EFFECTS OF WATER RECYCLING ON WATER QUALITY AND BOTTOM SOILS IN SHRIMP PONDS

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ABSTRACT

This study evaluated changes in chemical characteristics of production pond water, soils, and shrimp yields in response to water recycling through an oxidation pond. Nine 0.1-ha ponds were stocked with *Litopenaeus vannamei* post-larvae. Three ponds were stocked with a high density of shrimp (50 m^{-2}), three were stocked with a low density of shrimp (25 m^{-2}), and three others were stocked with a high density of shrimp while pond water was recycled through an adjacent pond of equal volume not stocked with shrimp. The density of shrimp in low-density and high-density-with-recycling treatments was equal when based on the total water area of production and recycling ponds. Mean shrimp yields for low-density (LD), high-density (HD), and high-density-recycling ponds (HDR) were 1,706 kg ha^{-1}, 4,648 kg ha^{-1}, and 4,534 kg ha^{-1}, respectively. There was no significant difference ($P > 0.05$) in yields between HD and HDR treatments or between LD and HDR treatments when based on total water surface area. Mean harvest weights of individual shrimp ranged from 22 to 25 g and were not different ($P > 0.05$) among treatments.

Recycling water from HDR ponds through an oxidation pond resulted in significant reductions in the mean mass weight of total nitrogen (TN) and total ammonia nitrogen (TAN) compared with HD ponds because HDR ponds used twice the water volume. The sum of the mean mass weight (kg) for water quality variables found in HDR ponds and oxidation ponds was significantly greater than the mean mass weight in HD ponds, except for nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), and TAN. No differences were noted for water quality in HDR and LD ponds. No differences were observed among treatments for soil pH; concentrations of carbon, sulfur, and nitrogen; soil respiration; and phosphorus absorption capacity. We concluded that recycling water from a production pond through an oxidation pond of equal volume had minimum to no effect on water quality and shrimp yields. The major operational disadvantages of recycling water were that pond space was put into nonproductive use as oxidation ponds, and 3.3 times more energy was used for aeration and water circulation. It would be better to stock two ponds at half the rate instead of doubling the volume of water per pond by recycling through an oxidation pond.

INTRODUCTION

Shrimp aquaculture pond water can become eutrophic when excessive amounts of fertilizer and feed are used to produce shrimp (Boyd, 1985). Feeds and fertilizers increase nitrogen and phosphorus concentrations in pond waters and stimulate the growth of phytoplankton, the base of the pond natural food web (Boyd, 1995). Green et al. (1997) estimated that feed accounted for 47 and 55% of added nitrogen and phosphorus, respectively, in semi-intensive shrimp ponds when using a 30% protein diet, and harvested shrimp accounted for 37% of applied nitrogen and 20% of applied phosphorus. Briggs and Funge-Smith (1994) estimated that 95% of the nitrogen and 71% of the phosphorus applied to intensive shrimp ponds was in the form of feed and fertilizers, but harvested shrimp accounted only for 24% of the nitrogen and 13% of the phosphorus. Thus, a portion of the nutrients in the feed consumed by shrimp is converted to shrimp flesh, but a greater proportion is wasted in the water column. Uneaten feed, dead phytoplankton, and other organic wastes are mineralized by microbial action to inorganic nutrients such as ammonia, nitrite, nitrate, phosphate, and carbon dioxide, which stimulate algal growth in the pond, sometimes leading to dense blooms (Boyd, 1985). It was estimated that the nutrients originating from the production of 1 kg of live weight of the culture species in ponds can lead to the production of 2 to 3 kg dry weight of phytoplankton (Boyd, 1985).

When pond management is intensified and stocking and feeding rates are increased beyond the capacity of the pond to assimilate nutrients, water quality deteriorates (Cole and Boyd, 1986). Water quality deterioration is first manifested by dissolved oxygen concentrations that become too low to support growth and life. In ponds without aeration, feeding rates should not be greater than 25 to 30 kg ha^{-1} d^{-1} because of the high probability of dissolved oxygen depletion at greater feeding rates (Tucker et al., 1979). Mechanical aeration can be used to sustain higher feeding rates, up to 100 to 120 kg ha^{-1} d^{-1} and prevent extremely low dissolved oxygen concentrations (Boyd, 1998). Wyban et al. (1988) obtained shrimp production (*L. vannamei*) of 2,852 kg ha^{-1} using 3.7 kW ha^{-1} in ponds stocked at 25 post-larvae m^{-2}. In ponds stocked at 45 post-larvae m^{-2}, Sandifer et al. (1991) obtained 7,500 kg ha^{-1} using 7.5 kW ha^{-1} of aeration and 17% water exchange. McIntosh et al. (1999) reported production of *L. vannamei* as high as 13,500 kg ha^{-1}. Ponds are stocked up to 160 post-larvae m^{-2}, aerated 24 h d^{-1} with 20 HP aerators ha^{-1} to sustain heterotrophic bacteria that decompose organic matter in suspension and metabolize nutrient wastes. However, production cannot be increased without limit, even if enough aeration is applied to prevent dissolved oxygen depletion at higher feeding rates because other water quality variables, such as ammonia, may impose limits on production (Boyd and Tucker, 1998).

A conventional management practice to resolve degraded water quality in shrimp production ponds is to exchange water

(Stern and Lettelier, 1992). During water exchange, pond water with high nutrient and algal concentrations is discharged from the pond and ideally replaced by water with lower nutrient and algal concentrations and greater dissolved oxygen concentration (Chien, 1992). Water exchange as a pond management tool must be used judiciously because of the potential negative impact effluents may have on receiving waters (Pruder, 1992). A study of semi-intensive shrimp farms in Honduras revealed that the increase in total nitrogen and total phosphorus between the intake and discharge was 0.24 and 0.04 mg l^{-1}, respectively (Teichert-Coddington, 1995). According to Dierberg and Kiattisimkul (1996), concentrations of total suspended solids, total nitrogen, total phosphorus, and biochemical oxygen demand in effluents from intensive shrimp ponds (stocked at 50 post-larvae m^{-2}) in Thailand are 461, 0.15, 0.53, and 28.9 mg l^{-1}, respectively.

An alternative to water exchange may be to recycle production pond water in an oxidation pond. In this scheme, production pond water is exchanged with oxidation pond water instead of estuarine water. Among the reasons for application of recycling systems are to minimize the spread of diseases (Boyd and Tucker, 1998); to conserve high-quality source waters (Treece, 2000); to improve growth performance because of greater control over water quality; and to decrease pond effluents. Usually a portion of the farm ponds is set aside as oxidation ponds to treat production pond effluents. In the oxidation ponds, organic matter is decomposed and nutrients are fixed.

A variety of shrimp pond water recycling schemes have been proposed or used (Fast and Menasveta, 1998). All rely on photosynthesis and biological and microbial decomposition to process organic matter and nutrients in oxidation ponds. The Choroen Pakphand Group (CP) operated a recirculation pond system for shrimp production at their Research and Development Center, Maeklong area, Thailand (Anonymous, 1996). Effluents from ten 0.5-ha shrimp culture ponds were discharged into four 0.55-ha treatment ponds and then circulated back into the production ponds. Treatments ponds sometimes included seaweeds or mollusks to help remove nutrients.

In Indonesia, shrimp water recycling was developed because of poor source water quality. A typical Indonesian recycling system consisted of 50% shrimp culture and 50% water reclamation (Anonymous, 1996). Shrimp pond effluents first entered a sedimentation pond, then fish/bivalve ponds, and lastly an aeration pond, before returning to the shrimp grow-out ponds.

Another proposed but untested system consists of a small intensive shrimp culture pond nested within a much larger extensive culture pond (Menasveta and Jarayabhand, 1998). Water would circulate through the intensive pond using low-energy water movers (Rogers and Fast, 1988) and discharge back into the extensive pond where suspended solids would settle and nutrients would stimulate primary and secondary productivity for a secondary aquaculture crop.

Little research has been done to evaluate the effectiveness in reducing the nutrient load either by proposed systems or those in use. Major disadvantages of recycling water are that pond space is put into non-productive use as treatment ponds and energy is used to circulate water. Instead of setting aside some ponds for treating production pond water, it may be more efficient simply to reduce the stocking densities of shrimp in all ponds. In that way all ponds are used for both production and oxidation purposes.

Bottom soils have been considered a major factor influencing water quality and aquatic animal production in ponds (Hajek and Boyd, 1994). Much of the recycling of organic matter into inorganic nutrients occurs at the pond bottom (Boyd, 1992). Excessive nutrient input may result in organic matter build-up on pond bottoms and high concentrations of partially oxidized or unoxidized components of nitrogen (NH_3, NO_2) and sulfur (H_2S), which may become stressful or toxic to shrimp. Organic input in a recycling system takes place in the unit where the culture organisms are offered feed. Water containing dissolved nutrients and suspended solids is circulated to the oxidation pond where they theoretically are mineralized or fixed. It is assumed, therefore, that water recycling would lessen the nutrient load on soils of the production pond. Many nutrients present in the soil, such as phosphorus, nitrogen, carbon, and sulfur, come from the organic matter inputs, so concentrations of these nutrients should be altered by lowering organic matter accumulation.

The objectives of this study were to evaluate effects on water quality, pond soils, and shrimp yields of recycling production pond water with a non-producing pond and to compare water recycling with the alternative of reducing stocking densities.

METHODS AND MATERIALS

Site Description

This experiment was conducted at the Alabama Department of Conservation and Natural Resources, Claude Peteet Mariculture Center (CPMC), Gulf Shores, Alabama. Ponds were lined with high-density polyethylene, and pond bottoms were covered with a 25-cm layer of natural soil. Ponds measured 1,075 m^2, and averaged 1 m deep. Ponds were filled with water pumped from the Intercostal Waterway, which connects Bon Secour Bay and Wolf Bay. Pond water salinity varied within a range of 11 to 16‰ during the experimental period.

Treatments

The experimental design consisted of three treatments with three replications each. Ponds were assigned randomly to treatments, and stocked with *Litopenaeus vannamei* as follows: 1) High-density stocking rate (50 post-larvae m^{-2}) and no water recycling (HD); 2) High density (50 post-larvae m^{-2}) with water recycling (HDR); and, 3) Low density (25 post-larvae m^{-2}) and no water recycling (LD).

Pond Preparation

Ponds were filled one week before stocking. After filling, the ponds were fertilized with 2 l of 38-8-0 liquid fertilizer three days before shrimp were stocked. A 1:16 mixture of motor oil and diesel fuel was applied evenly over the water surface in all ponds 24 h before stocking to eliminate or reduce populations of air-breathing insects. Ponds were stocked with specific pathogen-free *L. vannamei* post-larvae (PL 10-11) purchased from Shrimp Improvement Inc., Miami, Florida. Shrimp were stocked on 17 May and harvested 21 weeks later on 29 September 1999.

Water was not exchanged in any pond, but was added only to replace evaporation. Each replicate in the HDR treatment comprised two adjacent ponds, where one pond was the culture pond and the other was the oxidation pond. Water movement between the two ponds was accomplished by placing one 0.5-HP submersible pump at the deep end of the culture pond (50 cm from the bottom) and another 0.5-HP submersible pump at the shallow end (20 cm from the bottom) of the oxidation pond. Pumps were operated simultaneously 20 h d^{-1} (7 d wk^{-1}) to give a 7-d residence time in the oxidation pond.

All ponds, including oxidation ponds, were equipped with oxygen sensing and aerator activation systems (McGraw et al., in press), and one 1.5-kW propeller-aspirator type aerator. The automatic aerator activation system was programmed to maintain a dissolved oxygen concentration of 3.5 mg l^{-1} in the pond water. Shrimp were fed twice a day 7 d wk^{-1} with a 35%-protein pelleted feed (Burris Feed Mill, Franklinton, Louisiana). Daily feeding rate for all treatments was 5 kg ha^{-1} during the first week, 9 kg ha^{-1} during the second and third weeks, and 12 kg ha^{-1} during the fourth week. A nondestructive sample of 50 shrimp was taken weekly by cast net from each pond beginning the fifth week to monitor growth and to adjust the feeding rates. The initial daily feeding rate of 5% of body weight decreased to a final rate of 2.5% as shrimp increased in weight. The daily feed allowances were calculated using an assumed survival of 70% for the entire culture period. Equal quantities of feed were applied to all ponds in the same treatment. Trays were used to evaluate and verify feed consumption. The maximum daily feeding rate did not surpass 86 kg ha^{-1} for LD and 140 kg ha^{-1} for HD and HDR.

Water Quality

Chemical analyses of water were performed weekly. Samples of water in all ponds were taken with an 80-cm water column sampler (Boyd and Tucker, 1992) between 0630 and 0800 h. Subsamples of water were collected from three locations in the deep section of each pond and combined for analysis in the laboratory. Soluble reactive phosphorus (SRP), total phosphorus (TP), total nitrogen (TN), nitrite (NO_2-N), nitrate (NO_3-N), total ammonia nitrogen (TAN), and total suspended solids (TSS) were determined weekly. At least twice a month, 5-d biochemical oxygen demand (BOD_5) and chlorophyll *a* analyses were performed.

TP and TN were determined by persulfate digestion method (Clesceri et al., 1998). SRP was determined by persulfate oxidation method (Clesceri et al., 1998). TAN was determined by phenate method (Clesceri et al., 1998). NO_2-N was determined by the diazotization procedure (Boyd and Tucker, 1992). NO_3-N was analyzed by the Szechrome NAS reagent (diphenylamine sulfonic acid chromogene) method according to Gross and Boyd (1998). TSS was measured according to protocol presented by Boyd and Tucker (1992).

The BOD_5 method consists of placing the sample at 1:1 dilution in full, airtight 300-ml BOD bottles and incubating in the dark at 20°C for five days (Clesceri et al., 1998). Distilled water adjusted to the same salinity as the sample was used for dilution. Dissolved Oxygen (DO) was measured with a YSI BOD bottle probe and a YSI oxygen meter (Model 54 A). Frequent readings were taken in order to ensure that DO concentrations were not lower than 2 mg l^{-1}. Samples were reaerated after each reading. BOD nutrient buffer pillows (Hach Company, Loveland, Colorado), were used in dilution water for samples and blanks. Chlorophyll *a* was determined by acetone-methanol extraction according to pigment extraction from Pechar (1987).

Soil Analysis

Pond soil samples were collected before stocking and harvesting by taking a series of subsamples in an S-shaped pattern along the pond bottom from the deep to the shallow end. Samples collected before stocking were taken two days after filling of the ponds started, and samples collected before harvesting were taken a week before draining the ponds. Cores were taken to a depth of 10 cm, and cut into three segments: 0 to 2.5 cm, 2.5 to 5 cm, and 5 to 10 cm, according to methods described in Masuda and Boyd (1994). Soil core segments were dried in a forced-draft laboratory oven at 60°C. Soil samples were pulverized with a mechanical soil crusher (Custom Laboratory Equipment, Inc., Orange City, Florida) prior to analysis.

Soil was analyzed for pH in a 1:1 water-soil slurry (Boyd and Tucker, 1992). Total carbon analyses were made with a LECO Carbon Determinator Induction Furnace Analyzer EC12 (Leco Corporation, St. Joseph, Michigan). Total nitrogen was measured with a Leco Carbon-Hydrogen-Nitrogen Analyzer CHN 600 (Leco Corporation, St. Joseph, Michigan). Total sulfur was determined by incinerating the soil samples in a LECO Induction Furnace HP10 (Leco Corporation, St. Joseph, Michigan) and titrating the liberated sulfur with standard KIO_3 using a LECO Sulfur Titrator (Leco Corporation, St. Joseph, Michigan). Aerobic soil respiration was determined for the top 2.5 cm of each soil core according to Boyd (1995). Phosphorus absorption capacity (PAC) was determined according to Boyd and Munsiri (1996).

Data Analysis

Results of water quality determinations were averaged over time for each pond. Treatment means were averages of the replicate ponds in each treatment. Data were analyzed with a one-way analysis of variance using SAS StatView software, v. 5.0 (SAS Institute Inc., Cary, North Carolina). Significant differences among treatment means were determined by Fishers Protected Least Significant Difference (PLSD) test at a probability level of $P < 0.05$.

For the soil data analysis, the difference between the concentrations found just before harvesting and before stocking was determined for each soil variable. Treatment means were the averages of the differences (as specified above) of the replicate ponds in each treatment. A split plot design was used to analyze pH, sulfur, nitrogen, and carbon data ($P < 0.05$). Computer programming by SAS v. 6.12 (SAS Institute Inc., Cary, North Carolina) was used for data analyses. The whole plot was the pond and the split plot was the depth of soil within each pond. Soil respiration and phosphorus absorption capacity means were analyzed by one-way analysis of variance using SigmaStat v. 2.03 (SPSS, Chicago, Illinois) with a confidence level of $P < 0.05$.

RESULTS

Shrimp Production

Because of aerator failure, high mortality of shrimp occurred in one pond each of the LD and HDR treatments.

Table 1. Mean gross yields, average individual shrimp weight, food conversion ratio, survival, and kilowatt-hours (used for aeration in the production cycle) (± standard errors) for three different shrimp culture systems, low density (LD), high density (HD), and high density with recycling (HDR). The R (treatment column) represents the oxidation pond only of the HDR treatment. Numbers followed by different letters differ significantly within each column ($P < 0.05$).

Treatment	Gross Yield (kg ha^{-1})	Final Weight (g individual^{-1})	FCR	Survival (%)	Kilowatt-hours (kWh ha^{-1})
LD	1,706 ± 660.9 [a]	22.4 ± 2.95 [a]	5.6 ± 2.13 [a]	26.9 ± 7.26 [a]	8,984.2 ± 318.6 [a]
HD	4,648 ± 534.4 [b]	25.2 ± 0.73 [a]	3.4 ± 0.35 [a]	33.6 ± 2.93 [a]	13,123.7 ± 633.5 [b]
HDR	4,534 ± 629.8 [b]	24.0 ± 1.03 [a]	3.0 ± 0.04 [a]	34.9 ± 6.30 [a]	12,593.5 ± 1,020.9 [b]
R	--	--	--	--	3,623.3 ± 254.9 *

* R ponds were not included in the statistic model.
-- Does not apply.

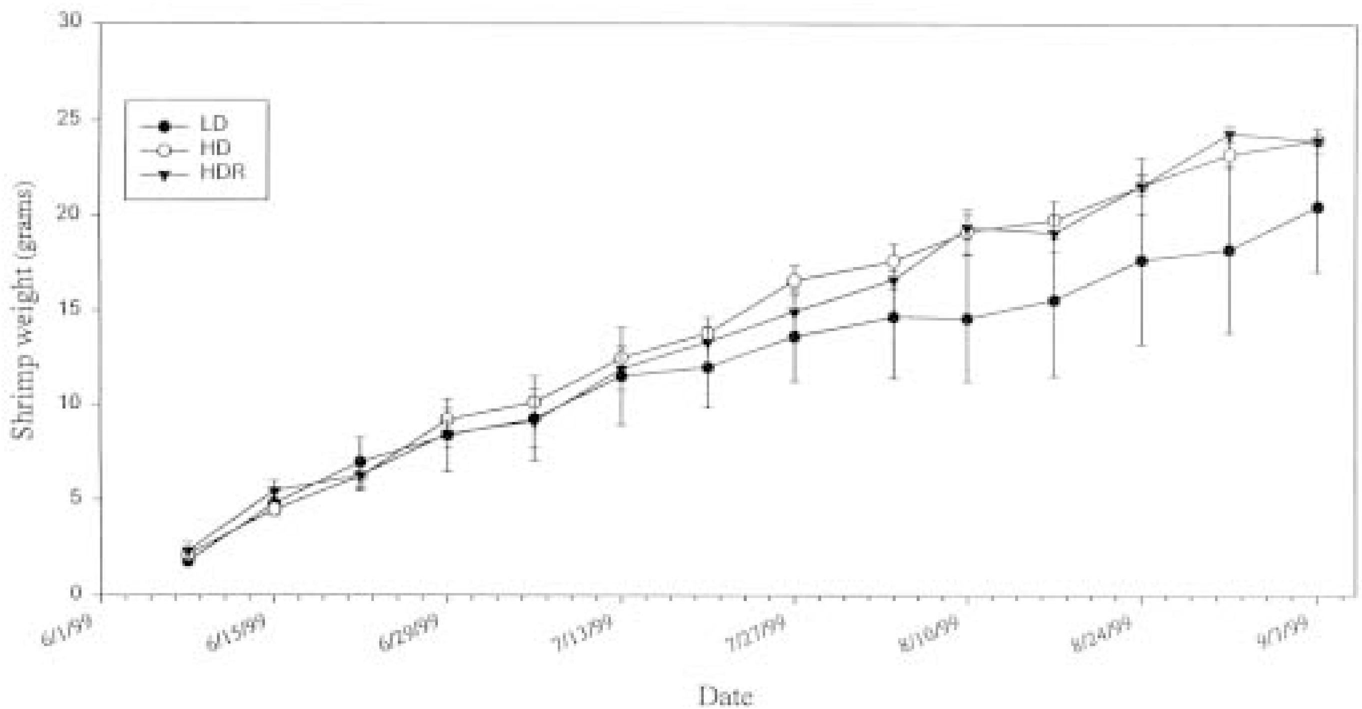

Figure 1. Shrimp growth under three different culture systems (means of three replicates in each treatment ± SE): low density (LD), high density (HD), high density with water recycling (HDR).

Table 2. Water quality variables (means of three replicates ± standard errors) for three different systems of shrimp culture: low density (LD), high density (HD), high density with recycling (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. Relevant comparisons were run among treatments; significance (S) and no significance (NS) differences are indicated within each column ($P < 0.05$).

Treatment	TSS (mg l^{-1})	SRP (mg l^{-1})	TP (mg l^{-1})	TN (mg l^{-1})	TAN (mg l^{-1})	NO_3-N (mg l^{-1})	NO_2-N (mg l^{-1})	BOD_5 (mg l^{-1})	Chlorophyll *a* (mg l^{-1})
LD	91.3 ± 4.32	0.28 ± 0.00	0.92 ± 0.04	4.95 ± 0.20	0.93 ± 0.15	0.06 ± 0.01	0.02 ± 0.01	18.53 ± 0.09	181.73 ± 24.09
HD	98.8 ± 3.06	0.18 ± 0.03	0.88 ± 0.07	5.18 ± 0.06	1.76 ± 0.17	0.11 ± 0.04	0.04 ± 0.00	20.37 ± 0.86	209.27 ± 11.60
HDR	93.1 ± 5.34	0.34 ± 0.01	0.98 ± 0.08	4.73 ± 0.07	0.74 ± 0.05	0.11 ± 0.09	0.02 ± 0.00	18.51 ± 1.02	178.10 ± 4.22
R	82.5 ± 1.10	0.51 ± 0.13	0.96 ± 0.15	3.84 ± 0.11	0.43 ± 0.08	0.07 ± 0.06	0.02 ± 0.00	14.12 ± 0.60	97.32 ± 30.22
HDR vs. HD	NS	S	NS	S	S	NS	NS	NS	NS
HDR vs. LD	NS	NS	NS	NS	NS	NS	NS	NS	NS
HD vs. LD	NS	S	NS	NS	S	NS	NS	NS	NS
HDR vs. R	S	NS	NS	S	NS	NS	NS	S	S

Data from these ponds were excluded from statistical analyses.

Mean shrimp gross yields for LD, HD, and HDR were 1,706, 4,648, and 4,534 kg ha^{-1}, respectively (Table 1). There was no significant difference between HD and HDR treatment yields. Based on a total water surface area of 2,150 m^{-2}, the HDR yield was 2,267 kg ha^{-1}, not significantly different from the LD yield. Mean harvest weights of individual shrimp ranged from 22 to 25 g and did not differ significantly among treatments (Table 1, Figure 1). Feed conversion ratios for LD, HD, and HDR treatments did not differ significantly and were 5.61, 3.40, and 3.02, respectively. Mean survival did not differ among treatments and was 27, 33.6, and 35% for LD, HD, and HDR treatments, respectively (Table 1).

Significantly less electricity (kWh) was required to maintain a minimum pond DO concentration (3.5 mg l^{-1}) in LD treatment ponds compared to HD and HDR treatment ponds (Table 1). However, there was no significant difference between HD and the culture unit of HDR treatments with respect to energy consumption for aeration.

Water Quality

No significant differences were observed among HD, HDR, and LD treatment means for TSS, TP, NO_3-N, NO_2-N, BOD_5, and chlorophyll *a* concentrations (Table 2, Figures 2 through 10). TN and TAN concentrations were greater in the HD treatment compared to the HDR treatment. The mean mass weight (Table 3) for TSS, SRP, TP, TN, and BOD_5 in HDR and R (HDR+R) were significantly higher than in the HD ponds. Mean mass weight for TAN, NO_3-N, NO_2-N, and chlorophyll *a* were not significantly different between HDR+R and HD. When comparing concentrations in the two units of the recycling system—HDR (culture ponds) and R (recycling ponds)—TSS, TN, BOD_5, and chlorophyll *a* were significantly higher in HDR.

Soils

No differences were found for soil pH, carbon, and nitrogen (Tables 4, 5, and 6) among treatments, among sample strata among treatments, or among sample depths within treatments. Sulfur concentration was significantly greater at the soil surface (0–2.5 cm and 5 cm) than at the deepest layer, but no significant differences were found among treatments (Table 7). No differences were found among treatments for net change of soil respiration and phosphorus absorption capacity in pond sediments (Tables 8 and 9).

DISCUSSION

Shrimp Production

In general, the shrimp yields in this experiment were as high as the yields found in other studies with similar culture conditions in the same research center; Hornsby (1997) obtained yields of 5,300 kg ha^{-1} in ponds stocked at 66 post-larvae m^{-2}, and McGraw et al. (in press) obtained yields of 2,970 to 3,975 kg ha^{-1} in ponds stocked at 33 post-larvae m^{-2}. In other research centers in the US, similar results have been found; Wyban et al. (1988) obtained 2,852 kg ha^{-1} from ponds stocked at 25 post-larvae m^{-2}. Higher yields (7,500 kg ha^{-1}) have been obtained by Sandifer et al. (1991), but using 7.5 kW ha^{-1} and 17% water exchange.

The stocking density of shrimp in the low-density treatment was equal to the stocking density of shrimp in the high-density-with-recycling treatment based on the total water area of production and recycling ponds. The mean HDR yield based

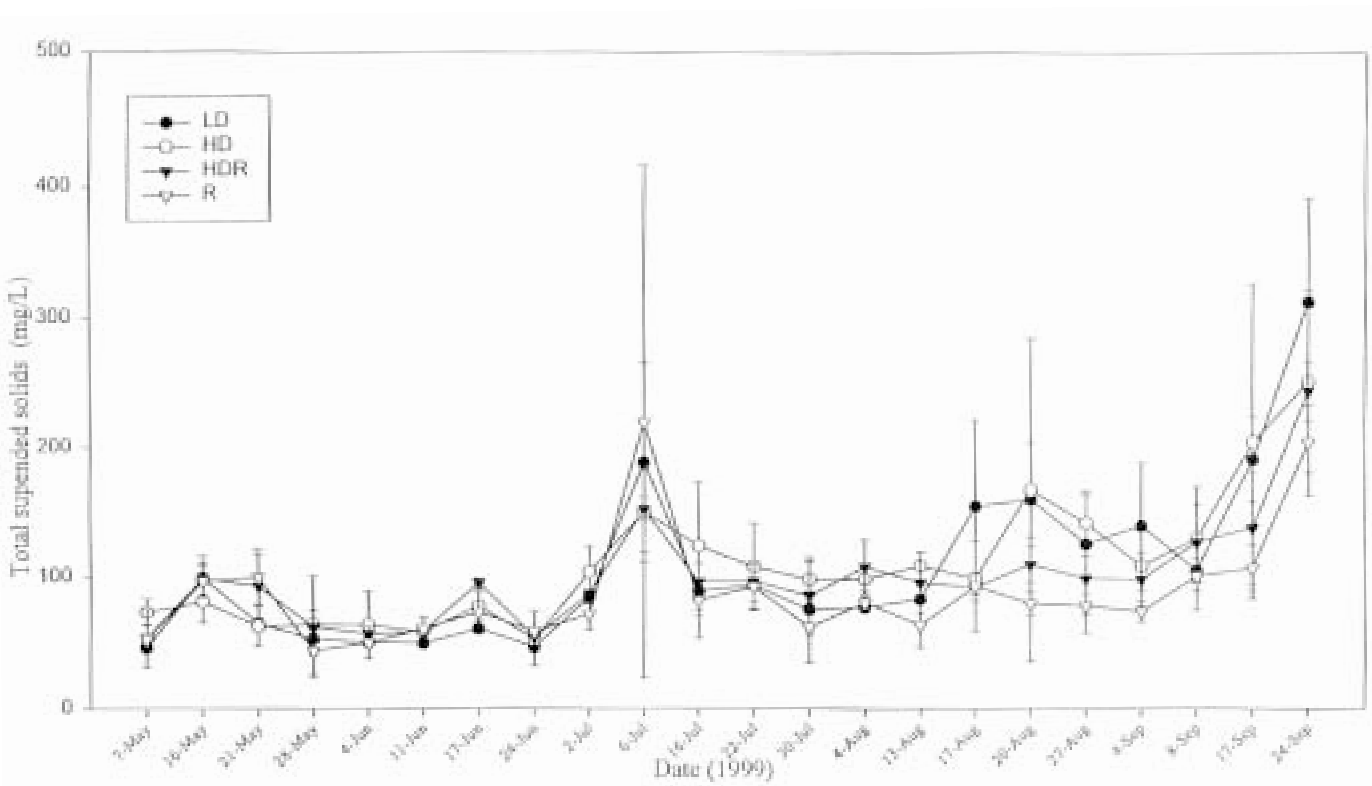

Figure 2. Mean total suspended solids (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

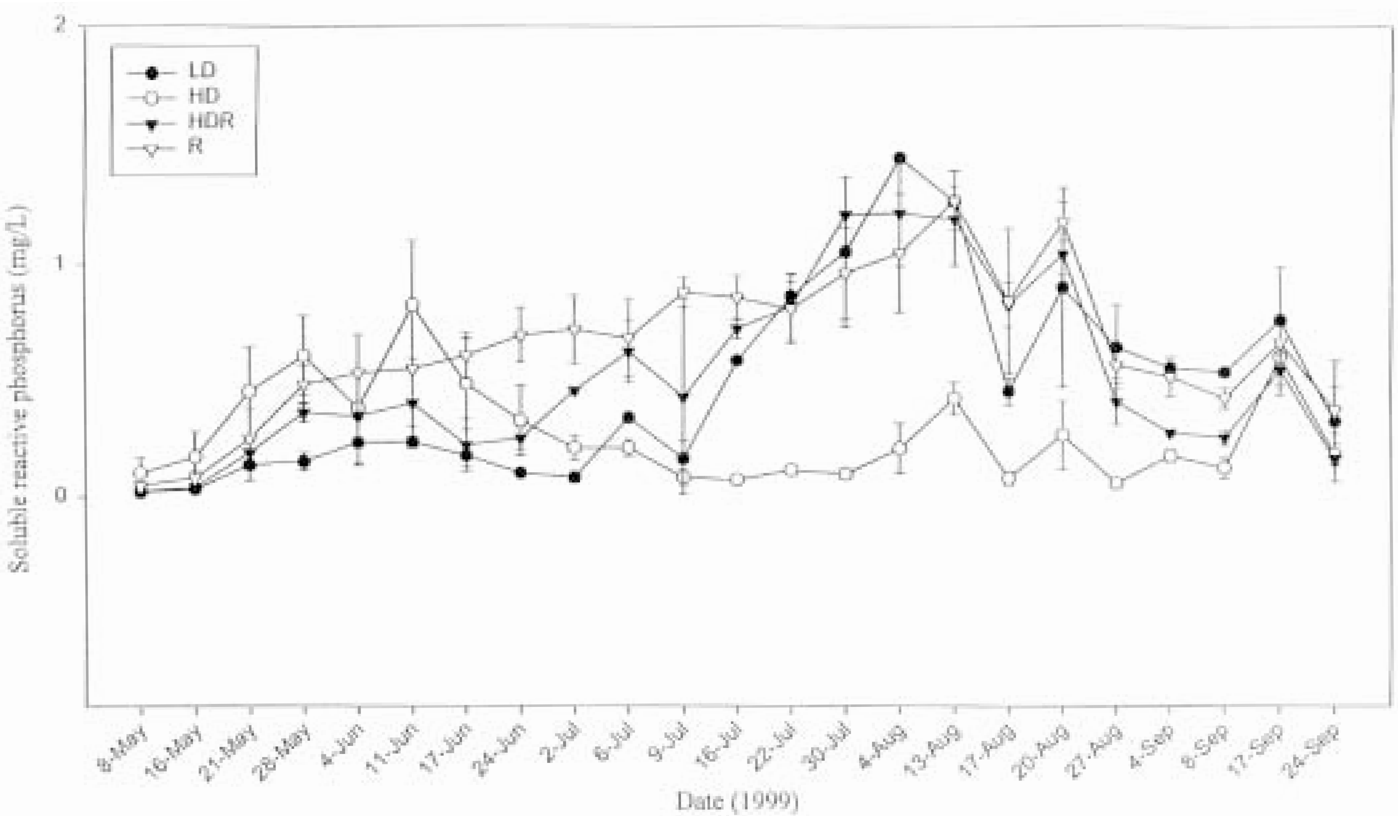

Figure 3. Mean soluble reactive phosphorus (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

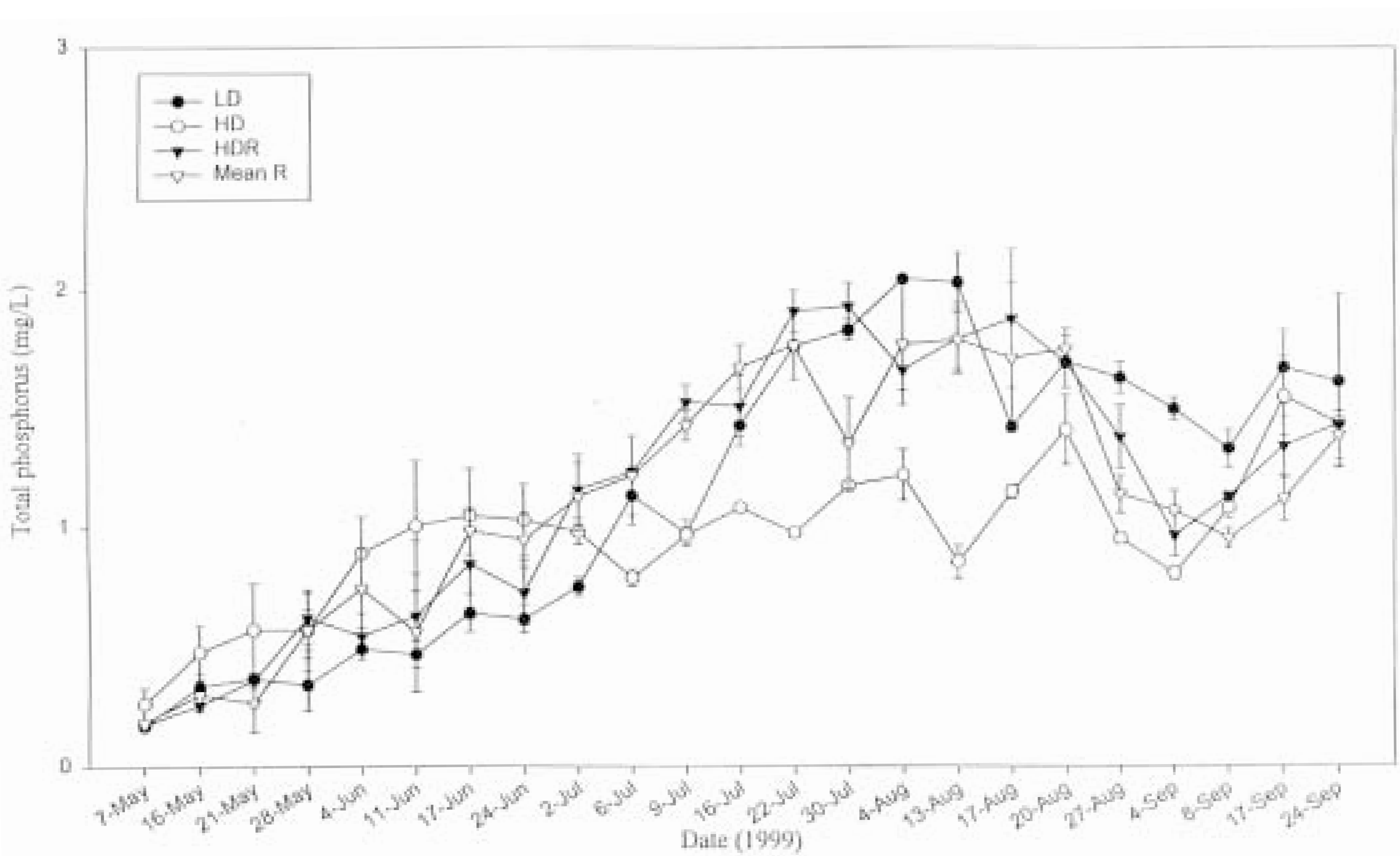

Figure 4. Mean total phosphorus (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

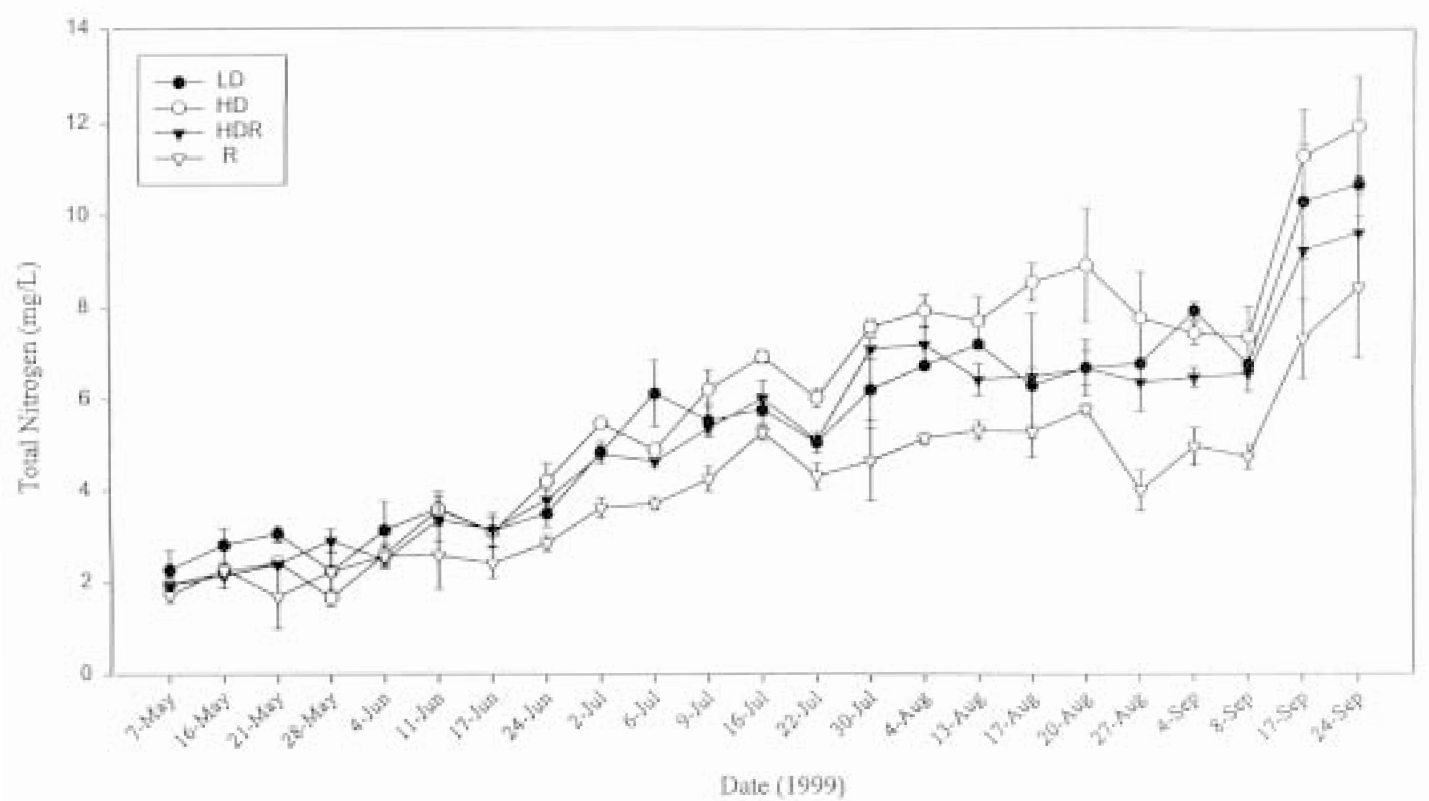

Figure 5. Mean total nitrogen (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling.

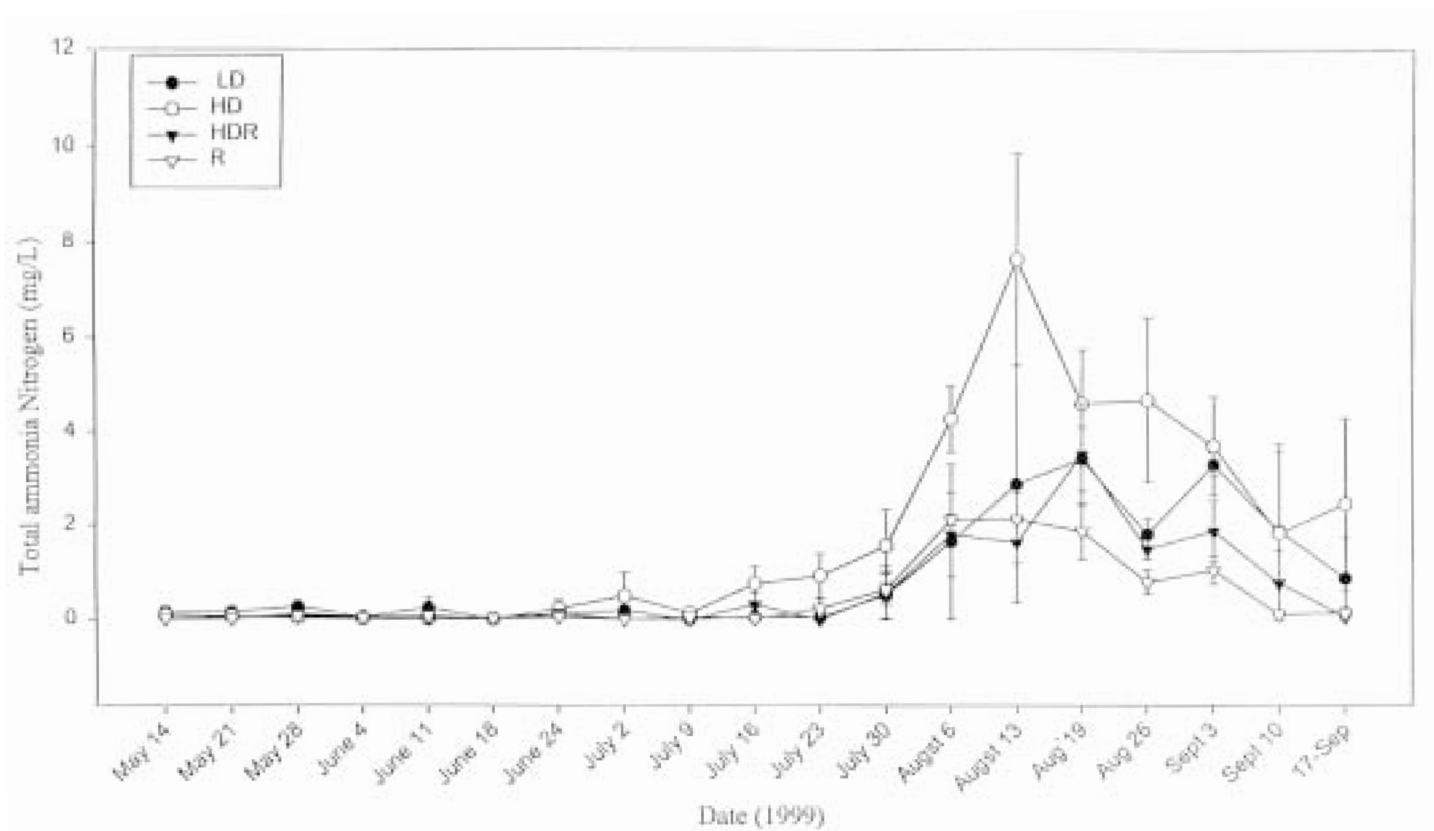

Figure 6. Mean total ammonia nitrogen (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

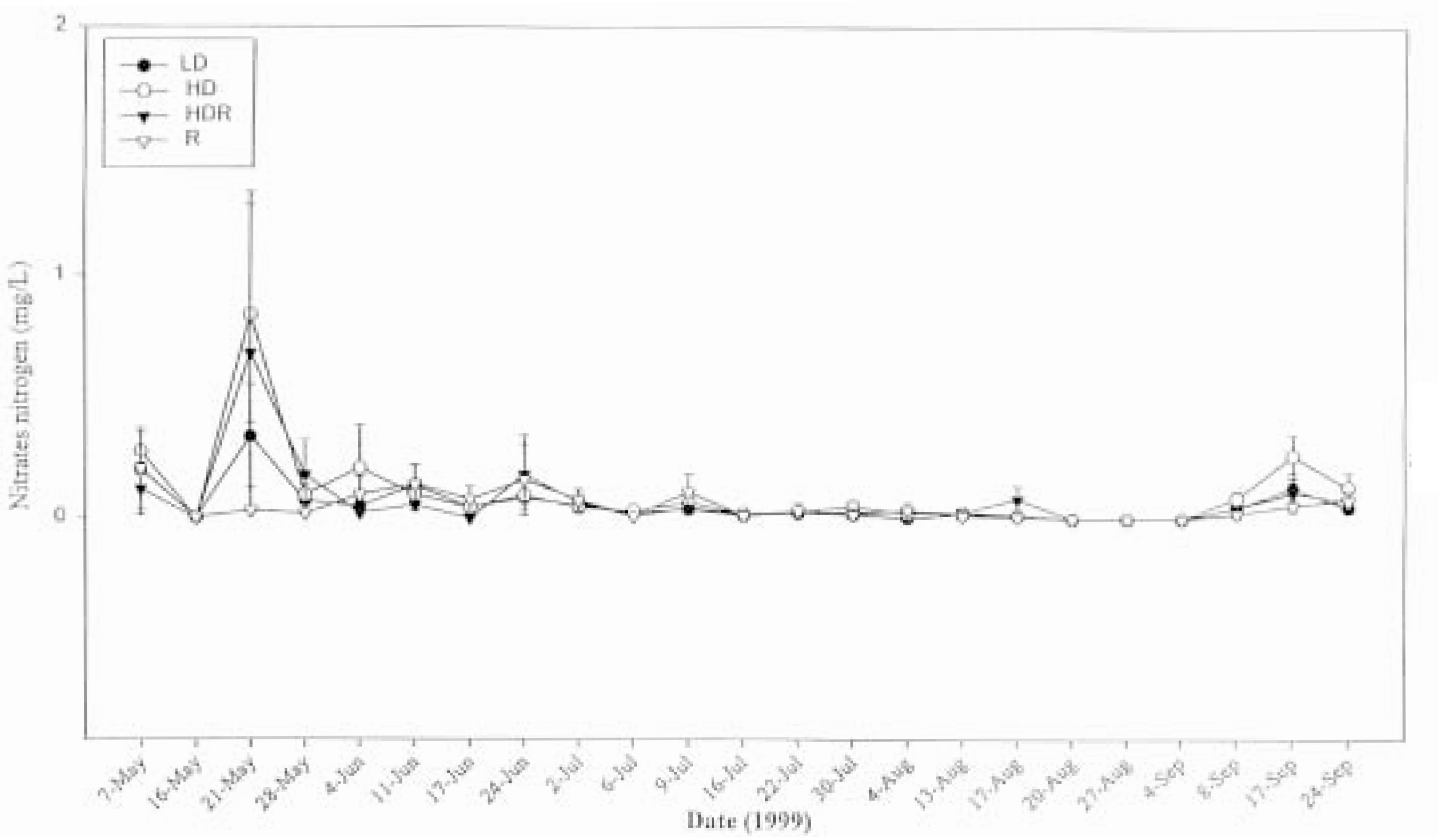

Figure 7. Mean nitrate-nitrogen (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

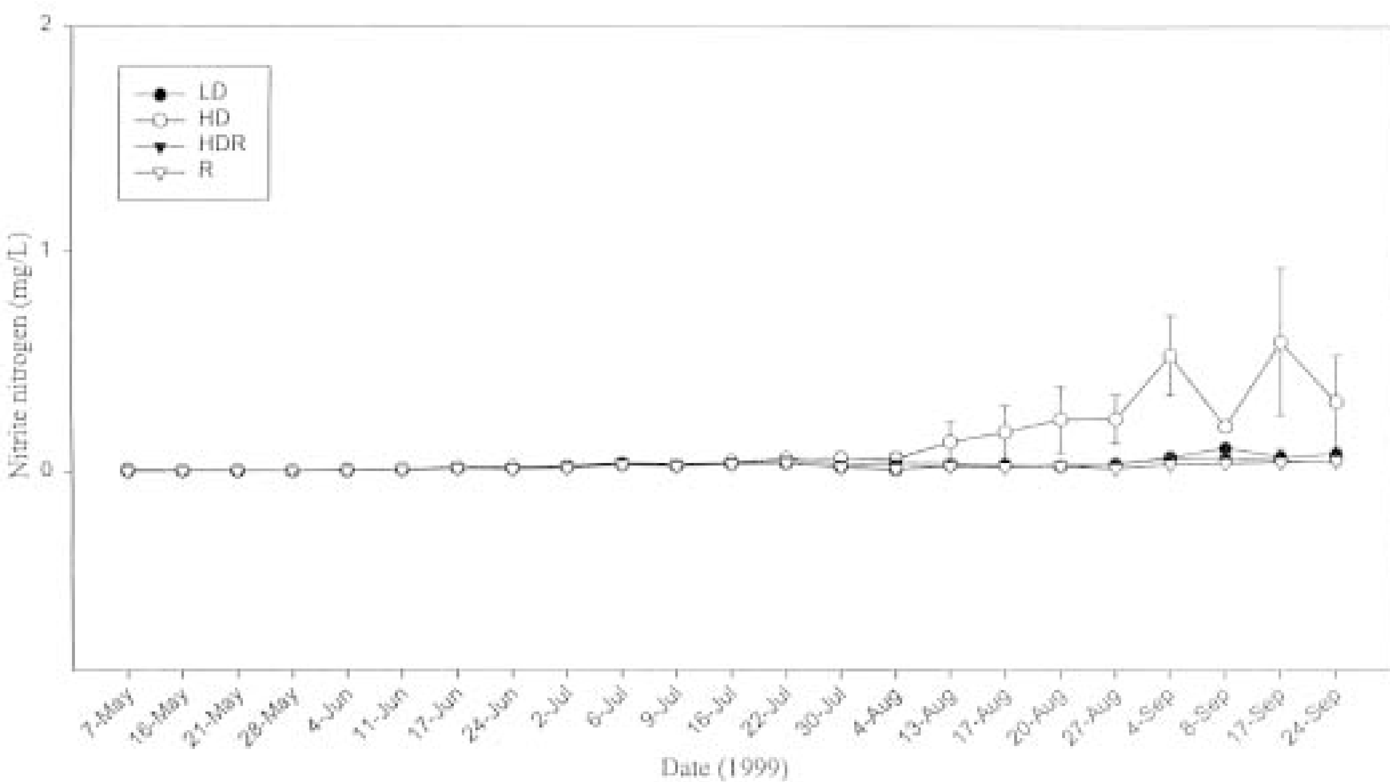

Figure 8. Mean nitrite-nitrogen (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

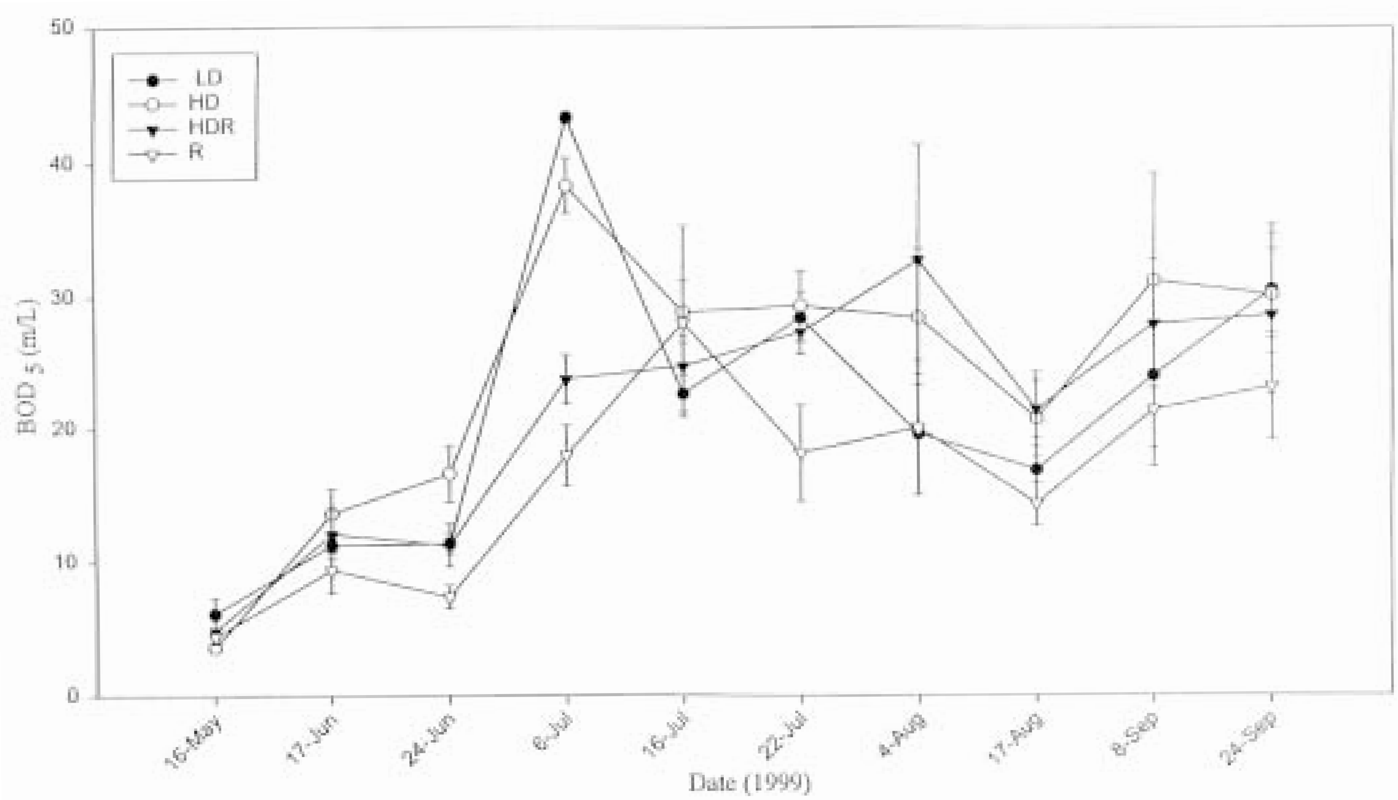

Figure 9. Mean biochemical oxygen demand (± SE) concentration in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

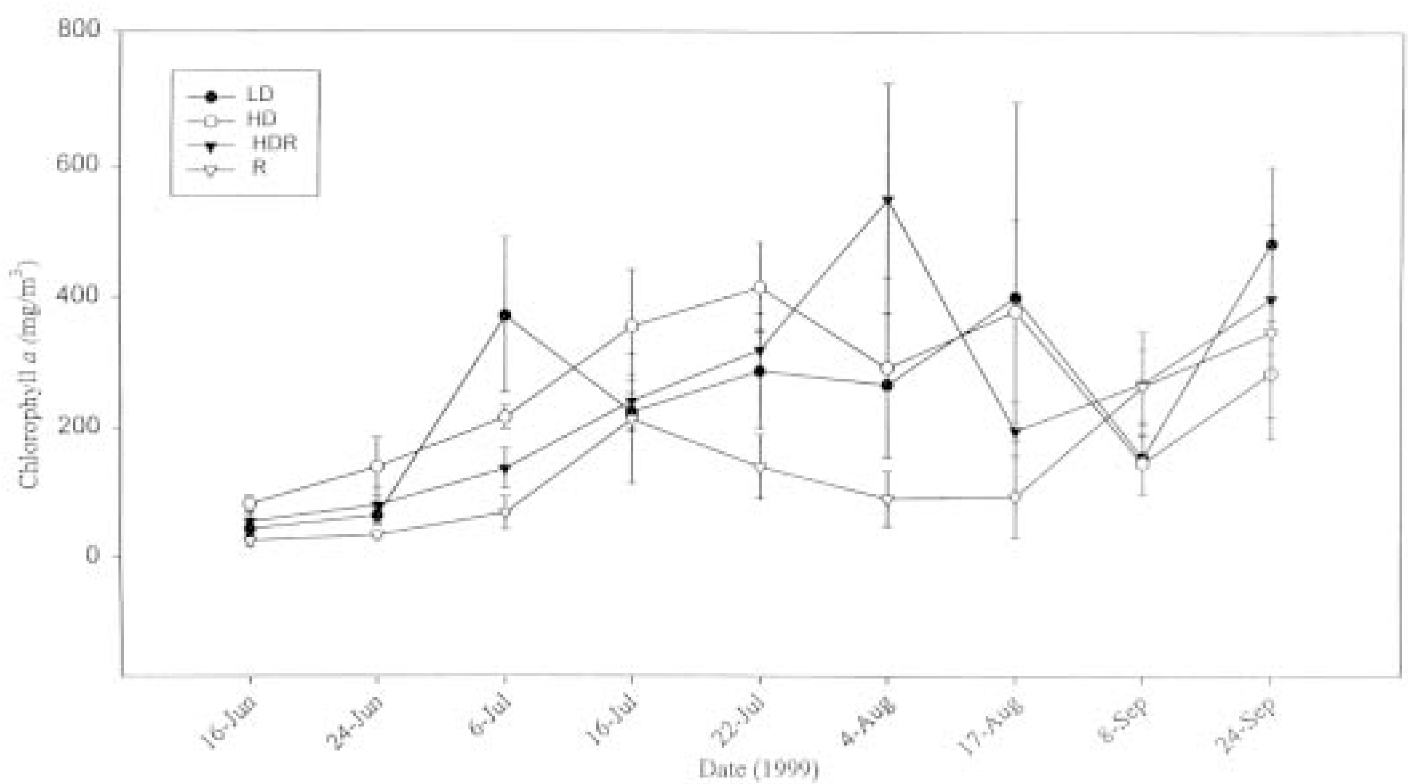

Figure 10. Mean chlorophyll *a* (± SE) concentrations in pond water during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

on the total area was 2,267 kg ha^{-1} and not significantly different from the mean LD yield of 1,706 kg ha^{-1}. These data suggest that yields cannot necessarily be increased merely by recycling production pond water through an oxidation pond. Instead of increasing the production intensity of one pond and recycling water through another non-production pond, it may be more efficient to stock both production and recycling ponds at a lower rate. In so doing, both ponds would be used for both production and oxidation, and no energy would be expended pumping water from pond to pond.

Survival was about half of what was expected. This is not attributed to management practices or water quality conditions, but to an overestimation of the post-larvae population reported by the supplier hatchery, since lower population counts were determined at the research site. However, survival calculations and feeding management practices were based upon the hatchery counts. Consequently, feed conversion ratios were high in all treatments because the daily feed allowances were calculated using an assumed survival of 70% for the whole culture period. Feed conversion ratios in the LD

Table 3. Mean mass weight (means of three replicates ± standard deviation) determined from water quality variables concentrations found in treatment ponds of 880 m^3 of water volume used to evaluate high density (HD) and high density with recycling (HDR) treatments. Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. Relevant comparisons were run among treatments; significance (S) and no significance (NS) differences are indicated within each column ($P < 0.05$).

Treatment	TSS (kg)	SRP (kg)	TP (kg)	TN (kg)	TAN (kg)	NO_3-N (kg)	NO_2-N (kg)	BOD_5 (kg)	Chlorophyll *a* (g)
HD	86.9 ± 2.69	0.16 ± 0.03	0.77 ± 0.06	4.56 ± 0.05	1.55 ± 0.15	0.10 ± 0.03	0.03 ± 0.00	17.93 ± 0.76	184.16 ± 10.21
HDR	81.9 ± 4.70	0.30 ± 0.01	0.86 ± 0.07	4.16 ± 0.06	0.65 ± 0.04	0.10 ± 0.08	0.02 ± 0.00	16.29 ± 0.90	156.73 ± 3.71
R	72.6 ± 0.97	0.45 ± 0.11	0.84 ± 0.13	3.38 ± 0.10	0.38 ± 0.07	0.06 ± 0.05	0.04 ± 0.00	12.42 ± 0.53	85.64 ± 26.60
HDR + R	154.5 ± 4.02	0.75 ± 0.08	1.70 ± 0.16	7.54 ± 0.13	1.03 ± 0.04	0.16 ± 0.11	0.06 ± 0.00	28.71 ± 1.28	242.37 ± 22.52
HDR vs. R	S	NS	NS	S	NS	NS	NS	S	S
(HDR + R) vs. HD	S	S	S	S	NS	NS	NS	S	NS

Table 4. Averages (from three replicates ± standard errors) of hydrogen ion concentrations expressed as pH found in soil samples collected before stocking and after harvest at different depths (cm) in each treatment: low density (LD), high density (HD), and high density with recycling (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. No significant differences were found within treatments or within layers of a treatment.

Treatment	pH					
	2.5 cm		*5.0 cm*		*10.0 cm*	
	Before Stocking	After Harvest	Before Stocking	After Harvest	Before Stocking	After Harvest
LD	5.86 ± 0.20	6.45 ± 0.05	5.2 ± 0.40	5.9 ± 0.00	5.72 ± 0.35	6.18 ± 0.25
HD	5.96 ± 0.06	6.42 ± 0.13	5.6 ± 0.10	5.6 ± 0.27	5.76 ± 0.27	6.13 ± 0.03
HDR	5.98 ± 0.25	6.32 ± 0.15	5.4 ± 0.50	6.1 ± 0.25	5.40 ± 0.30	6.10 ± 0.30
R*	5.51 ± 0.37	5.60 ± 0.13	5.3 ± 0.50	5.6 ± 0.66	5.51 ± 0.45	5.70 ± 0.36

* R ponds were not included in the statistical model.

Table 5. Averages (of three replicates ± standard errors) of carbon percentages found in soil samples collected before stocking (BS) and after harvest (AH) at different depths (cm) in each treatment: low density (LD), high density (HD), and high density with recycling (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. No significant differences were found within treatments or within layers on a treatment.

Treatments	Carbon Percentages								
	2.5 cm			*5.0 cm*			*10.0 cm*		
	BS	AH	Difference	BS	AH	Difference	BS	AH	Difference
LD	1.55 ± 0.15	1.11 ± 0.00	–0.44 ± 0.15	1.06 ± 0.17	0.85 ± 0.06	–0.21 ± 0.12	0.78 ± 0.04	0.71 ± 0.03	–0.07 ± 0.01
HD	1.65 ± 0.12	1.61 ± 0.27	–0.04 ± 0.23	1.00 ± 0.07	1.09 ± 0.32	0.09 ± 0.35	0.66 ± 0.05	0.58 ± 0.07	–0.08 ± 0.04
HDR	1.42 ± 0.04	1.05 ± 0.08	–0.37 ± 0.11	0.95 ± 0.04	0.83 ± 0.10	–0.12 ± 0.06	0.63 ± 0.08	0.66 ± 0.10	0.03 ± 0.02
R*	1.55 ± 0.41	1.66 ± 0.46	0.11 ± 0.11	0.82 ± 0.15	1.08 ± 0.46	0.26 ± 0.32	0.60 ± 0.12	0.49 ± 0.08	–0.11 ± 0.03

* R ponds were not included in the statistical model.

treatment were especially poor because the calculated survival was particularly poor.

The energy consumption in LD treatment ponds to maintain DO at 3.5 mg l^{-1} was lower than in HD and HDR treatments (Table 1) because feed inputs were lower (Figure 11). The HDR and HD treatments were managed similarly, but recycling HDR production pond water system did not cause a reduction in the amount of energy needed to maintain the minimum DO concentration above 3.5 mg l^{-1}. The HDR treatment required

Table 6. Averages (of three replicates ± standard errors) of total nitrogen percentages found in soil samples collected before stocking (BS) and after harvest (AH) at different depths (cm) in each treatment: low density (LD), high density (HD), and high density with recycling (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. No significant differences were found within treatments or within layers on a treatment.

Treatments	**Total Nitrogen Percentages**								
	2.5 cm			*5.0 cm*			*10.0 cm*		
	BS	AH	Difference	BS	AH	Difference	BS	AH	Difference
LD	0.14 ± 0.10	0.09 ± 0.01	–0.05 ± 0.01	0.08 ± 0.01	0.05 ± 0.01	–0.03 ± 0.00	0.04 ± 0.01	0.02 ± 0.00	–0.02 ± 0.01
HD	0.16 ± 0.01	0.16 ± 0.04	–0.00 ± 0.04	0.08 ± 0.01	0.09 ± 0.04	0.01 ± 0.04	0.04 ± 0.00	0.02 ± 0.01	–0.02 ± 0.01
HDR	0.14 ± 0.01	0.09 ± 0.01	–0.05 ± 0.02	0.07 ± 0.01	0.05 ± 0.01	–0.02 ± 0.02	0.04 ± 0.01	0.03 ± 0.00	–0.01 ± 0.01
R*	0.14 ± 0.03	0.16 ± 0.07	0.02 ± 0.05	0.05 ± 0.01	0.08 ± 0.04	0.03 ± 0.03	0.03 ± 0.01	0.03 ± 0.01	–0.00 ± 0.01

* R ponds were not included in the statistical model.

Table 7. Averages (of three replicates ± standard errors) of sulfur percentages found in soil samples collected before stocking (BS) and after harvest (AH) at different depths (cm) in each treatment: low density (LD), high density (HD), and high density with recycling (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. Numbers followed by different letters differ significantly within mean column or mean row ($P < 0.05$).

Treatments	**Sulfur Percentages**									
	2.5 cm			*5.0 cm*			*10.0 cm*			*Treatment Mean*
	BS	AH	Difference	BS	AH	Difference	BS	AH	Difference	
LD	0.13 ± 0.01	0.21 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	0.14 ± 0.02	0.07 ± 0.03	0.05 ± 0.00	0.06 ± 0.01	0.01 ± 0.01	0.053 ± 0.390 [a]
HD	0.12 ± 0.01	0.22 ± 0.03	0.10 ± 0.03	0.07 ± 0.01	0.18 ± 0.03	0.11 ± 0.02	0.04 ± 0.01	0.05 ± 0.01	0.01 ± 0.01	0.073 ± 0.060 [a]
HDR	0.11 ± 0.03	0.22 ± 0.03	0.11 ± 0.01	0.06 ± 0.00	0.13 ± 0.01	0.07 ± 0.03	0.06 ± 0.01	0.05 ± 0.02	–0.01 ± 0.02	0.058 ± 0.053 [a]
Depth Means			0.10 ± 0.04 [a]			0.08 ± 0.04 [a]			0.01 ± 0.02 [b]	
R*	0.09 ± 0.02	0.27 ± 0.03	0.18 ± 0.03	0.27 ± 0.06	0.17 ± 0.06	0.11 ± 0.06	0.10 ± 0.07	0.06 ± 0.03	–0.04 ± 0.09	

* R ponds were not included in the statistical model.

Table 8. Average (of three replicates ± standard errors) of soil respiration rates found in soil samples collected before stocking and after harvest at the first 2.5 cm of depth in each treatment: low density (LD), high density (HD), and high density with recycling (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. Numbers within the difference column followed by different letters differ significantly ($P < 0.05$).

Treatments	**Soil Respiration Rates (CO_2)** (mg cm^{-2} h^{-1})		
	Before Stocking	*After Harvest*	*Difference*
LD	5.44 ± 0.43	5.83 ± 1.11	0.39 ± 1.54 [a]
HD	5.03 ± 0.56	7.35 ± 0.54	2.32 ± 1.10 [a]
HDR	3.66 ± 0.38	6.74 ± 0.31	3.08 ± 0.08 [a]
R	5.25 ± 0.16	6.26 ± 0.32	1.01 ± 0.97 *

* R ponds were not included in the statistical model.

Table 9. Average (of three replicates ± standard errors) of phosphorus absorption capacity found in soil samples collected before stocking and after harvest at the first 2.5 cm of depth in each treatment: low density (LD), high density (HD), and high density with recirculation (HDR). Data reported for the HDR treatment represent only the culture pond. The R (treatment column) represents the oxidation pond only of the HDR treatment. Numbers in the difference column with different letters differ significantly ($P < 0.05$).

Treatments	**Phosphorus Absorption** (mg l^{-1})		
	Before Stocking	*After Harvest*	*Difference*
LD	2.02 ± 0.21	0.61 ± 0.05	1.40 ± 0.26 [a]
HD	2.25 ± 0.40	0.65 ± 0.35	1.60 ± 0.33 [a]
HDR	1.65 ± 0.08	0.20 ± 0.20	1.45 ± 0.16 [a]
R	1.93 ± 0.40	1.09 ± 0.51	0.85 ± 0.21 *

* R ponds were not included in the statistical model.

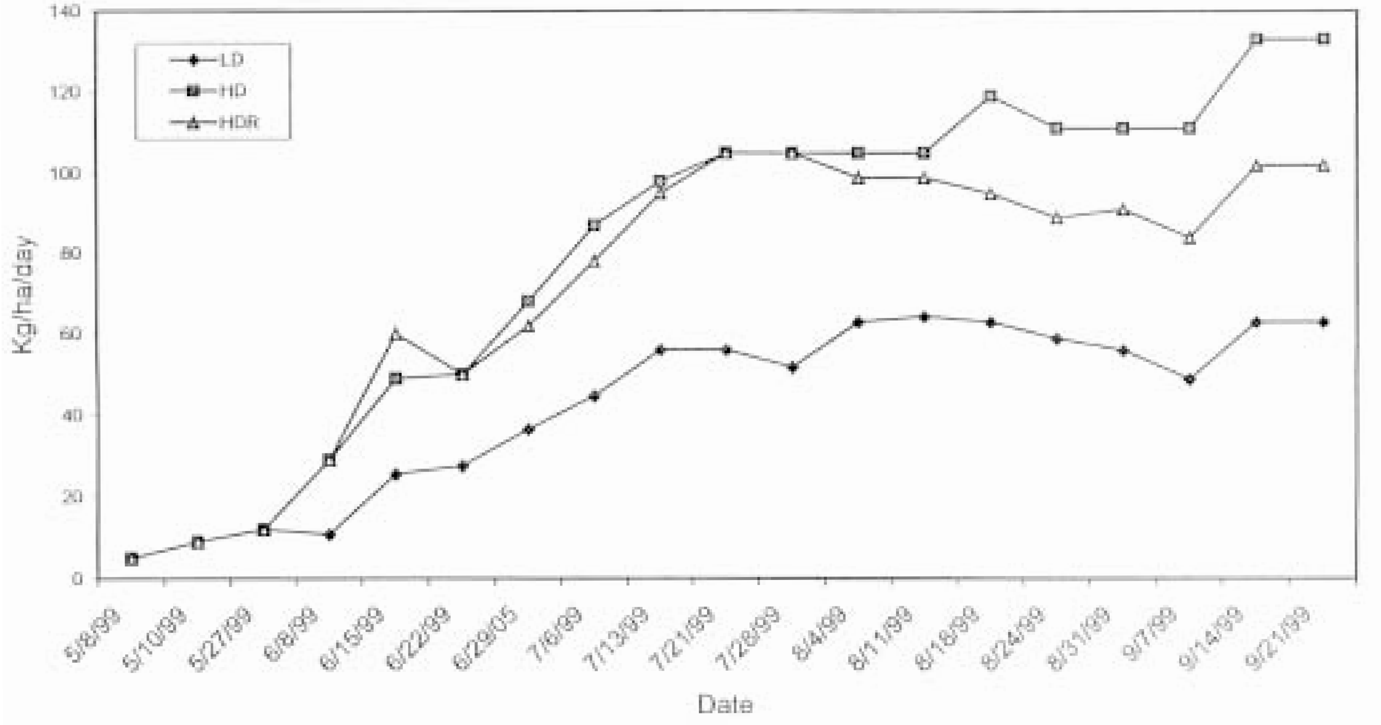

Figure 11. Feeding rates during the experimental period to test the effect of shrimp culture at low density (LD), high density (HD), and high density with water recycling (HDR).

27% more energy than the HD treatment to aerate ponds, if the energy to aerate the oxidation pond is added to that required to aerate the production pond (Table 1, p. 110).

Recycling incurred an additional cost for moving water between the two ponds. Two recycling pumps were operated simultaneously 20 h d^{-1}, consuming 0.5 kW each for a daily total of 186 kWh ha^{-1} or 27,342 kWh ha^{-1} for the whole cycle.

The total energy consumption of the HDR treatment, considering the additional energy in aerating the oxidation pond and the energy used to move the water, was 3.3 times the energy used in the HD treatment.

Water Quality

Effects of water recycling and the alternative of reducing stocking densities on water quality were evaluated by comparing the HDR and LD treatments, but no significant differences for water quality were observed between the two treatments. These results are expected because the total water volume per stocked shrimp was similar in both treatments. Results also suggest that no improvement in water quality was obtained by implementing a recycling system.

The results of comparison between LD and HD treatments were not expected. The HD treatment ponds were expected to have higher concentrations of nutrients and organic matter, but only TAN was significantly higher. Moreover, concentrations of SRP were actually higher in the LD than HD treatment, and all other variables were not significantly different between the two treatments (Table 2, p. 110).

Higher SRP concentrations were expected from HD treatment ponds compared to LD treatment ponds because of the greater quantity of feed used in the HD treatment. However, the SRP concentrations in the HD treatments were not only significantly lower than in the LD treatment but also lower than in HDR. This was also noticeable in the tendency through the experiment cycle (Figure 3, p. 112), where HD showed the lowest concentrations. The low concentrations of SRP in the HD treatment were not related to the presence of a greater amount of algae since no significant differences among treatments were found in chlorophyll *a* concentrations (Table 2, p. 110; Figure 10). It has to be considered that overfeeding took place and LD was more overfed than the other treatments. Phosphorus absorption capacity analyses were done to verify if the SRP concentrations were related to the soil phosphorus absorption; however, treatments did not differ significantly (Table 9).

To evaluate effects of recycling water to a non-culture pond, the comparison of HD and HDR was considered. Since the HDR treatment was using twice the water volume of the HD, it was expected that just by dilution the concentrations in the HDR treatments would be about half of the concentrations in the HD treatment. However, only TN and TAN concentrations were greater in the HD treatment compared to the HDR treatment. No water quality variable improvement was truly found that could be attributed to water recycling. When the mean mass weight determined from the water quality variable concentrations of culture and recycling pond were summed (HDR+R), they were significantly greater than the HD treatments or no significance differences were found (Table 3).

Soils

Differences between percentages found in initial and final samples did not differ ($P > 0.05$) within layers of the same treatment or when compared to other treatment layers for pH, carbon and nitrogen. Much of the nitrogen in soils is associated with organic matter (Alexander, 1977), so it is common that the pattern in soil nitrogen concentration in pond soils is similar to that of carbon, only in lower concentrations (Ghosh and Mohanty, 1981). Related to carbon results, the differences in soil respiration found between initial and final samples were not significantly different among any of the treatments. This suggests that water recycling did not lessen the nutrient load on soils of the culture unit of the recycling system.

Sulfur was significantly higher at the soil surface (0–2.5 cm and 5 cm) than at the deepest layer, but no significant differences because of treatment were found (Table 7). Sulfur is also contained in organic matter, and when it decomposes, sulfur is released as sulfide, which in the presence of oxygen is oxidized to sulfate (Boyd, 1990). Greater percentages of sulfur in the first two layers could have been generated by reduction of sulfate to sulfide followed by precipitation of sulfide as ferrous sulfide (Boyd, 1990).

CONCLUSIONS

Findings of this study indicate that recycling water through an oxidation pond did not cause improvement in any production variable, in water quality, or in pond soil conditions.

The major operational disadvantages of recycling water were that pond space was put into non-productive use as oxidation ponds and 3.3 times more energy was used for aeration and water circulation.

Recycling water through a non-production pond should not be used to intensify yields in the production pond. Rather, the shrimp should be stocked in all ponds at a lower density.

ANTICIPATED BENEFITS

The findings allowed a discussion of the feasibility of using water recycling to minimize the discharge of ponds effluents and the environmental implications of aquaculture with or without recycling.

This research has contributed to a better understanding of pond dynamics. It has also provided an environment for a Honduran graduate student to learn research techniques, sampling methods, water and soils analysis methods, and analytical protocol that are very useful to fill the need of research and improvement of sustainable aquaculture in Honduras.

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