Food Sec.
DOI 10.1007/s12571-011-0113-8

ORIGINAL PAPER

Integrated rice-fish farming in Bangladesh: meeting the challenges of food security

Nesar Ahmed · Stephen T. Garnett

Received: 30 November 2010 / Accepted: 4 January 2011

Abstract In order to meet the soaring demand for food, there is a need to increase rice and fish production in Bangladesh. In spite of the potential for rice-fish farming, rice monoculture remains the main farming system in Bangladesh. However, rice monoculture cannot provide a sustainable food supply without a cost to long-term environmental sustainability. We provide evidence that integrated rice-fish farming can play an important role in increasing food production as the integrated farming system is better than rice monoculture in terms of resource utilization, diversity, productivity, and both the quality and quantity of the food produced. The Cobb-Douglas production function model also suggests that higher yields can be achieved by increasing inputs in the integrated farming system. Integrated rice-fish farming also provides various socioeconomic and environmental benefits. Nevertheless, only a small number of farmers are involved in integrated rice-fish farming due to a lack of technical knowledge, and an aversion to the risks associated with flood and drought. We conclude that integrated rice-fish farming can help Bangladesh keep pace with the current demand for food through rice and fish production but requires greater encouragement if it is to realize its full potential.

N. Ahmed
School of Environmental and Life Sciences,
Charles Darwin University,
Darwin, NT 0909, Australia

S. T. Garnett
Research Institute for Environment and Livelihoods,
Charles Darwin University,
Darwin, NT 0909, Australia

Present Address:
N. Ahmed (✉)
Department of Fisheries Management,
Bangladesh Agricultural University,
Mymensingh 2202, Bangladesh
e-mail: nesar_2000@yahoo.com

Keywords Rice · Fish · Farmer · Integrated farming · Food security · Bangladesh

Introduction

Bangladesh is one of the poorest and most densely populated countries in the world, covering an area of 144,000 km^2 with a population of 164 million. The people of Bangladesh are commonly referred to as '*Macche-Bhate Bangali*' (i.e., the people made of fish and rice). Rice and fish have been an essential part of the life of Bangladeshi people from time immemorial. The staple foods of the people of Bangladesh are rice and fish. Rice is the foremost agricultural crop in Bangladesh with an annual production of over 29 million tons per annum (BRKB 2010), while annual fish production is 2.70 million tons (DoF 2010). The demand for rice and fish is constantly increasing in Bangladesh with nearly three million people being added each year to the population of the country (Chowdhury 2009). Nevertheless, integrated rice-fish farming offers a solution to this problem by contributing to food, income and nutrition. Not only the adequate supply of carbohydrate, but also the supply of animal protein is significant through rice-fish farming. Fish, particularly small fish, are rich in micronutrients and vitamins, and thus human nutrition can be greatly improved through fish consumption (Larsen et al. 2000; Roos et al. 2003).

The total area of rice fields in Bangladesh is about 10.14 million ha with an additional 2.83 million ha of inundated seasonal rice fields where water remains for about 4–6 months (BRKB 2010). The carrying capacities of these lands and waters are not fully utilized, but there exists tremendous scope for increasing fish production by integrating aquacul-

Published online: 20 January 2011

ture (Wahab et al. 2008). Integrated rice-fish production can optimize resource utilization through the complementary use of land and water (Frei and Becker 2005). Integration of fish with rice farming improves diversification, intensification, productivity, profitability, and sustainability (Ahmed et al. 2007; Nhan et al. 2007).

However, rice-fish farming remains marginal in Bangladesh because of socioeconomic, environmental, technological, and institutional constraints (Nabi 2008). Although rice-fish technology has been demonstrated successfully and a considerable number of farmers have been trained through various projects, this integration has yet to be widely practiced. Traditionally wild fish have been harvested from rice fields as many fish species prefer rice fields for reproduction (Li 1988; Fernando 1993; Little et al. 1996). The natural aggregation of fish in rice fields inspired the combination of rice farming with fish to increase productivity (Gurung and Wagle 2005). However, the introduction of high yielding varieties (HYV) of rice and accompanying pesticides reduced fish yields (Gupta et al. 2002).

Many reports suggest that integrated rice-fish farming is ecologically sound because fish improve soil fertility by increasing the availability of nitrogen and phosphorus (Giap et al. 2005; Dugan et al. 2006). The feeding behavior of fish in rice fields causes aeration of the water. Integrated rice-fish farming is also being regarded as an important element of integrated pest management (IPM) in rice crops (Berg 2001; Halwart and Gupta 2004). Fish play a significant role in controlling aquatic weeds and algae that carry diseases, act as hosts for pests and compete with rice for nutrients. Moreover, fish eat flies, snails and insects, and can help to control malaria mosquitoes and water-borne diseases (Matteson 2000). Interactions of fish and rice also help lower production costs because insects and pests are consumed by the fish. On the other hand, rice fields provide fish with planktonic, periphytic and benthic food (Mustow 2002). Shading by rice plants also maintains the water temperature favorable to fish during the summer (Kunda et al. 2008).

The aim of this study is to assess fish farming in rice fields as a competitive alternative to rice monoculture. The hypothesis here is that integrated rice-fish farming can provide socioeconomic benefits to the households of poor farmers, and more broadly play a significant role in contributing to food security of Bangladesh.

Methodology

Study area

The study was undertaken in the Mymensingh district of north-central Bangladesh (Fig. 1). Geographically, Mymensingh has been identified as the most important area for rice-fish farming because of the availability of low-lying rice fields, warm climate and fertile soil. Hydrological conditions are also favorable for rice-fish farming as this area is located within the monsoon tropics with an average annual rainfall of 2,500 mm (FAO 2000). Located just south of the foothills of the Himalayas, where monsoon winds turn east and northeast, the region around Mymensingh receives the second greatest average precipitation in Bangladesh after Sylhet. Moreover, the number of fish hatcheries has risen rapidly in recent years in the Mymensingh area. Within Mymensingh district a small number of farmers (around 100) are involved in rice-fish farming in Phulpur sub-district and received training in rice-fish farming from the Mymensingh Aquaculture Extension Project, funded by Danish International Development Assistance. Phulpur sub-district was therefore selected for the study.

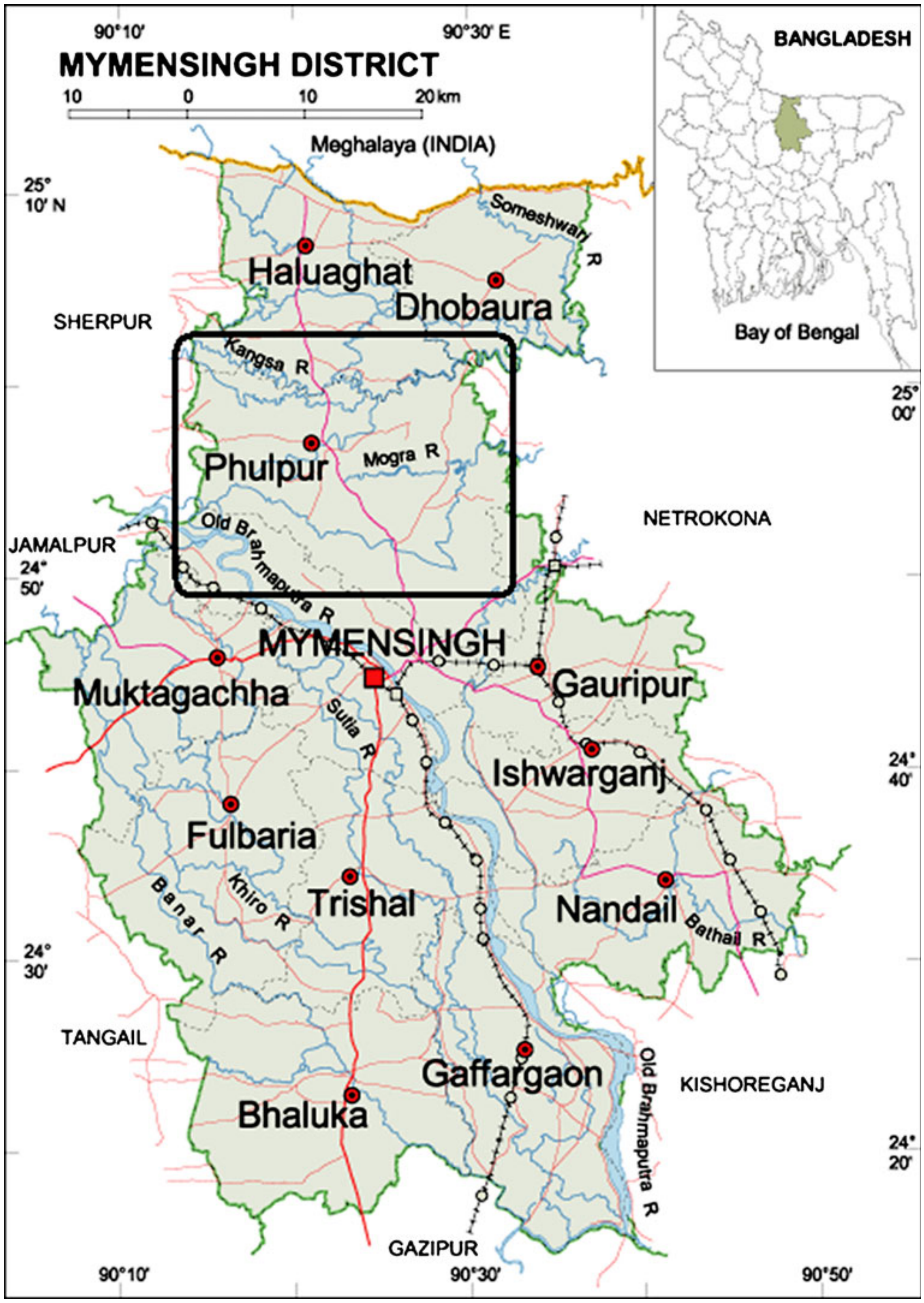
Data collection methods

Field research was conducted for a period of 9 months from September 2007 to May 2008. A combination of participatory, qualitative and quantitative methods was used for primary data collection (Table 1).

Questionnaire interviews with rice-fish farmers were preceded by preparation and testing of the interview schedule, and training of enumerators. The pre-survey activities included reconnaissance for the pilot survey, revision of survey instruments and preparation of the sampling frame. The questionnaire was prepared, following visits to rice-fish farms and interviews with farmers. Farmers were selected for questionnaire interviews through stratified random sampling based on the system they used for rice-fish farming (i.e., alternate and integrated). A total of 80 rice-fish farmers (37 alternate and 43 integrated farmers) were selected for in-depth data collection. The interviews with farmers were conducted in their houses and/or farm sites. The interviews, lasting about an hour, focused on rice-fish farming systems, cultural practices, productivity, production constraints, and socioeconomic benefits including food security. A more focused comparative examination of the two different farming systems was also performed. Several visits were made to selected farmers to observe farming practices.

Questionnaire interviews were also conducted with rice farmers (control group). A total of 172 rice farmers was selected through simple random sampling. Farmers were interviewed in their houses and/or farm sites, each interview lasting about an hour. A semi-structured questionnaire was used for interviews, covering rice farming systems, rice productivity and the identification of bottlenecks that could be encountered in rice-fish farming.

Fig. 1 Map of the study area for fish farming in rice fields



For the validation of collected information, cross-check interviews with key informants were conducted. A key informant is someone with special knowledge on a particular topic. Key informants are expected to be able to answer questions about the knowledge and behavior of others, and about the operations of the broader system. Cross-check interviews were conducted with government fisheries officers, agricultural extension workers, researchers, policymakers, and relevant non-governmental organizations (NGO) workers. Where information was found to be contradictory, further assessments were carried out. A total of 25 key informants was interviewed in their offices and/or while working in the field.

Data from questionnaire interviews were coded and entered into a database system using Microsoft Excel software for analysis using SPSS (Statistical Package for Social Science) to produce descriptive statistics. Results from the data analysis, in combination with qualitative information collected through various data collection methods, were used to describe rice-fish farming systems.

Table 1 Data collection methods and sample size for target groups

Target group	Farming system	Sample size	Data collection method	Information gathered
Rice-fish farmers	Alternate Integrated	37 43	Questionnaire interviews	Rice-fish farming systems, cultural practices, productivity, farming constraints, and socioeconomic benefits
Rice farmers	Rice monoculture	172	Questionnaire interviews	Rice farming systems, rice productivity, and overall constraints to be involved in rice-fish farming
Key informants	–	25	Cross-check interviews	Validation of collected information

Comparisons among different farming systems were made using an ANOVA *F*-test with a 2-tailed $P<0.05$ being taken to indicate that differences were statistically significant.

Production function model

We applied the Cobb-Douglas production function model to assess the production efficiency of rice-fish farming systems. Several studies have used a Cobb-Douglas production function analysis in aquaculture, for example catfish farming in Alabama (Nerrie et al. 1990), seabass and seabream farming in Greece (Karagiannis and Katranidis 2000), rice-fish culture in India (Goswami et al. 2004), and prawn and catfish farming in Bangladesh (Ahmed et al. 2008, 2010a). The Cobb-Douglas production function model has also been used to assess input-output relationships in agricultural productivity, including rice and wheat (Fulginiti and Perrin 1998; Ozsabuncuoglu 1998; Bakhshoodeh and Thomson 2001; Villano and Fleming 2006).

Five inputs[1] or explanatory variables (i.e., rice seed, fish seed, fish feed, fertilizer, and labor) were assumed to explain rice-fish farming by the Cobb-Douglas production function model. We hypothesised that using all five inputs will affect rice and fish production. Regression analysis (ordinary least square method) was used to determine the effect of these inputs. The Cobb-Douglas production function model of the following form was used for the analysis:

$$\text{Log } Y_i = \log a + b_1 \log X_{1i} + b_2 \log X_{2i} + b_3 \log X_{3i} + b_4 \log X_{4i} + b_5 \log X_{5i} + \log U_i$$

Where,

Y	Total food (rice and fish) production (kg/ha/year)
a	Constant parameter in the equation, mathematically interpreted as the intercept
X_1	Rice seed (kg/ha/year)
X_2	Fish stocking (quantity/ha/year)
X_3	Fish feed (kg/ha/year)
X_4	Fertilizer (kg/ha/year)
X_5	Labor (man-day/ha/year)
b_1-b_5	Coefficient of the relevant variables
U_i	Random error or disturbance term
i	Indexed observations (1, 2, 3 ………… n)

[1] According to Swann (1992), inputs in aquaculture can be classified as material inputs (seed, feed and fertilizer) and management input (labor).

Of the five explanatory variables specified in the model, all are within the control of producers. Other independent variables like water depth, water quality, color of water, and soil condition which might have affected production were excluded from the model on the basis of some preliminary estimations. Moreover, the management factor was not included in the model because specification and measurement of the management factor was inappropriate for this study, as the farm operator is both laborer and manager.

Results and discussion

Farming systems: alternate versus integrated

There are two types of rice-fish culture systems in the study area depending on bio-physical conditions. Fish culture in rice fields can be broadly classified as alternate and integrated. In the alternate system, rice and fish are grown rotationally, while they are grown concurrently in the integrated system. In general, integrated culture was practiced on the plain and medium lowlands under rainfed conditions, while alternate farming was performed in deeply flooded lowlands. According to the survey, 54% of farmers were involved in integrated rice-fish farming while the rest (46%) practised alternate farming.

A range of fish species are produced in rice fields, depending on the farming system. Alternate farmers mainly stock Indian major carp and exotic carp. In integrated culture the most common species are common carp, Nile tilapia, silver barb, and silver carp. However, many farmers reported that they avoid common carp because rice plants are uprooted and consumed if rice fields are stocked with common carp within 2 weeks of planting seedlings. In general, farmers do not attempt to stock any specific ratio of different fish species.

Alternate farming involves producing fish in rice fields during the monsoon. Fish fingerlings are stocked in June-July and are harvested primarily from November to December, a culture period of around 5–7 months. Alternate farmers avoid cultivation of monsoon season *aman*[2] rice with fish because of high water levels (up to 1.5 m). It is also thought to reduce fish growth, competing with fish for living space and placing demands on the farmer's limited capital. On the other hand, farmers avoid fish culture with *boro*[3] rice during the dry season from January to April, because of the lower availability of fish fingerlings. Many alternate farmers in deepwater rice fields cannot choose rice-fish integration because of water management problems. However, culture of deepwater rice with fish during the flood season, followed by dry season rice farming can be established in flood-prone rice field ecosystems (Dugan et al. 2006).

In the integrated system, *aman* rice culture takes place either in deep water or water with the rice floating during July–October. Stocking with fish fingerlings occurs in July–August with harvest in November, a culture period of around 4 months. Farmers' stock fish in rice fields 15–20 days after rice has been planted. Integrated farming requires skills and knowledge to grow rice and fish simultaneously. For example HYV rice needs at least 110 days to grow to maturity and a minimum of 1,000 mm water, while fish require a water depth of 150–200 mm. Nevertheless, integrated farmers avoid fish culture with dry season *boro* rice due to a scarcity of water.

Farm size and farming inputs

Size of farm may play an important role as it can reflect the availability of capital, managerial ability, and the potential to operate and use inputs as well as resources efficiently. The highest average farm size was found in integrated farming (0.33 ha), followed by rice monoculture (0.31 ha) and alternate farming (0.29 ha). However, there was no significant difference ($P>0.05$) between farm size and culture system. Integrated farmers had higher cropping intensity (percent of total cropped area against land area) at 193%, compared with 182% in rice monoculture and 177% in alternate farming (the percentage exceeds 100% because areas are harvested more than once each year).

There was a significant difference ($P<0.05$) in fish stocking rates between culture systems. The average annual stocking density of fish fingerlings was reported to be 4,917 per ha in alternate farming and 2,857 per ha in integrated farming. The average size of fingerlings stocked was 6–10 cm in alternate farming and 4–8 cm in integrated farming. Supplementary feed was applied by most farmers, although small-scale fish farming in rice fields is an extensive aquaculture system that primarily relies on the natural food (phytoplankton, zooplankton, periphyton, and benthos). In integrated culture, farmers mainly used on-farm inputs, such as rice bran, wheat bran and mustard oilcake. In addition to on-farm inputs, however, a few alternate farmers (16%) used fishmeal and industrial feed. The most common feeding frequency in alternate farming was once per day, while it was once or twice per week in integrated farming. There was a significant difference ($P<0.05$) in feeding rate between farming systems.

A variety of fertilizers such as urea, triple super phosphate (TSP) and muriate of potash (MP) were used for fish farming in rice fields. The purpose of using fertilizers was to grow natural fish food and improve soil fertility, thereby increasing fish and rice yields. The quantity of fertilizer used was related to the farming system (Table 2). There was a significant difference ($P<0.05$) in fertilization rate among culture systems. Integrated farmers with two rice crops used less fertilizer annually than alternate farmers with one rice crop, because the presence of fish increases soil fertility. Farmers growing only rice used the most fertilizer.

There was a significant difference ($P<0.05$) in labor input among farming systems. According to farmers, integrated rice-fish farming requires a higher labor input to strengthen dikes and excavate refuges. Farmers strengthen dikes to allow water inside the rice field during the monsoon to be deeper and to prevent the escape of stocked fish as well as entry of predatory fish. The refuge can take the form of a ditch or sump in a low-lying part of the rice field, providing fish with sufficient water depth and shelter, to survive during the dry season. Refuges also make fish easier to catch at the end of rice harvesting. Farmers usually converted 5% of the rice fields into a fish refuge although some farmers excavated more (6–10%). However, provision of a refuge was not practiced by many farmers who had small rice fields.

There was an insignificant difference ($P>0.05$) in the amount of *boro* rice seed used in different farming systems. Similarly, there was no significant difference ($P>0.05$) between integrated farming and rice monoculture in the amount of *aman* rice seeds utilized. Although most rice-only farmers produce two rice crops per year, about 10% of those interviewed would aim to produce three crops annually if irrigation facilities were available. However, most respondents thought that three crops would be too labor intensive as labor is required for land preparation,

[2] *Aman* is the main rice crop in Bangladesh, occupying about 53% of total rice area (Hossain et al. 2006). *Aman* rice is planted during the monsoon, beginning in June, and harvested in November-December.

[3] *Boro* rice is mostly transplanted in January and harvested in April.

Table 2 Inputs and outputs of different farming systems in 2007

Input and output	Alternate Mean ± SD	Integrated Mean ± SD	Rice monoculture Mean ± SD	F value	P value
Farm size (ha)	0.29±0.04	0.33±0.07	0.31±0.05	4.06	0.197[ns]
Rice seed (kg/ha/year)					
Boro	183±16	186±15	192±19	5.17	0.162[ns]
Aman	–	191±17	194±16	4.63	0.177[ns]
Fish stocking (fingerlings/ha/year)	4,917±721	2,857±453	–	9.59	0.003[b]
Fish feeding (kg/ha/year)	1,373±217	491±128	–	7.27	0.006[b]
Fertilization (kg/ha/year)					
Urea	211±39	177±38	217±43	9.24	0.021[b]
TSP	179±36	152±42	191±38	11.06	0.014[b]
MP	67±18	38±12	72±15	8.21	0.026[b]
Labor[a] (man–day/ha/year)	179±24	238±31	223±29	14.05	0.008[b]
Rice yield (kg/ha/year)					
Boro	4,986±332	4,917±278	4,989±317	10.47	0.087[ns]
Aman	–	5,261±312	4,702±305	15.38	0.007[b]
Fish yield (kg/ha/year)	1,108±217	259±98	–	9.12	0.021[b]

SD standard deviation

[a] A man-day was considered to be 8 h of work

ns not significant

[b] significant ($P<0.05$)

transplanting, weeding, fertilizing, pesticide spraying, harvesting and threshing of rice, rice drying, storage and marketing. In addition, three crops would incur high production costs and face more risks from flood and drought. Rice farmers were also reluctant to be involved in rice-fish farming because of lack of technical knowledge and water management problems.

Productivity

According to the survey, the highest average annual productivity[4] of rice per hectare was found in integrated farming (10,178 kg), followed by rice monoculture (9,691 kg) and alternate farming (4,986 kg). There was a significant difference ($P<0.05$) in rice yield among farming categories, because of the differences of inputs (seed, fertilizer and labor) and management skills. Table 2 shows that integrated farmers had a higher *aman* rice yield (5,261 kg/ha/year) than for *boro* rice (4,917 kg/ha/year) as the stocking of fish affected the *aman* rice yield positively. In contrast, farmers of rice alone had a lower *aman* rice yield (4,702 kg/ha/year) but slightly more *boro* rice (4,989 kg/ha/year). The highest average *boro* rice yield occurred in rice monoculture as a result of higher rates of fertilization, though differences among culture systems were insignificant ($P>0.05$).

It has been reported that the cultivation of fish in rice fields increases rice yields by 8–15% (Mishra and Mohanty 2004; Mohanty et al. 2004). This study showed that *aman* rice yield in integrated farming is 7% higher than *boro* rice because of the presence of fish. The results also show that *aman* rice yield in integrated farming is 12% higher than rice monoculture. The increase in rice yield was probably because the movement of fish helped to increase dissolved oxygen levels, stirred up soil nutrients, enhanced soil organic matter, and controlled plankton, organic detritus, aquatic insects and plants that compete with rice for nutrients and energy. However, the global average rice yield is lower in Bangladesh (4,000 kg/ha/crop) than in Australia, Egypt, Japan, and southern Europe (10,000 kg/ha/crop), where rice production is highly mechanized and fully irrigated (Frei and Becker 2005). According to Nabi (2008), irrigated rice fields in many parts of Bangladesh could produce three crops a year but irrigation facilities are limited although irrigation is potentially more important than rice-fish farming as an innovative technology.

The average annual yield of fish reported by respondents was 1,108 kg/ha in alternate farming and 259 kg/ha in integrated farming (Table 2). There was a significant difference ($P<0.05$) in fish yield between culture systems, because of the differences in inputs. A number of interdependent factors also affected growth rates and productivity of fish, including environmental factors, stocking and survival rate, the quality and quantity of feed supply, water quality and other aspects of farm management. The size of fish at stocking, the duration of culture, and the size at which the fish were harvested also influenced total yield. Yield of fish was higher under the alternate farming system due to a combination of higher inputs of fingerlings, feed and fertilizer, and a longer culture period. Moreover, alternate farmers stocked larger

[4] Productivity is a ratio between a unit of output and a unit of input. According to Mainuddin and Kirby (2009), three types of productivity can be distinguished: physical productivity, economic productivity and social or environmental productivity.

fingerlings which could have had a positive effect on survival and growth, and thus, also yield. Fish harvested under the alternate farming system were comparatively larger because the culture period was longer.

While rice production was higher in the integrated farming system, fish production in rice fields did not increase to the same extent due to extensive culture. Although alternate farmers produced a higher fish yield than integrated farmers, the productivity was low compared with pond-fish culture systems in Bangladesh, which average 3,500 kg/ha/year (ADB 2005). Besides low inputs and short duration of culture period, the shallow water in rice fields has lower oxygen content and a higher turbidity than water in ponds (Vromant et al. 2002). According to Dey and Prein (2003), annual fish production in rice fields can be increased by 600 kg/ha in shallow flooded areas and 1,500 kg/ha in deep flooded areas through community-based management. Also, Mohanty et al. (2004) observed fish yields of up to 1,026 kg/ha with a stocking density of 15,000 fry in rice fields within 4 months. These reports suggest that higher fish yields in rice fields can be obtained through increased inputs and better management practices.

Production efficiency

Regression analysis of the Cobb-Douglas production function model showed that the coefficient of multiple determinations (R^2) for different farming systems varies from 0.71 to 0.84 (Table 3), which indicates that 71–84% of the total variation in production of rice-fish farms can be explained by the five independent variables included in the model. It also indicates that excluded variables for farm production accounted for 16–29% of the variation. F–values are highly significant, implying that all the included explanatory variables are important for explaining the variation of different farming systems. The selected production functions have sufficient degrees of freedom for testing statistical significance and are stable with respect to the sign of their regression coefficients. All input coefficients had the appropriate positive sign in both alternate and integrated farming systems.

Table 3 Estimated values of coefficients and related statistics of the Cobb-Douglas production function

Explanatory variable	Regression coefficient	
	Alternate farming	Integrated farming
Y-intercept	3.19*** (0.72)	2.85*** (0.67)
Rice seed (X_1)	0.39** (0.14)	0.26*** (0.10)
Fish stock (X_2)	0.32*** (0.11)	0.37** (0.13)
Fish feed (X_3)	0.27** (0.09)	0.34** (0.11)
Fertilizer (X_4)	0.19* (0.08)	0.18* (0.05)
Labor (X_5)	0.24** (0.07)	0.21** (0.06)
Summary statistics		
R^2	0.71	0.84
F value	1,421.32***	1,719.56***
Return to scale Σb_i	1.41	1.36

Single (*), double (**) and triple (***) denote significant at 10%, 5% and 1% levels, respectively

Figures within parentheses indicate standard error

Of the five explanatory variables in the model, all regression coefficients in both farming systems are statistically significant at different levels (1–10%). Table 3 shows that the estimated coefficient of rice seed is 0.39 and 0.26 in the alternate and integrated farming system, respectively. This implies that a 1% increase in the input of rice seed, keeping other factors constant, would increase production by 0.39% and 0.26% in the alternate and integrated farming system, respectively. The regression coefficient for fish stocking rates was calculated at 0.32 and 0.37, which are significant at the 1% and 5% level in the alternative and integrated farming system, respectively. Similarly, fish feed, fertilizer and labor input had positive effects on farm production in both farming systems.

The sum of all the production coefficients (Σb_i) in the alternate farming system is 1.41. As it is greater than 1, the returns are likely to increase with the scale of the inputs; i.e., if all the inputs specified in the model are increased by a certain percentage, farm production will increase by a larger proportion. In the example above, if all inputs are increased by 1%, farm production should increase by 1.41% in the alternate farming system. Similarly, as Σb_i=1.36 in the integrated farming system, production will increase by 1.36% if all inputs are increased by 1%. The results suggest that there is scope to increase farm production in the alternate and integrated farming systems by applying more inputs of rice seed, fish fingerlings, fish feed, fertilizer, and labor.

Conceptual framework

In terms of production efficiency, none of the farming systems achieved optimum production levels. The Cobb-Douglas production function model indicates that low levels of inputs are used in both farming systems. On the basis of this, a conceptual framework was developed in order to maximize production as well as the efficiency of resource utilization (Fig. 2). The horizontal axis shows farmers' skills in integrated rice-fish farming, while the vertical axis represents farmers' skills in alternate farming. Point A represents farmers who grow only rice, and points B and C represent integrated and alternate farmers, respectively. Point D indicates the point farmers have to reach to maximize yield. Integrated and alternate farmers are hypothesised to move up both scales simultaneously. Integrated farmers who are

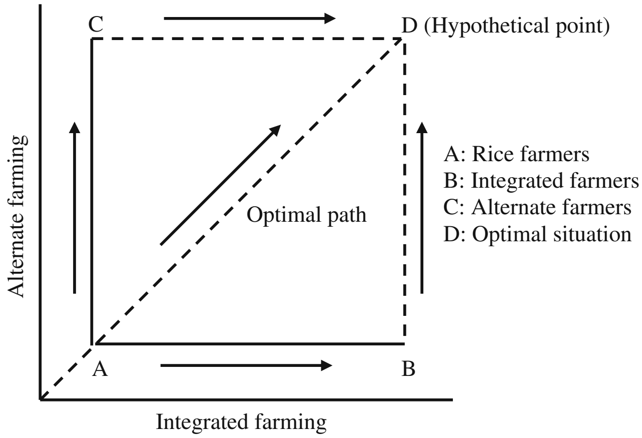


Fig. 2 A conceptual framework to optimize production from rice-fish farming (adapted from Horstkotte-Wesseler 1999)

skilled in rice-fish farming would be expected to change their perception towards the relatively high inputs of fish fingerlings and feed. On the other hand, alternate farmers who are skilled in fish farming would be expected to change their culture strategies towards integrated rice-fish farming. Progress of both farming systems is seen as complementary in which a move towards point D is recognized as the most desirable state.

Food security

Integrated rice-fish farming produces more food than alternate farming and rice monoculture (Fig. 3). Nevertheless, productivity in integrated farming is lower than it could be because of the low level of inputs. The Cobb-Douglas production function model of the present study suggests higher yields can be achieved by increasing inputs. Intensification of the fish culture in rice fields could also result in higher performance (Vromant et al. 2002). However, the most suitable level of intensity is mainly determined by the availability of resources and the farmer's management ability. According to Shang and Tisdell (1997), higher production can be obtained by improving existing culture techniques and practices, removing bottlenecks or a combination of these alternatives.

There is a strong association between food production and consumption. As a result of rice-fish farming, the households of integrated farmers are able to eat rice three times a day. Rice fields can potentially contribute considerable amounts of protein to fish farming households. Thus, the switch from rice monoculture to integrated rice-fish farming is not merely a change in cropping system, it is also a shift to a more balanced diet (i.e., rice and fish). The diet of integrated farmers' households contained significantly more fresh fish than that of alternate farmers. In the alternate system, fish farming is a cash crop, and thus 85% of the production was sold to local markets with only 15% consumed by the households. In contrast, farmers using the integrated system consider fish as a secondary crop in terms of economic return. Therefore, 40% of the fish production was consumed by the households with just 60% sold to local markets. It was reported that farmers' households tend to eat small fish and sell the bigger ones. In addition to animal protein, small fish are a valuable source of micronutrients, vitamins and minerals. These are eaten whole with bones and heads also contributing calcium, phosphorus, iron, zinc, and vitamins to the diets of poor families (Roos et al. 2002). Small fish are particularly important to the diets of children and lactating mothers, and their consumption results in a lower incidence of child blindness and infant mortality (Roos et al. 2007).

Several reports have suggested that rice monoculture is not environmentally sustainable in the long-term and is eroding the natural resource base (Berg 2001; Halwart and Gupta 2004; Frei and Becker 2005; Lu and Li 2006). Reduced fertilizer and pesticide use through the adoption of IPM is one long-term option to improve farm productivity in an environmentally friendly manner (Berg 2002; Gupta et al. 2002). Reduced application of fertilizers and pesticides in rice-based ecosystems conserve a great variety of aquatic flora and fauna (Halwart 2008). According to Rothuis et al. (1998), the main benefits of integrating rice and fish are environmental sustainability, system biodiversity, and decreased use of fertilizers and pesticides. Increased application of fertilizers and pesticides in rice monoculture has been releasing more radio-nuclides and residues leading to soil toxicity. Increased toxicity of the soil and water in rice fields has severely damaged the aquatic habitat, with the number of aquatic species in rice fields declining by 48–60% in Bangladesh (Ali 2004). Thus, the integrated rice-fish farming system can provide a sustainable alternative to rice monoculture, if farmers can take advantage of its environmental benefits.

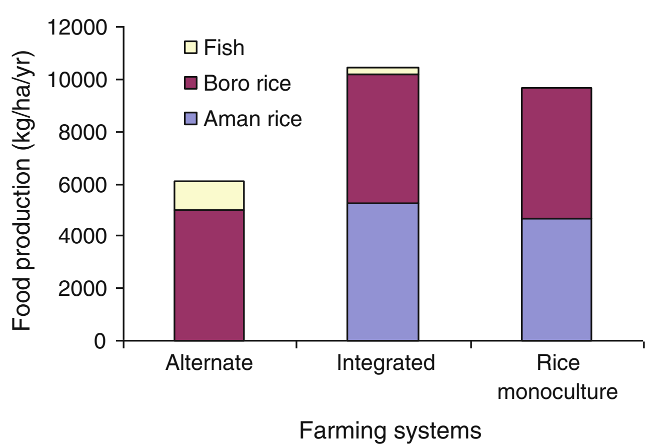


Fig. 3 Comparison of food production among different farming systems

Meeting the challenge of increasing food production will become difficult in Bangladesh as the population grows rapidly and the land available for farming declines. Nevertheless, integrated rice-fish farming can play an important role in increasing food production as this farming is better than rice monoculture in terms of food supply and environmental measures. Thus, the development of integrated rice-fish farming in Bangladesh would play an important role in contributing to food security. It is estimated that around 2.83 million ha of inundated seasonal rice fields are presently suitable for integrated rice-fish farming in Bangladesh (BRKB 2010). If fish production expanded to 25% of this potential area, the country would obtain an additional 183,243 tons of fish yearly (Table 4). Eventually rice production would increase by 395,493 tons per annum. Similarly, the country would get an additional 732,970 tons and 1.58 million tons per annum of fish and rice, respectively if fish farming expanded to the entire 2.83 million ha of seasonal rice fields. However, increased food production may still not be enough in the future as the population of Bangladesh will increase from 164 million to 222 million by 2050. Productivity would therefore have to be increased through intensification, as suggested in the conceptual framework. Moreover, integrated rice-fish farming will need to be extended across the 10.14 million ha of main rice fields, in addition to 2.83 million ha of seasonal rice fields, if food security in Bangladesh is to be ensured.

Despite this potential, however, integrated rice-fish farming technology has not yet improved food security in Bangladesh because of the low-level of adoption. To be sustainable, food production in Bangladesh should integrate resource management (Shankar et al. 2004). As has happened elsewhere (Ahmed and Garnett 2010; Ahmed et al. 2010b), integrated rice-fish farming warrants greater attention from development agencies and government organizations. According to Dey et al. (2005), the level of success of rice-fish farming in Bangladesh will depend on the local agro-ecological situation and the prevailing socioeconomic conditions.

Socioeconomic benefits

Fish farming in rice fields has also been associated with substantial social benefits, depending on production systems. Positive impacts appear to be highest among farmers involved in integrated rice-fish farming who tend to consume more food, have higher standards of living and greater purchasing power than other farmers, though this may be circular – wealthier farmers being more likely to take up integrated farming. Because of integration, the cultivation of fish has increased rice yield. Increased rice production has also increased availability of paddy straw, using for building houses, as cooking fuel and as fodder for cattle. As a result of fodder availability, milk and cow dung are available and cheap in the study area. Cow dung is used as a cooking fuel and as fertilizer, while milk is regarded as a suitable food for children. Farmers have also improved their housing conditions as income from rice-fish farming has been used to replace bamboo roofs and walls with tin sheets and wood. There has also been an increased number of bicycles and motorcycles for transport, improved access to health services and in the capacity to send children to school. Farmers have improved their drinking water supplies by sinking tube-wells and there has been an increase in communication technologies, such as radios and televisions, and particularly, mobile phones. However, the socioeconomic conditions of alternate and rice farmers have either stayed unchanged or diminished. These unsuccessful farmers explained that the principal reasons for their relative poverty were the lack of technical knowledge on integrated rice-fish farming and water management problems (i.e., flood and drought).

Across the study, the highest average annual net income for a farmer was estimated at US$633 in integrated farming, compared with US$508 in rice monoculture and US$368 in alternate farming. There was a significant difference ($P<0.05$) in income among categories of farmer. The integrated farmers obtained income both from fish production and increased rice production. Ofori et al. (2004) reported that

Table 4 Potential for food production from inundated seasonal rice fields in Bangladesh

Seasonal rice field (million ha)	Converted to integrated rice-fish farming (%)	Integrated rice-fish farming area (ha)	Average fish productivity [a] (kg/ha/year)	Total fish production (tons/year)	Increased rice yield [b] (kg/ha/year)	Total increased rice production (tons/year)
	25	707,500		183,243		395,493
2.83	50	1,415,000	259	366,485	559	790,985
	75	2,122,500		549,728		1,186,478
	100	2,830,000		732,970		1,581,970

[a] Average fish production as integrated farming was from Table 2

[b] *Aman* rice yield in integrated farming (5,261 kg/ha/yr) is higher than the rice monoculture (4,702 kg/ha/year), because of the presence of fish (from Table 2)

rice-fish systems had 5–11% higher revenue than rice monoculture.

The income of farmers was further explored by examining correlations with different factors. The analysis showed significant positive correlations between income and age of farmer, education, family size, farming experience, farm size, and cropping intensity (Table 5). Among these factors, age of farmers had the weakest relationship to income. There was a strong positive association between income and cropping intensity, followed by education of farmers and farming experience.

Although rice monoculture is still the dominant farming system in rural Bangladesh, rice-fish integration could provide a social, economic, environmental, and nutritionally viable alternative for resource-poor farmers. If rice monoculture is replaced by integrated rice-fish farming in Bangladesh, food production and socioeconomic conditions of farming households would be considerably increased.

Conclusions

In order to meet the soaring demand for food, there is a need for increased rice and fish production in Bangladesh. This study concludes that rice-fish integration could be a viable option for diversification. Such farm diversification will enhance food security. Integrated rice-fish farming increases rice yields and makes the rice field ecosystem an efficient and environmentally sound production system for rice and fish. Rice monoculture cannot alone provide a sustainable food supply, while integrated rice-fish farming is the best in terms of resource utilization, productivity and food supply. It is therefore suggested that integrated rice-fish farming is a sustainable alternative to rice monoculture.

Overall integrated rice-fish farming should play an important role in contributing to food security in Bangladesh. However, a number of significant challenges exist for the adoption of integrated rice-fish farming, particularly the lack of technical knowledge of farmers, and risks associated with flood and drought. These will need to be overcome if the benefits of rice-fish farming are to reach the millions of rural poor. A community-based approach could be an option to overcome constraints to the development of integrated rice-fish farming (Dey et al. 2005). If rice-only farmers were persuaded to switch to integrated rice-fish farming, their food supply would increase, and thus, the overall food security situation would be enhanced. Although integrated rice-fish farming increases the supply of food, this type of farming has not yet been attempted on a large scale in the country. It is, therefore, suggested that integrated rice-fish farming should be extended with the help of government organizations, NGOs, donor agencies, and other key stakeholders. In order to increase food supply, the government should promote integrated rice-fish farming throughout the country. Considering the role of integrated rice-fish farming, a much greater benefit could be obtained if future government policies encourage the expansion of integrated rice-fish farming, as well as the implementation of a workable strategy to bring it about. It is also necessary to provide institutional and organizational support, training facilities and technical support for sustainable rice-fish farming. Training and technical support would help to increase the knowledge of farmers, improve productivity and reduce risks.

The prospects for integrated rice-fish culture development in Bangladesh are considerable but determination is required to exploit the potential fully. A range of public and private sector investments and initiatives are needed to realize the potential for growth of this integration. Public-private partnerships offer potentially important opportunities for pro-poor agricultural development. Such collaborations have already contributed to food security in many developing countries (Spielman and Grebmer 2004). Moreover, applied research in areas such as small indigenous fish farming in rice fields may need to be given particular attention, considering nutritional benefits among household members including children and women. In addition, further research would be required on social, economic, environmental, and livelihood issues for the adoption of rice-fish farming in rural Bangladesh.

Table 5 Correlation with income and different factors by category of farmer

Factor	Income (r value)		
	Alternate farmer	Integrated farmer	Rice farmer
Age	0.24*	0.27*	0.33*
Education	0.64**	0.72***	0.61**
Family size	0.28*	0.34*	0.37*
Farm size	0.36*	0.49**	0.44**
Farming experience	0.59**	0.61**	0.64***
Cropping intensity	0.71***	0.89***	0.76***

Single (*), double (**) and triple (***) denote significant at 10%, 5% and 1% levels, respectively

Acknowledgments The study was supported through the Australian Government Endeavor Research Fellowship. It was a part of the first author's postdoctoral research at the School of Environmental and Life Sciences, Charles Darwin University, Australia. We are grateful to three anonymous reviewers for their very helpful and constructive comments. The views and opinions expressed herein are solely those of the authors.

References

ADB. (2005). *An evaluation of small-scale freshwater rural aquaculture development for poverty reduction*. Manila: Asian Development Bank.

Ahmed, N., & Garnett, S. T. (2010). Sustainability of freshwater prawn farming in rice fields in southwest Bangladesh. *Sustainable Agriculture, 34*, 659–679.

Ahmed, N., Wahab, M. A., & Thilsted, S. H. (2007). Integrated aquaculture-agriculture systems in Bangladesh: potential for sustainable livelihoods and nutritional security of the rural poor. *Aquaculture Asia, 12*(1), 14–22.

Ahmed, N., Ahammed, F., & Brakel, M. V. (2008). An economic analysis of freshwater prawn *Macrobrachium rosenbergii* farming in Mymensingh, Bangladesh. *The World Aquaculture Society, 38*, 37–50.

Ahmed, N., Alam, M. F., & Hasan, M. R. (2010). The economics of sutchi catfish (*Pangasianodon hypophthalmus*) aquaculture under three different farming systems in rural Bangladesh. *Aquaculture Research, 41*, 1668–1682.

Ahmed, N., Allison, E. H., & Muir, J. F. (2010). Rice fields to prawn farms: a blue revolution in southwest Bangladesh? *Aquaculture International, 18*, 555–574.

Ali, A. M. S. (2004). Technological change in agriculture and land degradation in Bangladesh: a case study. *Land Degradation and Development, 15*, 283–298.

Bakhshoodeh, M., & Thomson, K. J. (2001). Input and output technical efficiencies of wheat production in Kerman, Iran. *Agricultural Economics, 24*, 307–313.

Berg, H. (2001). Pesticide use in rice and rice-fish farms in the Mekong Delta, Vietnam. *Crop Protection, 20*, 897–905.

Berg, H. (2002). Rice monoculture and integrated rice-fish farming in the Mekong delta, Vietnam - economic and ecological considerations. *Ecological Economics, 41*, 95–107.

BRKB. (2010). *Rice statistics in Bangladesh*. Gazipur: Bangladesh Rice Knowledge Bank, Bangladesh Rice Research Institute.

Chowdhury, M. R. (2009). *Population challenge facing Bangladesh*. CW Post Campus, New York: Long Island University.

Dey, M. M., & Prein, M. (2003). Participatory research at landscape level: flood-prone ecosystems in Bangladesh and Vietnam. In B. Pound, S. S. Snapp, C. McDougall, & A. Braun (Eds.), *Managing natural resources for sustainable livelihoods: Uniting science and participation*. London: Earthscan and IDRC.

Dey, M. M., Prein, M., Haque, A. B. M. M., Sultana, P., Dan, N. C., & Hao, N. V. (2005). Economic feasibility of community-based fish culture in seasonally flooded rice fields in Bangladesh and Vietnam. *Aquaculture Economics and Management, 9*, 65–88.

DoF. (2010). *Fisheries statistical yearbook of Bangladesh 2008–2009*. Dhaka: Fisheries Resources Survey System, Department of Fisheries, Ministry of Fisheries and Livestock.

Dugan, P., Dey, M. M., & Sugunan, V. V. (2006). Fisheries and water productivity in tropical river basins: enhancing food security and livelihoods by managing water for fish. *Agricultural Water Management, 80*, 262–275.

FAO. (2000). *Forest resources of Bangladesh—country report*. FAO Working Paper 15, Forest Resources Assessment Programme, Forestry Department, Food and Agriculture Organization of the United Nations, Rome, Italy.

Fernando, C. H. (1993). Rice field ecology and fish culture: an overview. *Hydrobiologia, 259*, 91–113.

Frei, M., & Becker, K. (2005). Integrated rice-fish culture: coupled production saves resources. *Natural Resources Forum, 29*, 135–143.

Fulginiti, L. E., & Perrin, R. K. (1998). Agricultural productivity in developing countries. *Agricultural Economics, 19*, 45–51.

Giap, D. H., Yi, Y., & Lin, C. K. (2005). Effects of different fertilization and feeding regimes on the production of integrated farming of rice and prawn *Macrobrachium rosenbergii* (De Man). *Aquaculture Research, 36*, 292–299.

Goswami, M., Biradar, R. S., & Hastiadas, R. (2004). Techno-economic viability of rice-fish culture in Assam. *Aquaculture Economics and Management, 8*, 309–318.

Gupta, M. V., Sollows, J. D., Mazid, M. A., Rahman, A., Hussain, M. G., & Dey, M. M. (2002). Economics and adoption patterns of integrated rice-fish farming in Bangladesh. In P. Edwards, D. C. Little, & H. Demaine (Eds.), *Rural aquaculture* (pp. 41–54). Oxford: CABI International.

Gurung, T. B., & Wagle, S. K. (2005). Revisiting underlying ecological principles of rice-fish integrated farming for environmental, economical and social benefits. *Our Nature, 3*, 1–12.

Halwart, M. (2008). Biodiversity, nutrition and livelihoods in aquatic rice-based ecosystems. *Biodiversity: Journal of Life on Earth, 9*, 36–40.

Halwart, M. & Gupta, M. V. (2004). *Culture of fish in rice fields*. Food and Agriculture Organization of the United Nations and the WorldFish Center, p 83.

Horstkotte-Wesseler, G. (1999). Socioeconomics of rice-aquaculture and IPM in the Philippines: synergies, potentials and problems. International Center for Living Aquatic Resource Management (ICLARM), Manila, Philippines, ICLARM Technical Report 57, 225.

Hossain, M., Bose, M. L., & Mustafi, B. A. A. (2006). Adoption and productivity impact of modern rice varieties in Bangladesh. *The Developing Economics, XLIV-2*, 149–166.

Karagiannis, G., & Katranidis, S. D. (2000). A production function analysis of seabass and seabream production in Greece. *The World Aquaculture Society, 31*, 297–305.

Kunda, M., Azim, M. E., Wahab, M. A., Dewan, S., Roos, N., & Thilsted, S. H. (2008). Potential of mixed culture of freshwater prawn (*Macrobrachium rosenbergii*) and self recruiting small species mola (*Amblypharyngodon mola*) in rotational rice-fish/prawn culture systems in Bangladesh. *Aquaculture Research, 39*, 506–517.

Larsen, T., Thilsted, S. H., Kongsbak, K., & Hansen, M. (2000). Whole small fish as a rich calcium source. *British Journal of Nutrition, 83*, 191–196.

Li, K. (1988). Rice-fish culture in Asia: a review. *Aquaculture, 71*, 173–186.

Little, D. C., Surintaraseree, P., & Taylor, N. I. (1996). Fish culture in rain fed rice fields of northeast Thailand. *Aquaculture, 140*, 295–321.

Lu, J., & Li, X. (2006). Review of rice-fish farming systems in China—one of the globally important ingenious agricultural heritage systems (GIAHS). *Aquaculture, 260*, 106–113.

Mainuddin, M., & Kirby, M. (2009). Agricultural productivity in the lower Mekong Basin: trends and future prospects for food security. *Food Security, 1*, 71–82.

Matteson, P. C. (2000). Insect-pest management in tropical Asian irrigated rice fields. *Annual Review Entomology, 5*, 549–574.

Mishra, A., & Mohanty, R. K. (2004). Productivity enhancement through rice-fish farming using a two-stage rainwater conservation technique. *Agricultural Water Management, 67*, 119–131.

Mohanty, R. K., Verma, H. N., & Brahmanand, P. S. (2004). Performance evaluation of rice-fish integration system in rainfed medium and ecosystem. *Aquaculture, 23*, 125–135.

Mustow, S. E. (2002). The effects of shading on phytoplankton photosynthesis in rice-fish fields in Bangladesh. *Agriculture, Ecosystems and Environment, 90*, 89–96.
Nabi, R. (2008). Constraints to the adoption of rice-fish farming by smallholders in Bangladesh: a farming systems analysis. *Aquaculture Economics and Management, 12*, 145–153.
Nerrie, B. L., Hatch, L. U., Engle, C. R., & Smitherman, R. O. (1990). The economics of intensifying catfish production: a production function analysis. *The World Aquaculture Society, 21*, 16–24.
Nhan, D. K., Phong, L. T., Verdegem, M. J. C., Duong, L. T., Bosma, R. H., & Little, D. C. (2007). Integrated freshwater aquaculture, crop and livestock production in the Mekong delta, Vietnam: determinants and the role of the pond. *Agricultural Systems, 94*, 445–458.
Ofori, J., Abban, E. K., Otoo, E., & Wakatsuki, T. (2004). Rice-fish culture: an option for smallholder Sawah rice farmers of the West African lowlands. *Ecological Engineering, 24*, 235–241.
Ozsabuncuoglu, I. H. (1998). Production function for wheat: a case study of Southeastern Anatolian Project (SAP) region. *Agricultural Economics, 18*, 75–87.
Roos, N., Leth, T., Jackobsen, J., & Thilsted, S. H. (2002). High vitamin A content in some small indigenous fish species in Bangladesh: perspectives for food-based strategies to reduce vitamin A deficiency. *International Journal of Food Science Nutrition, 53*, 425–437.
Roos, N., Islam, M. M., & Thilsted, S. H. (2003). Small indigenous fish species in Bangladesh: contribution to vitamin A, calcium and iron intakes. *Journal of Nutrition, 133*, 4021S–4026S.
Roos, N., Wahab, M. A., Chamnan, C., & Thilsted, S. H. (2007). The role of fish in food-based strategies to combat vitamin A and mineral deficiencies in developing countries. *Journal of Nutrition, 137*, 1106–1109.
Rothuis, A. J., Nhan, D. K., Richter, C. J. J., & Ollevier, F. (1998). Rice with fish culture in the semi-deep waters of the Mekong Delta, Vietnam: a socio-economical survey. *Aquaculture Research, 29*, 47–57.
Shang, Y. C., & Tisdell, C. A. (1997). Economic decision making in sustainable aquaculture development. In J. E. Bardach (Ed.), *Sustainable aquaculture*. Honolulu: Wiley.
Shankar, B., Halls, A., & Barr, J. (2004). Rice versus fish revisited: on the integrated management of floodplain resources in Bangladesh. *Natural Resources Forum, 28*, 91–101.
Spielman, D. & Grebmer, K. V. (2004). *Public-private partnerships in agriculture research: an analysis of challenges facing*. Environment and Production Technology Division, EPTD Discussion Paper No. 113, International Food Policy Research Institute, Washington DC 20006, USA.
Swann, L. (1992). *A basic overview of aquaculture*. West Lafaette: Purdue University.
Villano, R., & Fleming, E. (2006). Technical inefficiency and production risk in rice farming: evidence from Central Luzon Philippines. *Asian Economic Journal, 20*, 29–46.
Vromant, N., Nam, C. Q., & Ollevier, F. (2002). Growth performance and use of natural food by *Oreochromis niloticus* (L.) in polyculture systems with *Barbodes gonionotus* (Bleeker) and *Cyprinus carpio* in intensively cultivated rice fields. *Aquaculture Research, 33*, 969–978.
Wahab, M. A., Kunda, M., Azim, M. E., Dewan, S., & Thilsted, S. H. (2008). Evaluation of freshwater prawn-small fish culture concurrently with rice in Bangladesh. *Aquaculture Research, 39*, 1524–1532.

Nesar Ahmed is a professor in the Department of Fisheries Management, Bangladesh Agricultural University. He obtained his PhD from the Institute of Aquaculture, University of Stirling, UK through a Department for International Development (DFID) UK scholarship and won the Endeavour Research Fellowship of the Australian Government for Postdoctoral Research at Charles Darwin University, Australia. Nesar has over 15 years research experience and has worked with a range of international donor agencies, including ADB, DANIDA, DFID, FAO, IFS, USAID, World Bank, and WorldFish Center. Nesar has published extensively on a wide range of aquaculture and fisheries issues with articles appearing in peer reviewed journals such as Ambio, Aquaculture Economics and Management, Aquaculture International, Aquaculture Research, Australian J. Agricultural and Resource Economics, Farm Management, Marine Policy, Sustainable Agriculture, and World Aquaculture Society. Nesar has also published over 30 magazine articles on food security, poverty alleviation and livelihood issues which have appeared in Aquaculture Asia, Aquaculture News, Fish Farmer, Fish Farming International, Global Aquaculture Advocate, Shellfish News, and World Aquaculture. His current research focuses on an ecosystem approach to integrated aquaculture-agriculture and environment in relation to climate change.

Stephen Garnett is a professor at the Research Institute for Environment and Livelihoods, Charles Darwin University, Australia. He is an environmental scientist with an interest in the knowledge needed to live sustainably in the tropics. Educated at the Australian National University and James Cook University, he has spent most of the last 30 years in the Australian tropics. He joined the staff of Charles Darwin University in May 2004 as Professor of Tropical Knowledge and was Director of the School for Environmental Research from 2007 to 2010. Professor Garnett is recognized nationally and internationally for research on conservation management, particularly of threatened species. He has more recently become involved in a range of research related to climate change and environment, natural resource management, and the application of tropical knowledge for the purpose of improving livelihoods and conservation outcomes.