
ELSEVIER
Volume 96, issue 12, December 2009
ISSN 0378-3774
96 (12) 1683–1860 (2009)
Agricultural
Water Management
an International Journal

Agricultural Water Management 96 (2009) 1844–1850

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Impact of high-density stocking and selective harvesting on yield and water productivity of deepwater rice–fish systems

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ARTICLE INFO

Article history:
Received 4 September 2008
Accepted 18 August 2009
Available online 6 September 2009

Keywords:
Water conservation
Water quality
Rice equivalent yield
Indian major carps
Growth performance

ABSTRACT

We examine the productivity of deepwater rice–fish systems and management strategies that include high-density initial stocking and selective harvesting. All species of fish and prawns grow faster after 120 days of rearing, probably due to periodic selective harvesting that minimizes the competition for food and space, as well as physiological stress at reduced density. We observe a higher survival rate, a lower apparent feed conversion ratio (1.77) and higher fish yield (14.1%) in rice–fish culture with selective harvesting (T_1) than in rice–fish culture without selective harvesting (T_2). The highest paddy yield was recorded in T_1, primarily due to the higher number of panicles per m^2 (139.5) and the number of filled grains per panicle (111.5). The increase in paddy yield over rice mono-cropping was higher in T_1 (25%) than T_2 (16.9%). The smaller number of panicles (122.2/m^2) and filled grains (98.5 per panicle) in rice mono-cropping was probably due to the absence of fish and prawns in the field as fish and prawns improve soil fertility, recover lost energy, and adjust energy flow by consuming plankton, weeds, insects and bacteria that compete with rice for nutrients. The highest rice equivalent yield (38.5 t ha^{-1}), the output value-cultivation cost ratio (1.56) and net water productivity (Rs. 7.30/m^3) in deepwater rice–fish culture was recorded when selective harvesting was practiced. This eco-friendly dual production system (rice and fish) and on-dyke horticulture, which generate near-term lucrative returns and generates employment opportunities, can be adopted and expanded in lowlands and waterlogged areas.

1. Introduction

In India, agriculture contributes nearly one-fourth of the national GDP and sustains livelihoods for about two-thirds of the population. To meet the food requirement of 1.5 billion people by 2050, food grain production must increase by 185% (Mohanty et al., 2008). This will require greater productivity, crop diversification, and cropping intensity. However, presently, there is little scope for horizontal expansion of agriculture and aquaculture due to rapid industrialization and urbanization. India's per capita availability of land has declined from 0.5 ha to 0.15 ha, as its population now exceeds 1070 million, including an undernourished population of 270 million. Vertical expansion by integrating compatible farming components that require less space and time is one approach towards increasing farm productivity, improving livelihoods, enhancing food security, and reducing environmental degradation.

The most challenging constraint in aquaculture technology is the high cost of inputs, especially fish feed and fertilizer. Further, stocking of healthy fingerlings of more than 100 mm is an essential management measure. However, inadequate land-based nursery ponds and financial constraints in developing new infrastructure facilities impede the desired stocking programme. With these constraints and available resources, the rice field ecosystem provides an opportunity for producing advanced fingerlings, as a part of the stocking programme.

Further, out of 44.5 million ha of rice-cultivated land in India, 20 million ha are suitable for adoption of a rice–fish integration system, mainly in rainfed medium lands, waterlogged/low lands, and in canal commands. However, only 0.23 million ha are presently under rice–fish culture (Mohanty et al., 2004). This low degree of adoption, exploitation, and yield is primarily due to (1) the introduction of high-yielding rice varieties involving the use of pesticides that have impeded fish culture in paddy fields, (2) shorter rearing durations for fish, (3) insufficient water availability, (4) lack of water management measures, and (5) erratic monsoons. Achieving higher productivity from these under-utilized areas is needed, particularly in the eastern region. Bringing these lands under an integrated rice–fish system with suitable scientific intervention and water conservation/monitoring measures, would help compensate for economic losses in rice production brought about by natural calamities.

Rice–fish culture could be a viable option for diversification for smallholder rice farmers in low lands with soil and water

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doi:10.1016/j.agwat.2009.08.006

conservation structures and reliable sources of water for irrigation (Ofori et al., 2005). Integrated rice–fish farming not only accommodates crop diversification, enhances productivity, and increases income, but also distributes the risk (both biological and economic), as two or more subsystems are involved, instead of a single-commodity farming system. Hence, rice–fish integration can enhance efforts to develop ecological agriculture that generates maximum benefit using available energy and materials.

Fish rearing in rice fields is a 2000-year-old practice that is probably the most promising alternative to rice mono-cropping. Adding fish to the rice field ecology helps increase production and generates social, economic, and ecological benefits (Costa-Pierce, 1992; Xiao, 1995; Halwart et al., 1996; Rothuis et al., 1998; Bandyopadhyay and Puste, 2001). Fish culture in this ecosystem is concurrent or rotational with rice, carried out at four intensities: traditional (capture), low intensity culture (without feed and fertilizer), medium intensity (only fertilization) and high-density culture (with feed and fertilizer). In most countries, rice–fish farming is characterized by intensive rice cultivation and extensive fish culture, where fish yields are usually very low, about 300 kg ha^{-1} (Nhan et al., 1998). Rice–fish farming systems, as part of an integrated ecosystem in line with the local cultural, environmental, and economic conditions are composed of complementary sub-agricultural ecosystems and play important ecological service roles (Fernando, 1993), such as bio-control, nitrogen fixation and landscape combination. Although, several authors have examined different aspects of rice–fish farming (Brahmanand et al., 2006; Lu and Li, 2006), no work has been conducted regarding how to enhance water productivity of the rice–fish farming system. Given this backdrop, an attempt was made to enhance the yield, economic output and water productivity of the deepwater rice–fish system following the principle of high-density stocking and selective harvesting.

2. Materials and methods

An on-farm experiment was carried out in Khentalo village (Latitude 20°15′N and Longitude 86°03′E) of Cuttack district, Orissa, India, for three crops during 2004–2005 to 2006–2007. A patch of 2.0 ha waterlogged area was converted into two units of a deepwater rice–fish system. There were two experimental conditions such as rice–fish culture with selective harvesting (T_1) and rice–fish culture without selective harvesting (T_2). An adjacent land of 1.0 ha was utilized for deepwater rice mono-cropping without fish (T_3), to study the impact of fish and prawns on rice yield. Fish culture alone without rice (T_4) was also undertaken in an adjacent pond of 0.5 ha area, to study the economics and water productivity of the system. Half of the land in T_1 and T_2 was excavated to a depth of 100 cm and the excavated soil was utilized for peripheral dyke construction to a height of 2.5 m (Fig. 1).

The deepwater long-duration rice variety *Durga* (CR 683-123) was transplanted in the unexcavated land (50% area, 5000 m^2) of T_1 and T_2 and 100% area of T_3 during 3rd week of July in the 1st, 2nd and 3rd year for this study. The rice areas in T_1, T_2 and T_3 were divided into four sub-plots each. The rice was transplanted at a spacing of 20 cm × 20 cm (between rows and plants). The fertilizers were applied at the rate of 80 kg N ha^{-1} as urea (173.9 kg ha^{-1}), 60 kg P_2O_5 ha^{-1} as single super phosphate (375 kg ha^{-1}) and 40 kg K_2O ha^{-1} as muriate of potash (64.5 kg ha^{-1}). Half of the N and the full dose of P and K were applied as a basal dose at the time of transplanting. The rest of the nitrogen was applied in two equal split doses during tillering and panicle initiation (30 and 60 DAT). Crop growth and yield parameters were recorded at regular intervals. No pesticide was used in the experimental plots to prevent fish mortality. The final yield and yield attributes of crops were recorded at the time of harvest. Standard agronomic and aquaculture practices were adopted.

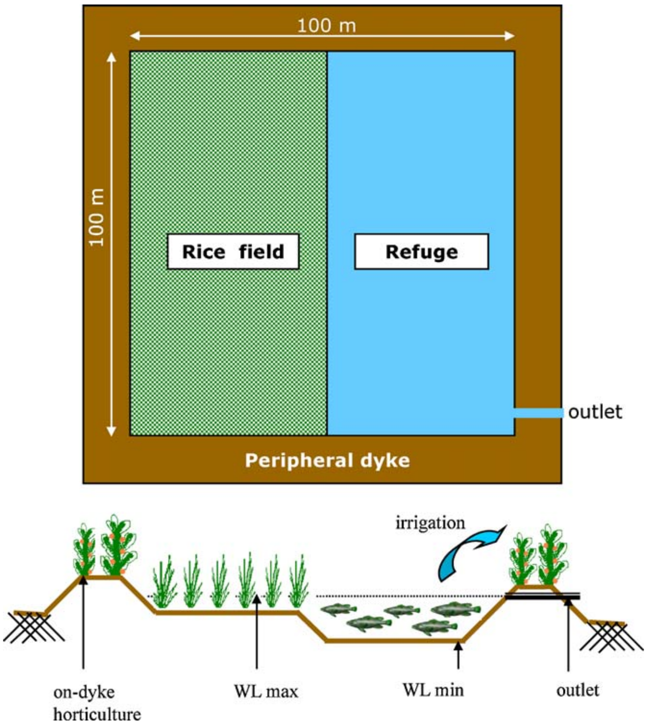

Fig. 1. Lay out of the deepwater rice–fish system (1 ha unit).

Pre-stocking refuge and pond preparation (T_1, T_2 and T_4) that include horizontal and longitudinal ploughing followed by the application of lime ($CaCO_3$) at 750 kg ha^{-1}, raw cattle dung (RCD) at 7000 kg ha^{-1} as a basal dose and fertilizer (Urea:Single Super Phosphate, 1:1) at 3 ppm was carried out. Seven days after the refuge and pond preparation (3rd week of July), early fish fingerlings (3.0–4.8 g mean body weight, MBW) and prawn juveniles of *Macrobrachium rosenbergii* (1.2 g MBW) were stocked at the rate of 100,000 ha^{-1}. The composition of the stocked species was 25:25:15:15:20 (*Catla catla*:*Labeo rohita*:*Cirrhinus mrigala*:*Cyprinus carpio*:*Macrobrachium rosenbergii*, 12,500:12,500:7500:7500:10,000) in the excavated refuge (5000 m^2) of the T_1, T_2 and T_4. Supplemental feeding was provided at a ratio of 55:35:10 (rice bran:mustard oil cake:fish meal) at 6%, 5%, 4% and 2.5% of MBW, twice a day, during 1st, 2nd, 3rd and 4th month to harvesting, respectively. The estimated crude protein (%) of feed ingredients was 8.8, 37.3 and 52.4 respectively for rice bran, mustard oil cake and fish meal. Periodic manuring with RCD at 500 kg ha^{-1} and liming at 200 kg ha^{-1} were carried out at 15-day intervals to maintain the plankton population in the ecosystem.

Periodic observations on water quality, soil quality, growth parameters of fish and prawns, yield and yield components, hydrological and water balance related studies were made at regular intervals at the experimental site. Selective harvesting of fish and prawns was undertaken twice at 120 says and 165 days after stocking in each crop. Fish and prawn rearing continued for 210 days. After harvesting of the rice and fish, a low-duty second crop (black gram, *Phaseolus mungo*) was grown in the designated rice area in T_1, T_2 and T_3. On the entire peripheral dyke of each unit, brinjal (*Solanum melongena*) and ladies finger (*Hibiscus esculentus*) were grown on both sides (800 numbers each) at a spacing of 50 cm between plants. In the middle of the embankment, dwarf varieties of papaya and banana were grown alternatively at a spacing of 1.5 m as an additional component. These plants were irrigated using the refuge and pond water.

Major physico-chemical parameters of refuge and pond water, such as dissolved oxygen (DO), temperature, pH, turbidity; total alkalinity, total suspended solids, CO_2 and salinity were monitored *in situ* every day between 0700 and 0800 h using standard methods (APHA, 1995; Biswas, 1993). These parameters were crosschecked using a Multi-parameter Water Analyzer (YK-611, Yeo-Kal Electronics Pty. Ltd., Australia). NH_4^+ was determined spectrophotometrically with the indophenol blue method, while chlorophyll *a* was determined using the acetone extraction method (Strickland and Parsons, 1972). Primary productivity using the "Oxygen method" (APHA, 1995), plankton estimation, nutrient analysis and monthly observations of soil quality (available N, available P, organic carbon and pH) were studied using standard methods (Biswas, 1993).

The weekly growth study was carried out by sampling prior to feeding so that complete evacuation of gut was ensured. Weekly mean body weight (MBW), per day increment (PDI), survival (SR%), biomass (kg), feed requirement, percentage of feed, feed requirement per day and apparent feed conversion ratio (AFCR) were estimated as described by Mohanty (1999).

To assess the output from the experimental plot as a single unit, rice equivalent yield (REY) was computed, considering the proportional area devoted to rice and fish cultivation and the farm gate selling prices of rice, fish fingerlings, prawns and marketable fish as 5.00, 2.50, 120.00 and 50.00 rupees (Rs.), respectively. Economic indices of water productivity (net consumptive water use index, Rupees m^{-3}) were estimated as suggested by Boyd (2004) and James et al. (2005). The ratio of the output value to the cost of cultivation of the integrated farming system was estimated. The cost of the excavated refuge and pond, assuming a life span of 15 years, which is a fixed cost, was added (depreciated cost) to the yearly variable cost of cultivation. The cost of the excavated refuge and pond was estimated to be Rs. 135,000 ha^{-1}. The operational cost includes the cost of feed at Rs. 14/kg; fish seed at Rs. 200 per 1000 early fingerlings; prawn seed at Rs. 0.5 per seed; raw cow dung at Rs. 500 per 1000 kg; labour at Rs. 70 per man day; lime at Rs. 4.50/kg and other costs (plant material, fertilizer, etc.).

3. Results and discussion

3.1. Excess water conservation and management

The annual rainfall at the study site ranged from 951.6 mm to 2218 mm. The normal (mean) annual rainfall was 1485 mm. During 2004–2005 and 2006–2007, the annual rainfall was greater than average while it was nearly normal (1453 mm) during 2005–2006. In 2004–2005, the monthly rainfall during all the monsoon months was greater than the 30-year average; whereas in 2005–2006 and 2006–2007, it was, lower than average. However, in all cases, the water levels in the refuges and pond were observed to be sufficient for short-duration aquaculture (>1 m most of the period) until the end of January. The water available in the surrounding paddy field was also sufficient during the entire study period. There was no need of irrigating the *kharif* paddy. Considering the availability of water in the refuge, if needed, life saving irrigation can easily be provided to the rice and other crops during less rainfall years.

3.2. Soil quality

Soils of the experimental plots were clay, having an acidic pH (6.6–6.8). The composition of sand, silt and clay was 36.6%, 19%, and 44.4 %, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.16–0.19, 7.9–10.1 and 1.28–1.63, respectively at the beginning of the experiment which was improved later (Table 1). This was likely due to (1) the additional nutrients from the fish feed and feces and (2) fish grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling, minimizing N losses (Cagauan, 1995) and facilitating P release from the sediment (Breukelaar et al., 1994). No distinct trends between the treatments were observed and sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee, 1967).

3.3. Water quality in relation to fish production

Water quality is a dynamic property of an integrated rice–fish system and is influenced by chemical, biological and physical factors. These factors ultimately regulate the aquatic environment and the productivity of rice–fish farming systems. The recorded mean minimum and mean maximum values of various water and sediment quality parameters are presented in Table 1. Total suspended solids and the dissolved oxygen concentration show a decreasing trend with the advancement of the rearing period. Higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point in time, the remaining water quality parameters and plankton population did not register any specific trend between

Table 1
Minimum, maximum and average values of water and soil quality parameters in the different treatments of deepwater rice–fish integration system.

Parameters	Rice–fish system with selective harvesting (T_1)	Rice–fish system without selective harvesting (T_2)	Only rice (T_3)	Only fish (T_4)
pH	6.7–8.6 (7.63)	6.9–8.5 (7.31)	6.7–8.1 (7.52)	6.6–8.6 (7.8)
Dissolved oxygen (ppm)	3.8–9.3 (5.1)	3.3–8.4 (4.9)	4.4–8.9 (6.1)	5.2–8.4 (5.7)
Temperature (°C)	27.8–31.2 (28.4)	27.7–31.3 (28.4)	27.9–31.5 (28.7)	27.9–31.6 (28.7)
Total alkalinity (ppm)	79–117 (106)	68–109 (94)	73–107 (88)	88–132 (113)
Dissolved organic matter (ppm)	1.3–6.2 (3.2)	1.45–4.8 (3.4)	0.55–3.6 (2.6)	0.5–4.4 (2.9)
Total suspended solids (ppm)	160–362 (213)	132–297 (225)	60–257 (177)	72–357 (237)
NH_4^+ water (ppm)	0.31–0.88 (0.65)	0.34–0.97 (0.68)	0.41–0.91 (0.59)	0.4–0.96 (0.66)
Chlorophyll *a* (mg m^{-3})	20–51.5 (36.7)	21.1–62.2 (41.1)	18.8–31.3 (22.3)	19.7–60.2 (32.8)
Total plankton (units l^{-1})	4.4×10^3–2.3×10^4 (1.4×10^4)	2.9×10^3–6.7×10^4 (3.3×10^4)	9.4×10^2–1.8×10^4 (7.3×10^3)	9.4×10^3–9.8×10^4 (4.3×10^4)
Nitrite—N (ppm)	0.009–0.06 (0.03)	0.012–0.072 (0.037)	0.011–0.07 (0.033)	0.01–0.07 (0.034)
Nitrate—N (ppm)	0.06–0.51 (0.36)	0.05–0.49 (0.37)	0.16–0.61 (0.36)	0.09–0.6 (0.32)
Phosphate—P (ppm)	0.07–0.34 (0.21)	0.06–0.33 (0.21)	0.13–0.54 (0.26)	0.08–0.38 (0.3)
Available-N in soil (mg 100 g^{-1})	18.1–21.1 (19.8)	17.9–21.6 (19.3)	20.1–21.9 (20.3)	19.4–21.8 (20.1)
Available-P in soil (mg 100 g^{-1})	1.3–2.69 (2.21)	1.28–2.93 (2.23)	1.63–2.89 (2.11)	1.6–2.9 (2.17)
Organic carbon in soil (%)	0.44–0.76 (0.61)	0.49–0.82 (0.64)	0.57–0.75 (0.63)	0.52–0.8 (0.6)
Soil pH	6.6–7.1 (7.04)	6.8–7.1 (7.01)	6.8–7.1 (6.94)	6.8–7.1 (6.9)

Figures in parentheses represent mean values.

Table 2
Treatment-wise rice, fish and rice equivalent yield (average of three experimental years).

Treatment	Rice area (m^2)	Refuge/pond area (m^2)	Total area (m^2)	Rice yield ($t ha^{-1}$)	Fish yield ($t ha^{-1}$)	Rice equivalent yield ($t ha^{-1}$)
Deep water rice mono-crop	10,000	–	10,000	2.6	–	2.6
Rice–fish (no selective harvesting)	5000	5000	10,000	3.04	6.1	35.5
Rice–fish (with selective harvesting)	5000	5000	10,000	3.25	6.96	38.5
Only fish and prawn culture without selective harvesting	–	5000	5000	–	5.6	58.0

The farm gate selling prices of rice, fish fingerling, prawn and marketable fish were Rs. 5.00, Rs. 2.50, Rs. 120.00 and Rs. 50.00, respectively.

the treatments. Diatoms and green algae mainly dominated the phytoplankton population while the zooplankton population was dominated by copepods and rotifers. In all the treatments, average primary production in the first month of cultivation ranged from 87.6 mg to 137 mg C m^{-3} h^{-1}, which improved further (407.5 ± 38.3 mg C m^{-3} h^{-1}) with the advancement of rearing period. Low primary production in the initial phase of rearing was probably due to the fixation of nutrient ions by suspended soil/clay particles as well as rich organic matter (Mohanty, 2003).

From a fish rearing point of view, various hydro-biological parameters prevailing in the different treatments were within the optimum ranges and did not fluctuate drastically. This was probably due to the similar levels of inputs in all the treatments in the form of organic manure, inorganic fertilizer and periodic liming. The decreasing trend in DO in all the treatments (except rice mono-crop) with the advancement of the fish rearing period, attributed to the fluctuations in plankton density and a gradual increase in biomass, resulting in higher oxygen consumption. Most warm water fish species require a minimum DO of 1 ppm for survival and 5 ppm for ideal growth and maintenance (Yaro et al., 2005). However, in this study the DO level did not drop below 3.3 ppm in any treatment. The presence of fish decreases in the DO and the pH, compared to rice mono-cropping, especially when supplemental feed is given. Moreover, fish stimulate the growth of phytoplankton and increase the chlorophyll *a* concentration (Frei and Becker, 2005). Gradual increases in nitrite, nitrate, and ammonia were attributed to intermittent fertilization, increased levels of metabolites and decomposition of unutilized feed in the absence of water replenishment (Mohanty et al., 2004).

The most important factor limiting aquatic photosynthesis in rice fields is the shading that results from the growing rice biomass (Mustow, 2002). In addition to competition for light, rice also competes with the field water's photosynthetic active biomass (PAB) for available nutrients, especially N, which is the most limiting nutrient in rice fields (Heckman, 1979; Kropff et al., 1993). At the onset of the experiment, the higher pH values (7.3–7.6), together with DO (6.6–7.2) and chlorophyll *a* values (36–42.2) suggest that an autotrophic pathway was dominated within the aquatic phase of the rice fields. However, with the increase in rice biomass, the chlorophyll *a* concentration (20.4–24.6), NH_4^+ (0.31–0.34), pH (6.7–6.9), and DO (3.3–4.4) decreased, indicating reduced aquatic photosynthesis. This suggests that the autotrophic pathway lost importance. With increasing rice biomass, the surface feeder (*C. catla*) and column feeder (*L. rohita*) fishes gradually switch from feeding on plankton and algal biomass to supplemental feed, a process that results in an interspecific competition with bottom feeders. This is in agreement with the findings of Chapman and Fernando (1994) and Vromant et al. (2004).

In general, the poor growth performance of cultured species takes place at pH < 6.5 (Mount, 1973), while higher values of total alkalinity (>90 ppm) indicates a more productive ecosystem. Increased plankton density also reflects higher nutrient status of the water body. The plankton density always has a profound effect on water quality and fish production (Smith and Piedrahita, 1988; Yaro et al., 2005). In this experiment, fluctuating trends in plankton density (7.3×10^3–4.3×10^4) were recorded in different treatments (Table 1), which ultimately reflected the fish and rice yields in the T_1 and T_2 (Table 2). The availability of CO_2 for phytoplankton growth is linked to total alkalinity (Mohanty, 2003), while water having 20–150 ppm total alkalinity produced a suitable amount of CO_2 to permit plankton production. In this study, the recorded minimum and maximum range of total alkalinity was 68 ppm to 132 ppm, which was maintained due to periodic liming.

3.4. Growth and yield performance of rice

The rice variety '*Durga*' (CR 683-123) was grown under three different treatments. The highest grain yield was recorded in T_1. This was mainly due to higher numbers of panicles per m^2 (139.5) and numbers of filled grains per panicle (111.5). The percentage increase in grain yield over rice mono-cropping was however, higher in T_1 (25%) than in T_2 (16.9%). The smaller numbers of panicles (122.2/m^2) and filled grains (98.5 per panicle) in rice mono-cropping were probably due to the absence of fish and prawns in the field as fish and prawns improve soil fertility, recover lost energy, and adjust energy flow by consuming plankton, weeds, insects and bacteria that compete with rice for nutrients. Furthermore, fish help in enhancing carbon availability to plants by releasing carbon dioxide. Due to breaking of the soil surface and oxidization of the layers, the supply of oxygen increases, promoting root growth and tillering capability of rice plants. Growth and yield performance of rice was enhanced in T_1 and T_2 (Table 3), as compared with T_3. The presence of fish in rice fields helps improves the physico-chemical properties of arable soil, accelerates the growth rate of rice plants, and increase the dry matter and leaf area index at different growth stages, thus promoting photosynthesis and grain filing (Yang et al., 2006). Between T_1 and T_2, the higher rice yield was recorded in T_1 (3.25 t ha^{-1}), probably due to the lower chlorophyll *a* and plankton density (Table 1) that minimized the competition for nutrients

Table 3
Rice yield attributes in the deepwater rice–fish system.

Treatments	Number of panicles/m^2	Number of filled grain/panicle	Straw yield ($t ha^{-1}$)	Test weight (g)	Rice yield ($t ha^{-1}$)	Increase in grain yield over rice mono-crop (%)
Rice mono-crop (T_3)	122.2^c	98.5^c	3.18^c	25.7^a	2.60^c	–
Rice–fish without selective harvesting (T_2)	130.2^b	106.2^b	3.61^b	25.6^a	3.04^b	16.9
Rice–fish with selective harvesting (T_1)	139.5^a	111.5^a	3.94^a	25.8^a	3.25^a	25

In a column, means with different superscript letters indicate significantly different ($p < 0.05$) based on DMRT.

Table 4
Details of the selective harvesting at different days after stocking (DAS) in the rice–fish system.

Species composition (25:25:15:15:20)	Selective harvesting						Final survival rate (%)
	1st cull (120 DAS)		2nd cull (165 DAS)		Final harvesting (210 DAS)		
	MBW (g)	NH	MBW (g)	NH	MBW (g)	NH	
Catla catla	66.7 (53.5)	4000[a] –	192.6 (122.5)	2000[b] –	387.5 (178.5)	1008[b] (4113[b])	56.06 (32.9)
Labeo rohita	39.6 (27.2)	3000[a] –	98.4 (89.5)	3000[a] –	205.0 (101.0)	1690[b] (6720[b])	61.52 (53.76)
C. mrigala	44.0 (43.3)	2000[a] –	145.0 (115.0)	1500[b] –	275.0 (185.5)	1807[b] (4297[b])	70.76 (57.29)
C. carpio	57.7 (58.0)	1000[a] –	175.5 (140.2)	1500[b] –	340.0 (217.8)	833[b] (2734[b])	44.44 (36.45)
M. rosenbergii	28.8 (27.3)	1500[c] –	52.2 (43.5)	3500[c] –	78.2 (53.0)	630[c] (4669[c])	56.3 (46.7)

MBW, mean body weight, NH, number harvested. Figures in parentheses represent results of T_2. DAS represents days after stocking.

[a] Sold as fingerling @ Rs. 2.50/pc.

[b] Sold in market @ Rs. 50/kg.

[c] Sold in market @ Rs. 120/kg.

with the rice plants. This result is in agreement with the findings of Heckman (1979) and Kropff et al. (1993).

3.5. Impact of selective harvesting on growth, survival and yield of fish and prawn in rice–fish system

At a fixed population density, a higher growth rate was recorded for *C. catla* followed by *C. Carpio* and *C. Mrigala* (Table 4) in T_1. In T_2, a higher growth rate was recorded for *C. carpio* (Figs. 2 and 3). Similarly, the growth performance of *M. rosenbergii* was much higher in T_1 than in T_2. The impact of selective harvesting on the overall growth performance and yield of fish and prawns (Table 5) was reflected in the higher growth of all species after 120 days of rearing (Fig. 2) and a higher yield in T_1. A higher survival rate and a lower apparent feed conversion ratio (AFCR) were recorded in T_1. As density-dependent growth performance takes place at higher population densities (Mohanty, 2004), selective harvesting helped in reducing the size heterogeneity, weight distribution, and stunting growth of fish and prawns. Further, due to selective harvesting, the yields of fish and prawns were enhanced by 14.1%, while the AFCR increased by 26.5% (Table 5). The condition factor of cultured species was less than 1.0 (0.87–0.97) at the initial three weeks of rearing (monsoon phase) and improved thereafter (1.06–1.27) with gradual improvement in water quality (post-monsoon) in both T_1 and T_2.

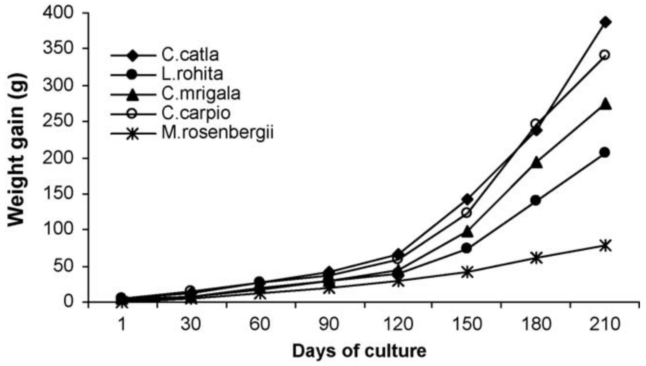

Fig. 2. Impact of selective harvesting on the growth performance of fish and prawns in the deepwater rice–fish system.

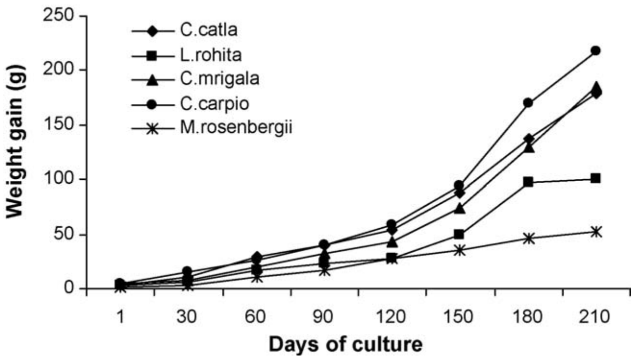

Fig. 3. Growth performance of the fish and prawns in the deepwater rice–fish system, without selective harvesting.

In both T_1 and T_2, bottom feeders (*C. carpio* and *C. mrigala*) registered better growth rates than column feeders (*L. rohita*), probably due to their superior feed utilizing capability and their high degree of tolerance to fluctuations of DO and TSS. Among bottom feeders, the growth performance of *C. carpio* appears to be much better than that of *C. mrigala* in both T_1 and T_2. The higher growth rates of *C. catla* (surface feeder), *C. carpio* and *C. mrigala* were attributed to their effective utilization of ecological niches and the rich detrital food web that was maintained through periodic manuring, liming and fertilization.

The comparatively slow growth and lower survival rate in T_2 was probably due to the fact that, under crowded conditions, fish and prawns suffer from stress due to aggressive feeding interactions and eat less, resulting in a retardation of growth (Zonneveld and Fadholi, 1991; Bjoernsson, 1994) and low survival (Procarione et al., 1999). Significantly higher yield ($p < 0.05$) and species-wise faster individual growth performance ($p < 0.05$) in T_1 than in T_2 probably were due to the periodic selective harvesting that minimized the competition for food and space among the cultured species.

An interesting trend in the growth performance of freshwater prawn, *M. rosenbergii*, was observed when grown together with fish in the rice–fish system. Higher growth was recorded in T_1 than in T_2 probably due to the periodic harvesting after 120 days of rearing (Table 4). Significantly higher mean body weights ($p < 0.05$) were recorded at 165 and 210 days of rearing. At 120 days after stocking (DAS), 61% of the population was below 20 g mean body weight (MBW) in T_1, which reduced sharply to 7.3% at 210 DAS. In T_2, 62% of the population was below 20 g MBW, which only declined to 23.7% at 210 DAS. Similarly, at 210 DAS, 12.5% of the population attained a MBW > 80 g in T_1, while none of the

Table 5
Impact of selective harvesting on the growth performance and yield of fish and prawns.

Species stocked	Initial MBW (g)	Per day increment, PDI (g)			Yield (t) from refuge	AFCR
		120 DAS	120–165 DAS	165–210 DAS		
C. catla	3.7	0.52	$2.8^{438.4}$	$4.33^{54.6}$	1.042 (0.734)	
L. rohita	3.0	0.30	$1.3^{333.3}$	$2.36^{81.5}$	0.760 (0.678)	
C. mrigala	4.8	0.33	$2.24^{578.7}$	$2.88^{28.5}$	0.802 (0.797)	1.77
C. carpio	4.0	0.45	$2.62^{482.2}$	$3.65^{39.3}$	0.604 (0.595)	(2.24)
M. rosenbergii	1.2	0.23	0.52^{126}	$0.57^{0.1}$	0.275 (0.247)	
			Total biomass=		3.48 (3.05)	

Figures in parentheses represent results of rice–fish culture without selective harvesting. Figures in superscript indicate percentage increase over previous PDI. AFCR is the apparent feed conversion ratio. DAS represents days after stocking. MBW is mean body weight.

population reached the target of 80 g MBW by 210 DAS in T_2. This reduction in growth in T_2 was probably due to the competition for food, space and physiological stress at higher density. This result agrees to the findings of Mohanty (2004).

Male freshwater prawns (*M. rosenbergii*) exhibit a high degree of heterogeneous individual growth (HIG), while the size distribution of the female population is rather homogeneous (Tidwell et al., 2003). Usually, three male morphotypes (SM—stunted male, OCM—orange clawed male and BCM—blue clawed male) represent three developmental stages of the male maturation process, undergoing transformation from SM $\gg$ OC $\gg$ BC. The SMs are the initial stage of the developmental pathway. The OCMs are sub-dominant and represent high somatic growth. The BCMs represent the terminal stage in the morphotypic transformation pathway. Once a set of prawns reaches the terminal stage, it inhibits the transformation of other morphotypes to successive stages, leading to a wide range of variation in the growth pattern. However, in this experiment of 210 days, the harvest of stunted males, orange clawed males, blue clawed males, virgin females and berried females in the T_1 were 7.3%, 39%, 36%, 14.7% and 3% respectively, while they were 23.7%, 27.3%, 11%, 13.5% and 24.5% respectively in T_2. In T_1, the periodic removal of berried females helped in promoting morphotypic transformation and the male maturation process. The periodic removal of blue-clawed males also minimized the stunted male population to 7.3% at 210 DAS, which was 22.6% at 165 DAS.

3.6. Effect of fish and prawn on the growth and yield of rice

The nitrogen, phosphorous, and potassium contents of the soil and water increase significantly when fish are stocked in rice fields (Oehme et al., 2007). The movements of fish and prawns in shallow water break the surface membrane formed by the microorganisms covering the soil. This helps increase the oxygen level in the soil and elevates its oxidation and reduction potential during the rice growth period. These changes effectively increase the utilization rate of soil nutrients by the rice plants. Therefore, fish in the rice–fish system promote more efficient use and distribution of NPK, while they also improve soil fertility and minimize the loss of fertilizer. Higher dry weights of the whole rice plant, NPK and chlorophyll contents of the leaves and stronger root system are usually observed in rice–fish systems. The larger surface area of the leaves and the higher content of chlorophyll increase the efficiency of photosynthesis (Yang et al., 2006). This helps in accumulation of more carbohydrates, thus increasing the number of effective ears, grains per ear, and grain weight.

In this study, the rice yield was not more than 3.25 t ha^{-1} in the presence of fish and 2.6 t ha^{-1} in rice mono-cropping. The higher water levels in this system likely decreased the number of panicles per m^2 and the rice yield. Vromant et al. (2002) reported that the increased water levels lowered the rice yield at a rate of 0.06 t ha^{-1} cm^{-1}. However, this high water level has a positive impact on fish growth and survival, though decreasing the rice yield. Bottom feeder fish such as common carp, are known to bring minerals and organic matter from the sediment into suspension through feeding activity. This results in increased water turbidity and particulate inorganic mater (PIOM) in the rice field, P release from the sediment and establishes contact between the benthic and pelagic compartments, which are otherwise fully separated. Moreover, the fish stimulate the growth of phytoplankton and increase the chlorophyll *a* concentration (Frei and Becker, 2005) in rice fields, thus competing with rice for nutrients and energy, resulting in a low rice yield, as in the case of T_2.

3.7. On-dyke horticulture and rabi (summer) crop

The peripheral dyke of the system was utilized for growing vegetables and other fruit trees including papaya and banana to make the system more economically viable. In this study, banana performed better than papaya, in terms of yield and survival. The average yields of brinjal, ladies finger, banana and papaya were 240 kg, 185 kg, 92 bunches and 435 kg per ha of rice–fish units respectively. The average yield of post-paddy second crop (black gram) was 0.78 t ha^{-1}. Before intervention, the study site was only a mono-cropped area. However, after post-paddy second crop, the cropping intensity of the site increased from 100% to 150%.

3.8. System's rice equivalent yield (REY) and water productivity

The highest REY (Table 2) was recorded in the T_4 (58.0) followed by T_1 (38.5), T_2 (35.5) and T_3 (2.6). The highest OV–CC ratio (1.56) in the rice–fish farming was recorded when selective harvesting was practiced (Table 6). The net returns from the different treatments were calculated to compute water productivity

Table 6
Ratio of the output value (OV) to the cost of cultivation (CC) of the integrated farming system (average of three experimental years).

Treatment	Output value (Rs. ha^{-1})	Cultivation cost (Rs. ha^{-1})	Net return (Rs. ha^{-1})	OV–CC ratio
Deep water rice mono-crop	13,000	10,900	2,100	1.19
Rice–fish (no selective harvesting) + A + B	193,095	143,098	49,997	1.35
Rice–fish with selective harvesting + A + B	208,220	133,685	74,535	1.56
Only fish & prawn culture without selective harvesting + B	297,090	224,780	72,310	1.32

(A) Low-duty second crop (black gram, *Phaseolus mungo*); (B) on-dyke horticulture; 1 USD = 47 INR.

considering the selling price of the additional produce from the on-dyke horticulture and low-duty second crop such as banana, papaya, brinjal, ladies finger, and black gram at Rs. 50.00 per bunch, Rs. 4.00 kg^{-1}, Rs. 5.00 kg^{-1}, Rs. 7.00 kg^{-1} and Rs. 15.00 kg^{-1}, respectively. The economic indices of gross water productivity were Rs. 12.52/m^3, Rs. 11.32/m^3, Rs. 0.96/m^3 and Rs. 16.83/m^3 for T_1, T_2, T_3 and T_4 respectively. In the rice–fish culture, enhanced gross (Rs. 12.52/m^3) and net (Rs. 7.30/m^3) water productivity were recorded when selective harvesting was practiced (T_1). This was probably due to the periodic income gained by selling the harvested fingerlings and the enhanced growth rates and yields of fish and prawns.

3.9. Economic evaluation

Rice–fish culture has the potential to enhance the net returns per unit-farmed area, as fish and prawns have a high market value compared to rice. Further, rice–fish culture makes multiple use of the rice field, thereby maximizing the utilization of land and water resources and can increase the production value of rice fields. In this study, the net returns from the rice–fish culture ranged between Rs. 49,997 ha^{-1} (T_2) and Rs. 74,535 ha^{-1} (T_1). This is a 23–35 fold increase relative to T_3 (Table 6). Moreover, in the rice–fish culture, when selective harvesting was practiced, the net return was enhanced further by 49%. This infers that the initial high stocking density, followed by selective harvesting in rice–fish culture is more beneficial than traditional rice–fish farming.

4. Conclusions

Rice–fish system in India promises ecologically sound and economically successful management of the waterlogged and lowland ecosystems. Recognition of its multi-ecological functions, such as its role in preserving biological diversity, protecting food security, and enriching soil quality must be achieved. In light of the present situation of India's rice–fish farming, basic research on rice–fish ecosystems should be emphasized, including research on the basic techniques of rice–fish farming, integrated techniques, and the technology required for engineering intervention. In rainfed lowland and waterlogged areas, *in situ* conservation of rainwater, short-duration aquaculture with rice, integration of horticulture on the embankment, and utilization of conserved water for growing low-duty *rabi* crops seems to be a viable solution for increasing the income of small and marginal farmers. This eco-friendly dual production system (rice and fish) in *kharif* and on-dyke horticulture that generate near-term lucrative returns and employment opportunities can be adopted and expanded in lowlands and waterlogged areas.

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