GLOBAL EXPERIMENT: OPTIMIZATION OF NITROGEN FERTILIZATION RATE IN FRESHWATER TILAPIA PRODUCTION PONDS

Eighth Work Plan, Thailand Feeds and Fertilizers Research 1 (FFR1T)
Progress Report

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ABSTRACT

Two experiments were conducted in eighteen 200-m^2 earthen ponds at the Asian Institute of Technology, Thailand, for 91 days from 4 June to 3 September 1998. The first experiment was designed to: 1) determine the optimal rate of nitrogen fertilization; 2) determine which of the nitrogen fertilization rates evaluated to produce Nile tilapia (*Oreochromis niloticus*) had the greatest profitability; and 3) develop a full-cost enterprise budget for the fertilization level that resulted in the greatest profitability. Treatment ponds with triplicates each were fertilized with TSP at a rate of 8 kg P ha^{-1} wk^{-1} and with urea at 0, 10, 20, and 30 kg N ha^{-1} wk^{-1}. Sex-reversed male Nile tilapia, 10.1 to 10.9 g in size, were stocked at 1,000 kg ha^{-1} in all ponds (10 fish m^{-2}). For the second experiment, sex-reversed male Nile tilapia were also stocked at 1,000 kg ha^{-1}, but with respective fish sizes of 4.6 to 4.8 g, 10.1 to 10.5 g, and 21.3 to 21.8 g in each of the three treatments which were conducted in triplicate ponds. These various fish sizes resulted in stocking densities of 22, 10, and 5 fish m^{-2} for each of the three treatments, respectively. Ponds were fertilized with urea and TSP at a rate of 30 kg N and 8 kg P ha^{-1} wk^{-1}. All ponds for both experiments received sodium bicarbonate weekly to attain and maintain the minimum alkalinity (75 mg l^{-1} as $CaCO_3$) based on weekly measurements of alkalinity in pond water. The experiments showed that higher nitrogen inputs generally resulted in better growth performance of Nile tilapia. Growth in the treatment without N inputs ceased before day 50, which was earlier than growth ceased in the treatments with varied inputs of N (around day 70). During the entire culture period, the estimated fish biomass was highest in the treatment with 30 kg N ha^{-1} wk^{-1}, intermediate in the treatments with 10 and 20 kg N ha^{-1} wk^{-1}, and lowest in the treatment without N inputs. Nile tilapia yield was highest in the treatment with 30 kg N ha^{-1} wk^{-1} (2,409.6 ± 46.4 kg ha^{-1}), intermediate in the treatments with 10 and 20 kg N ha^{-1} wk^{-1} (2,172.8 ± 153.8 and 1,935.2 ± 165.9 kg ha^{-1}, respectively), and lowest in the treatment without N inputs (1,221.2 ± 44.0 kg ha^{-1}). The partial budget analysis indicated that the treatment with 30 kg N ha^{-1} wk^{-1} was most profitable. The full-cost enterprise budget showed that US$11.90 net return could be produced from a 200-m^2 pond in this treatment during a three-month culture period. All parameters of fish growth performance were significantly better in the treatments stocked with medium and large fish than in the treatment stocked with small fish. Survival rate was highest in the large-size treatment, intermediate in the medium-size treatment, and lowest in the small-size treatment. Individual fish growth rates were significantly higher in the treatment stocked with larger fish. However, the estimated fish biomass and yields were highest in the medium-size treatment, intermediate in the large-size treatment, and lowest in the small-size treatment.

INTRODUCTION

Nile tilapia (*Oreochromis niloticus*) are commonly grown in semi-intensive culture using fertilizers to increase primary production and fish food (Boyd, 1976; Diana et al., 1991). There is voluminous literature on pond fertilization, documenting many conflicting and inconsistent results based on various types of fertilizer, rates of input, and methods and frequency of application (Coleman and Edwards, 1987). Efficient production systems require optimal use of nutrient inputs. Among a large number of nutrients required to stimulate phytoplankton growth, nitrogen, phosphorus, and occasionally carbon are the most common limiting nutrients in natural water and fish ponds (Lin et al., 1997). The research of the Pond Dynamics/Aquaculture Collaborative Research Support Program (PD/A CRSP) has addressed enhancement of primary productivity through additions of inorganic and organic fertilizers to ponds. However, the findings on optimal nitrogen, phosphorus, and carbon inputs required to improve fish yields at the PD/A CRSP sites appear to be inconsistent, and further research is needed. Higher nutrient inputs increased fish production at all PD/A CRSP sites, but optimal inputs of nitrogen, phosphorus, and carbon were not well defined (Lin et al., 1997).

Fertilization rates in PD/A CRSP experiments were much greater than rates reported for earlier pond fertilization research (Lin et al., 1997). In an often-cited series of fertilization experiments conducted in Malaysia, Hickling (1962) used less than 1.1 kg P and 1.1 N ha^{-1} wk^{-1}. In Israel, the standard fertilizer dose was 2.3 kg P and 6.5 kg N ha^{-1} wk^{-1} (Hepher, 1962a; 1962b). The highest rates of phosphorus and nitrogen used in most experiments in the USA were 1.26 and 3 kg ha^{-1} wk^{-1}, respectively (Swingle, 1947; Boyd, 1976; Boyd and Sowles, 1978; Murad and Boyd, 1987; Boyd, 1990). Rates in Europe seldom exceeded 1 kg ha^{-1} wk^{-1} for nitrogen and phosphorus (Mortimer, 1954). However, rates used in Malaysia, USA, Israel, and Europe gave low fish production. Also, in all of the studies cited above, phosphorus was the most important limiting nutrient.

Therefore, the purposes of this study were to:

1) Determine the optimal rate of nitrogen fertilization (in the presence of adequate phosphorus and carbon) to obtain optimum primary productivity and optimum yields of Nile tilapia in freshwater production ponds;
2) Determine which of the nitrogen fertilization rates evaluated to produce Nile tilapia in freshwater production ponds had the greatest profitability;
3) Develop a full-cost enterprise budget for the fertilization level that resulted in the greatest profitability; and
4) Investigate the relationship between initial fish size and pond carrying capacity.

METHODS AND MATERIALS

Two experiments were conducted in a randomized complete block design in eighteen 200-m^2 ponds at the Asian Institute of Technology, Thailand. The first experiment involved culture of Nile tilapia using four nitrogen fertilization rates. The second experiment was to determine the relationship between initial fish size and pond carrying capacity with the same nitrogen and phosphorus input rates as those of experiment 1.

For the first experiment, all ponds were fertilized with triple superphosphate (TSP) at a rate of 8 kg phosphorus (P) ha^{-1} wk^{-1} and nitrogen (N) as urea at 0, 10, 20, and 30 kg N ha^{-1} wk^{-1}. All treatments were done in triplicate. Initial pond fertilization took place two weeks prior to stocking of fish. Sodium bicarbonate was added weekly to attain and maintain the minimum alkalinity (75 mg l^{-1} as $CaCO_3$) based on weekly measurements of alkalinity in pond water. Sex-reversed male Nile tilapia were stocked at 1,000 kg ha^{-1} at a size of 10.1 to 10.9 g in all ponds on 4 June 1998. The stocking density was 10 fish m^{-2} in all ponds.

For the second experiment, sex-reversed male Nile tilapia were also stocked on 4 June 1998 at 1,000 kg ha^{-1}, but with respective fish sizes of 4.6 to 4.8 g, 10.1 to 10.5 g, and 21.3 to 21.8 g in each of the three treatments which were conducted in triplicate ponds. These various fish sizes resulted in stocking densities of 22, 10, and 5 fish m^{-2} for each of the three treatments, respectively. All ponds were fertilized with urea and TSP at a rate of 30 kg N and 8 kg P ha^{-1} wk^{-1} and treated with sodium bicarbonate in the same way as experiment 1.

Water depth in all ponds was maintained at 1 m throughout the experiment by adding water weekly to replace evaporation and seepage losses.

Most parameters of pond water quality were analyzed with water column samples taken from the center of each pond from a walkway. Parameters of pond water quality, including total nitrogen (TN), total ammonium nitrogen (TAN), total phosphorus (TP), Secchi disk visibility, total alkalinity, chlorophyll *a*, pH, and primary productivity (gross and net), were analyzed at 1000 h during the second week (11 June 1998), midway (23 July 1998), and final week (1 September 1998) of the experiment using standard methods (APHA, 1980) modified by Egna et al. (1987). Dissolved oxygen (DO), pH, and temperature measurements were made on these three sampling dates at 0600, 1000, 1600, 1800, and 0600 h the following morning at 5-cm, 25-cm, 50-cm, and 75-cm depths in the water column. Total alkalinity and total hardness were determined weekly at 1000 h for calculating the amount of sodium bicarbonate required to maintain the minimum alkalinity as defined above.

During the experiment, approximately 10% of the initial stock was seined, counted, and bulk-weighed biweekly for each pond. All fish were harvested on 3 September 1998 after 91 days of culture. Daily weight gain (g $fish^{-1}d^{-1}$), yield (kg $pond^{-1}$), and extrapolated yield (kg ha^{-1}) were calculated. Fish biomass on the sampling dates was estimated by the measured mean fish weight from sampling and the number of fish surviving. It was assumed that surviving fish number decreased linearly from the beginning to end of experiments.

Data from both experiments were analyzed statistically by regression analysis and analysis of variance (ANOVA) using the SPSS 7.0 statistical software package. Differences were considered significant at an alpha level of 0.05. All means were reported with ± 1 standard error (SE).

A partial budget analysis was conducted to determine which fertilization rate yielded the greatest profitability, and a full-cost enterprise budget was developed for the fertilization rate that yielded the greatest profitability (Shang, 1990). The economic analyses were based on the current local market prices expressed in US dollar (US$1 = 40 baht) in Thailand. Prices of urea and TSP were $0.200 and $0.325 kg^{-1}, respectively. Market value of Nile tilapia fingerlings around 30 g size was $1.50 kg^{-1}. To simplify the analyses, the prices for stocked and harvested fingerlings were fixed at $1.50 kg^{-1}. Total fixed costs in the full-cost enterprise budget were derived from a previous study (Engle and Skladany, 1992).

RESULTS

Experiment 1

Among the three experimental treatments, higher N inputs generally resulted in better growth performance of Nile tilapia (Table 1; Figures 1, 2, and 3). But survival rates were not significantly different among all treatments ($P > 0.05$). Differential growth of Nile tilapia among all treatments was observed at the first sampling (Figure 1). Growth in the treatment without N inputs ceased before day 50, which was earlier than in the treatments with N inputs (around day 70) (Figure 1). Final mean weight, mean daily weight gain, and gross and net fish yields were significantly higher ($P < 0.05$) in the treatments with N inputs than in the treatment without N inputs. There were no significant differences ($P > 0.05$) for

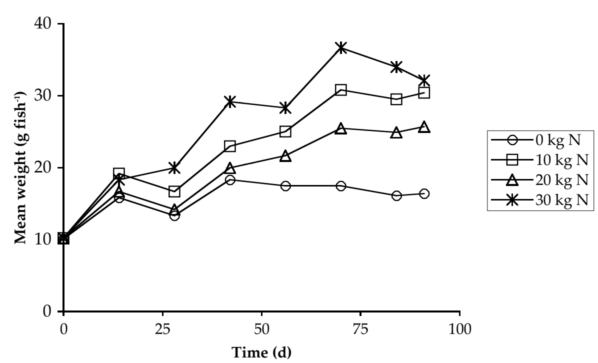

Figure 1. Growth of Nile tilapia in the treatments with 0, 10, 20, and 30 kg N ha^{-1} wk^{-1} during the 91-day experiment.

Table 1. Growth performance of Nile tilapia in ponds fertilized at different N application rates (kg ha^{-1} wk^{-1}) in the 91-day experiment.

Performance	Treatment			
	0	10	20	30
Initial Biomass (kg $pond^{-1}$)	20.3 ± 0.0 a	20.4 ± 0.1 a	20.4 ± 0.1 a	20.4 ± 0.2 a
Initial Mean Wt. (g $fish^{-1}$)	10.1 ± 0.0 a	10.2 ± 0.0 a	10.2 ± 0.0 a	10.2 ± 0.1 a
Final Biomass (kg $pond^{-1}$)	24.4 ± 0.9 a	43.5 ± 3.1 b	38.7 ± 3.3 b	48.2 ± 0.9 bc
Final Mean Wt. (g $fish^{-1}$)	16.4 ± 0.9 a	30.4 ± 1.3 bc	25.7 ± 1.1 b	32.1 ± 1.3 bc
Mean DWG (g $fish^{-1}$ d^{-1})	0.07 ± 0.01 a	0.22 ± 0.01 b	0.17 ± 0.01 b	0.24 ± 0.02 bc
Net Fish Yield (kg $pond^{-1}$)	4.2 ± 0.9 a	23.1 ± 3.2 b	18.3 ± 3.4 b	27.8 ± 1.0 bc
Extrapolated Net Fish Yield (kg ha^{-1})	207.8 ± 43.9 a	1,154.5 ± 157.7 b	915.2 ± 167.8 b	1,389.6 ± 49.3 bc
Gross Fish Yield (kg $pond^{-1}$)	24.4 ± 0.9 a	43.5 ± 3.1 b	38.7 ± 3.3 b	48.2 ± 0.9 bc
Extrapolated Gross Fish Yield (kg ha^{-1})	1,221.2 ± 44.0 a	2,172.8 ± 153.8 b	1,935.2 ± 165.9 b	2,409.6 ± 46.4 bc
Survival (%)	74.9 ± 4.0 a	71.5 ± 4.3 a	75.0 ± 3.7 a	75.2 ± 1.7 a

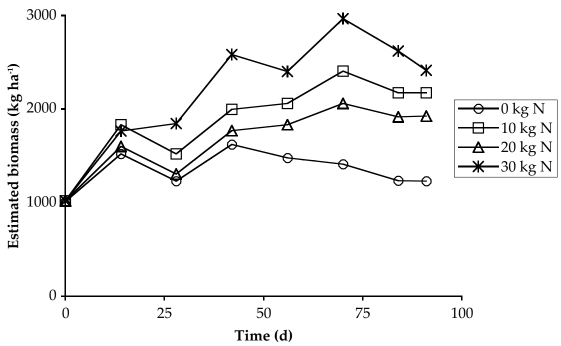

Figure 2. Estimated fish biomass in the treatments with 0, 10, 20, and 30 kg N ha^{-1} wk^{-1} during the 91-day experiment.

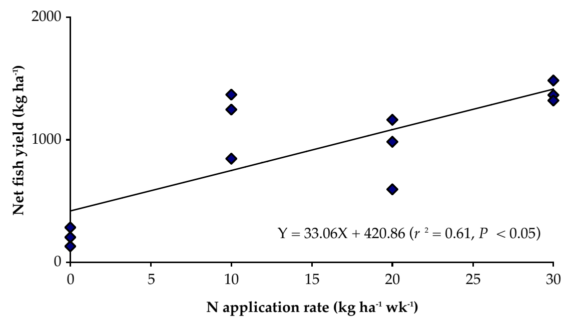

Figure 4. Relationship between net fish yield and nitrogen input rate in the first experiment.

those growth parameters among the treatments with N inputs. During the entire culture period, the estimated fish biomass was highest in the treatment with 30 kg N, intermediate in the treatments with 10 and 20 kg N, and lowest in the treatment without N inputs (Figure 2). The estimated fish biomass decreased earlier in the treatment without N inputs (around day 40) than in the treatments with various N inputs (around day 70) (Figure 2). The yield of Nile tilapia was highest in the treatment with 30 kg N ha^{-1} wk^{-1} (2,409.6 ± 46.4 kg ha^{-1}), intermediate in the treatments with 10 and 20 kg N ha^{-1} wk^{-1} (2,172.8 ± 153.8 and 1,935.2 ± 165.9 kg ha^{-1}, respectively), and lowest in the treatment without N inputs (1,221.2 ± 44.0 kg ha^{-1}) (Figure 3). The relationship between net fish yield and N inputs (Figure 4) can be expressed as:

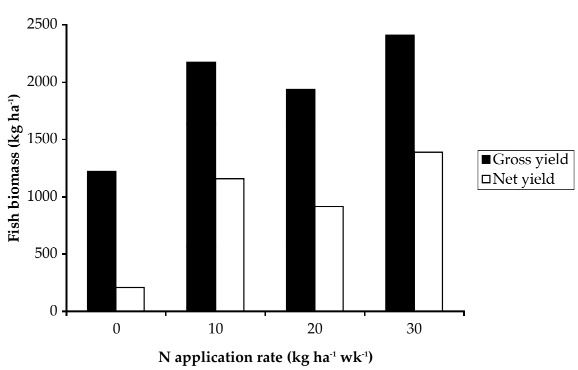

Figure 3. Gross and net fish yields in the treatments with 0, 10, 20, and 30 kg N ha^{-1} wk^{-1} in the 91-day experiment.

$$Y = 33.06X + 420.86 \ (r^2 = 0.61, P < 0.05)$$

where

Y = net fish yield and
X = N input

which shows that net fish yield generally increases with increasing N inputs.

Water quality parameters varied among treatments in the experiment (Table 2). There were no significant differences ($P > 0.05$) among any parameters during initial measurements. Water temperature and pH ranged from 29.3 to 37.0°C and 6.4 to 9.1, respectively, throughout the experimental period in all ponds. The DO concentration at dawn fluctuated over the entire culture period, but there were no significant differences ($P > 0.05$) among treatments. The final concentrations of TAN and TN increased with increasing N input and were significantly higher ($P < 0.05$) in the treatments with N inputs than in the treatment without N inputs. However, there were no significant differences ($P > 0.05$) in final concentrations of both TAN and TN among the treatments with various N inputs. TP concentration was not significantly different ($P > 0.05$) among all treatments during the entire experimental period. To maintain the minimal alkalinity, the total amount of sodium bicarbonate added to ponds was 22.1 ± 4.2, 28.5 ± 2.9, 26.0 ± 0.7, and 24.3 ± 9.7 kg for the treatments with 0, 10, 20, and 30 kg N, respectively. However, the alkalinity concentrations declined from approximately 150 to 50 mg l^{-1} during the first half of the culture period, and remained close to 50 mg l^{-1} during the second half (Figure 5). There were no significant differences ($P > 0.05$) in alkalinity concentrations among all treatments

Table 2. Mean values of water quality parameters measured at the initial, midway and final weeks in ponds fertilized with different N application rates (kg ha^{-1} wk^{-1}) in the 91-day experiment.

Parameter	Treatment			
	0	10	20	30
DO AT DAWN (mg l^{-1})				
Initial	1.57 ± 0.67 ^{a}	0.91 ± 0.50 ^{a}	1.63 ± 0.52 ^{a}	1.02 ± 0.18 ^{a}
Midway	1.99 ± 0.40 ^{a}	0.49 ± 0.10 ^{a}	1.52 ± 0.53 ^{a}	1.27 ± 0.62 ^{a}
Final	2.43 ± 0.28 ^{a}	1.52 ± 0.57 ^{a}	1.67 ± 0.77 ^{a}	1.12 ± 0.33 ^{a}
pH				
Initial	6.8–7.5	6.7–8.3	6.9–7.2	6.7–7.5
Midway	7.1–7.4	7.3–7.8	7.2–7.9	7.3–8.5
Final	7.1–7.7	6.4–8.0	7.1–8.2	7.1–9.1
TOTAL NITROGEN (mg l^{-1})				
Initial	1.95 ± 0.03 ^{a}	1.68 ± 0.28 ^{a}	3.00 ± 1.07 ^{a}	2.61 ± 0.83 ^{a}
Midway	4.42 ± 1.58 ^{a}	5.54 ± 1.49 ^{a}	3.95 ± 0.12 ^{a}	9.07 ± 3.57 ^{a}
Final	3.15 ± 0.38 ^{a}	5.58 ± 0.40 ^{b}	6.77 ± 0.31 ^{b}	7.85 ± 1.32 ^{b}
TAN (mg l^{-1})				
Initial	0.55 ± 0.24 ^{a}	0.11 ± 0.02 ^{a}	0.30 ± 0.13 ^{a}	0.46 ± 0.22 ^{a}
Midway	0.01 ± 0.01 ^{a}	0.09 ± 0.08 ^{a}	0.86 ± 0.26 ^{b}	0.91 ± 0.15 ^{b}
Final	0.45 ± 0.14 ^{a}	1.14 ± 0.14 ^{b}	1.75 ± 0.03 ^{b}	1.28 ± 0.33 ^{b}
TOTAL PHOSPHORUS (mg l^{-1})				
Initial	0.51 ± 0.06 ^{a}	0.77 ± 0.07 ^{a}	0.38 ± 0.04 ^{a}	0.74 ± 0.26 ^{a}
Midway	0.24 ± 0.04 ^{a}	0.67 ± 0.21 ^{a}	0.34 ± 0.10 ^{a}	0.64 ± 0.08 ^{a}
Final	0.42 ± 0.10 ^{a}	0.81 ± 0.22 ^{a}	0.59 ± 0.22 ^{a}	1.06 ± 0.11 ^{a}
TOTAL ALKALINITY (mg l^{-1} as $CaCO_3$)				
Initial	146 ± 8.7 ^{a}	159 ± 17.7 ^{a}	148 ± 11.4 ^{a}	137 ± 17.7 ^{a}
Midway	59 ± 2.4 ^{a}	37 ± 2.9 ^{a}	47 ± 2.9 ^{a}	61 ± 20.1 ^{a}
Final	55 ± 4.1 ^{a}	45 ± 10.3 ^{a}	65 ± 2.9 ^{a}	73 ± 14.3 ^{a}
CHLOROPHYLL *A* (mg m^{-3})				
Initial	72 ± 15.6 ^{a}	80 ± 13.4 ^{a}	39 ± 8.5 ^{a}	51 ± 6.1 ^{a}
Midway	31 ± 5.6 ^{a}	126 ± 37.2 ^{a}	67 ± 29.7 ^{a}	147 ± 75.2 ^{a}
Final	30 ± 8.1 ^{a}	84 ± 9.2 ^{b}	40 ± 16.3 ^{a}	205 ± 25.0 ^{c}

^{a,b,c} Mean values with different superscript letters in the same row are significantly different ($P < 0.05$).

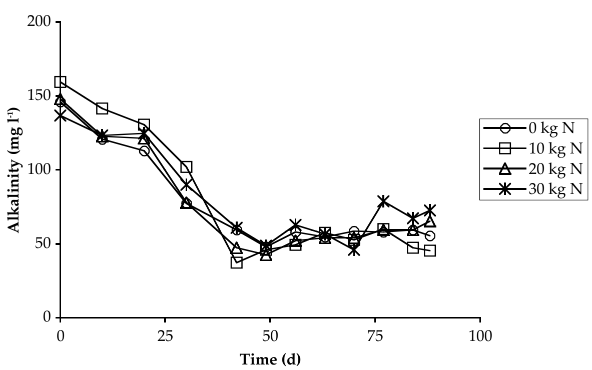

Figure 5. Change in alkalinity concentration in the treatments with 0, 10, 20, and 30 kg N ha^{-1} wk^{-1} over the 91-day experiment.

Table 3. Partial budget analysis for Nile tilapia cultured in ponds fertilized with different N application rates (kg ha^{-1} wk^{-1}) in the 91-day experiment (budget items in US$ pond^{-1}).

Item	Treatment			
	0	10	20	30
Income (selling fish)	36.60	65.25	58.05	72.30
Added Income (A)	----	28.65	21.45	35.70
Cost for Urea	0	1.30	2.60	3.90
Added Cost from Urea (B1)	----	1.30	2.60	3.90
Cost of $NaHCO_3$	17.13	22.10	20.15	18.83
Added Cost from $NaHCO_3$ (B2)	----	4.98	3.03	1.70
Ratio of Added Income to Added Cost	----	4.6	3.8	6.4
Profit (A - B1 - B2)	----	22.38	15.83	30.10

during the entire culture period. The final concentrations of chlorophyll *a*, from highest to lowest, were measured in ponds with treatments of 30, 10, 20, and 0 kg N ha^{-1} wk^{-1}. The final concentrations of chlorophyll *a* were significantly different ($P < 0.05$) by treatment; concentrations in treatments with 30 and 10 kg N ha^{-1} wk^{-1} were significantly higher ($P < 0.05$) than those in treatments with 20 and 0 kg N ha^{-1} wk^{-1}.

The partial budget analysis indicated that the treatment with 30 kg N ha^{-1} wk^{-1} was most profitable, giving the highest profit and ratio of added income to added cost (Table 3). The full-cost enterprise budget showed that $11.90 net return could be produced from a 200-m^2 pond in the treatment with 30 kg N ha^{-1} wk^{-1} during a three-month culture period (Table 4).

Table 4. A full-cost enterprise budget for Nile tilapia cultured in ponds fertilized with 30 kg N ha^{-1} wk^{-1} in the 91-day experiment.

Item	Unit	Price (US$)	Quantity (kg $pond^{-1}$)	Value (US$ $pond^{-1}$)
GROSS REVENUE (A)				
Harvested Tilapia	kg	1.50	48.2	72.30
COST				
Variable Cost				
Fingerlings	kg	1.50	20.4	30.60
Urea	kg	0.20	19.6	3.90
TSP	kg	0.33	12.0	3.90
$NaHCO_3$	kg	0.78	24.3	18.83
Interest on Operating Capital	year	12%	0.25	1.70
Total Variable Cost				58.93
Fixed cost				
Pond Depreciation and Equipment	ha*year	133.75	0.02*0.25	0.68
Interest on Fixed Capital	year	12%	0.25	0.80
Total Fixed Cost				1.48
TOTAL COST (B)				60.40
NET RETURNS (A - B)				11.90
BREAK-EVEN PRICE	kg	1.25		

Table 5. Growth performance of Nile tilapia stocked at different sizes in the 91-day experiment.

Performance	Treatment		
	Small Fish (4.6 g)	*Medium Fish* (10.2 g)	*Large Fish* (21.0 g)
Initial Biomass. (kg $pond^{-1}$)	20.5 ± 0.2 [a]	20.4 ± 0.2 [a]	20.4 ± 0.1 [a]
Initial Mean Wt. (g $fish^{-1}$)	4.6 ± 0.1	10.2 ± 0.1	21.0 ± 0.1
Final Biomass (kg $pond^{-1}$)	30.7 ± 2.0 [a]	48.2 ± 0.9 [c]	40.9 ± 0.5 [b]
Final Mean Wt. (g $fish^{-1}$)	13.8 ± 0.5	32.1 ± 1.3	48.7 ± 1.2
Mean DWG (g $fish^{-1}$ d^{-1})	0.10 ± 0.00 [a]	0.24 ± 0.02 [b]	0.30 ± 0.01 [bc]
Net Fish Yield (kg $pond^{-1}$)	10.2 ± 2.1 [a]	27.8 ± 1.0 [bc]	20.5 ± 0.5 [b]
Extrapolated Net Fish Yield (kg ha^{-1})	507.3 ± 106.3 [a]	13,89.6 ± 49.3 [bc]	1,024.2 ± 24.8 [b]
Gross Fish Yield (kg $pond^{-1}$)	30.7 ± 2.0 [a]	48.2 ± 0.9 [bc]	40.9 ± 0.5 [b]
Extrapolated Gross Fish Yield (kg ha^{-1})	1,532.3 ± 99.9 [a]	2,409.6 ± 46.4 [bc]	2,044.2 ± 26.4 [b]
Survival (%)	50.3 ± 4.8 [a]	75.2 ± 1.7 [b]	86.4 ± 1.6 [c]

[a,b,c] Mean values with different superscript letters in the same row are significantly different ($P < 0.05$).

Experiment 2

All parameters of fish growth performance were significantly better ($P < 0.05$) in the treatment stocked with medium and large fish than those stocked with small fish (Table 5). Survival rate was highest in the large-size treatment, intermediate in the medium-size treatment and lowest in the small-size treatment ($P < 0.05$). Individual fish growth rates were significantly higher ($P < 0.05$) in the treatment stocked with larger fish (Table 5; Figure 6). However, the estimated fish biomass was highest in the medium-size treatment, intermediate in the large-size treatment, and lowest in the small-size treatment (Figure 7). The highest gross and net fish yields were achieved in the medium-size treatment (Table 5; Figure 8).

Water temperature and pH ranged from 29.3 to 37.0°C and 6.7 to 9.1, respectively, throughout the experimental period in all ponds. There were no significant differences ($P < 0.05$) in water quality among all treatments during the entire culture period (Table 6).

The partial budget analysis indicated that stocking with medium-size fish was most profitable, giving the highest profit and ratio of added income to added cost (Table 7). The partial budget for experiment 1 (Table 3) shows that this same treatment was also the most profitable of all fertilization rate treatments.

DISCUSSION

Addition of nitrogen fertilizer significantly increased Nile tilapia yields. Higher N inputs generally resulted in higher phytoplankton standing crops, giving higher tilapia yields. The nitrogen inputs at rates of 10, 20, and 30 kg ha^{-1} wk^{-1} in ponds

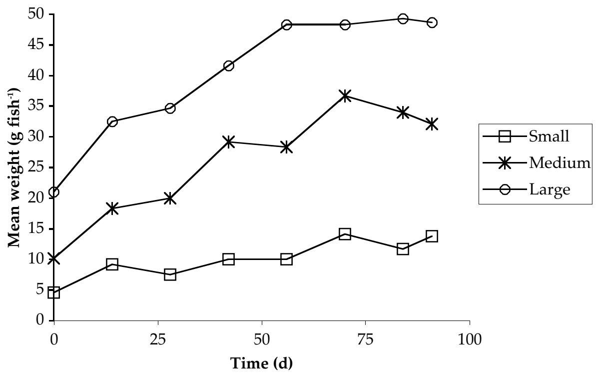

Figure 6. Growth of Nile tilapia in the small-, medium-, and large-size treatments during the 91-day experiment.

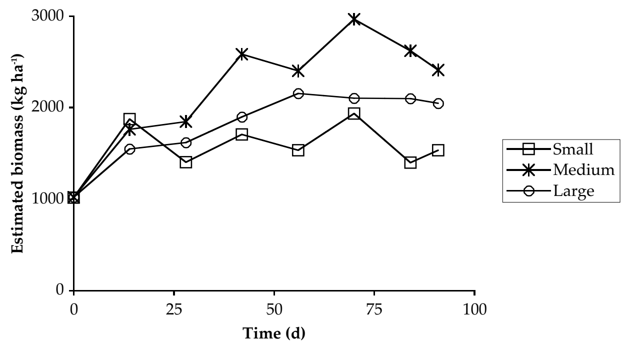

Figure 7. Estimated fish biomass in the small-, medium-, and large-size treatments during the 91-day experiment.

Table 6. Mean values of water quality parameters measured at the initial, midway, and final weeks in ponds stocked with Nile tilapia at different sizes in the 91-day experiment.

Parameter	Treatment		
	Small fish (4.6 g)	*Medium fish* (10.2 g)	*Large fish* (21.0 g)
DO AT DAWN ($mg\ l^{-1}$)			
Initial	2.05 ± 0.22 [a]	1.02±0.18 [a]	2.09 ± 0.35 [a]
Midway	1.01 ± 0.06 [a]	1.27±0.62 [a]	0.69 ± 0.27 [a]
Final	1.60 ± 0.76 [a]	1.12±0.33 [a]	1.32 ± 0.40 [a]
pH			
Initial	6.9–7.3	6.7–7.5	6.7–7.3
Midway	7.1–7.8	7.3–8.5	7.2–7.5
Final	7.1–8.2	7.1–9.1	7.1–9.0
TOTAL NITROGEN ($mg\ l^{-1}$)			
Initial	1.60 ± 0.14 [a]	2.61 ± 0.83 [a]	2.54 ± 0.85 [a]
Midway	5.40 ± 0.72 [a]	9.07 ± 3.57 [a]	5.93 ± 1.08 [a]
Final	8.16 ± 0.90 [a]	7.85 ± 1.32 [a]	9.37 ± 3.94 [a]
TAN ($mg\ l^{-1}$)			
Initial	0.19 ± 0.07 [a]	0.46 ± 0.22 [a]	0.32 ± 0.23 [a]
Midway	0.70 ± 0.22 [a]	0.91 ± 0.15 [a]	0.68 ± 0.36 [a]
Final	2.00 ± 0.65 [a]	1.28 ± 0.33 [a]	1.19 ± 0.40 [a]
TOTAL PHOSPHORUS ($mg\ l^{-1}$)			
Initial	0.41 ± 0.10 [a]	0.74 ± 0.26 [a]	0.48 ± 0.03 [a]
Midway	0.26 ± 0.02 [a]	0.64 ± 0.08 [a]	0.50 ± 0.06 [a]
Final	0.50 ± 0.14 [a]	1.06 ± 0.11 [a]	0.87 ± 0.15 [a]
TOTAL ALKALINITY ($mg\ l^{-1}$ as $CaCO_3$)			
Initial	151 ± 7.7 [a]	137 ± 17.7 [a]	133 ± 7.4 [a]
Midway	48 ± 6.9 [a]	61 ± 20.1 [a]	40 ± 4.2 [a]
Final	55 ± 7.0 [a]	73 ± 14.3 [a]	55 ± 3.7 [a]
CHLOROPHYLL *A* ($mg\ m^{-3}$)			
Initial	53 ± 17.7 [a]	51 ± 6.1 [a]	52 ± 3.8 [a]
Midway	48 ± 13.0 [a]	147 ± 75.2 [a]	86 ± 21.9 [a]
Final	68 ± 35.8 [a]	205 ± 25.0 [ab]	162 ± 52.4 [a]

[a,b,c] Mean values with different superscript letters in the same row are significantly different ($P < 0.05$).

fertilized with 8 kg P ha^{-1} wk^{-1} brought N:P ratios to 1.25:1, 2.5:1, and 3.75:1, respectively. The best fish growth performance was achieved in the treatment with the highest N input and N:P ratio. This finding confirms previous results of CRSP experiments which indicated optimal rates of 28 kg N ha^{-1} wk^{-1} and 7 kg P ha^{-1} wk^{-1}, giving a 4:1 N:P ratio (Knud-Hansen et al., 1991; Lin et al., 1997). Nile tilapia ceased to grow at around day 70 in all treatments with N inputs, indicating that the pond carrying capacity was around 2,000 to 2,500 kg ha^{-1}. With chemical fertilization alone, maximum fish production is about 15 kg ha^{-1} d^{-1} (Boyd, 1990), which is similar to the highest net fish yield (15.3 kg ha^{-1} d^{-1}) achieved in this 91-day experiment.

Table 7. Partial budget analysis for Nile tilapia stocked at small, medium, and large sizes in the 91-day experiment (budget items in US\$ pond^{-1}).

Item	Treatment		
	Small fish (4.6 g)	*Medium fish* (10.2 g)	*Large fish* (21.0 g)
Income (selling fish)	46.05	72.30	61.35
Added Income (A)	----	26.25	15.30
Cost for $NaHCO_3$	15.28	18.83	19.53
Added Cost from $NaHCO_3$ (B)	----	3.55	4.25
Ratio of Added Income to Added Cost	----	7.4	3.6
Profit (A - B)	----	22.70	11.05

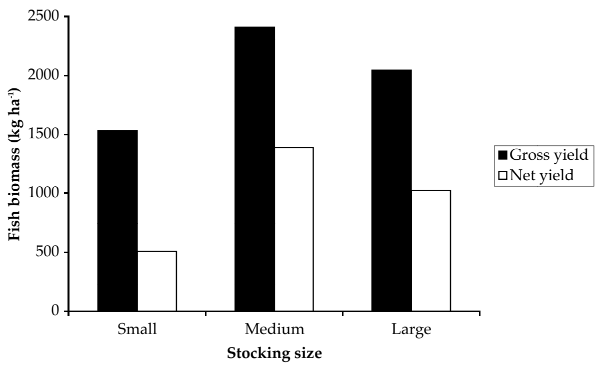

Figure 8. Gross and net fish yields in the small-, medium-, and large-size treatments in the 91-day experiment.

However, the net fish yield would have been 19.9 kg ha^{-1} d^{-1} and much higher profit could have been produced if tilapia had been harvested before growth ceased around day 70, suggesting the importance of timing for fish harvest in optimization of pond production systems.

The optimal N and P input rates determined in PD/A CRSP experiments are much higher than those used in most previous pond experiments, ranging from 1.0 to 6.5 kg N and 1.0 to 2.3 kg P ha^{-1} wk^{-1} (Swingle, 1947; Mortimer, 1954; Hickling, 1962; Hepher, 1962a, 1962b; Boyd, 1976; Boyd and Sowles, 1978; Murad and Boyd, 1987; Boyd, 1990). The annual fish yields in those studies were generally below 1,000 kg ha^{-1}. In addition to higher fertilizer inputs, the fish stocking rates were also much higher in most PD/A CRSP experiments (10,000 to 20,000 fish ha^{-1}) with extrapolated annual fish yields of 3,000 to 5,000 kg ha^{-1} (Lin et al., 1997). The highest extrapolated net yield obtained in the present study is around 5,500 kg ha^{-1} yr^{-1}, which could have reached 7,000 kg ha^{-1} yr^{-1} if fish had been harvested around day 70.

In the second experiment, there were no significant differences in all water quality parameters among treatments. It is not clear why fish yields were significantly different among treatments. The stocking densities were 5, 10, and 22 fish m^{-2} in the large-, medium-, and small-size treatments, respectively. With the same stocked biomass in all treatments, growth rates of individual fish were proportional to stocking size, but inversely proportional to stocking density. The latter indicated density-dependent growth occurred; however, fish yields were significantly different among treatments, with the highest fish yields achieved in the medium-size treatment.

With the development of Nile tilapia cage culture in rivers in northeast Thailand, there are strong demands for large fingerlings (30 to 50 g) to stock cages. Small-scale farmers nurse Nile tilapia fry to such sizes and sell them at around \$1.50 kg^{-1}, which is much higher than the price of marketable adult Nile tilapia. Farmers commonly nurse fry in fertilized ponds supplemented with artificial feed. In the present study, however, Nile tilapia were nursed at a very high density in ponds with fertilizer only, resulting in high yields. The results of this study imply that moving fish from high-density to low-density conditions when fish growth ceases or pond carrying capacity is reached could be a good strategy. Also, these results may provide small-scale farmers with a technically and economically effective strategy to optimize resource utilization and maximize profits.

ANTICIPATED BENEFITS

This is the first in a series of experiments to determine optimal rates of nitrogen, phosphorus, and carbon additions to ponds for fish production. Results of these trials will provide N, P, and C application rates to obtain fish yields with the greatest profit. Development of a full-cost enterprise budget for the fertilization rate that results in the greatest profitability will assist host country and international economists and planners in their evaluation of fish culture systems. Additionally, identification of optimal nutrient application rates would reduce the environmental impact of pond effluents.

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