Integrated Cage-Cum-Pond Culture Systems With High-Valued Stinging Catfish (*Heteropneustes fossilis*) in Cages and Low-Valued Carps in Open Ponds

Eleventh Work Plan, Production System Design and Integration Research 3A (11PSDR3A)
Final Report

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Printed as Submitted

Abstract

An experiment was conducted over 237 days at Bangladesh Agricultural University to adapt an integrated cage-cum-pond system to local conditions in Bangladesh, to determine appropriate stocking density of fish in cages, to assess growth and production of fishes in both cages and open ponds, and to assess the economic and environmental benefits of this integrated system.

Stinging catfish and carp were stocked in cages and open water of ponds to give caged to open-pond fish ratios of 0.5:1, 1:1, 1.5:1, and 2:1 as four treatments with three replicates each. Stinging catfish fingerlings with a mean weight of 12.6 g were stocked at 50, 100, 150, and 200 fish per 0.85-m^3 cage, while fingerlings of silver carp (*Hypophthalmichthys molitrix*), catla (*Catla catla*), rohu (*Labeo rohita*) and common carp (*Cyprinus carpio*) were stocked at 100 fish per pond with a species ratio of 2:2:3:3 in open water of all ponds. Commercial pelleted feed (30% crude protein) was given to caged fish twice daily at a rate of 10% body weight per day. No feed or fertilizer was added into open water of the ponds.

Survival of caged catfish was low, ranging from 39.33% to 60.67% with the highest survival in the 1:1 treatment. Caged catfish in all treatments grew slowly, giving daily weight gains of about 0.06 g $fish^{-1}$. Net yields in the 0.5:1 and 1:1 treatments were 0.10 and 0.18 kg m^{-3} $crop^{-1}$, respectively, while the other two treatments gave negative net yields. FCRs were extremely high in the 0.5:1 and 1:1 treatments (131 and 148, respectively), while FCRs were negative in the 1.5:1 and 2:1 treatments (-66 and -311, respectively). Survival of open-pond carps was high, ranging from 71.67% to 100% without significant differences for each carp species among all treatments. All carp species grew steadily throughout the experimental period, with daily weight gains of 0.76 to 1.62 g $fish^{-1}$. Net and gross yields of all carps were significantly higher in the 1:1, 1.5:1 and 2:1 treatments than in the 0.5:1 treatment. Overall FCRs were best in the 2:1 treatment (0.42), intermediate in the 1:1 and 1.5:1 treatments (0.76 and 0.59, respectively), and poorest in the 0.5:1 treatment (0.86). Net revenues were positive but low in all treatments. This experiment demonstrated the potential of the cage-cum-pond integrated culture system, but more research is needed.

INTRODUCTION

The integrated cage-cum-pond culture system includes high-valued fish species fed with artificial diets in cages suspended in ponds, and filter-feeding fish species stocked to utilize natural foods derived from cage wastes. This integrated system has been developed and practiced using combinations of catfish-tilapia (Lin, 1990; Lin and Diana, 1995) and tilapia-tilapia (Yi et al., 1996; Yi, 1997; Yi and Lin, 2000, 2001). Although cages were set up in Nile tilapia monoculture ponds in previous work, this integrated system can be applied to polyculture systems. In polyculture, ponds are stocked with several species of different feeding habits together. It is impossible to target feeding to only the high-valued species at large in ponds. Compared to the nutrient utilization efficiency of about 30% in most intensive culture systems (Beveridge and Phillips, 1993; Acosta-Nassar et al., 1994), the nutrient utilization efficiency could reach more than 50% in integrated cage-cum-pond systems, resulting in the discharge of fewer nutrients to receiving waters (Yi, 1997).

Rural pond aquaculture in Bangladesh is mainly semi-intensive polyculture of both Indian major and Chinese carps, with low average production of 2.8 tons $ha^{-1}year^{-1}$ (DoF, 2001). Pond production systems in many countries are increasingly reliant on external resources (feed and/or fertilizer) to supplement or stimulate autochthonous food production for fish. Such a system often discourages small-scale farmers because of the low return on investment. On the other hand, such poor farmers have limited financial resources to adapt their whole ponds to culture high-valued species using expensive artificial feed. The integrated cage-cum-pond system provides an opportunity for small-scale farmers to use their limited resources to include small amount of high-valued species in their ponds, to generate more income and improve their livelihood. This can be achieved through marketing high-valued species, improved nutrient utilization efficiency, and reduced fertilizer cost, because fish in open water can utilize cage wastes and no fertilization is required. In Bangladesh, stinging catfish (*Heteropneustes fossilis*) is an important, high-valued indigenous species, and can be cultured in cages at high densities due to its air-breathing ability. Stinging catfish may be a suitable species for stocking cages in order to develop an integrated cage-cum-pond culture system in Bangladesh.

The specific objectives of this study were to:

1. Adapt the integrated cage-cum-pond systems developed by Aquaculture CRSP to local conditions in Bangladesh;
2. Determine appropriate stocking density of selected fish species in cages;
3. Assess growth and production of fishes in both cages and open ponds; and
4. Assess the economic and environmental benefits of this integrated system.

METHODS AND MATERIALS

This experiment was conducted in 12 earthen ponds of 100 m^2 in surface area and average depth of 1.5 m at the Field Laboratory of the Faculty of Fisheries, Bangladesh Agricultural University, Mymensingh, from 5 September 2003 to 29 April 2004. Stinging catfish and carps were stocked in cages and open water of ponds to give caged to open-pond fish ratios of 0.5:1, 1:1, 1.5:1, and 2:1 as four treatments with three replicates each. Stinging catfish fingerlings with a mean weight of 12.6 g were stocked at 50, 100, 150, and 200 fish per 0.85-m^3 cage, while fingerlings of silver carp (*Hypophthalmichthys molitrix*), catla (*Catla catla*), rohu (*Labeo rohita*) and common carp (*Cyprinus carpio*) were stocked at 100 fish per pond with a species ratio of 2:2:3:3 in open water. One cage (1 x 1 x 1 m) was suspended 15 cm above the pond bottom at the middle of each pond, giving a water volume of 0.85 m^3. Cages were made with iron rods covered by net, and were supported by two vertical and one horizontal bamboo poles for each cage. Carps and stinging catfish were stocked on 5 September 2003, however, stinging catfish suffered from high mortality in the first month, and was restocked on 16 October 2003. All caged catfish were counted and bulk weighed biweekly, while open-pond carps were sampled monthly using a cast net. All fish were harvested on 29 April 2004.

Commercial pelleted feed (30% crude protein) was supplied on a feeding tray (42 x 26 x 4 cm), which was hung in each cage. Caged fish were fed twice daily at 10% body weight per day. Feed ration was adjusted fortnightly based on sampling weight and observed mortality of catfish. No feed or fertilizer was added into the open water of the ponds.

Water depth in ponds was maintained at 1 m deep during the experimental period. Water was added biweekly into ponds to replace losses through evaporation and seepage. Water quality parameters were measured on 15-day intervals at 1000 h, using standard methods (APHA et al., 1999). A portable digital DO meter (Lutron, DO-5509) and pH meter (CORNING, 445) was used to measure dissolved oxygen (DO) and pH, respectively. Column water samples were taken at 1000 h for analyses of other water quality parameters. Total alkalinity and chlorophyll *a* were determined following APHA et al. (1999). Soluble reactive phosphorus (SRP), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N) and total ammonia nitrogen (TAN) were determined using a HACH Kit (DR 2010), while total nitrogen (TN) and total phosphorus (TP) were determined using a HACH Kit (DR-4000).

Nutrient utilization efficiency in terms of nitrogen and phosphorus was calculated based on nutrients inputted from pelleted feed and harvested by fish. TN and TP contents in monthly feed samples and fish samples at stocking and harvest were determined using the methods described by Black et al. (1965).

An analysis was conducted to determine economic returns of the integrated cage-cum-pond culture system for each treatment (Shang, 1990). The analysis was based on market prices in Bangladesh for harvested fish and all other items, which was expressed in Bangladesh TK (USD 1 = 60 TK). Market prices of harvested carps and stinging catfish were 50 and 300 TK kg^{-1}. Market prices of carp and catfish fingerlings (2 and 3 TK $piece^{-1}$, respectively) and pelleted feed (15 TK kg^{-1}) were used.

Data were analyzed statistically by one-way analysis of variance and linear regression (Steele and Torrie, 1980) using SPSS (version 11.0) statistical software (SPSS Inc., Chicago, USA). Differences were considered significant at an alpha of 0.05. Means were given with ± standard error (S.E.).

RESULTS

Survival of stinging catfish in cages was low, ranging from 39.33% to 60.67%. The highest survival was obtained in the 1:1 treatment, followed by the 0.5:1, 2:1, and 1.5:1 ($P < 0.05$; Table 2). Stinging catfish in all treatments grew slowly but in a similar pattern, showing linear growth during the first two months, almost no growth during the middle two and a half months, then linear growth again in the last two months (Figure 1). Mean catfish weight at harvest was not significantly different among treatments ($P > 0.05$), giving similar daily weight gain of about 0.06 g $fish^{-1}$ (Table 1). There were no significant differences in net yields among the four treatments ($P > 0.05$; Table 1), with net yield ranging from –0.47 to 0.18 kg m^{-3}. Gross yields were positively correlated with stocking densities of stinging catfish in cages ($r = 0.87$, $P < 0.001$). FCRs were extremely high in the 0.5:1 and 1:1 treatments (131 and 148, respectively), while FCRs were negative in the 1.5:1 and 2:1 treatments (-66 and -311, respectively) (Table 1).

Survival of carps was high, ranging from 71.67% to 100% without significant differences among treatments for each carp species ($P > 0.05$, Table 2). All carp species grew steadily throughout the experimental period, with daily weight gains of 0.76–1.62 g $fish^{-1}$ for silver carp, 0.29–0.61 g $fish^{-1}$ for catla, 0.37–0.68 g $fish^{-1}$ for rohu, and 0.32–0.42 g $fish^{-1}$ for common carp (Figure 2; Table 2). All growth and production parameters for silver carp were not significantly different among treatments ($P > 0.05$), while those of catla and rohu were significantly poorer in the 0.5:1 treatment than in other treatments ($P < 0.05$, Table 2). The growth and production parameters were best in the 1:1 treatment, intermediate in the 1.5:1 and 2:1 treatments, and poorest in the 0.5:1 treatment ($P < 0.05$, Table 2). Net and gross yields of all carps were significantly higher in the 1:1, 1.5:1 and 2:1 treatments than in the 0.5:1 treatment ($P < 0.05$, Table 2).

Combined gross and net yields of carps and stinging catfish were not significantly different among treatments from 1:1 to 2:1 ($P > 0.05$), but were significantly higher than in the 0.5:1 treatment ($P < 0.05$, Table 3). Overall FCRs were best in the 2:1 treatment (0.42), intermediate in the 1:1 and 1.5:1 treatments (0.76 and 0.59, respectively), and poorest in the 0.5:1 treatment (0.86) ($P < 0.05$; Table 3).

Water temperature measured at 1000 h ranged from 17.0 to 30.5 °C, while DO concentration at 1000 h fluctuated between 1.8 and 9.2 mg L^{-1} without significant differences among treatments ($P > 0.05$, Figure 3, Table 4). Overall mean and final values of pH in the 0.5:1 treatment were significantly higher than those in other treatments ($P < 0.05$), which did not differ each other significantly ($P > 0.05$). Total alkalinity was quite high and changed in a similar pattern in all treatments (Figure 3). Final values of total alkalinity were not significantly different among treatments ($P > 0.05$), however, the overall mean values were highest in the 2:1 treatment, intermediate in the 0.5:1 and 1:1 treatments, and lowest in the 1.5:1 treatment ($P < 0.05$, Table 4). Final concentrations of NO_3-N and TP did not differ among treatments ($P > 0.05$). However, the overall mean values of NO_3-N were significantly higher in treatments with higher densities in cages ($P < 0.05$), while the overall mean TP concentrations were significantly higher in 0.5:1 and 1:1 treatments compared to the 1.5:1 and 2:1 treatments ($P < 0.05$, Table 4). Overall mean concentrations of chlorophyll *a* were not significantly different among treatments ($P > 0.05$), while the final concentrations were highest in the 1:1 treatment, intermediate in the 0.5:1 treatment, and lowest in the 1.5:1 and 2:1 treatments ($P < 0.05$). The final and overall mean values of all other measured water quality parameters did not differ among treatments ($P > 0.05$, Table 4). Concentrations of TAN and nitrite nitrogen remained at low levels in most of the experimental period, while nitrate nitrogen and TN showed more fluctuation throughout the experiment (Figure 4). Concentrations of SRP, TP, TSS, and chlorophyll *a* fluctuated throughout the experiment, and all but TP exhibited increasing trends towards the end of the experiment (Figures 5 and 6).

Caged stinging catfish in the 0.5:1 treatment incorporated 1% of input nitrogen, catfish in the 1:1 and 2:1 treatments harvested about 0.54% of input nitrogen, while the incorporated nitrogen percentage in the 1.5:1 treatment was negative ($P < 0.05$, Table 5). More than 99% of input nitrogen entered into the ponds as waste. Nitrogen recovered by silver carp ranged from 10.78% to 14.71% without significant differences among treatments. The nitrogen recovery percentage by catla in the 0.5:1 treatment (5.97%) was not significantly different from that in the 1:1 treatment (5.56%), but were significantly higher than those in the 1.5:1 and 2:1 treatments (4.51% and 2.81%, respectively) ($P < 0.05$). Nitrogen recovery percentages by rohu were highest in the 0.5:1 and 1:1 treatments (15.50% and 13.29%, respectively), intermediate in the 1.5:1 treatment (11.99%), and lowest in the 2:1 treatment (8.91%) ($P < 0.05$). The nitrogen recovered by common carp in the 0.5:1 and 1:1 treatments (11.84% and 14.37%, respectively) was significantly higher than in the 1.5:1 and 2:1 treatments (8.49% and 6.70%) ($P < 0.05$). The total nitrogen recovery by all fish, ranging from 29.74% to 49.02%, decreased with increasing stocking density of stinging catfish in cages, while nitrogen in wastes, ranging from 50.98% to 70.26%, increased with increasing stocking density of stinging catfish in cages ($r = 0.81$, $n = 12$, $P < 0.01$).

Caged stinging catfish incorporated -9.3% to 2.32% of input phosphorus from feed without significant differences among treatments, and more than 97% of phosphorus entered into the ponds as waste (Table 5). Phosphorus recovery by silver carp was not significantly different among all treatments, while recoveries by catla and rohu were significantly higher in the 0.5:1, 1:1, and 1.5:1 treatments than in the 2:1 treatment ($P < 0.05$). Common carp recovered significantly higher percentages of input phosphorus in the 0.5:1 and 1:1 treatments than in the 1.5:1 and 2:1 treatments ($P < 0.05$). The total phosphorus recovery by all fish, ranging from 42.75% to 69.86%, decreased with increasing stocking density of stinging catfish in cages, while phosphorus in wastes, ranging from 30.14% to 57.25%, increased with increasing stocking density of stinging catfish in cages ($r = 0.80$, $n = 12$, $P < 0.01$).

Revenues from harvested catfish in all except 1.5:1 treatments exceeded the cost for catfish fingerlings (Table 6). Revenues from carps in the 0.5:1 treatment were significantly lower than those in other treatments ($P < 0.05$), which did not significantly differ from each other (Table 6). Gross revenues were highest in the 2:1 treatment, intermediate in the 1:1 and 1.5:1 treatments, and lowest in the 0.5:1 treatments ($P < 0.05$). Costs related to the catfish increased significantly with stocking density ($P < 0.05$). Net returns were 618 TK pond^{-1} in the 1:1 treatment, which was significantly higher than those in other treatments (325–351 TK; Table 6).

DISCUSSION

Survival of the air-breathing stinging catfish was quite low, compared with other air-breathing fish such as hybrid catfish (*Clarias macrocepharus* x *C. gariepinus*). Survival rate of caged hybrid catfish ranged from 54% to 92% (Lin et al., 1989; Lin, 1990), which was higher than in the present experiment (39.33 to 60.67%). Mass mortality occurred during the first three weeks after first stocking of the stinging catfish in this experiment, and hooks were found in the stomachs of many fish. Due to unavailability of artificially produced stinging catfish fingerlings, wild seeds were purchased from fishing farmers. For the second stocking, the low survival rate might also have been caused by low quality of wild seed and high stocking density.

Stinging catfish is an indigenous and high-valued fish species in Bangladesh. However, little research and no breeding programs have been undertaken to improve growth and production performance of this species. This is a common problem for indigenous fish species in many countries. Growth of stinging catfish was very poor in the present experiment. Density might not be the main reason, evidenced by the non-significant growth differences across stocking densities. Poor quality of wild catfish fry and low temperature may be the main reasons for poor growth. This experiment was conducted during September-April, most of which (November-February) was winter. Low temperature could cause low feed intake and resultant poor growth. Due to low survival and extremely poor growth, FCRs were very high and even negative.

Survival of all carps was very high in this experiment, thought Survival of catla was slight lower than the other species. Survival of catla in presence of silver carp was also lower in other studies, due mainly to food and space competition between these two species (Wahab et al., 1994). Growth and yields of carps in the present experiment were generally good. Net and gross yields of carps ranged from 1.5 to 2.6, and 2.4 to 3.5 t ha^{-1} year^{-1}. The extrapolated annual yields were comparable to those reported by Yi et al. (in press) but higher than those in other studies (Haq et al., 1994; Wahab et al., 1999; Hossain et al., 2001) conducted using carp polyculture at the same location.

Net and gross yields were significantly lower in the lowest density catfish treatment than in higher density treatments, due mainly to higher feed inputs and resultant higher loading of waste nutrients from cages to open ponds. In integrated cage-cum-pond culture systems, waste derived from cages can effectively support growth of filter-feeding species such as Nile tilapia in the open-pond, and the growth of open-pond fish increases with increasing nutrient loading from cages (Lin, 1990; Lin and Diana, 1995; Yi et al., 1996; Yi, 1997; Yi and Lin, 2000, 2001). However, waste released from cages to ponds in the present experiment was mainly in the form of feed materials instead of metabolic wastes of catfish, which may explain the good growth of common carp.

Nutrients released from cage wastes fertilized ponds at rates of 0.25–0.92 kg N and 0.04–0.16 kg P ha^{-1} day^{-1} in the system with stinging catfish and carps, which were similar to releases (0.62–1.09 kg N and 0.12–0.22 kg P ha^{-1} day^{-1}) in a cage-cum-pond culture system with tilapia and tilapia (Yi et al., 1996), but lower than rates (1.75 kg N and 0.37 kg P ha^{-1} day^{-1}) in tilapia-tilapia and hybrid catfish-tilapia systems (3.71-8.06 kg N and 1.01-2.20 kg P ha^{-1} day^{-1}; Lin and Diana, 1995; Lin and Yi, 2003). Compared to other cage-cum-pond systems, fish yields achieved in the present experiment corresponded to nutrient loading from cages. The optimal ratio of caged catfish to open-pond carps, and consequent optimal nutrient loading from cages, could not be determined due to poor survival and growth of caged catfish.

Although low to negative net yields of stinging catfish were recorded in this experiment, revenues from selling the catfish were more than the cost of catfish seeds in all except the 1.5:1 treatment. This was due mainly to the premium price of stinging catfish even at small size. The high value stinging catfish has potential to be cultured in a cage-cum-pond system, but further improvements are needed. Cage-cum-pond systems might open up a new horizon of pond fish culture for both poor and rich fish growers in Bangladesh and South Asia. However, availability and quality of catfish seed is a constraint for such a system. Alternative available air-breathing fish species in Bangladesh, such as indigenous *Clarias* catfish, African catfish (*Clarias gariepinus*) and climbing perch (*Anabas testudineus*), may be potential candidates to be cultured in cages of similar systems.

Anticipated Benefits

This technology may be further improved and adopted to the local conditions in Bangladesh. It could provide small-scale rural farmers an opportunity to generate more income and improve their livelihood using their scare resources if it is successfully developed. Such development could benefit small-scale rural farmers in Asia, where integrated systems are practiced.

Acknowledgements

The authors wish to acknowledge the Bangladesh Agricultural University (BAU) for providing the field and laboratory facilities. The assistance of the Director of BAU Research System is thankfully recognized for administrative support. M.S. Kabir, A.J.M. Rakibullah, M.B. Hossain, and the staff of BAU Fisheries Field Laboratory and Water Quality and Pond Dynamics Laboratory are greatly appreciated for field and lab assistance. Derun Yuan and Aye Aye Mon of AIT are thanked for their contribution to data analysis and report preparation.

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Table 1. Performance of stinging catfish stocked in each treatment.

Performance	Ratio of Caged Catfish to Open-Pond Carps			
	0.5:1	1:1	1.5:1	2:1
STOCKING				
Total Weight (kg cage^{-1})	0.64±0.00^{a}	1.27±0.01^{b}	1.88±0.00^{c}	2.54±0.02^{d}
Mean Weight(g fish^{-1})	12.7±0.1	12.7±0.1	12.6±0.0	12.7±0.1
HARVEST				
Total Weight (kg cage^{-1})	0.72±0.04^{a}	1.42±0.05^{b}	1.49±0.17^{b}	2.41±0.36^{c}
Mean Weight (g fish^{-1})	25.0±0.4	23.5±0.5	25.1±1.2	25.1±1.4
Daily Weight Gain (g fish^{-1} day^{-1})	0.06±0.00	0.06±0.00	0.06±0.01	0.06±0.01
Net Yield (kg m^{-3})	0.10±0.05	0.18±0.07	-0.47±0.19	-0.15±0.45
Gross Yield (kg m^{-3})	0.84±0.05^{a}	1.67±0.06^{b}	1.75±0.20^{b}	2.84±0.42^{b}
FCR	131	148	-66	-311
Survival (%)	57.33±2.67^{ab}	60.67±1.45^{a}	39.33±3.06^{c}	47.67±4.67^{bc}

* Mean values with different superscripts in the same row were significantly different ($P < 0.05$).

Table 2. Performance of carps stocked in each treatment.

Performance	Ratio of Caged Catfish to Open-Pond Carps			
	0.5:1	1:1	1.5:1	2:1
Silver Carp				
STOCKING				
Total Weight (kg pond^{-1})	0.50±0.01	0.49±0.02	0.47±0.01	0.45±0.02
Mean Weight (g fish^{-1})	25.0±0.6	24.5±0.9	23.6±0.5	22.4±0.1
HARVEST				
Total Weight (kg pond^{-1})	3.84±0.53	6.82±1.40	6.60±0.44	6.91±0.55
Mean Weight (g fish^{-1})	205.2±25.8	365.9±77.8	349.0±32.2	407.2±6.3
Daily Weight Gain (g fish^{-1} day^{-1})	0.76±0.11	1.44±0.33	1.37±0.13	1.62±0.03
Net Yield (t ha^{-1} crop^{-1})	0.33±0.05	0.63±0.14	0.61±0.04	0.65±0.06
Gross Yield (t ha^{-1} crop^{-1})	0.38±0.05	0.68±0.14	0.66±0.05	0.69±0.06
Survival (%)	93.33	93.33	95.00	85.00
Catla				
STOCKING				
Total Weight (kg pond^{-1})	0.53±0.00	0.51±0.02	0.47±0.01	0.48±0.02
Mean weight (g fish^{-1})	26.5±0.1	25.6±1.1	23.3±0.5	24.0±1.0
HARVEST				
Total Weight (kg pond^{-1})	1.62±0.08^{a}	2.45±0.14^{b}	2.54±0.21^{b}	2.42±0.09^{b}
Mean Weight (g fish^{-1})	94.9±6.9^{a}	139.1±8.2^{b}	157.0±15.8^{b}	169.3±6.0^{b}
Daily Weight Gain (g fish^{-1} day^{-1})	0.29±0.03^{a}	0.48±0.04^{b}	0.56±0.06^{b}	0.61±0.02^{b}
Net Yield (t ha^{-1} crop^{-1})	0.11±0.01^{a}	0.19±0.02^{b}	0.21±0.02^{b}	0.19±0.01^{b}
Gross Yield (t ha^{-1} crop^{-1})	0.16±0.01^{a}	0.25±0.01^{b}	0.25±0.02^{b}	0.24±0.01^{b}
Survival (%)	86.67	88.33	81.67	71.67
Rohu				
STOCKING				
Total Weight (kg pond^{-1})	2.87±0.03	2.90±0.08	2.76±0.03	2.80±0.05
Mean Weight (g fish^{-1})	95.6±1.0	96.8±2.7	91.9±1.0	93.4±1.9
HARVEST				
Total Weight (kg pond^{-1})	5.48±0.35^{a}	7.03±0.19^{b}	7.06±0.48^{b}	7.46±0.20^{b}
Mean Weight (g fish^{-1})	182.8±11.6^{a}	234.46±6.4^{b}	238.1±16.9^{b}	254.8±12.6^{b}
Daily Weight Gain (g fish^{-1} day^{-1})	0.37±0.05^{a}	0.58±0.03^{b}	0.62±0.08^{b}	0.68±0.05^{b}
Net Yield (t ha^{-1} crop^{-1})	0.26±0.03^{a}	0.41±0.02^{b}	0.43±0.05^{b}	0.47±0.02^{b}
Gross Yield (t ha^{-1} crop^{-1})	0.55±0.03^{a}	0.70±0.02^{b}	0.70±0.05^{b}	0.75±0.02^{b}
Survival (%)	100.00	100.00	98.89	97.75
Common Carp				
STOCKING				
Total Weight (kg pond^{-1})	2.39±0.12	2.27±0.19	1.71±0.16	1.72±0.01
Mean Weight (g fish^{-1})	79.7±4.0^{a}	75.8±6.3^{a}	57.2±5.3^{b}	57.4±0.2^{b}
HARVEST				
Total Weight (kg pond^{-1})	4.67±0.07^{a}	6.48±0.03^{c}	5.05±0.25^{ab}	5.48±0.34^{b}
Mean Weight (g fish^{-1})	155.7±2.4^{a}	223.6±5.0^{b}	187.7±11.1^{ab}	198.5±22.6^{ab}
Daily Weight Gain (g fish^{-1} day^{-1})	0.32±0.02^{a}	0.62±0.01^{b}	0.55±0.03^{b}	0.60±0.10^{b}
Net Yield (t ha^{-1} crop^{-1})	0.29±0.02^{a}	0.42±0.02^{c}	0.33±0.02^{b}	0.38±0.03^{bc}
Gross Yield (t ha^{-1} crop^{-1})	0.47±0.01^{a}	0.65±0.01^{c}	0.51±0.02^{ab}	0.55±0.03^{b}
Survival (%)	100.00	96.67	90.00	93.33
All Carps				
Net Yield (t ha^{-1} crop^{-1})	0.99±0.10^{a}	1.65±0.17^{b}	1.58±0.09^{b}	1.69±0.08^{b}
Gross Yield (t ha^{-1} crop^{-1})	1.56±0.09^{a}	2.28±0.16^{b}	2.12±0.10^{b}	2.23±0.08^{b}

* Mean values with different superscripts in the same row were significantly different ($P < 0.05$).

Table 3. Combined performance of stinging catfish and carps in each treatment.

Performance	Ratio of Caged Catfish to Open-Pond Carps			
	0.5:1	1:1	1.5:1	2:1
Initial Fish Biomass (kg pond^{-1})	6.92±0.13^{a}	7.45±0.20^{b}	7.30±0.16^{ab}	8.00±0.07^{c}
Final Fish Biomass (kg pond^{-1})	16.34±0.98^{a}	24.21±1.63^{b}	22.73±1.20^{b}	24.69±0.47^{b}
Biomass Gain (kg pond^{-1})	9.42±1.09^{a}	16.76±1.72^{b}	15.43±1.05^{b}	16.69±0.41^{b}
Net Fish Yield (t ha^{-1} crop^{-1})	1.07±0.01^{a}	1.80±0.02^{b}	1.18±0.01^{b}	1.56±0.01^{b}
Gross Fish Yield (t ha^{-1} crop^{-1})	1.63±0.11^{a}	2.42±0.17^{b}	2.27±0.10^{b}	2.47±0.04^{b}
Overall FCR	0.86±0.08^{a}	0.76±0.09^{ab}	0.59±0.02^{bc}	0.42±0.03^{c}

* Mean values with different superscripts in the same row were significantly different ($P < 0.05$).

Table 4. Final and overall mean values of water quality parameters each treatment.

Parameters	Ratio of Caged Catfish to Open-Pond Carps			
	0.5:1	1:1	1.5:1	2:1
Final values				
DO (mg L^{-1})	2.93±0.22	2.67±0.15	2.90±0.61	3.37±0.52
Temperature (C)	29.0±0.0	29.0±0.0	29.0±0.0	29.0±0.0
pH	7.55±0.15^{a}	7.05±0.09^{b}	6.86±0.04^{b}	7.01±0.11^{b}
Total Alkalinity (mg L^{-1})	148±9	132±10	146±8	165±6
TAN (mg L^{-1})	0.29±0.05	0.22±0.03	0.24±0.04	0.35±0.10
NO_3-N (mg L^{-1})	0.03±0.00	0.03±0.01	0.03±0.01	0.06±0.01
NO_2-N (mg L^{-1})	0.01±0.00	0.00±0.00	0.01±0.00	0.01±0.00
TN (mg L^{-1})	0.97±0.12	1.03±0.20	1.17±0.03	1.33±0.22
SRP (mg L^{-1})	0.33±0.12	0.19±0.07	0.10±0.02	0.16±0.03
TP (mg L^{-1})	1.19±0.39	1.24±0.18	1.08±0.12	0.97±0.14
TSS (mg L^{-1})	117±4	136±4	152±15	156±14
Chlorophyll *a* (µg L^{-1})	151±35^{ab}	179±9^{a}	96±7^{b}	104±6^{b}
Secchi Disk Visibility (cm)	19±1^{ab}	17±0^{a}	18±1^{b}	18±1^{b}
Overall mean values				
DO (mg L^{-1})	4.98±0.90	4.27±0.98	4.32±0.82	4.32±0.87
Temperature (C)	26.0±2.4	26.0±2.4	26.0±2.4	26.0±2.4
pH	7.66±0.23^{a}	7.32±0.21^{b}	7.29±0.22^{b}	7.30±0.21^{b}
Total Alkalinity (mg L^{-1})	154±22^{b}	143±22^{ab}	132±17^{a}	169±20^{c}
TAN (mg L^{-1})	0.25±0.17	0.25±0.12	0.40±0.67	0.37±0.17
NO_3-N (mg L^{-1})	0.02±0.01^{a}	0.04±0.02^{a}	0.06±0.02^{b}	0.08±0.03^{c}
NO_2-N (mg L^{-1})	0.01±0.00	0.01±0.00	0.01±0.01	0.01±0.01
TN (mg L^{-1})	1.14±0.54	1.06±0.29	1.23±0.43	1.22±0.33
SRP (mg L^{-1})	0.24±0.06	0.16±0.07	0.16±0.09	0.24±0.29
TP (mg L^{-1})	1.39±0.35^{a}	1.42±0.44^{a}	1.00±0.23^{b}	1.00±0.28^{b}
TSS (mg L^{-1})	98±24	109±23	99±21	99±22
Chlorophyll *a* (µg L^{-1})	127±38	141±35	138±45	128±35
Secchi Disk Visibility (cm)	19±2^{ab}	17±2^{a}	20±3^{b}	20±3^{b}

* Mean values with different superscripts in the same row were significantly different ($P < 0.05$).

Table 5. The efficiency of nutrient recovery from feed in different treatments.

Parameter	Ratio of Caged Catfish to Open-Pond Carps			
	0.5:1	1:1	1.5:1	2:1
NITROGEN				
Total Input (g)	493.18±13.28[a]	1,009.91±21.62[b]	1,184.44±51.05[c]	1,800.09±75.02[d]
Recovered by Caged Catfish				
(g)	5.01±1.57	5.51±0.77	-9.58±3.73	11.18±17.36
(%)	1.00±0.30[a]	0.54±0.07[ab]	-0.84±0.35[b]	0.54±0.97[ab]
Recovered by Silver Carp				
(g)	73.17±14.07[a]	134.05±32.41[ab]	146.82±12.54[b]	191.59±21.42[b]
(%)	14.71±2.45	13.42±3.49	12.37±0.72	10.78±1.66
Recovered by Catla				
(g)	29.45±2.07[a]	55.95±2.74[b]	53.52±7.17[b]	50.40±0.69[b]
(%)	5.97±0.37[a]	5.56±0.38[ab]	4.51±0.53[b]	2.81±0.13[c]
Recovered by Rohu				
(g)	76.85±10.14[a]	133.77±9.98[b]	143.09±18.23[b]	158.95±13.35[b]
(%)	15.50±1.72[a]	13.29±1.22[a]	11.99±1.07[ab]	8.91±1.03[b]
Recovered by Common Carp				
(g)	58.41±3.06[a]	144.72±7.08[c]	99.65±10.58[b]	120.09±12.65[bc]
(%)	11.84±0.44[a]	14.37±1.01[a]	8.49±1.11[b]	6.70±0.80[b]
Total N Recovered by Fish				
(g)	242.89±27.66[a]	473.99±45.56[b]	433.49±30.84[b]	532.21±16.26[b]
(%)	49.02±4.30[a]	47.17±5.59[ab]	36.52±1.29[bc]	29.74±2.14[c]
Total N Wasted				
(g)	250.29±14.55[a]	535.92±67.16[b]	750.95±24.70[c]	1,267.88±89.93[d]
(%)	50.98±4.30[a]	52.83±5.59[ab]	63.48±1.29[bc]	70.26±2.14[c]
PHOSPHOROUS				
Total Input (g)	84.14±2.27[a]	172.29±3.69[b]	202.07±8.71[c]	307.09±12.80[d]
Recovered by Caged Catfish				
(g)	1.98±0.53	2.56±0.52	-1.76±1.47	5.79±4.62
(%)	2.32±0.58	1.48±0.29	-0.93±0.77	1.77±1.47
Recovered by Silver Carp				
(g)	18.01±3.44[a]	34.74±7.66[b]	37.86±2.22[b]	49.38±3.86[b]
(%)	21.23±3.51	20.37±4.88	18.74±0.78	16.24±1.96
Recovered by Catla				
(g)	8.25±0.80[a]	16.38±1.42[b]	15.30±1.90[b]	14.40±0.47[b]
(%)	9.80±0.84[a]	9.55±1.04[a]	7.58±0.86[a]	4.69±0.12[b]
Recovered by Rohu				
(g)	15.64±2.18[a]	28.40±0.67[b]	31.19±3.75[b]	31.47±2.24[b]
(%)	18.48±2.17[a]	16.52±0.71[a]	15.33±1.24[a]	10.33±1.09[b]
Recovered by Common Carp				
(g)	15.24±1.78[a]	32.68±2.00[c]	25.42±2.46[b]	29.78±2.43[bc]
(%)	18.03±1.66[a]	19.02±1.48[a]	12.68±1.54[b]	9.71±0.78[b]
Total P Recovered by Fish				
(g)	59.12±7.99[a]	114.79±10.28[b]	108.01±6.11[b]	130.82±0.50[b]
(%)	69.86±7.63[a]	66.95±7.48[a]	53.39±0.94[ab]	42.75±1.88[b]
Total P Wasted				
(g)	25.01±5.74[a]	57.51±13.96[a]	94.06±3.03[b]	176.28±13.08[c]
(%)	30.14±7.63[a]	33.05±7.48[a]	46.61±0.94[ab]	57.25±1.88[b]

Table 6. Economic analysis for each treatment.

Parameter (TK $Pond^{-1}$)	Ratio of Caged Catfish to Open Pond Carps			
	0.5:1	1:1	1.5:1	2:1
GROSS REVENUE				
Catfish	216±13[a]	427±15[b]	446±50[b]	724±107[c]
Carps	781±47[a]	1,139±82[b]	1,062±52[b]	1,114±38[b]
Total	997±57[a]	1,566±82[b]	1,508±99[b]	1,838±76[c]
OPERATION COST				
Catfish Fingerlings	150±0[a]	300±0[b]	450±0[c]	600±0[d]
Carps Fingerlings	200±0	200±0	200±0	200±0
Cage	110±0	110±0	110±0	110±0
Pelleted Feed	165±4[a]	338±0[b]	397±17[c]	603±25[d]
Total	625±4[a]	948±0[b]	1,157±17[c]	1,513±25[d]
NET RETURNS	371±52[a]	618±87[b]	351±83[a]	325±51[a]

* Mean values with different superscript letters in the same row were significantly different ($P < 0.05$).

Figure 1. Growth of stinging catfish for each treatment.

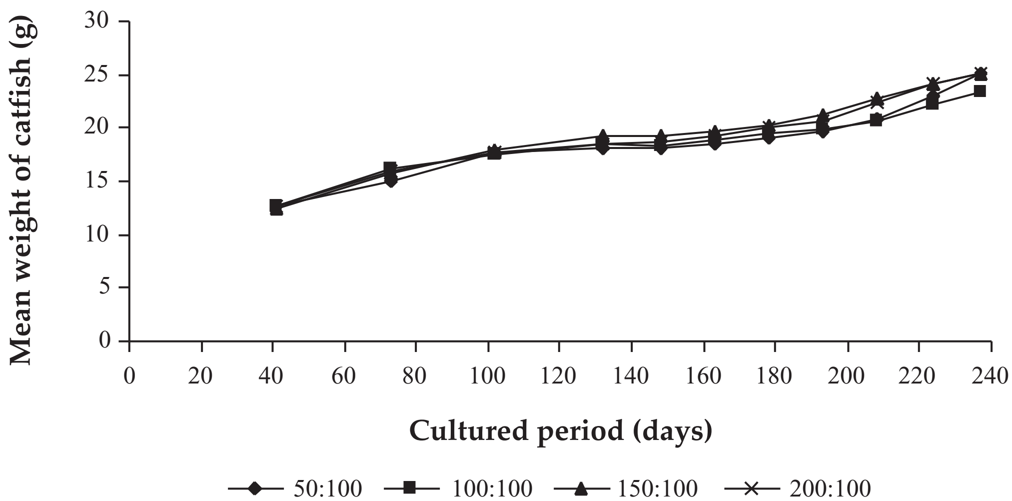


Figure 2. Growth of carps in open ponds for each treatment.

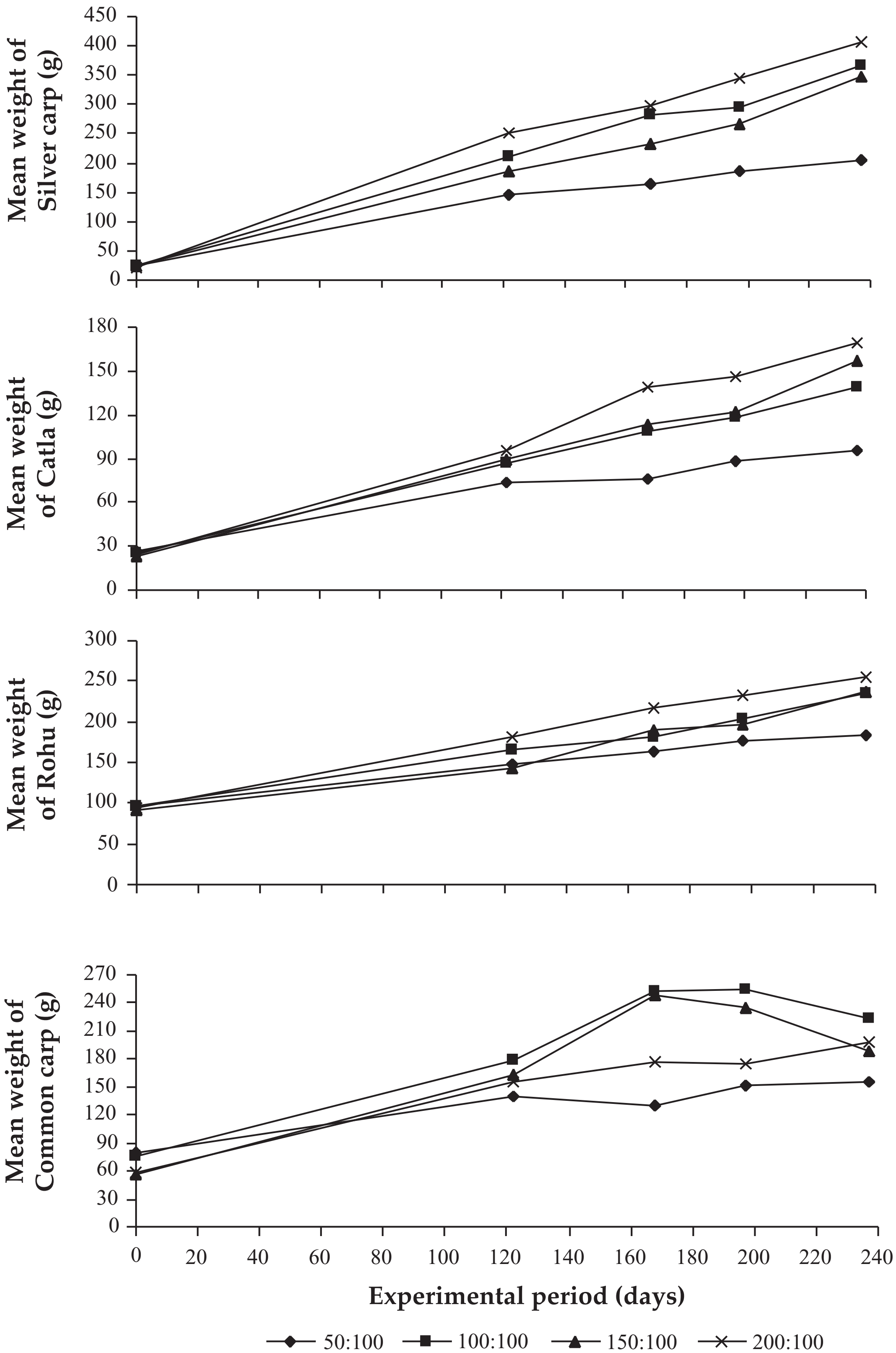


Figure 3. Changes of DO, pH, and total alkalinity at 1000 h in each treatment.

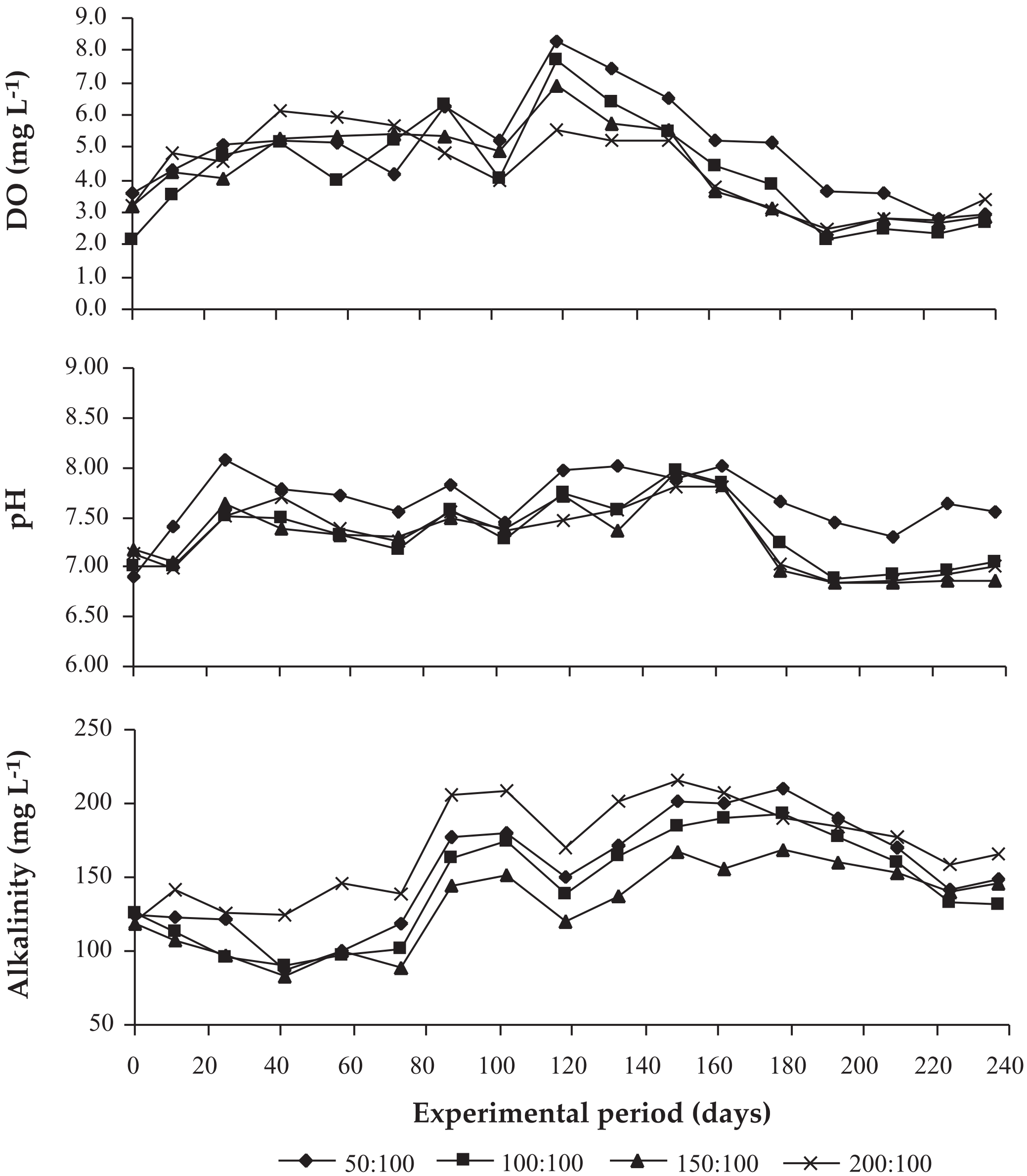


Figure 4. Changes in total ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, and total nitrogen at 1000 h in each treatment.

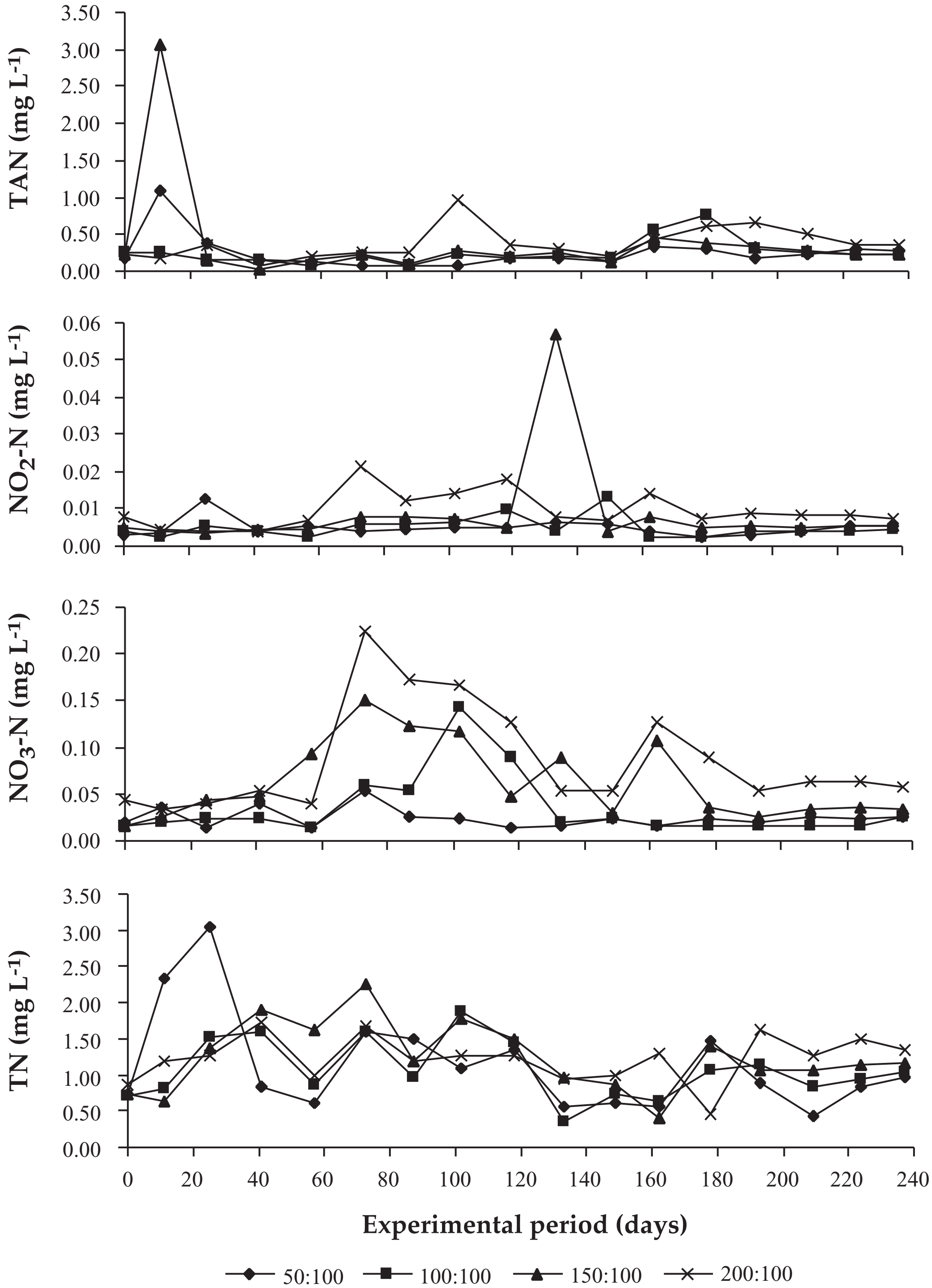


Figure 5. Changes in total phosphorous and soluble reactive phosphorus at 1000 h in each treatment.

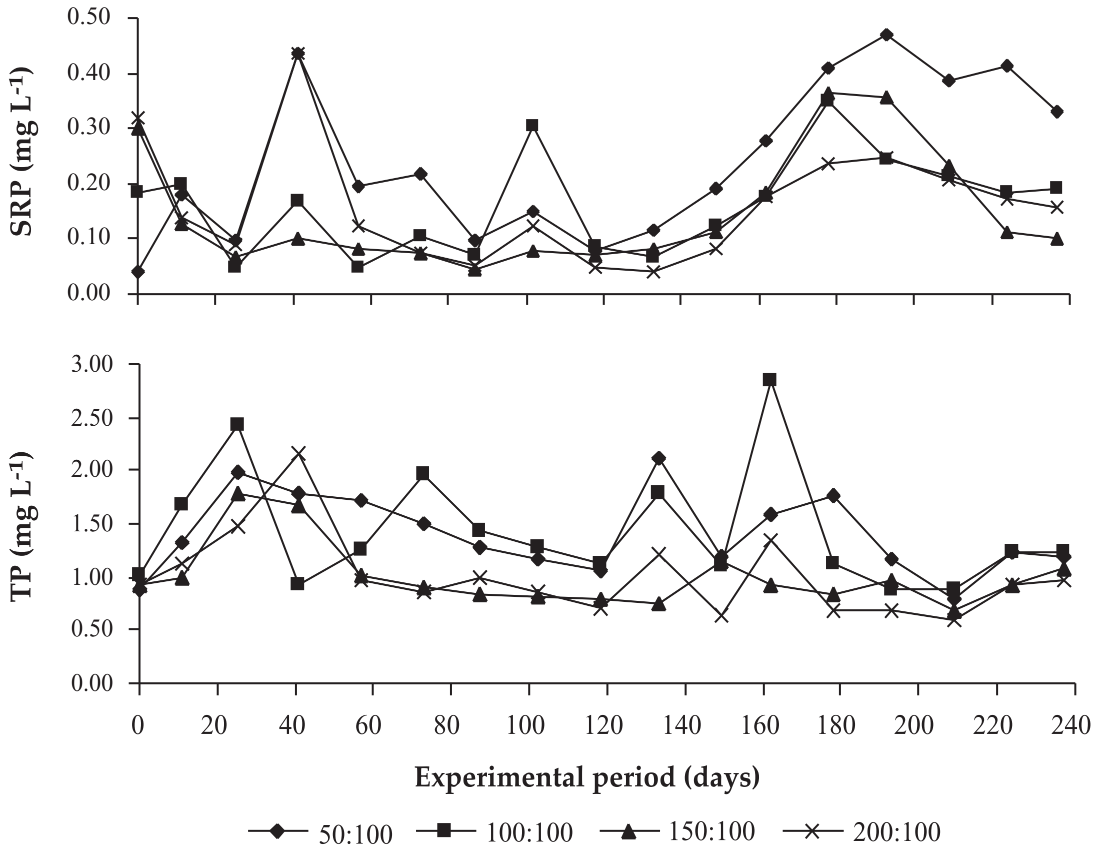
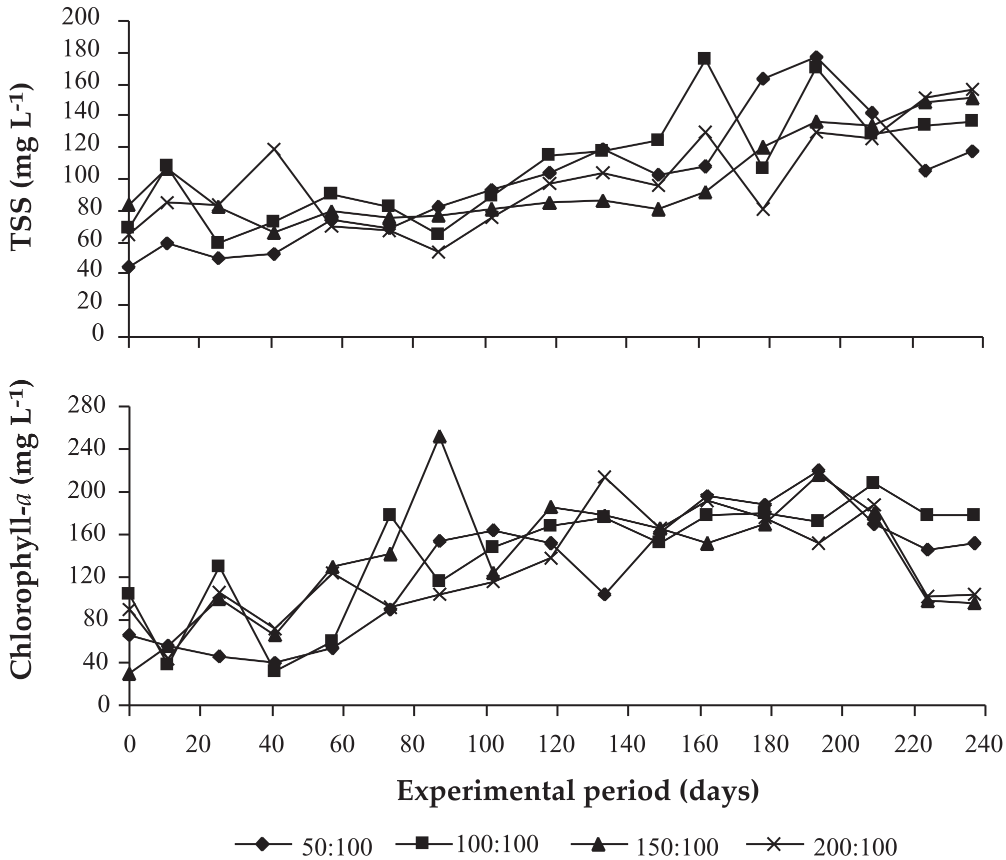


Figure 6. Changes in total suspended solids and chlorophyll a at 1000 h in each treatment.



Cite as: [Author(s), 2005. Title.] In: J. Burright, C. Flemming, and H. Egna (Editors), Twenty-Second Annual Technical Report. Aquaculture CRSP, Oregon State University, Corvallis, Oregon, [pp. ___.]