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Impact of phased harvesting on population structure, feed intake pattern and growth performance of *Macrobrachium rosenbergii* DeMan (giant freshwater prawn) in polyculture with carps in concurrent rice–fish culture

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Abstract This study was carried out to study the impact of phased harvesting on the population structure, feed intake pattern and growth performance of *Macrobrachium rosenbergii* in polyculture with carps in a deepwater rice–fish system. There were two experimental conditions—rice–fish culture with phased harvesting (T_1) and rice–fish culture without phased harvesting (T_2)— and a control, which consisted of rice monoculture without fish (T_3). In the T_1 trial, 61% of the population had a mean body weight (MBW) <20 g 120 days after stocking (DAS), which fell significantly to 7.3% at 210 DAS. However, in the T_2 trial, 62% of the population had a MBW <20 g at 120 DAS, which only fell to 23.7% at 210 DAS. Similarly, at 210 DAS, 12.5% of the population attained a MBW >80 g in the T_1 trial, while none of the population reached a MBW >80 g in the T_2 trial. The removal of fast-growing individuals in T_1 improved the prospects of other smaller individuals to achieve their individual growth potential. This step also disrupted the continuation of the socially induced differential growth rates, resulting in a wide variation in size within the population over time. The matrix of dietary overlap(s) of cultured species revealed that the degree of food preference was more similar between *Cyprinus carpio* and *M. rosenbergii* (0.9), while it overlapped poorly between *Catla catla* and *M. rosenbergii* (0.42). This high similarity index between bottom dwellers is evidence of the strong possibility that these bottom dweller compete for food. Natural and supplemental feed together with phased harvesting boosted the production of freshwater prawns (550 kg ha^{-1}) in the T_1 trial, while a 11.3% reduction in production was recorded in the T_2 trial.

Keywords Heterogeneous individual growth · *Macrobrachium rosenbergii* · Population structure · Satiation index · Rice–fish culture

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Introduction

Culture of the giant freshwater prawn, *Macrobrachium rosenbergii*, has drawn the attention of aquaculturists and fish farmers in many parts of the world because of its fast growth, adaptability to the polyculture environment and artificial feed, greater disease resistance than its marine counterparts and high market demand. The popularity of this species has resulted in it receiving the increasing attention of researchers in the search for innovative culture technology (New 2002). Much of the more recent research has been directed towards intensifying the production of *M. rosenbergii* without hampering average harvest sizes or deteriorating the quality of the water—i.e. in developing a 'best management practices' (BMPs) model (Tidwell et al. 2005)—and also evaluating its performance in a polyculture system in both earthen ponds (Daniels et al. 1995; New 2002; Haque et al. 2003; Tidwell et al. 2003) as well as other types of ecosystems (Uddin et al. 2006), mainly in a rice–fish system (Costa-Pierce 1992; Sadek and Moreau 1998; Lan et al. 2006; Mohanty et al. 2008; Kunda et al. 2008). In a monoculture system, the stocking of advanced juveniles between 0.3–0.5 g typically results in a production of 1,000 kg ha^{-1}, with a mean harvest weight of 30 g per individual; however, approximately 2,000 kg ha^{-1} or more with a mean harvest weight of more than 30 g per individual can be achieved under BMP (Tidwell et al. 2005). In a polyculture system, the yield is usually <500 kg ha^{-1}, but it is highly profitable as the polyculture approach generally involves a comparatively low stocking density of prawns and is economically lucrative as the pond can be managed exclusively for fish, thus requiring no special management considerations for prawns. The polyculture approach not only improves the ecological balance but also helps in increasing the performance of prawns relative to the monoculture or bi-species culture (Haque et al. 2003).

Mechanisms through which the stocking of an additional species contributes to increased food availability and improved environmental conditions largely depend on its specific place in the food web. In natural habitats, freshwater prawns prefer to forage on benthos and zooplankton. Since these natural food organisms grow well in the organic matter-rich paddy field environment, the culture of *M. rosenbergii* in a deepwater rice–fish system under polyculture provides an excellent economic opportunity for small-scale farmers. The integration of rice–fish and prawn culture is an ideal option for resource-poor farmers in Asia, where the efficiency of water, land and nutrient utilization can be improved (Halwart and Gupta 2004). However, there is a need to enhance the productivity and income by a suitable farming approach.

In freshwater prawn farming, several management practices (grading, added substrate, etc.) have proven to be effective in increasing production. However, the combination of these technologies (BMPs) has not been widely adopted in at the farmer's level and/or commercial culture because of the increased investment required. Given this background, I have made an attempt to enhance the productivity of the deepwater rice–fish and prawn system following simple management strategies, such as high-density initial stocking followed by selective/phased harvesting when the growth curve of the fish/prawns starts to slow down. As the removal of larger individuals from the stock through selective/phased harvesting helps smaller individuals achieve their growth potential and also improves water quality, this strategy would appear to be quite logical for short-duration rice–fish culture systems. An attempt was also made to study the population structure, feed intake pattern and growth performance of the giant freshwater prawn in a polyculture system that includes Indian major carps in a rice field refuge.

Materials and methods

An on-farm experiment was carried in Cuttack district (Lat. 20°15/N and Long. 86°03/E), Orissa, India, for three crops during 2004–2006. A patch of 2.0 ha waterlogged area was converted into two units of deepwater rice-fish system. Two treatments such as rice-fish culture with phased harvesting (T_1) and rice-fish culture without phased harvesting (T_2) was undertaken, each using one unit of rice-fish system. Another 1.0 ha adjacent land was kept as control i.e., rice monoculture without fish exclusively for deepwater rice mono crop only (T_3), to study the impact of fish and prawn on rice yield. 50% of the land (T_1 and T_2) was excavated up to a depth of 100 cm and the excavated soil was utilized for peripheral dyke construction up to a height of 2.5 m (Fig. 1). Due to unavoidable constraints in farmer's field, the experiment was carried out with three different treatments without replication and was repeated over years. Therefore, this on-farm study is descriptive in nature and mainly comparative study of differences between the productions responses were carried out using the data from the repeated experiment over 3 years.

Deepwater rice variety CR 683-123 was transplanted in unexcavated land (50% area, 5,000 m^2) in the T_1 and T_2 system and 100% area in the T_3 system during the third week of July in the first, second and third year of this study (2004, 2005 and 2006). The area under rice cultivation in the T_1, T_2 and T_3 systems were divided into four sub-plots in each trial. Rice plants were transplanted with a spacing of 20 × 20 cm (between rows and plants) in

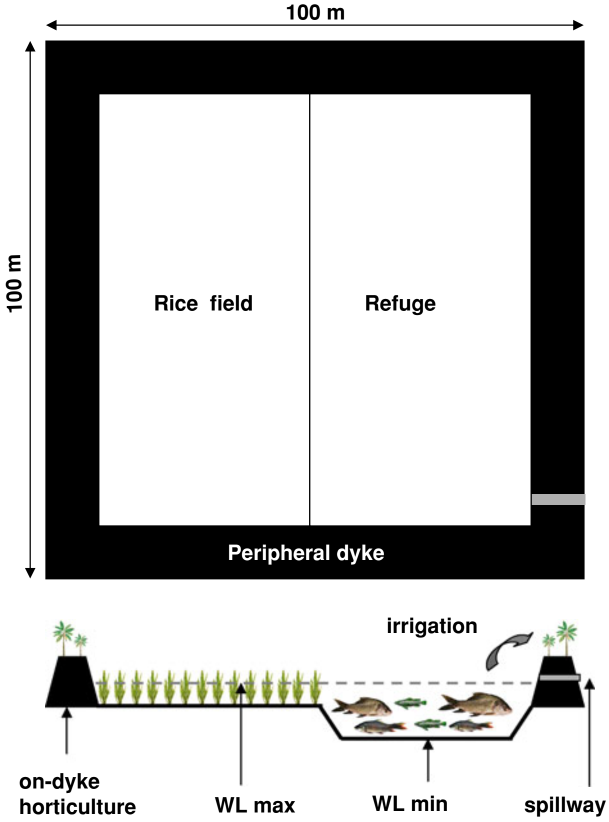


Fig. 1 Layout of 1-ha deepwater rice–fish system. *WL* Water level

all treatments. The fertilizer application rate was 80:60:40 (N:P:K) ha^{-1}. About 50% of the N and full doses of P and K were applied as the basis dose at the time of transplanting. The remainder of the N was applied in two equal doses during the tillering and panicle initiation stages, respectively (30 and 60 days after transplanting, DAT). Crop growth and yield parameters were recorded at regular intervals. No pesticide was used in the experimental plots to prevent fish mortality. Final yield and yield attributes of crops were recorded at the time of harvest. Standard agronomic and aquaculture practices (ICAR 1997; Sinha 1998) with a similar management strategy were followed during the three experimental trials.

Pre-stocking refuge (T_1 and T_2) preparation, such as horizontal and longitudinal ploughing followed by the application of lime ($CaCO_3$) at 750 kg ha^{-1}, raw cattle dung (RCD) at 7,000 kg ha^{-1} as a basal dose and fertilizer (urea:single super phosphate, 1:1) at 3 ppm, was carried out on days 1, 3 and 5, respectively, prior to stocking. About 7 days after refuge preparation (third week of July), early fish fingerlings [mean body weight (MBW) 3.0–4.8 g] and juveniles of *M. rosenbergii* (MBW 1.2 g) were stocked at a density of 100,000 ha^{-1} with a species composition of 25:25:15:15:20 (*Catla catla*:*Labeo rohita*:*Cirrhinus mrigala*:*Cyprinus carpio*:*M. rosenbergii*: 12,500:12,500:7500:7500:10,000) in the excavated refuge (5,000 m^2) of the T_1 and T_2 system. Supplemental feeding was provided as rice bran:mustard oil cake:fish meal (55:35:0) at 6, 5, 4 and 2.5% of MBW, twice a day, during the first four months leading up to harvesting, respectively. Periodic manuring with RCD at 500 kg ha^{-1} and liming at 200 kg ha^{-1} were carried out at 15-day intervals in the refuge to maintain the plankton population in the eco-system.

Phased/selective harvesting of fish and prawns in T_1 was undertaken twice, at 120 and 165 days after stocking (DAS). For each crop, fish and prawn rearing continued for 210 days. An artificial substrate, mainly broken asbestos and cement pipes, covering 10% of the bottom area of the refuge, was provided in a horizontal orientation for *M. rosenbergii* in order to prevent cannibalism during the moulting phase. Weekly evaluation of the interim weight distribution (%) and morphotypic existence (%) through sampling, using cast nets, was carried out. Since larger blue-clawed male individuals and virgin females within the population negatively impact on the growth and survival of smaller individuals, the former were removed from the T_1 system at 120 and 165 DAS. During phased harvesting, repeated netting in the refuge for removal of the bigger sized fish and cast netting for removal of larger/blue-clawed male and virgin female prawn individuals was carried out. The target was to remove 50% of the population during the two phased harvests.

Gut contents, degree of satiation (Mohanty 2003a), electivity indices of different food components (Ivlev 1961), frequency, abundance and matrix of dietary overlaps (Johnson 1999) were determined in order to study the food preference and feed intake pattern of cultured species. Each study year, 18 individuals of each species were sacrificed for this purpose. The weekly growth rate was studied by sampling prior to feeding so that complete evacuation of gut was ensured. Weekly MBW, per day increment (PDI), survival (SR, %), biomass (kg), feed requirement, percentage of feed consumed, feed requirement per day and apparent feed conversion ratio (AFCR) was estimated as described by Mohanty (1999).

Observations of water quality, soil quality, fish and prawn growth parameters, yield and yield components were carried out at regular intervals at the experimental site. Major physico-chemical parameters of 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 hours using standard methods (Biswas 1993; APHA 1995); these were cross checked using a multi-parameter water analyzer (YK-611; Yeo-Kal Electronics, 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) was studied using standard methods (Biswas 1993).

The net return and the ratio of the output value to the cost of cultivation (OV:CC) of the integrated farming system was estimated (Mohanty et al. 2008) taking into account the farm gate selling price of rice, fish fingerlings, prawns and marketable fish as 5.00, 2.50, 120.00 and 50.00 rupees (Rs.), respectively. The cost of the excavated refuge/pond, assuming a life span of up to 15 years, which is a fixed cost, was added (depreciated cost) to the yearly variable cost of cultivation. The cost of the excavated refuge/pond was estimated to be Rs. 135,000 ha^{-1}. The operational cost includes the cost of feed at Rs. 14.00 kg^{-1}; fish seed at Rs. 200.00 per 1,000 early fingerling; prawn seed at Rs. 0.5 per seed; raw cow dung at Rs. 500.00 per 1,000 kg; labor at Rs. 80.00 per man-day; lime at Rs. 4.50 per kg; other costs (cost of plant material, fertilizer etc.)

Results and discussion

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

At a fixed stocking density, a higher growth rate was recorded for *C. catla* followed by *C. Carpio* and *C. Mrigala* (Table 1) in the rice–fish culture with phased harvesting (T_1), while in the rice–fish culture without phased harvesting (T_2), a higher growth rate was

Table 1 Details of phased harvesting (T_1) on different days after stocking in concurrent rice-fish system

Species composition (25:25:15:15:20)	Cull harvesting						Final survival (%)
	First cull (120 DAS)		Second cull (165 DAS)		Final harvesting (210 DAS)		
	MBW (g)	NH	MBW (g)	NH	MBW (g)	NH	
M. rosenbergii	28.8	1,500^{a}	52.2	3,500^{a}	78.2	630^{a}	56.3
	(27.3)	–	(43.5)	–	(53.0)	(4,669^{a})	(46.7)
C. catla	66.7	4,000^{b}	192.6	2,000^{c}	387.5	1,008^{c}	56.06
	(53.5)	–	(122.5)	–	(178.5)	(4,113^{c})	(32.9)
L. rohita	39.6	3,000^{b}	98.4	3,000^{b}	205.0	1,690^{c}	61.52
	(27.2)	–	(89.5)	–	(101.0)	(6,720^{c})	(53.76)
C. mrigala	44.0	2,000^{b}	145.0	1,500^{c}	275.0	1,807^{c}	70.76
	(43.3)	–	(115.0)	–	(185.5)	(4,297^{c})	(57.29)
C. carpio	57.7	1,000^{b}	175.5	1,500^{c}	340.0	833^{c}	44.44
	(58.0)	–	(140.2)		(217.8)	(2,734^{c})	(36.45)

MBW Mean body weight, *NH* number harvested, *DAS* days after stocking

Figures in parenthesis represent results T_1

[a] Sold in market at Rs. 120/kg

[b] Sold as fingerling at Rs. 2.50 per/pc

[c] Sold in market at Rs. 50/kg

Table 2 Impact of phased harvesting (T_1) on growth performance and yield of fish and prawns

Species stocked	Initial MBW(g)	Per day increment (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)	

Numbers in parenthesis represent results of rice–fish culture without phased harvesting (T_2); superscripts indicate percentage increase over previous PDI

AFCR Apparent feed conversion ratio, *PDI* per day increment

recorded for *C. carpio*. Similarly, the growth performance of *M. rosenbergii* was much higher in T_1 than T_2. The impact of phased harvesting on the overall growth performance and yield of fish and prawn (Table 2) was reflected in the higher growth of all species after 120 days of rearing and a higher yield in T_1 (14.1% increase over T_2). Similarly, a higher survival and lower apparent feed conversion ratio was also recorded in T_1 than in T_2. In both T_1 and T_2, the condition factor of cultured species was <1.0 (0.87–0.97) during the initial weeks of rearing (monsoon phase) but improved there after (1.06–1.27) with a gradual improvement in water quality (post-monsoon).

In both T_1 and T_2, bottom feeder fishes (*C. carpio* and *C. mrigala*) registered a better growth rate than that of *L. rohita* (column feeder), probably due to its superior feed utilizing capability and high degree of tolerance to fluctuations of DO and TSS concentration. Among bottom feeders, the growth performance of *C. carpio* appeared to be much better than that of *C. mrigala* in both T_1 and T_2. The higher growth rate of *C. catla* (surface feeder), *C. carpio* and *C. mrigala* (bottom feeders) were attributed to their effective utilization of ecological niches and the presence of a rich detrital food web that was maintained through periodic manuring, liming and fertilization. The comparatively slow growth and lower survival in T_2 was probably due to the fact that, under crowded conditions, fish suffer from stress due to aggressive feeding interactions and eat less, resulting in growth retardation (Zonneveld and Fadholi 1991; Bjoernsson 1994) and low survival (Procarione et al. 1999). The higher yield and species-specific higher individual growth performance in T_1 than T_2 was probably due to the periodic phased harvesting that minimized the competition for food and space among the cultured species.

Size heterogeneity and weight distribution of M. rosenbergii

An interestingly trend in the growth performance of *M. rosenbergii* was observed when this species was grown together with fish in the rice–fish system. Higher growth was recorded in T_1 than in T_2 probably due to periodic harvesting after 120 days of rearing (Fig. 2). Based on R^2 statistics, individual regression fit with a high degree of predictability (Fig. 2). However, the slopes are not significantly different, although there is a visible difference in growth performance after the first phased harvesting (120 days onwards). This result was probably due to the fact that phased harvesting started after 120 days of rearing and the culture period was only for 210 days. In $T_{1,}$, at 120 DAS 61% of the population has a mean

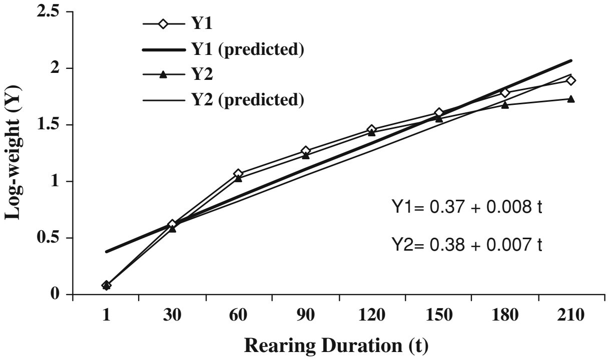


Fig. 2 Impact of phased harvesting on growth performance of *Macrobrachium rosenbergii* in concurrent rice-fish culture

Table 3 Size heterogeneity and weight distribution (%) of *M. rosenbergii* on different days of rearing in a deepwater rice–fish system in T_1

Days after stocking	Weight distribution (%)					
	<20 g	20–40 g	40–60 g	60–80 g	>80 g	MBW (g)
First cull, 120 DAS	61	39	–	–	–	28.8 (27.3)
	(62)	(38)	–	–	–	
Second cull, 165 DAS	30.0	33	34	3.0	–	52.2 (43.5)
	(42)	(33.3)	(24.7)	(–)	–	
Harvesting, 210 DAS	7.3	16.2	28.5 (33.9)	35.5 (11)	12.5	78.2 (53.0)
	(23.7)	(31.4)			(–)	

Figures in parenthesis represent results of rice-fish culture without phased harvesting (T_2)

MBW <20 g, which fell sharply to 7.3% at 210 DAS; in T_2, 62% of the population had a mean MBW <20 g, which only fell to 23.7% at 210 DAS. Similarly, at 210 DAS, 12.5% of the population attained a MBW >80 g MBW in T_1, while none of the population reached the target of 80 g MBW by 210 DAS in T_2 (Table 3). This reduction in growth in T_2 was probably due to the competition for food, space and physiological stress at higher density, which is in agreement with the findings of Mohanty (2004).

In Vietnam, the reported individual mean weight and net production of the freshwater prawn *M. rosenbergii* in a rice–fish system was between 32–38 g and 194–373 kg ha^{-1}, respectively, in a 210-day culture period with a stocking density varying from 10,000 to 40,000 post-larvae ha^{-1} (Lan et al. 2006). In Israel, a mean harvest weight of 46–48 g in a monoculture system of *M. rosenbergii* and 30 g in a polyculture system of *M. rosenbergii* with tilapia was obtained in rice fields during a 90-day culture period, with an average yield of 429–845 kg ha^{-1} in the monoculture system and 254 kg ha^{-1}in the polyculture system (Sadek and Moreau 1998). In Bangladesh, an average annual production of 390 kg ha^{-1} of freshwater prawns has been recorded in a polyculture system with finfish at a low density (Asaduzzaman et al. 2006). However, in the study reported here, the natural and supplemental feed, along with phased harvesting, boosted the production of freshwater prawn (550 kg ha^{-1}) in T_1 while in T_2, a reduction of 11.3% in production was recorded (Table 2). On the other hand, the surface feeder (*C. catla*) and column feeder (*L. rohita*) fed on the natural and supplemental food resources without—or with very little—competition from the freshwater prawn (Table 7), which did not affect the feed intake pattern and growth. Further, neither chlorophyll *a* nor plankton density varied significantly among the treatments, indicating insufficient grazing pressure on natural food by animals. Therefore, theoretically, the stocking density of the surface feeder (*C. catla*) and column feeder (*L. rohita*) had no negative impact on the growth performance of *M. rosenbergii*.

Morphotypic existence and population structure of M. rosenbergii

Among the various intrinsic and extrinsic factors associated with the culture of scampi, heterogeneous individual growth (HIG) represents a serious threat to farmers, resulting in heavy economic losses. *Macrobrachium rosenbergii* is known to exhibit a complex social organizational hierarchy consisting of morphologically distinct dominant, subdominant and subordinate groups. The predominance of a definite social hierarchy among the male morphotype increases the differential growth pattern within these prawns. The males show a high degree of HIG, while the size distribution of the female population is rather homogeneous (Tidwell et al. 2003). Three male morphotypes [stunted male (SM), orange-clawed male (OCM) and blue-clawed male (BCM)] usually represent the three developmental stages of the male maturation process, undergoing transformation from SM >> OC >> BC. The SMs are subordinate and not territorial, and they are the initial stage of the developmental pathway; OCMs are subdominant, representing highly somatic growth; BCMs represent the terminal stage in the morphotypic transformation pathway. Once a set of prawns reaches the terminal morphotype stage, it inhibits the transformation of other morphotypes to successive stages. This leads to a wide range of variation in the growth pattern. However, in this experiment of 210 DAS, the existence of stunted males (runt), OCMs, BCMs (dominant), virgin females and berried females in T_1 was 7.3, 39, 36, 14.7 and 3%, respectively (Table 4), while it was 23.7, 27.3, 11, 13.5 and 24.5%, respectively, in T_2. In T_1, the periodic removal of berried females, however, helped in facilitating morphotypic transformation and the male maturation process. The periodic removal of the BCMs (dominant) also minimized the 'runt' population to 7.3% at 210 DAS, which was 22.6% at 165 DAS in T_1. The removal of fast-growing individuals in T_1 improved the prospects of other smaller individuals to achieve their growth potential and also succeeded in disrupting the continuation of the socially induced, differential growth rates that result in a wide variations in size within the population over time.

Table 4 Impact of phased harvesting (T_1) on population structure and morphotypic existence (%) of *M. rosenbergii*

Morphotypes	Days after stocking (DAS)		
	120	165	210
Stunted male (runt) (subordinate)	34 (30)	22.6 (26)	7.3 (23.7)
Orange clawed male (subdominant)	22 (24)	30.9 (26)	39 (27.3)
Blue clawed male (dominate)	– (–)	2.5 (–)	36 (11)
Virgin female	44 (46)	31 (41.7)	14.7 (13.5)
Berried female	– (–)	13 (6.3)	3 (24.5)

Figures in parenthesis represent the results of rice-fish culture without phased harvesting (T_2)

Impact of fish and prawns on yield and yield components of rice

Rice variety CR-683-123 was grown under three different treatments (T_1, T_2 and T_3). The highest grain yield was recorded in T_1, mainly due to the contribution of a higher number of panicles m^{-2} (139.5) and number of filled grains per panicle (111.5). The percentage increase in grain yield over the rice monocrop was, however, higher in T_1 (25%) than in T_2 (16.9). The lower number of panicles (122.2/m^2) and filled grains per panicle (98.5/panicle) in the rice mono-crop was probably due to the absence of fish and prawns in the field, which helps to improve soil fertility, recover lost energy, and adjust energy flow by consuming plankton, weeds, insect and bacteria that compete with rice for nutrients (Mohanty 2003b; Mohanty et al. 2008). Between T_1 and T_2, the higher rice yield was recorded in the T_1 system (3250 kg ha^{-1}), probably due to the lower chlorophyll *a* (36.7 mg m^{-3}) and plankton density ($1.4 \times 10^4\ l^{-1}$) that minimized the competition for nutrients with rice plants. This result is in agreement with the findings of Heckman (1979) and Kropff et al. (1993).

Sediment and water quality in relation to prawns, fish and rice yield

The soil type of the experimental area was alluvial, and the textural class was acidic clay (pH 6.6–6.8), with the proportions of sand, silt and clay being 36.6, 19 and 44.4% respectively. Organic carbon and available N and P in the soil ranged between 0.16–0.19% and 7.9–10.1 and 1.28–1.63 mg 100 g^{-1}, respectively, at the initial stage of intervention, subsequently improving with the advancement of the crop cycle (Table 5). This improvement was likely due to: (1) additional nutrients from fish feed and fish feces, and (2) fish grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient recycling and minimizes N losses (Cagauan 1995) and facilitating P release from the sediment (Breukelaar et al. 1994). However, no distinct trend between the treatments was observed, and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee 1967).

When a rice field is stocked with fish, the nitrogen, phosphorous, and potassium (NPK) contents of the soil and water increases significantly (Oheme et al. 2007). Fish movements in the rice field break the surface membrane formed by the microorganisms covering the soil, increasing the DO level in the soil and elevating its oxidation and reduction potential during the period of rice growth. These changes improve the oxygen content and effectively increase the utilization rate of soil nutrients and thus the rice yield, as in the case of T_1 and T_2. Fish in the rice–fish system promote a more efficient use and distribution of NPK, thus reducing the loss of fertilizer and increasing soil fertility (Mohanty et al. 2008).

The recorded mean minimum and mean maximum values of various water quality parameters are presented in Table 5. Total suspended solid (TSS) and DO concentration showed a decreasing trend with the advancement of the crop cycle, while slightly higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the crop cycle. Other water quality parameters were within the suitable range for fish and freshwater prawn in the rice field refuge (Boyd and Zimmermann 2000; New 2002) and at any given point of time, these parameters and plankton population did not register any specific trend between the treatments. This lack of a trend was probably due to similar levels of input in all the treatments in the form of organic manure, inorganic fertilizer and periodic liming.

The abundance of plankton recorded in the present experiment (Table 5) was comparable to that found in normal fish culture ponds (Azim et al. 2004). Diatoms and green

Table 5 Minimum, maximum and average values of water and soil quality parameters in a concurrent rice–fish system

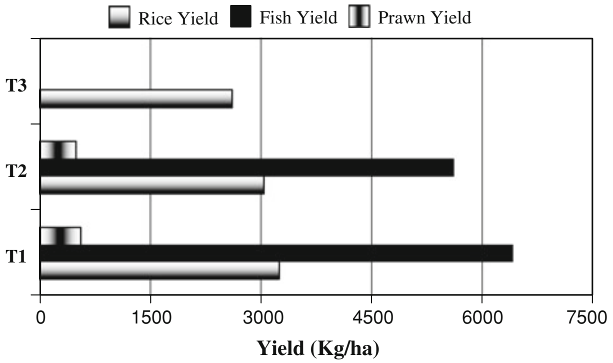
Parameters	T_1	T_2	T_3
Water pH	6.7–8.6 (7.63)	6.9–8.5 (7.31)	6.7–8.1 (7.52)
Dissolved oxygen (ppm)	3.8–9.3 (5.1)	3.3–8.4 (4.9)	4.4–8.9 (6.1)
Temperature (°C)	27.1–31.2 (28.4)	27.1–31.3 (28.4)	27.2–31.5(28.7)
Total alkalinity (ppm)	79–117 (106)	68–109 (94)	73–107 (88)
Dissolved organic matter (ppm)	1.3–6.2 (3.2)	1.45–4.8 (3.4)	0.55–3.6 (2.6)
TSS (ppm)	160–362 (213)	132–297 (225)	60–257 (177)
NH_4^+ water (ppm)	0.31–0.88 (0.65)	0.34–0.97 (0.68)	0.41–0.91 (0.59)
Chlorophyll-a (mg m^{-3})	20–51.5 (36.7)	21.1–62.2 (41.1)	18.8–31.3 (22.3)
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)
Nitrite—N (ppm)	0.009–0.06 (0.03)	0.012–0.072 (0.037)	0.011–0.07(0.033)
Nitrate—N (ppm)	0.06–0.51 (0.36)	0.05–0.49 (0.37)	0.16–0.61 (0.36)
Phosphate—P (ppm)	0.07–0.34 (0.21)	0.06–0.33 (0.21)	0.13–0.54 (0.26)
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)
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)
Organic carbon in soil (%)	0.44–0.76 (0.61)	0.49–0.82 (0.64)	0.57–0.75 (0.63)
Soil pH	6.6–7.1 (7.04)	6.8–7.1 (7.01)	6.8–7.1 (6.94)

Figures in parenthesis represent mean values

TTS Total soluble solid

algae mainly dominated the phytoplankton population while the zooplankton population was dominated by copepods and rotifers. Plankton density always has a profound effect on water quality and is therefore directly relationship with fish production (Smith and Piedrahita 1988; Yaro et al. 2005). In this experiment, a fluctuating trend in plankton density (7.3×10^3–3.3×10^4) was recorded in the different treatments (Table 5), which ultimately reflected the fish and rice yield in T_1 and T_2 (Fig. 3). In all the treatments, average primary production in the first month of cultivation ranged between 87.6–137 mg C m^{-3} h^{-1}, which improved further (407.5 ± 38.3 mg C m^{-3} h^{-1}) with the advancement of the crop cycle. 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 2003a).

Fig. 3 Prawn, fish and rice yield in concurrent rice–fish culture under the three trial conditions. *T_1* rice–fish culture with phased harvesting, *T_2* rice–fish culture without phased harvesting, *T_3* control (rice monoculture without fish)



The decreasing trend in DO in all of the treatments (except the rice mono-crop) with the advancement of the fish rearing period attributed to 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, 3 ppm for comfort 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 results in a decrease in the DO and pH value compared to rice mono-crop, especially when supplemental feed is given (Frei and Becker 2005). In general, cultured species show a poor growth performance at $pH < 6.5$ (Mount 1973), while higher values of total alkalinity (>90 ppm) indicate a better productive eco-system, and increased plankton density reflects the higher nutrient status of the water body. The availability of CO_2 for phytoplankton growth is related to total alkalinity (Mohanty 2003a), with water having 20–150 ppm total alkalinity producing suitable quantities of CO_2 to support plankton production. However, the recorded minimum and maximum total alkalinity during the experimental period (Table 5) was 68 and 117 ppm, respectively, which was maintained due to periodic liming. Gradual increases in nitrite, nitrate and ammonia were attributed to intermittent fertilization, increased level 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 competing 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 high pH values (7.3–7.6) together with high DO levels (6.6–7.2 ppm) and chlorophyll *a* values (36–42.2 mg m^{-3}) 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 mg m^{-3}), NH_4^+ (0.31–0.34 ppm), pH (6.7–6.9) and DO (3.3–4.4 ppm) decreased, which is an indication of reduced aquatic photosynthesis and suggests that the autotrophic pathway lost importance. With increasing rice biomass, the surface feeder (*C. catla*) and column feeders (*L. rohita*) gradually switched from feeding on plankton/algal biomass to supplemental feed and to a diet primarily composed of detritus (Table 6). This process results in interspecific competition (Table 7) with bottom feeders (*C. mrigala*, *C. carpio* and *M. rosenbergii*), which is in agreement with the findings of Chapman and Fernando (1994) and Vromant et al. (2004).

Table 6 Average percentage of individual gut content volume (abundance) and percentage of analyzed species in which the mentioned food components were found (frequency) in the deepwater rice–fish system

Food component	Abundance (%)					Frequency (%)				
	1	2	3	4	5	1	2	3	4	5
Supplemental feed	61.7+	49.3+	56.7+	46.1+	45.8+	77.8	77.8	72.2	88.8	83.3
Phytoplankton	4.3−	5.1−	11.2−	2.7−	2.3−	72.2	83.3	94.4	66.6	55.6
Zooplankton	1.6−	4.3−	5.9−	1.9−	1.4−	44.4	83.3	88.8	72.2	44.4
Detritus + Mud	21.0−	15.4−	5.6−	32.1+	29.1+	77.8	22.2	11.1	88.9	94.4
Benthos	16.4−	1.0−	–	12.2−	12.2−	61.1	5.5	–	55.6	44.5

1, *M. rosenbergii*; 2, *L. rohita*; 3, *C. catla*; 4, *C. carpio*; 5, *C. mrigala*; +, more than; −, less than

Table 7 Matrix of dietary overlap(s) of fingerling to advanced fingerling stage of fish and prawn in the deepwater rice–fish system

Species	*C. catla*	*L. rohita*	*C. mrigala*	*C. carpio*	*M. rosenbergii*
C. catla	–	0.7	0.52	0.52	0.42
L. rohita	–	–	0.56	0.52	0.45
C. mrigala	–	–	–	0.85	0.83
C. carpio	–	–	–	–	0.9
M. rosenbergii	–	–	–	–	–

Food preference and intake pattern of fish and prawn in the rice-fish system

In the rice–fish integration system, phytoplankton and zooplankton were the most preferred food item for *C. catla* and *L. rohita*, while mud and detritus were highly preferred by *C. mirgala*, *C. carpio* and *M. rosenbergii* (Table 6). However, quantity-wise, the most consumed food items were artificial supplemental feeds. Among the bottom dwellers (*C. mrigala*, *C. carpio* and *M. rosenbergii*), phytoplankton and benthos were preferred more by *M. rosenbergii*, while zooplankton and detritus were more preferred by *C. carpio* and *C. mrigala*, respectively. Among the bottom feeders, the growth performance of *C. carpio* appeared to be much better than that of *C. mrigala*, probably due to the superior feed utilizing capability of the former (Sinha 1998). Omnivorous feeding behavior was observed for each species except *C. catla*, while the degree of omnivorous feeding behavior was high in *M. rosenbergii*, which agrees with the findings of Lee et al. (1980). The estimated degree of satiation (index of gutfulness) at the fingerling stage was high in *C. carpio*, followed by *C. catla, L. rohita, C. mrigala* and *M. rosenbergii* in descending order. The highest satiation index was observed for *C. carpio* and the lowest for *C. catla* at the advanced fingerlings stage (Table 8). The comparative degree of satiation indicated a distinct declining trend from the fingerling stage to the advanced fingerling stage in each species. This was probably due to the relatively low nutritional value of the ingested matter (mud and debris) and comparatively lower preference for artificial feed at the initial stage of rearing. These results lend support to the findings of Spataru (1976). The intestine index ($I.I = L_1/SL$; where L_1 = length of intestine and SL = standard length of fish) values of all analyzed fish varied from 6.7 to 9.8, and no correlation was found with the standard length. These higher values of intestine index are typical of planktivorous, detritivorous and phytobenthophagous fishes.

Table 8 Estimated degree of satiation (F_I) of fish and prawn in the deepwater rice–fish system

Species	F_I			
	Fingerling stage in T_1	Advanced fingerling stage in T_1	Fingerling stage in T_2	Advanced fingerling stage in T_2
C. catla	5.9 ± 0.5	2.7 ± 0.4	5.4 ± 0.6	3.1 ± 0.4
L. rohita	5.1 ± 0.3	4.1 ± 0.5	5.1 ± 0.5	4.1 ± 0.6
C. mrigala	4.7 ± 0.3	4.2 ± 0.3	4.9 ± 0.5	4.4 ± 0.4
C. carpio	6.2 ± 0.5	5.3 ± 0.4	6.6 ± 0.4	5.7 ± 0.5
M. rosenbergii	5.2 ± 0.4	4.7 ± 0.1	5.6 ± 0.3	4.9 ± 0.1

$F_I = w \times 100/W$; where, w is the weight of the gut content and W is the weight of an individual fish/prawn

Positive indices of electivity were observed for phytoplankton during the monsoon (winter), while they were negative for zooplankton during the same period. Negative indices of electivity for zooplankton (−0.16 to −0.44) of all species were recorded during the monsoon (winter: August–November) and improved thereafter. This was probably due to rich detrital food web in the initial phase of rearing when raw cattle dung was applied at 7,000 kg ha^{-1} for refuge preparation prior to stocking. However, positive indices of electivity for zooplankton were observed during December only in case of *C. catla, L. rohita* and *C. carpio*. Similarly, positive indices of electivity (0.07–0.38) for phytoplankton were observed for all species during August–October (monsoon), while these were negative thereafter, probably due to an increased density of zooplankton. The matrix of dietary overlap(s) of cultured species in the deep water rice–fish integration system (Table 7) revealed that the degree of food preference was more similar between *C. carpio* and *M. rosenbergii* (0.9), while it was poorly overlapped between *C. catla* and *M. rosenbergii* (0.42). This high similarity index between bottom dwellers established a stronger possibility of competition for food among each other.

System's economic evaluation

Rice-fish culture has the potential to enhance the net return per unit area farmed, as fish and prawn have a high market value than to rice. In addition, rice–fish culture systems make multiple use of the rice field, thereby maximizing the utilization of land and water resources, and they can increase the production value of rice fields. In the study reported here, net return from rice–fish culture ranged between Rs. 49,997.00 ha^{-1} in T_2 to Rs. 74,535.00 ha^{-1} in T_1 (1 USD = approx. 47 INR), which is a 23–35 fold increase relative to T_3 (Rs. 2100.00). Moreover, the in rice–fish culture, when phased harvesting was practiced, the net return was enhanced further by 49%. Similarly, the OV:CC ratio was higher in T_1 (1.56) than in T_2 (1.35) and T_3 (1.19), inferring that the initial high stocking density, followed by phased harvesting, in concurrent rice–fish culture is more beneficial than traditional rice-fish farming.

Conclusion

The culture of *M. rosenbergii* in polyculture with carps in a concurrent rice–fish system provides an excellent economic opportunity for small-scale farmers as there is an improvement in the efficiency of water, land and nutrient utilization. Although several management practices, such as grading, added substrate, among others, in combination (BMPs), have increased the production of giant freshwater prawn, the poor adoption of BMPs at the farmer's level is mainly due to the increased investment required. However, without much input/investment, the growth performance and production of *M. rosenbergii* can be enhanced, if a simple strategy of high-density initial stocking followed by phased harvesting is practiced. This practice is designed to minimize the major limiting factors of seasonal culture, the limited duration of the growing season and the growth-impacting social interactions. The removal of fast-growing individuals from the population not only improves the prospects of smaller individuals to achieve their individual growth potential, but it also succeeds in disrupting the continuation of the socially induced, differential growth rates, which results in a wide variation in size within the population over time. Moreover, in rice–fish culture, when phased harvesting is practiced, the net return was enhanced further by 49%. The high similarity index (degree of food preference) between

C. carpio and *M. rosenbergii* infers the strong possibility that they compete for food at the bottom layer; this can be avoided through the total exclusion or reduction in the density of *C. carpio* in the species composition so that the performance of freshwater prawn will improve further in this system.

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