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Rice-soft shell turtle coculture effects on yield and its environment

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ABSTRACT

Although traditional rice-fish farming (involving extensive aquaculture and low fish yields) can supply food and protect the environment, the economic viability and environmental effects are unknown for intensive rice-aquaculture systems that use high quantities of feed to produce high fish yields. Here, we studied an intensive, soft-shelled turtle (*Pelodiscus sinensis*) farm to determine whether an intensive rice-turtle system can produce high yields of turtle and rice without negatively affecting water and soil quality. Using a 6-year field survey and a 2-year field experiment, we compared the three production systems: rice monoculture (RM), rice-turtle coculture (RT), and turtle monoculture (TM). The field survey indicated that turtle yield did not significantly differ between RT and TM, and that rice yield did not significantly differ between RM and RT. The field survey also showed that soil nitrogen (N) and phosphorus (P) were increased in TM but not in RT even though the same quantities of N and P were applied to TM and RT. In the field experiment, yields were similar for rice in RT vs. RM and were similar for turtles in RT vs. TM. Levels of N and P in field water were significantly higher in TM than in RT or RM. At the end of the field experiment, N and P levels in soil had significantly increased in TM but not in RM or RT. Only 20.4% of feed-N and 22.8% of feed-P were used by turtles in TM, resulting in large quantities of feed-N and feed-P remaining in the environment. In RT, however, some of the feed-N and -P that was unused by turtles was taken up by the rice plants. The results suggest that integrating intensive turtle aquaculture with rice culture can result in high yields and low environmental impacts.

1. Introduction

Because overfishing, pollution, coastal development, and climate change are threatening global marine biodiversity and fish stocks (Garcia and Rosenberg, 2010; Pauly et al., 2002), the farming of aquatic organisms, i.e., aquaculture, is considered a viable way to meet the human demand for aquatic products (Cressey, 2009; Costello et al., 2012; Naylor et al., 2000). Marine and freshwater aquaculture provides nearly 50% of the world's supply of seafood and 13% of the world's animal-source protein (excluding eggs and dairy) (Bush et al., 2013). Freshwater aquaculture that raises fish and other freshwater animals in ponds, lakes, canals, cages, or tanks is becoming a major part of aquaculture because of the increased cost and pollution in marine aquaculture (Troell et al., 2014). Freshwater aquaculture, however, requires large quantities of water that are also needed for irrigation, drinking, household use and industrial use (Foley et al., 2011; Liu and Yang, 2012). In addition, new suitable land is limited, and intensive, high-yield freshwater aquaculture has generated environmental concerns (e.g., water pollution and the spread of disease) (Cao et al., 2007; Li et al., 2011a,b). Thus, new aquaculture approaches are required to meet the increasing need for aquatic protein.

Rice fields can provide a suitable environment for a wide range of aquatic animals, such as freshwater prawns, shrimp, crabs, and turtles (Fernando, 1993; Halwart, 2006). The culturing of fish with rice in paddy fields is a traditional practice in China and many other Asian countries (Halwart and Gupta, 2004; Ruddle, 1982; You, 2006). By efficiently using the same land resources to concurrently or serially produce both carbohydrate and animal protein, rice–fish farming has substantial potential for securing food supplies and alleviating poverty in rural areas (Ahmed and Garnett, 2011; Halwart and Gupta, 2004; Xie et al., 2011). It can also help conserve the environment. In rice–fish farming, the use of pesticides can be reduced or even eliminated (Berg, 2002; Dwiyana and Mendoza, 2008) because fish reduce weeds (by consuming or uprooting them) and consume some insect pests (Frei et al., 2007; Vromant et al., 2002b; Vromant et al., 2003; Xie et al., 2011). Raising fish in rice fields can also reduce fertilizer requirements for rice because

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rice plants can use the unconsumed fish feed and because fish feces can serve as organic fertilizers (Frei and Becker, 2005a; Oehme et al., 2007). In addition, rice–fish farming can reduce some problems generated by freshwater aquaculture. For example, nutrients in the effluents generating by the raising of fish can be absorbed by rice plants, which reduces a potential source of pollution (Hu et al., 2013; Ding et al., 2013). Thus, integrating rice culture with aquaculture can result in an efficient use of resources and a cleaner and more healthful rural environment.

In recent decades, rice culture integrated with aquaculture (e.g., rice–carp, rice–crab, and rice–prawn) has developed rapidly in China and other Asian countries. As of 2012, the area of rice-field aquaculture in China had increased to 2.23 Mha (Fishery Bureau of China's Ministry of Agriculture, 2013). In Bangladesh, rice-field aquaculture has been established as a national strategy for food security, poverty alleviation, and resource conservation (Ahmed and Garnett, 2011; Ahmed et al., 2014; Dey et al., 2013; Haque et al., 2014). Indonesia has also recently set a national target of allocating 1 million ha for rice–fish farming. In India, the organic farming of rice and giant river prawns as rotational crops is part of the Indian Organic Aquaculture Project (Nair et al., 2014).

The Chinese soft-shelled turtle *Pelodiscus sinensis* is an aquatic animal of great economic value because of its high protein content and medicinal uses (Chen et al., 2009; Shi et al., 2008). In China, this turtle has recently been cultured widely in an industrial manner (Shi et al., 2008; van Dijk, 2000), and soft-shelled turtle production reached 0.33Mt in 2012 (Fishery Bureau of China's Ministry of Agriculture, 2013). The rapid increase in soft-shelled turtle production has been the consequence of intensive farming operations that include high animal densities, massive feed inputs, and substantial inputs of chemicals. These intensive farming operations have resulted in environmental damage and the spread of disease (He and Hu, 2012; Wu et al., 2014; Xu, 2000). For example, Cai et al. (2013) reported that among the effluents generated by various kinds of aquaculture, turtle culture effluents contained the largest concentrations of pollutants (total nitrogen, total phosphorous, chemical oxygen demand, and total suspended solids).

To reduce these problems, the Ministry of Agriculture of the People's Republic of China has encouraged turtle farmers to transform turtle monocultures into rice–turtle cocultures. Since 2005, rice–turtle coculture on large-scale commercial farms has been expanding in southern China (Li et al., 2011a,b). Unlike the traditional rice-fish systems that use low quantities of feed and small field areas for fish and that do not negatively affect rice yield or the environment (Halwart and Gupta, 2004; Xie et al., 2011), the large-scale commercial rice-turtle farms are intensive operations that use relatively high quantities of commercial feed to achieve high turtle yield and significant farmer profits (Li et al., 2011a,b; Hu et al., 2015). However, it is unknown whether the rice or turtle yield can be maintained at the levels of rice monoculture or turtle monoculture and whether the pollution generated by turtle monoculture can be avoided at these large-scale and commercial rice–turtle coculture farms.

We therefore conducted a 6-year field survey and a 2-year field experiment to determine whether the integrated culturing of turtles with rice can achieve high yields of turtle and rice without negatively affecting water quality or the soil environment.

2. Materials and methods

2.1. Study site and rice-turtle system

We conducted this study at a large farm managed by an agricultural company (Qingxi Soft-Shelled Turtle Company) located in Deqing County, Zhejiang Province, China (30°33′N, 119°32′E). An adjacent rice farm that was managed by the same company was also used as described in the next section. The area is flat, and the principal crop is rice, which is grown from May to November. The climate is subtropical monsoon with a mean annual air temperature of 14°C and a mean annual precipitation of 1379 mm.

The large turtle farm was started in 1994, when a 300-ha section of a rice field was modified by constructing an 80-cm high concrete ridge around the border; the area within the ridge was used for raising turtles in the summer and was planted with wheat or vegetable crops in the winter. Since 2010, about 200 ha of the turtle farm was modified for the coculture of turtles and rice. The turtle is a common variety, named Qing-Xi, of the indigenous species *P. sinensis*. In this rice-turtle coculture system, the turtles are retained in the rice field all year, but they are temporarily driven to a refuge in the middle of the field when rice is transplanted (in June) and harvested (in November). The refuge area represents about 10% of the total field area.

2.2. Field survey

2.2.1. Field selection

To compare turtle yields in turtle monoculture (TM) and rice-turtle coculture (RT), and to compare rice yields in rice monoculture (RM) and RT, we conducted a 6-year (2010–2015) field survey of the turtle farm, where TM and RT were practiced, and in a nearby rice farm where only RM was practiced. The turtle and rice farms are located the same village and have similar climates and soil types. We randomly selected six fields of TM and six fields of RT (about 1.2 ha per field) within the turtle farm, and six fields of RM (about 1.2 ha per field) within the rice farm. The first year of RT culture in the six RT fields was 2010; these were TM fields before 2010.

The rice variety cultured in RM and RT fields was Qing-Xi No. 8. Each TM and RT field had the same initial population density of turtles, which was 6000 ha^{-1}. Young turtles (150 g each) were added to TM and RT fields after rice was transplanted in spring. The turtles were harvested in early November when rice was harvested.

2.2.2. Application of nitrogen (N), phosphorus (P), and pesticides

Without influencing normal field operations, we recorded the applications of fertilizers, pesticides, and feeds during the rice growing season. The quantities of fertilizer-N and -P or feed-N and -P were recording as kg of N or P per ha per year. The total application of pesticides was expressed as kg of active ingredient (a.i.) per ha per year.

2.2.3. Measurement of rice grain and turtle yields

Each year, yields were determined from all surveyed fields when the farmer harvested turtles from entire TM fields and turtles and rice from entire RT fields. Rice yield was measured as air-dried weight, and turtle yield was measured as fresh weight. Rice and turtle yields are expressed as ton ha^{-1}. The turtle yield was determined in accordance with the approved guidelines of the Zhejiang University Experimental Animal Management Committee.

2.2.4. Measurement of soil organic matter, N, and P

After rice was harvested in 2010 (the beginning of the field survey), 2012, and 2015, soil samples (0–15 cm) were collected from each surveyed field. Soil samples were air-dried and digested by the K_2SO_4-$CuSO_4$-Se method. N and P contents were analyzed with a San^{++} Continuous Flow Analyzer (Skalar, Netherlands) (Lu, 1999).

2.2.5. Statistical analysis

The general linear model (GLM) in SPSS (V.20.0) was used to perform two-way ANOVAs with year as a random factor, culture type (RM, RT, or TM) as a fixed factor, and rice yields, turtle yields, total-N applied, and total-P applied as dependent variables. For rice yield, the analysis concerned RM vs. RT. For turtle yield, the analysis concerned TM vs. RT. One-way ANOVA was used to assess changes in soil N and P with year as a fixed factor. Before the analysis, data were log-transformed to meet assumptions of normality and homogeneity.

2.3. Field experiment

2.3.1. Experimental design

We conducted a 2-year field experiment (2013–2014) to further assess rice and turtle yields, total N and P in field water and soil, and the balance of N and P in the three culture systems. The field for experiment was the rice monoculture field. The experiment had a randomized block design with three treatments and four replications or blocks. The three treatments were (1) rice monoculture (RM), (2) rice-turtle coculture (RT), and (3) turtle monoculture (TM). Each of the 12 plots (8 m × 10 m per plot) was separated by concrete ridges, and each had an independent water inlet and outlet. The three treatments were randomly assigned to the plots in the blocks.

Four weeks after germination, rice seedlings were transplanted into the RT and RM plots, with 30 cm between rows and 30 cm between hills (four seedlings per hill) within the rows. In RT and TM plots, the turtle population density was 6000 ha^{-1}, which is the standard density used in rice–turtle coculture farms in the area. Young turtles (150 g each) were added 5 days after rice was transplanted in RM and RT plots. All plots were irrigated at the time of transplanting and were then permanently flooded to 30–50 cm depth until harvest. No pesticide was applied for rice in either RM or RT plots. No fertilizer was used in RT plots, but 217.5 kg ha^{-1} of N and 67.5 kg ha^{-1} of P were applied for rice in RM plots. Turtles were fed with a formula feed containing 7.88% N and 2.26% P twice per day at about 07:00 and 17:00 throughout the experiment. The daily amount of turtle feed added was about 1.5% (0.5% at 7:00 and 1% at 17:00) of the turtle fresh body mass per plot, and this amount of course increased as the turtles grew. The same quantity of feed was added to RT and TM plots. By the end of the experiment, a total of 3.07 ton ha^{-1} of feed had been applied to the RT and TM plots. This mixed fish feed contained 7.88% N and 2.26% P, and thus the feed-N and feed-P inputs (totals for both years) were 242.31 kg $ha^{-1}$and 69.49 kg ha^{-1}, respectively, for RT and TM plots. In both years, the experiment was terminated 116 days after rice was transplanted.

2.3.2. Measurement of N and P in field water

At 30, 45, and 90 days after rice was transplanted in the second year of the experiment (2014), water samples were collected from the inlet, middle, and outlet of each plot. Water was collected at 09:00 with a 2-L water sampler. Water samples were passed through a 0.064-mm net to remove phytoplankton, zooplankton, and particulate organic matter. Total N was determined by alkaline potassium persulfate oxidation digestion and UV spectrophotometry, and total P was determined by potassium persulfate oxidation digestion and ammonium molybdate spectrophotometry (Fu and Zhang, 2013).

2.3.3. Determination of rice and turtle yields

Rice grain and straw, and gross turtle yields were determined by harvesting the rice and turtles from entire plots. Grain and straw yields were expressed as tons of air-dried grain or straw per ha. Gross turtle yield was expressed as tons of fresh turtle biomass per ha. Net turtle yield was calculated by subtracting mass before stocking from the total mass at harvest. Turtle yield was determined in accordance with the approved guidelines of the Zhejiang University Experimental Animal Management Committee.

2.3.4. Measurement of N and P in soil

At the start and at the end of the experiment, five surface soil samples (0–15 cm) were collected from each plot and combined to provide one soil sample per plot. Soil samples were air-dried. Soil N and P were analyzed as described in the field survey.

2.3.5. Estimations of N and P balances

Before rice and turtles were harvested in the second year of the experiment, five hills of rice and five turtles were randomly collected from each plot. Rice grain and straw were separated. Feed samples were collected during the application of turtle feed. Samples of rice grain, straw, turtles, and turtle feed were oven-dried at 65 °C and then ground. All samples were digested using the K_2SO_4-$CuSO_4$-Se method, and the total N and P were analyzed using a San^{++} Continuous Flow Analyzer (Skalar, Netherlands) (Lu, 1999).

Output of N or P in each harvest fraction was determined by multiplying the concentrations of N or P in the rice and turtle samples by dry biomass. The total quantities of N or P in harvested fractions (the output quantities) were subtracted from the input quantities (the N or P applied in turtle feed and rice fertilizer). A positive value following subtraction indicated that some portion of input N or P was not used by rice or turtles but had either remained in the plot (in soil, water, or other organisms) or had moved into the surrounding environment via volatilization, leaching, or drainage. A negative value following subtraction indicated that in addition to containing N or P applied in turtle feed or rice fertilizer, harvest fractions contained N or P from indigenous sources, i.e., from the soil, irrigation water, biological nitrogen fixation, or rain deposition. We did not attempt to identify these indigenous sources because we were primarily concerned with the net balance of N and P in the plots. We assumed that the effects of indigenous sources of N and P were similar across the plots.

2.3.6. Statistical analysis

Total N and P concentrations in field water were compared among the three treatments (RM, RT, and TM) with repeated measures (sampling several times in a year) ANOVA. Data for rice grain yield, rice straw yield, total turtle yield, and net turtle yield were subjected to two-way ANOVAs with year as a random factor and treatment (RM, RT, or TM) as a fixed factor. For rice grain and straw yields, the comparison concerned RM vs. RT. For gross and net turtle yields, the comparison concerned TM vs. RT.

Paired *t*-tests were used to compare total N and P in soil at the start vs. the end of the field experiment; this was done separately for each treatment (RM, RT, and TM). Data for N and P in harvested fractions (rice grain, rice straw, turtle, and environment) were subjected to one-way ANOVAs using the general linear model (GLM) in SPSS (V.20.0). All data were log-transformed to meet the assumptions of normality and homogeneity before analysis. Means among the three treatments were compared by LSD at the 5% confidence level.

3. Results

3.1. Field survey

3.1.1. Rice yields, turtle yields, and pesticide use

In the 6-year field survey, turtle yield was not lower ($F = 0.23$, $P = 0.651$) in rice–turtle coculture (RT) than in turtle monoculture (TM) (Fig. 1a). Rice yield also was not lower ($P > 0.05$) in RT than in

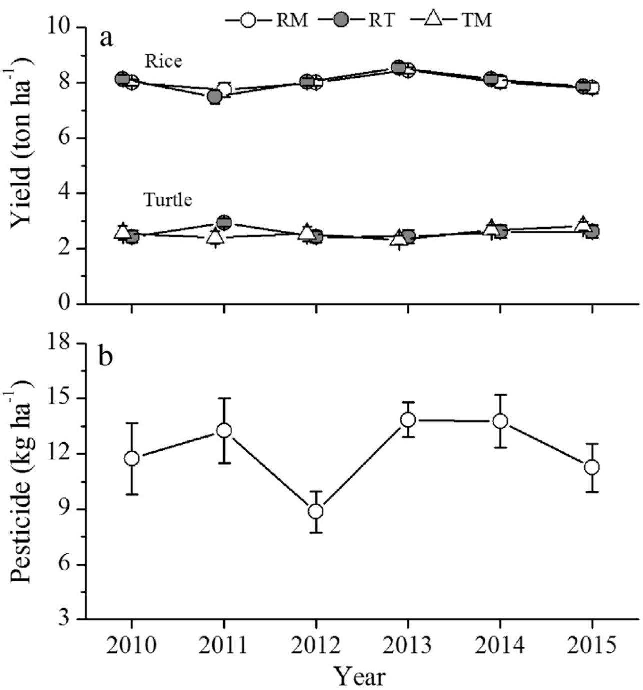

Fig. 1. Rice and turtle yields (a) and pesticide use (b) in a 6-year field survey of rice monoculture (RM), rice-turtle coculture (RT), and turtle monoculture (TM) in China. The turtle is *Pelodiscus sinensis*. Values are means ± S.E.

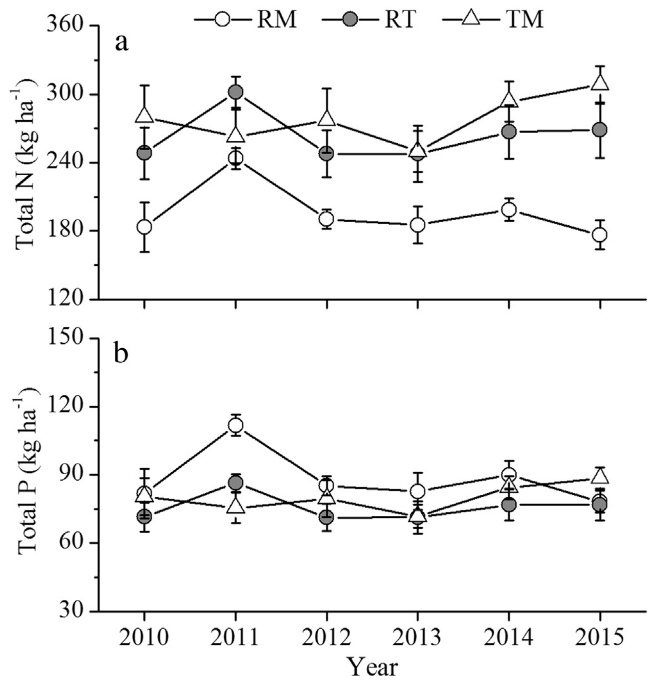

Fig. 2. Total nitrogen input (a) and total phosphorous input (b) in a 6-year field survey of rice monoculture (RM), rice-turtle coculture (RT), and turtle monoculture (TM) in China. The turtle is *Pelodiscus sinensis*. Values are means ± SE.

rice monoculture (RM) (Fig. 1a). For RT, no pesticide was applied for rice pest control, but the average yearly input of pesticides in RM was 12.12 a.i. kg ha^{-1}(Fig. 1b).

3.1.2. Input of N and P

In the farms surveyed, fertilizers were the sources of N and P for rice in RM, and turtle feed was the only source of N and P in RT and TM. No fertilizers were applied to RT and TM fields during the study. The total amount of N input significantly differed ($F = 25.288$, $P = 0.001$) among RM, RT, and TM fields (Fig. 2a). Nitrogen input was significantly higher ($P < 0.05$) in RT and TM than in RM fields, but did not differ ($P > 0.05$) between RT and TM fields. Total P did not significantly differ ($F = 1.153$, $P > 0.05$) among RM, RT, and TM fields (Fig. 2b).

3.1.3. Soil N and P

Soil N and P significantly declined ($P < 0.05$) 2 years after the TM system had been changed into an RT system, but soil N and P in TM fields remained at the same level ($P > 0.05$) (Fig. 3). At the end of the survey (2015), soil N and P did not significantly differ between RM and RT fields ($P > 0.05$), but soil N and P were significantly higher ($P < 0.05$) in TM than in RM or RT fields (Fig. 3).

3.2. Field experiment

3.2.1. Rice and turtle yields

Rice grain yield did not significantly differ between RT and RM ($F = 0.517$, $P = 0.504$, Table 1), but rice straw yield was significantly greater in RT than in RM ($F = 11.358$, $P = 0.02$, Table 1). Gross and net yields also did not differ between RT and TM plots (for gross yield, $F = 3.625$, $P = 0.106$; for net yield, $F = 3.024$, $P = 0.115$) (Table 1).

3.2.2. N and P in field water

Both total N and P in field water significantly differed among the culture systems (for total N, $F = 7.411$, $P = 0.013$; for total P, $F = 4.838$, $P = 0.042$). Total N and P in field water was significantly greater ($P > 0.05$) in TM than in RM or RT plots but did not significantly differ ($P > 0.05$) between RM and RT plots (Fig. 4).

3.2.3. Changes in soil N and P

Total soil N did not significantly change ($P > 0.05$) during the field experiment (start values vs. end values) in RM or RT plots but significantly increased ($P < 0.05$) in TM plots (Fig. 5a). Total P in soil

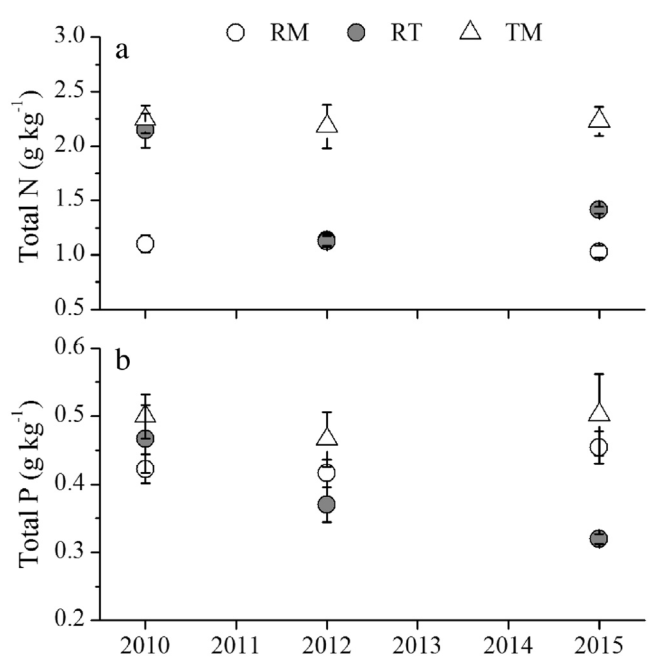

Fig. 3. Soil nitrogen (a) and soil phosphorous (b) in a 6-year field survey of rice monoculture (RM), rice-turtle coculture (RT), and turtle monoculture (TM) in China. The turtle is *Pelodiscus sinensis*. Values are means ± SE.

Table 1
Turtle and rice yields in a 2-year field experiment with rice monoculture (RM), rice-turtle coculture (RT), and turtle monoculture (TM) in China. The turtle is *Pelodiscus sinensis*.

	Treatment		
Yields	RM	RT	TM
Rice (ton ha^{-1})			
Grain yield	7.67 ± 0.15^a	7.46 ± 0.26^a	
Straw yield	4.67 ± 0.04^b	4.98 ± 0.09^a	
Turtle (ton ha^{-1})			
Gross yield		1.56 ± 0.01^a	1.48 ± 0.03^a
Net yield		1.15 ± 0.01^a	1.09 ± 0.03^a

Values are means ± SE ($n = 4$). Means in a row followed by different letters are significantly different ($P < 0.05$).

significantly increased ($P < 0.05$) in RM and TM plots but did not change ($P > 0.05$) in RT plots (Fig. 5b).

3.2.4. Balance of N and P

N and P in rice grains did not significantly differ between RM and RT plots (for grain-N, $F = 0.452$, $P = 0.769$; for grain-P, $F = 0.517$, $P = 0.504$) (Fig. 6). However, N and P in straw were significantly greater in RT than in RM plots (for straw-N, $F = 11.358$, $P = 0.010$; for straw-P, $F = 11.358$, $P = 0.020$) (Fig. 6). N and P in turtles (based on net yield) did not significantly differ between TM and RT plots (for turtle-N, $F = 3.626$, $P = 0.106$; for turtle-P $F = 3.625$, $P = 0.106$) (Fig. 6). Apparent N and P remaining in the environment (total input minus total output) significantly differed among the three treatments (for environmental-N, $F = 788.512$, $P = 0.000$; for environmental-P, $F = 1673$, $P = 0.000$). According to calculations, 79.6% of feed-N and 77.2% of feed-P were lost to the environment in TM plots, whereas no feed-N was lost to the environment and only 25.6% of feed-P was lost to the environment in RT plots (Fig. 6). For RM, no input fertilizer-N was lost, but 47.5% of fertilizer-P was lost to the environment (Fig. 6).

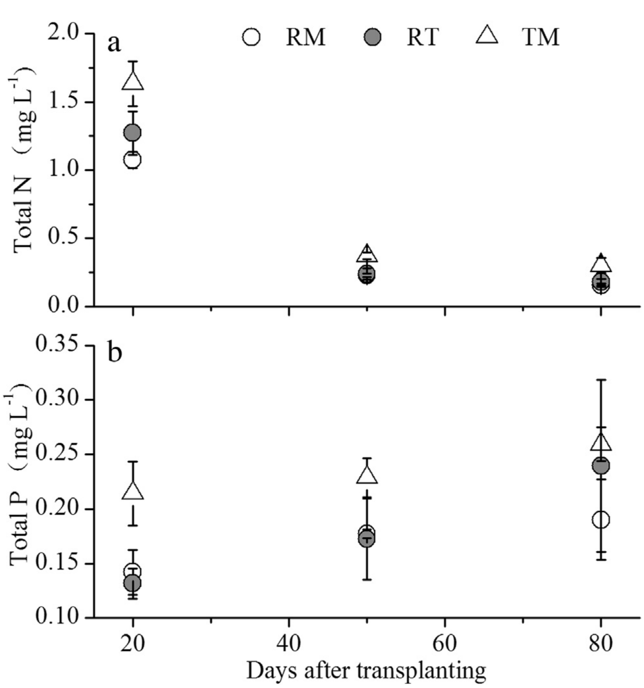

Fig. 4. Total nitrogen (a) and total phosphorous (b) in field water during the growing season in a field experiment in China. RM: rice monoculture, RT: rice-turtle coculture; TM: turtle monoculture. The turtle is *Pelodiscus sinensis*. Values are means ± SE.

4. Discussion

Our field survey and field experiment showed that turtle yield did not decrease relative to turtle monoculture when turtles were cocultured with rice. Moreover, coculture produced 8.3 ± 0.17 t ha^{-1} of rice each year (Fig. 1a). Turtle yield may not have decreased in coculture with rice because rice plants may improve the environment for turtles. The shading provided by rice plants, for example, can reduce the water temperature and light intensity at the water surface (Xie et al., 2011), which could lower thermal stress and thus greatly benefit turtles on hot summer days. Rice plants can also improve the water quality for turtles by reducing N and P concentrations (Fig. 4). Decreased ammonia levels might also reduce toxic stress to turtles (Rangel-Mendoza et al., 2014). Although ammonia-N levels in water were not measured in the current study, a previous study found that ammonia levels were significantly lower in fish coculture with rice rather than in fish monoculture (Xie et al., 2011).

The field survey and field experiment also showed that rice grain yield was not lower in rice–turtle coculture than in rice monoculture, even though no chemical fertilizer or pesticide was applied to plots with rice–turtle co-culture (Figs. 1 and 2). Some researchers have argued that integrating rice culture with aquaculture may reduce rice yield because some field space is required for animal refuges (Lightfoot et al., 1992). Some studies reported that integrating aquaculture in rice fields did reduce rice yield (Rothuis et al., 1998; Dwiyana and Mendoza, 2008). In many other studies, however, the culturing of fish with rice did not significantly decrease rice yield and even increased riceyield (Vromant et al., 2002a; Mohantyet al., 2004; Frei and Becker, 2005b; You, 2006; Wu et al., 2010; Hu et al., 2013; Ren et al., 2014; Tsuruta et al., 2011). In an experiment in India, for example, rice yield was 4.9–8.6% greater with rice–fish coculture than with rice monoculture (Mohanty et al., 2004). A meta-analysis by Ren et al. (2014) found that rice–fish farming increased rice yield. Fish farming may increase rice yield because rice plants are healthier in fields with fish than in fields without fish (Vromant et al., 2002a; Mohanty et al., 2004). In the current study, the culturing of turtles with rice did not reduce grain yield and increased straw yield (Table 1), even though 10% of the field was used for turtle refuges.

N and P are the two main pollutants produced by intensive aquaculture (Schneider et al., 2005; Wu et al., 2014). Because feed is incompletely used by aquatic animals, eutrophication usually occurs in intensive aquaculture systems and in the surrounding areas (Abimorad et al., 2009; Lucas et al., 2010; Qin et al., 2007). In our field experiment, only 20.4% of feed-N and 22.8% of feed-P were converted into turtle body mass in turtle monoculture, resulting in large quantities of N and P remaining in the environment (Fig. 6). In our field survey, soil N and P levels were high with turtle monoculture (Fig. 3), even though sludge was removed every 2 years.

In the rice-aquaculture system, however, N and P in the unconsumed feed can be used by rice plants (Xie et al., 2011; Hu et al., 2013). Besides producing fecal matter, turtles excrete excess N in the form of ammonia and urea that can be directly used by rice (Ip et al., 2012; Lee et al., 2007). This use of N and P by rice plants may result in low N and P accumulation in the environment. Our field survey showed that levels of soil N and P were significantly lower with rice–turtle coculture than with turtle monoculture (Fig. 3). Our field experiment also showed that levels of N and P in field water and soil were significantly lower with rice–turtle coculture than with turtle monoculture (Figs. 4 and 5). Although we cannot determine exactly how much feed-N and -P were used by rice plants in rice–turtle coculture, our calculations in the field experiment indicate that rice plants take up substantial quantities of N and P in the rice–turtle coculture system (Fig. 6). As a

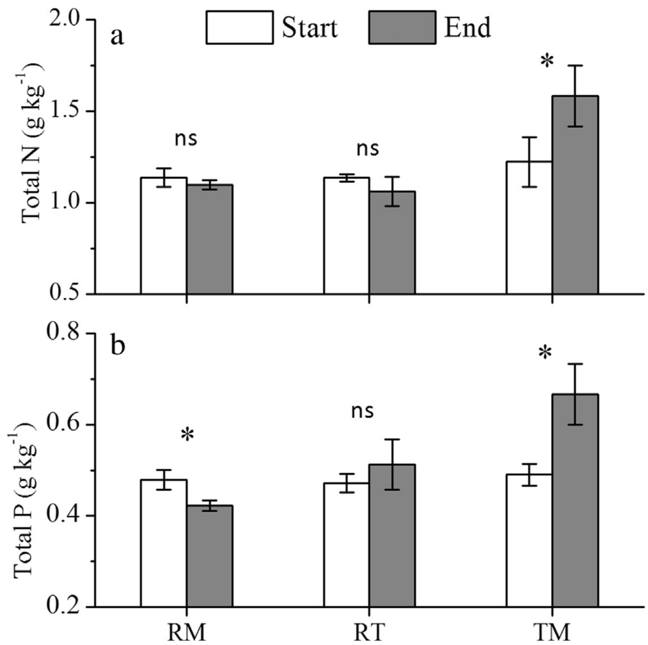

Fig. 5. Soil nitrogen (a) and soil phosphorus (b) at the start vs. the end of the field experiment in China. RM: rice monoculture, RT: rice-turtle coculture, TM: turtle monoculture. The turtle is *Pelodiscus sinensis*. Values are means ± SE. An asterisk (*) indicates a significant difference, and ns indicates no significant difference between values at the start vs. those at the end of the experiment according to paired *t*-tests at $P < 0.05$.

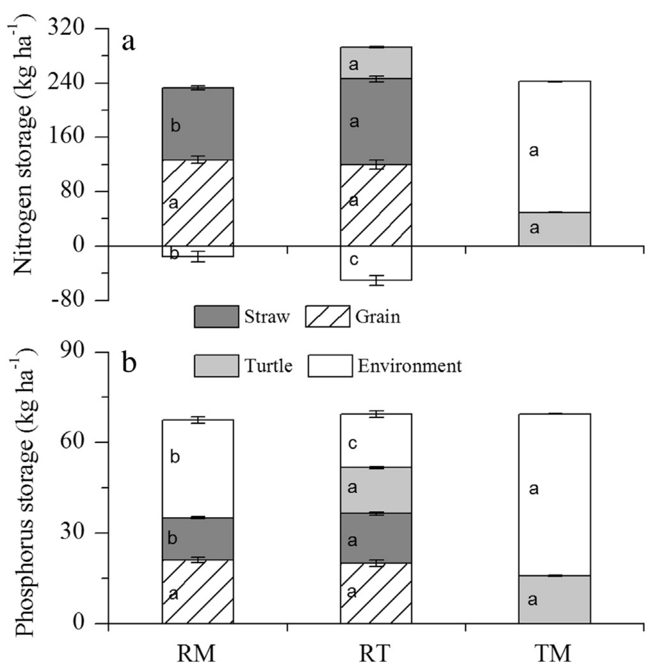

Fig. 6. Nitrogen storage (a) and phosphorus storage (b) in rice grain, rice straw, turtles, and the environment in a field experiment with rice monoculture (RM), rice-turtle coculture (RT), and turtle monoculture (TM) in China. The turtle is *Pelodiscus sinensis*. Values are means ± SE. A negative mean for environmental N indicates that rice and/or turtles, in addition to obtaining N from feed, obtained N from environmental sources. A positive value for environmental N or P indicates that N or P was lost to the environment. Bars with the same shading and pattern but with different letters are significantly different according to the LSD test at $P < 0.05$.

consequence, integrating rice culture with turtle culture can reduce N and P accumulation in field water and soil, and thereby reduce the chance of eutrophication (Hu et al., 2013; Ding et al., 2013).

Freshwater aquaculture is an important source of aquatic protein for humans, especially in inland areas (Cressey, 2009; Garaway et al., 2013). As the global population continues to increase, however, freshwater and land available for aquaculture are becoming scarce. Freshwater aquaculture now faces the challenge of satisfying the demand for aquatic protein despite scarce water and land resources. Although intensive freshwater aquaculture can greatly increase aquaculture yields, it generates environmental problems (Broughton and Walker, 2010). The results of our study indicate that the intensive culturing of turtles with rice can produce large yields while reducing environmental problems. With the integration of intensive aquaculture and rice production, freshwater aquaculture should be able to expand in spite of limitations in the availability of land and water.

5. Conclusion

Integrating intensive turtle culture with rice culture can produce substantial turtle yields and stable rice yields. Moreover, rice–turtle coculture can reduce the quantities of feed-N and feed-P that accumulate in the environment and can thus reduce the potential for environmental pollution resulting from intensive turtle monoculture.

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