environ. 619-620: 319-327.

Cao CG, Jiang Y, Wang JP, Yuan PL, Chen SW (2017). "Dual character" of rice–crayfish culture and strategy for its sustainable development. Chin. J. Eco-Agric. 25(9): 1245-1253.

Deng QH, Pan XH (2008). Effects of rice–duck mutualism on diseases insect pests and weeds and economic benefits. Agric. Sci. Technol. 1(128-133): 138.

Deng QH, Pan XH, Wu JF, Shi QH (2007). Ecological effects and economic benefits of rice–duck farming. Chin. J. Ecol. 4: 582–586.

Dey A, Sarma K, Kumar U, Mohanty S, Kumar T, Bhatt BP (2019). Prospects of rice-fish farming system for low lying areas in Bihar, India. Organic Agric. 9(1): 99-106.

Dugan PJ, Dey MM, Sugunan VV (2006). Fisheries and water productivity in tropical river basins: enhancing food security and livelihoods by managing water for fish. Agric. Water. Manag. 80(1): 262-275.

FAO (2017). Food security and nutritional status of the World in 2017: enhance defense ability and promote peace and food security. Rome.

Feng JF, Li FB, Zhou XY, Xu CC, Fang FP (2016). Nutrient removal ability and economical benefit of a rice-fish co-culture system in aquaculture pond. Ecological engineering: J. Eco-technol. 94: 315-319.

Feng JF, Li FB, Zhou XY, Xu CC, Fang FP (2019). Impact of rice-fish/shrimp co-culture on the N2O emission and NH3 volatilization in intensive aquaculture ponds. Sci. Total Environ. 655: 284-291.

Fiorini A, Boselli R, Maris SC, Santelli S, Ardenti F, Capra F, Tabaglio V (2020). May conservation tillage enhance soil C and N accumulation without decreasing yield in intensive irrigated croplands? Results from an eight-year maize monoculture. Agric. Ecosyst. Environ. 296: 106926.

Gedik K, Kongchum M, DeLaune RD, Sonnier JJ (2017). Distribution of arsenic and other metals in crayfish tissues (Procambarus clarkii) under different production practices. Sci. Total Environ. 574: 322-331.

Haque MM, Little DC, Barman BK, Wahab MA (2010). The adoption process of rice field-based fish seed production in Northwest Bangladesh: an understanding through quantitative and qualitative investigation. J. Agric. Educ. Ext. 16(2): 161-177.

Huang HZ, Huang XZ (2012). Technologies for fishes raising in paddy fields. Mod. Agric. Sci. Technol. (Zool. Sci.). 8: 337-343 (in Chinese).

Hu ZQ, Wu S, Ji C, Zou JW, Zhou QS, Liu SW (2016). A comparison of methane emissions following rice paddies conversion to crab-fish farming wetlands in southeast China. Environ. Sci. Pollut. Res. 23(2): 1505-1515.

Iwai N, Koyama N, Tsuji S, Maruyama A (2018). Functions of indigenous animals in paddy fields: an in situ experiment on their effects on water quality, phytoplankton, weeds, soil structure, and rice growth. Paddy Water Environ. 16(1): 89-98.

Korikanthimath VS, Manjunath BL (2009). Integrated farming systems for sustainability in agricultural production. Indian J. Agron. 54(2): 140-148.

Lee YS, Kim KS, Lim SG, Im JH, Han HG, Soh HY, Cheong CJ (2015). Effect of fertilizer addition on water quality and fingerling production of loach (Misgurnus anguillicaudatus) in natural outdoor ponds. J. Environ. Biol. 36(3): 557-563.

Li CF, Cao CG, Wang JP, Zhan M, Yuan WL, Shahrear A (2008). Nitrogen losses from integrated rice–duck and rice-fish ecosystems in southern China. Plant Soil. 307: 207–217.

Li CF, Cao CG, Wang JP, Zhan M, Yuan WL, Shahrear A (2009). Nitrous Oxide (N2O) Emissions from Wetland Rice–duck Cultivation Systems in Southern China. Arch. Environ. Contam. Toxicol. 56(1): 21-29.

Li FB, Sun ZP, Qi HY, Zhou XY, Xu CC, Wu DX, Fang FP, Feng J, Zhang N (2019). Effects of Rice-Fish Co-culture on Oxygen Consumption in Intensive Aquaculture Pond. Rice Sci. 26(1): 50-59.

Li J, Lai X, Liu HM, Yang DL, Zhang GL (2018). Emergy Evaluation of Three Rice Wetland Farming Systems in the Taihu Lake Catchment of China. Wetlands 38(6): 1121-1132.

Li KQ, Huang H, Ren ZM (2003). Technical demonstration and efficiency of rice–duck agroecosystem and frequoscillation pest-killing lamp in Hunan. China Rice. 5:35–37 (in Chinese).

Liu SW, Hu ZQ, Wu S, Li SQ, Li ZF, Zou JW (2016). Methane and Nitrous Oxide Emissions Reduced Following Conversion of Rice Paddies to Inland Crab Fish Aquaculture in Southeast China. Environ. Sci. Technol. 50(2): 633-642.

Master Station of Whole Country Aquatic Product Technology, Society of China Aquatic Product, Ocean University of Shanghai (2018). Industry development report of rice-fish integrated planting and breeding in China. Chongqing Aquatic Product. 4: 9-19

Ma XH, Che XQ, Wang JS, Sang HX (2019). The structure of spider communities in crab paddies and conventional paddies. Chinese J. Eco-Agric. 27(8): 1157-1162.

McLaughlin D, Kinzelbach W (2015). Food security and sustainable resource management. Water Resource Res. 51(7): 4966-4985.

Min JS, Kong XZ (2016). Research progress of non-point source pollution of agriculture in China. J. Huazhong Agric. University (Soc. Sci. Ed.) 2: 59-66.

Mofidian S, Sadeghi SM (2015). Evaluation of Integrated Farming of Rice and Duck on Rice Grain Yield in Gilan, Iran. Acta Univ. Agric. Silvic. Mendelianae Brun. 63(4): 1161-1168.

Mohanty RK, Thakur AK, Ghosh S, Patil DU (2010). Impact of rice-fish-prawn culture on rice field ecology and productivity. Indian J. Agricu. Sci. 80(6): 597-602.

Morone P, Koutinas A, Gathergood N, Arshadi M, Matharu A (2019). Food waste: Challenges and opportunities for enhancing the emerging bio-economy. J. Clean. Prod. 221: 10-16.

Nayak PK, Nayak AK, Panda BB, Lal B, Gautam P, Poonam A, Shahid M, Tripathi R, Kumar U, Mohapatra SD, Jambhulkar NN (2018). Ecological mechanism and diversity in rice based integrated farming system. Ecol. Indic.: Integrating, Monitoring, Assessment, Manag. 91: 359-375.

Nhan DK, Phong LT, Verdegem MJ, Duong LT, Bosma RH, Little DC (2007). Integrated freshwater aquaculture, crop and livestock production in the Mekong delta, Vietnam: determinants and the role of the pond. Agric. Syst. 94(2): 445-458.

Peng TS (2012). Technical measures for high yield of raising fishes in paddy fields. J. Rural Anim-Breed. Technol. (Aquac.). 8: 42-43 (in Chinese).

Pinstrup-Andersen P (1999). Towards ecologically sustainable world food production. Ind. Environ. 22(2-3): 10-13.

Reddy PP (2016). Integrated Crop–Livestock Farming Systems. In: Sustainable Intensification of Crop Production. Springer, Singapore. Pp 357-370.

Saiful Islam AHM (2016). Integrated Rice-Fish Farming System in Bangladesh: An Ex-ante Value Chain Evaluation Framework. In: Gatzweiler F von Braun J. (eds) Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development. Springer, Cham. Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development. Pp 289-322.

Sheng F, Cao CG, Li CF (2018). Integrated rice–duck farming decreases global warming potential and increases net ecosystem economic budget in central China. Environ. Sci. Pollut. Res. 25(23): 22744-22753.

Si GH, Yuan JF, Peng CL, Xia XG, Cheng JP, Xu XY, Jia PA, Xie YY, Zhou JX (2019). Nitrogen and phosphorus circulation characteristics and equilibrium state in rice-shrimp co-culture mode. Chinese Journal of Eco-agriculture 27(9): 1309-1318.

Suh JH (2014a). An institutional and policy framework to foster integrated rice–duck farming in Asian developing countries. Int. J. Agric. Sustain. 13(4): 294-307.

Suh JH (2014b). Theory and reality of integrated rice–duck farming in Asian developing countries: a systematic review and SWOT analysis. Agric. Syst. 125: 74-81.

Technology Extension Main Station of Aquatic Product of Zhejiang Province (2012). Models and technology of paddy fields integration planting and breeding in Zhejiang Province. China Aquatic Prod 3: 47-48 (in Chinese).

Teng Q, Hu XF, Cheng C, Luo ZQ, Luo F, Xue Y, Jiang YJ, Mu Z, Liu LM, Yang MY (2016). Ecological effects of rice–duck integrated farming on soil fertility and weed and pest control. J. Soils Sediments. 16(10): 2395-2407.

Tsuruta T, Yamaguchi M, Abe S, Iguchi K (2011). Effect of fish in rice-fish culture on the rice yield. Fish. Sci. 77(1): 95-106.

Wang JX, Li Y, Wang XD, Wang YC (2017). Present situation and forecast of pesticide application in China. Agriculture Outlook of AO 2: 1-5.

Wang QS, Huang PS, Zhen RH, Jing LM, Tang HB, Zhang CY (2004). Effect of rice–duck mutualism on nutrition ecology of paddy field and rice quality. Chin. J. Appl. Ecol. 15(4): 639-645.

Wang SL (2004). Rice, fishes, frogs and shrimps intergrowth, feeding the frogs with shrimps for increasing benefits. Handbook of Becoming Rich by Fishery (in Chinese).

Xu GC, Liu X, Wang QS, Yu XC, Hang YH (2017). Integrated rice–duck farming mitigates the global warming potential in rice season. Sci. Total Environ. 575: 58-66.

Xu M, Ma XZ, Wang W (2014). Effects of different cultivation patterns on rice yield and crab in rice-crab culture system. Scientia Agricultura Sinica. 47(9): 1828-1835.

Yang HS, Yu DG, Zhou JJ, Zhai SL, Bian XM, Weih M (2018). Rice–duck co-culture for reducing negative impacts of biogas slurry application in rice production systems. J. Environ. Manag. 213: 142-150.

Yu SM, Jin QY (editor-in chief) (2006). New technique of rice–duck mutualism. China agricultural science & technology publishing house, Beijing, first edition, August. Pp 34-35.

Yu SM, Jin QY, Ouyang YN, Xu DH (2004b). Efficiency of controlling weeds, insect pests and diseases by raising ducks in the paddy fields. Chin. J. Biol. Control. 2: 99-102 (in Chinese with English abstract).

Yu SM, Ouyang YN, Zhang QY, Peng G, Xu DH, Jin QY (2005). Effects of rice–duck farming system on Oryza sativa growth and its yield. Chin. J. Appl. Ecol. 16(7): 1252-1256.

Yu SM, Jin QY, Ouyang YN, Zhang QY, Xu DH, Shi SJ (2004a). The key technology and its characteristic of pollution-free of rice–duck mutualism. Agric. Environ. Dev. 6(8-9): l5 (in Chinese).

Yu SM, Jin QY, Zhu LF, Ouyang YN, Xu DH (2008). Effect on rice yield and economic benefits of duck numbers in paddy fields. Zhejiang Agric. Sci. 1: 68-71 (in Chinese).

Zhang JA, Ouyang Y, Huang ZX (2008). Characterization of Nitrous Oxide（N2O）Emission from a Rice–duck Farming System in South China. Arch. Environ. Contam. Toxicol. Arch. Environ. Contam. Toxicol. 54(2): 167-172

Zhang JE, Lu JX, Zhang GH, Luo SM (2002). Study on the function and benefit of rice–duck agro-ecosystem. Ecol. Sci. 21(1): 6-10. (in Chinese with English abstract).

Zhang J, Hu LL, Ren WZ, Guo L, Tang JJ, Shu MA, Chen X, (2016). Rice-soft shell turtle co-culture effects on yield and its environment. Agriculture, Ecosystems & Environment: Int. J. Sci. Res. Rel. Agric. Food Prod. Biosph. 224: 116-122.

Zhang S, Zhang QL, Chen XS, Jia ZB, Shangguan QH, Lü L, Chang XQ, Yang XL, Chen QZ (2009c). Effects of different cultivation model on the major rice diseases and insect pests occurrence. J. Huazhong Agric. Univ. 4: 426-430 (in Chinese with English abstract).

Zheng HB, Huang H, Chen C, Fu ZQ, Xu HQ, Tan SD, She W, Liao XL, Tang JW (2017). Traditional symbiotic farming technology in China promotes the sustainability of a flooded rice production system. Sustain. Sci. 12(1): 155-161.

Zheng HB, Huang H，Li DQ, Li XM, Fu ZQ, Chen C (2014). Assessment of nomadic rice–duck comple ecosystem on energy and economy. Ecol. Proc. 3: 20.

Zhou YY, Zhang S (2011). Raising fishes in the paddy fields. New Agric. 6: 52–53 (in Chinese).

Zhu BQ (2000). Culturing Rana grylio for pest control in paddy field. Chin. J. Biol. Control. 4: 186-187. (in Chinese with English abstract).