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Effects of Two Densities of Caged Monosex Nile Tilapia, *Oreochromis niloticus*, on Water Quality, Phytoplankton Populations, and Production When Polycultured with *Macrobrachium rosenbergii* in Temperate Ponds

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Abstract

The effects of different densities of caged Nile tilapia, *Oreochromis niloticus*, on water quality, phytoplankton populations, prawn, and total pond production were evaluated in freshwater prawn, *Macrobrachium rosenbergii*, production ponds. The experiment consisted of three treatments with three 0.04-ha replicates each. All ponds were stocked with graded, nursed juvenile prawn (0.9 ± 0.6 g) at 69,000/ha. Control (CTL) ponds contained only prawns. Low-density polyculture (LDP) ponds also contained two cages (1 m^3; 100 fish/cage) of monosex male tilapia (115.6 ± 22 g), and high-density polyculture (HDP) ponds had four cages. Total culture period was 106 d for tilapia and 114 d for prawn. Overall mean afternoon pH level was significantly lower ($P \leq 0.05$) in polyculture ponds than in CTL ponds but did not differ ($P > 0.05$) between LDP and HDP. Phytoplankton biovolume was reduced in polyculture treatments. Tilapia in the LDP treatment had significantly higher ($P \leq 0.05$) harvest weights than in the HDP treatment. Prawn weights were higher ($P \leq 0.05$) in polyculture than prawn monoculture. These data indicate that a caged tilapia/freshwater prawn polyculture system may provide pH control while maximizing pond resources in temperate areas.

Managing stable phytoplankton populations is a major challenge in earthen pond aquaculture, especially if the cultured species does not graze phytoplankton directly (Hepher et al. 1989). Dense phytoplankton blooms with high photosynthetic rates can result in elevated pH levels (>10.0) in the afternoon, causing physical and physiological stress (Boyd and Tucker 1998) and even prawn mortality (Straus et al. 1991). Methods used to control high pH have included algicides (Osunde et al. 2003), chemical intervention with acids or buffers (Boyd et al. 1978; Pote et al. 1990), water exchange (McGee and Boyd 1983), and mechanical stirring (Paerl and Tucker 1995; Tucker and Steeby 1995). However, each of these methods has serious risks or practical limitations. Algicides may be toxic (Osunde et al. 2003), flushing is commercially impractical, and buffers or acids temporarily address the symptoms but not the actual problem.

Biological controls have shown the potential to be both highly selective (Moriarty and Moriarty 1973; Datta and Jana 1998; Turker et al. 2003a) and cost-effective (Perschbacher 1995). Nile tilapia, *Oreochromis niloticus*, have the ability to filter-feed on phytoplankton (Perschbacher and Lorio 1993; Turker et al. 2003a, 2003b) and, concomitantly, produce a second crop of marketable animal in polyculture systems (Dos Santos and Valenti 2002). Tilapia and freshwater prawn have been shown to be good complimentary species (Brick and Stickney 1979; Rouse and Stickney 1982; Meriwether et al. 1984; Rouse et al. 1987; Gracia-Perez and Alston 2000; Dos Santos and Valenti 2002). Garcia-Perez et al. (2000) reported that polyculture of free-swimming tilapia in prawn

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ponds increased economic returns by 21%. However, when tilapia are unconfined, there is the potential of negative species interaction including competition over food, unintended and uncontrolled reproduction by tilapia, and the need to manually separate the two species at harvest. These negative factors can be eliminated by confining the tilapia in cages (Pagan-Font 1975; Guerrero 1982; Petersen 1982; Rouse and Stickney 1982; Heinen et al. 1987; Garcia-Perez and Alston 2000). Tidwell et al. (2000a) reported that polyculture of prawn and tilapia in cages increased total pond productivity by 81%. However, cage confinement might reduce the ability of tilapia to efficiently harvest phytoplankton for pH control.

Some studies have indicated that confined tilapia may still be effective biological controls but that their ability to control algae may be density dependent. Dunseth (1977) reported that tilapia stocked at a pond surface area of $0.25/m^2$ did not affect algae populations when compared with ponds without tilapia. However, Perschbacher and Lorio (1993) found that caged Nile tilapia provided control over phytoplankton populations in channel catfish, *Ictalurus punctatus*, production ponds when stocked at surface densities of $0.5/m^2$. Wang et al. (1998) showed that tilapia stocked in net pens at $0.32/m^2$ improved water quality and increased shrimp, *Penaeus chinensis*, yields. Tilapia polyculture has the potential of improving water quality in prawn ponds and to increase profits through improved prawn yields and increased total pond production (prawn + tilapia). However, to date most prawn and tilapia polyculture research has been conducted at fairly extensive stocking rates and under tropical or subtropical conditions.

In temperate climates, more intensive prawn production technologies have been developed to compensate for the shorter, temperature-restricted growing season (Tidwell et al. 2000b, 2002, 2004). Also, phytoplankton taxa may differ under temperate conditions. The impacts and feasibility of prawn and tilapia polyculture need to be evaluated under temperate conditions with an abbreviated growing season (110–120 d). The objective of this study was to evaluate the effect of two densities of cage-confined tilapia on water quality variables, specifically pH, in prawn production ponds and determine the effects on phytoplankton populations, prawn production, prawn population structure, and tilapia growth and survival.

Materials and Methods

Experimental System

The experiment was carried out in nine 0.04-ha earthen, rectangular ponds (1.5-m depth) located at the Aquaculture Research Center, Kentucky State University (KSU), Frankfort, Kentucky, USA. Ponds were drained and allowed to dry 4 wk prior to stocking. Vertically oriented polyethylene "construction/safety fence" panels measuring 120 cm wide with a mesh size of 7.0×3.5 cm were suspended from metal fence posts to increase available surface area by 50% (Tidwell et al. 2000b). On May 20, 2003, water from a reservoir was passed through a 1000-μm filter sock to fill each pond to a depth of 0.50 m. All ponds were treated with 22.4 kg/ha $CuSO_4$ to kill filamentous algae. On 23 May, 7.5 L/ha of liquid fertilizer (NPK, 0:45:0) was added along with 45.0 kg/ha of dried distiller's grains to initiate a phytoplankton bloom. Water was added to achieve a depth of 1.5 m and maintained at this level for the duration of the experiment. The experiment consisted of three treatments with three replicates each. Treatments were as follows: prawn monoculture (control; CTL), prawn/low-density tilapia polyculture (LDP), and prawn/high-density tilapia polyculture (HDP). The LDP contained two cages of tilapia and the HDP four cages of tilapia with a total of 100 fish/cage, respectively.

All ponds were equipped with a 0.5-horsepower aerator (Airolator, Kansas City, MO, USA) modified with a "deep-draw" tube operated nightly (1600–0800 h) to aerate and prevent stratification (Tidwell et al. 2002) and a 0.5-horsepower circulator that was operated during the day (0800–1600 h). The circulator consisted of an aerator motor mounted horizontally at a depth of 0.5 m. The use of circulators was discontinued on 5 August based on undesirable water quality from bioturbation of pond sediments.

Water Quality

Dissolved oxygen (DO) concentrations in all ponds were monitored twice daily (0800 and 1600 h) using a YSI Model 85 meter (Yellow Springs Instruments, Yellow Springs, OH, USA). Surface and bottom pond pH and temperature for all ponds were monitored twice daily (0800 and 1600 h) using a YSI Model 60 meter. Total ammonia-nitrogen (TAN) and nitrite-nitrogen were monitored three times per week using an HACH DR/2500 spectrophotometer (Hach Company, Loveland, CO, USA). Unionized ammonia-nitrogen was calculated from TAN, and afternoon pond temperature and pH values were recorded for the pond that day (Boyd 1990). Alkalinity, total hardness, and calcium hardness were monitored once weekly according to procedures for an HACH FF-2 test kit.

Algae

A chlorophyll-*a* sample was obtained from each pond monthly using procedures outlined by the HACH chlorophyll-*a* field test kit and analyzed using a DU 640 UV/Visual spectrophotometer (Beckman Coulter Inc., Fullerton, CA, USA). A 1-L Kemmerer bottle was used to sample two different locations in each pond at a depth of 30 cm every 2 wk for phytoplankton. The subsamples were pooled and a 22-mL aliquot of the water sample was preserved with 3% formalin and refrigerated until analysis. An inverted microscope was used for phytoplankton cell counts using a stratified counting procedure (Venrick 1978). Samples were enumerated at 560× and 140× magnification using the Utermöhl (1958) technique. Frequently encountered smaller forms were identified at 560×, in 10 or more random fields, and rarer larger forms were identified using a 140× scan of the entire chamber. Prescott (1951) and Anagnostidis and Komarek (1988) were used as taxonomic keys and to group phytoplankton by taxonomic division for data analyses.

Phytoplanktons were categorized into six groups: chlorophytes or green algae, cyanoprokaryota or blue-green algae, bacillariphytes or diatoms, flagellates, euglenoids, and dinoflagellates. Percent contributions of each, based on cell counts, were arcsine transformed prior to analysis. Results were analyzed using ANOVA to determine differences between treatments and presented in their non-arcsine-transformed state to facilitate interpretation. Biovolume of frequently encountered species was calculated according to Hillerbrand et al. (1999) for those dates on which differences in percent contribution of algal divisions were found. Conversion to biovolume equivalents affords more realistic comparison of biomass present given the four orders of magnitude difference in cell size.

Tilapia

Sex-reversed male Nile tilapia, *O. niloticus*, were shipped by truck from a commercial hatchery (Southern Farm Tilapia, Louisburg, NC, USA) and received on May 27, 2003. They were maintained in four 2450-L flow-through raceways until pond stocking. On 29 May, tilapia were graded using #62 and #74 grader bars to remove the largest and smallest of the population. Fish retained from the graded population were used for stocking. A subsample of 300 individuals were anesthetized with 25 mg/L clove oil and individually weighed (115.6 ± 22.0 g) using an Ohaus Scout II scale (Ohaus Corp., Florham Park, NJ, USA); total length was also measured (18.5 ± 1.0 cm). On 30 May, tilapia were counted and weighed into groups of 25 fish (Doran 8000 XL scale; Perkins Scale Corp., Lexington, KY, USA) and stocked in rotation until each cage achieved a density of 100 fish/cage. Cages were 1-m^3 round cages constructed of 1.75-mm plastic mesh. On 2 June, tilapia were diagnosed with the fungal disease *Saprolegnia* spp. Fish were removed from their respective cages where they were given a 1-h bath treatment of $KMnO_4$ at 4 mg/L and then placed back into their assigned cages. For the following 8 d, dead fish were removed and recorded. The *Saprolegnia* spp. outbreak ceased as morning water temperature rose above 21 C. Recorded mortalities were replaced on 10 June with fish remaining from the initial cage stocking. Tilapia were fed an extruded diet containing 32% protein (Rangen Inc., Buhl, ID, USA) to apparent satiation once daily in the afternoon (1400–1500 h). Every 3 wk, tilapia ($N \geq 10$) were dip netted from each cage, individual lengths and weights determined and recorded, and fish returned to their respective cages.

The culture period for tilapia was 106 d. On 12 September, individual tilapia cages were harvested. A final count was conducted to determine survival, and bulk weight was recorded for each cage to determine final average weight and production. A random sample of three individuals from each cage was processed to determine dress-out percentages.

Prawn

Postlarval (PL) prawns, *Macrobrachium rosenbergii*, were shipped by air from a commercial hatchery (Aquaculture of Texas, Weatherford, TX, USA) and nursed in a greenhouse at KSU for 60 d. PLs were held in 3680-L tanks with horizontal substrate and fed a 40% protein salmonid diet (Rangen Inc.) based on percent body weight each day, and water quality was monitored. On 3 June, juvenile prawn were size graded using a #14 grader bar, and those retained (top grade) were used for stocking purposes. Individual weights of 400 prawns were determined to establish an initial stocking weight (0.9 $\pm$ 0.6 g) using an Ohaus electronic balance. Juveniles were hand counted into groups of 100 and stocked in rotation between ponds until the desired pond stocking density of 69,160/ha was achieved in each pond.

Prawn were fed one-half the daily ration twice daily (0900 and 1400 h) using a sinking 32% protein prawn diet (Farmer's Feed, Lexington, KY, USA) distributed evenly across the pond surface. Prawn feeding was based on a schedule from Coyle et al. (2003). Prawn were sampled ($N \geq 30$) every 3 wk to determine average weights.

The culture period for prawn was 114 d. On 23 September, water levels in each pond were lowered to 0.5 m. On 24 September, substrates were removed and each pond was seined at least three times. Remaining water was drained and remaining prawns were harvested by hand. Prawns were rinsed in clean water, and then, bulk weight and total count were recorded to determine final production, average weight, and survival by pond. Random samples of $\geq$300 individuals from each pond were individually weighed and categorized into their respective sexual morphotypes (Tidwell et al. 1999)

Economics

Economic analyses for prawn monoculture and prawn/tilapia polyculture were calculated using the enterprise budget method. Fixed costs were based on the initial assumption of a hypothetical farm with a single 0.4-ha pond. This model was directly adopted from the small-scale Kentucky aquaculture farm model proposed in Dasgupta and Tidwell (2003). Hence, the total annual fixed cost was \$2498.67 for monoculture, \$2678.17 for LDP, and \$2982.67 for HDP, which accounts for the tilapia cages (cage cost = \$35.90/cage, life span = 5 yr) and a power take-off tractor (PTO)-powered aerator (cost = \$500, life span =5 yr) used in the HDP treatment only.

Operating costs and output prices were adopted from Dasgupta and Tidwell (2003) and modified to include the additional expense of stocking and feeding tilapia and the extra fuel cost and maintenance associated with the PTO aerator. Feed prices were assumed to be \$396/mt and \$484/mt for prawn and tilapia diets, respectively. Juvenile prices were at \$0.08/head and \$1.00/head for prawn and tilapia, respectively. Output prices were kept at \$12.10/kg and \$4.40/kg for prawn and tilapia, respectively.

Statistical Analysis

A one-way ANOVA analysis was used to compare water quality and prawn harvest data between treatments. If differences were identified as significant by ANOVA ($P \leq 0.05$), means were separated using the least significant difference test (Zar 1984). An ANOVA was used to determine if chlorophyll-*a* data were different between treatments. For analysis of algae abundance and biovolume, differences were considered significant at $P \leq 0.10$. This higher level of significance was chosen in light of the multiplicative errors of time, sample size, counting method, biovolume conversion, and Type 1 error. A two-sample *t*-test was used to compare biovolume measurements between the HDP and the CTL treatments only. A two-sample *t*-test was used to compare tilapia harvest data between polyculture treatments. Feed conversion ratio (FCR) was calculated as follows: FCR = feed fed/weight gain (Tidwell et al. 1999) based on the amount of sinking diet for the prawn and floating diet for the tilapia. Specific growth rate (SGR) was calculated as follows: SGR (%/d) = $([(\ln W_f - \ln W_i)/T] \times 100)$, where W_f is the final weight, W_i the initial weight, and T the total days of the study (Webster et al. 2000). Production–size index (PSI) was calculated as follows: production (kg/ha) × average weight (g) ÷ 1000 (Tidwell et al. 2000a).

Results

Water Quality

There was no significant difference ($P > 0.05$) between treatments in overall means for temperature, unionized ammonia-nitrogen, chlorophyll-*a*, alkalinity, total hardness, or calcium hardness (Table 1). There were no significant differences ($P > 0.05$) in morning DO concentrations between treatments (6.5 mg/L, overall). However, afternoon DO concentrations in the CTL ponds (8.4 mg/L) were significantly higher ($P \leq 0.05$) than in either polyculture treatment, with the concentration in the LDP treatment (7.7 mg/L) significantly higher ($P \leq 0.05$) than in the HDP treatment (7.4 mg/L). Significant differences ($P \leq 0.05$) for monthly afternoon DO concentrations are shown in Fig. 1.

Over the duration of the study, overall means for surface morning pH values were significantly higher ($P \leq 0.05$) in CTL ponds (7.9) than in polyculture ponds (7.8), as were afternoon surface means (8.3 and 8.2, respectively). Overall means for afternoon bottom pH were again significantly higher ($P \leq 0.05$) in CTL ponds (8.3) than in polyculture ponds (8.0), while differences between LDP and HDP treatments were not significantly different ($P > 0.05$). Monthly means for bottom pH levels in the afternoon (the most critical points) are shown in Fig. 2.

There was no significant difference ($P > 0.05$) in overall TAN concentrations between polyculture treatments (1.0 mg/L), but these were significantly greater ($P \leq 0.05$) than concentrations in monoculture CTL ponds (0.7 mg/L). Monthly TAN concentrations between treatments are shown in Fig. 3. Overall nitrite-nitrogen

TABLE 1. *Treatment mean of water quality parameters sampled in the 114-d experiment.*

Variable	Treatment: Control	Treatment: Low-density polyculture	Treatment: High-density polyculture
Temperature (C)	25.9 ± 0.3^a	25.6 ± 0.5^a	25.6 ± 0.3^a
Oxygen (mg/L)			
Morning	6.8 ± 0.4^a	6.6 ± 0.5^a	6.3 ± 0.5^a
Afternoon	8.4 ± 0.2^a	7.7 ± 0.3^b	7.41 ± 0.1^c
pH			
Morning			
Surface	7.9 ± 0.1^a	7.8 ± 0.0^b	7.8 ± 0.0^b
Bottom	7.9 ± 0.1^a	7.8 ± 0.1^a	7.7 ± 0.1^a
Afternoon			
Surface	8.3 ± 0.1^a	8.0 ± 0.1^b	8.0 ± 0.1^b
Bottom	8.3 ± 0.1^a	8.0 ± 0.1^b	8.0 ± 0.1^b
TAN (mg/L)	0.7 ± 0.0^b	1.0 ± 0.2^a	1.0 ± 0.0^a
Unionized ammonia (mg/L)	0.1 ± 0.0^a	0.1 ± 0.0^a	0.1 ± 0.0^a
Nitrite-nitrogen (mg/L)	0.1 ± 0.0^c	0.2 ± 0.1^b	0.2 ± 0.0^a
Chlorophyll-*a* (μg/L)	13.4 ± 6.8^a	15.6 ± 3.8^a	24.5 ± 13.1^a
Alkalinity (mg/L)	85.4 ± 1.1^a	87.8 ± 0.7^a	87.2 ± 4.7^a
Hardness (mg/L)	128.0 ± 1.3^a	126.6 ± 6.0^a	128.7 ± 1.9^a
Calcium hardness (mg/L)	94.4 ± 1.2^a	96.5 ± 3.7^a	95.2 ± 1.9^a

TAN, total ammonia-nitrogen. Treatment means within a row followed by different superscripts are significantly different ($P \leq 0.05$) by ANOVA.

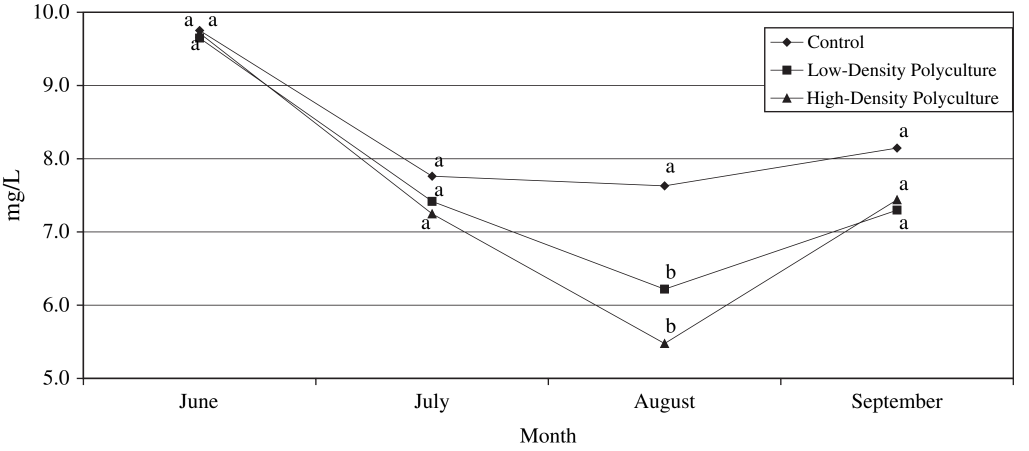

FIGURE 1. *Monthly means for afternoon oxygen concentrations for each treatment. Different letters indicate significant differences* ($P \leq 0.05$).

concentrations followed a gradient, with the concentration in the HDP treatment (0.2 mg/L) significantly higher ($P \leq 0.05$) than in the LDP treatment (0.2 mg/L), which was significantly higher ($P \leq 0.05$) than in the CTL ponds (0.1 mg/L).

Eighty-two genera of phytoplankton, from six algal divisions, were identified during the experiment. Chlorophytes, bacillariophytes, and cyanoprokaryota dominated in terms of numeric counts and species diversity. Other algal divisions identified included cryptophytes, euglenoids, and dinoflagellates. The green algae, *Scenedesmus* spp., dominated in terms of algae abundance and number of identified species. The most common cyanoprokaryophyta observed during the experiment were *Aphanocapsa delicatissima*, *Dactylococcopsis rhaphidiodes*, *Microcystis aeruginosa*, and *Planktothrix* sp. The most frequently encountered genera in CTL ponds was the chlorophyte *Scenedesmus quadricauda* var. *maxima* and the cyanoprokaryota *Planktothrix* sp., found in 50% or more of the phytoplankton samples. In the LDP and

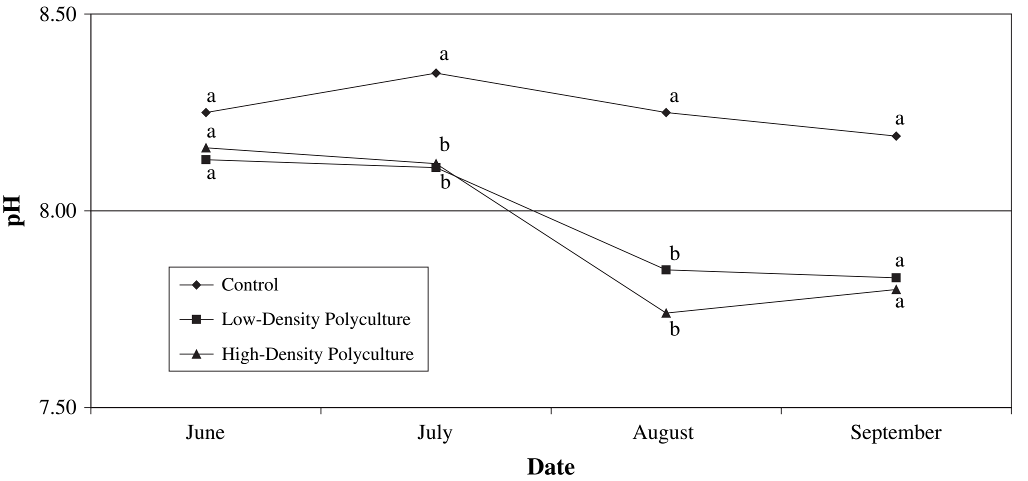

FIGURE 2. *Monthly means for afternoon pH sampled at pond bottom for each treatment. Different letters indicate significant differences* ($P \leq 0.05$).

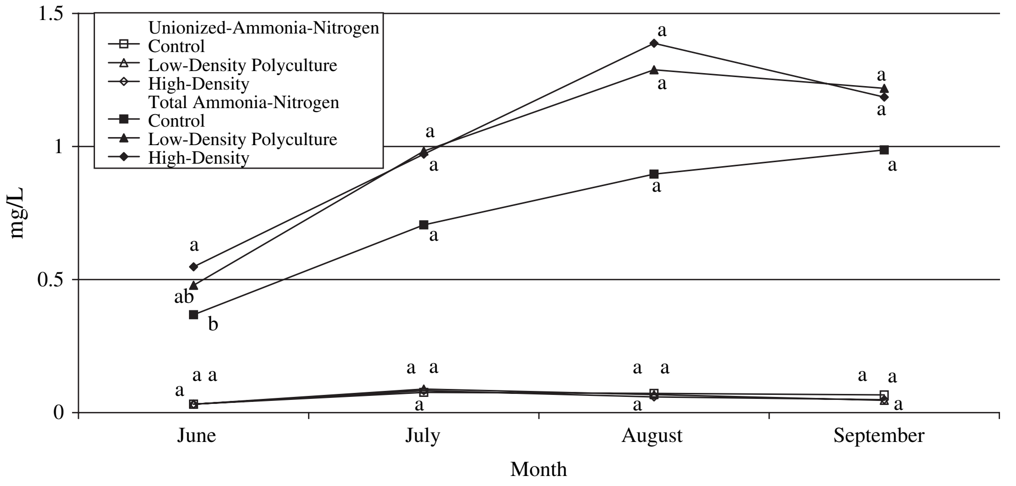

FIGURE 3. *Monthly means for total ammonia-nitrogen and unionized ammonia-nitrogen concentrations for each treatment. Different letters indicate significant differences (*$P \le 0.05$*).*

HDP treatments, *D. raphioides* and *Scenedesmus* spp. were the most frequently encountered genera (found in 50% or more of the phytoplankton samples).

There was no significant difference between treatments ($P > 0.10$) in dinoflagellate abundance. On sampling dates 6 June, 20 June, 24 August, and 9 September, there were no significant differences ($P > 0.10$) between treatments in terms of percent contribution of each algae group. However, at the 7 August sampling, ponds without tilapia had a significantly lower percentage ($P \le 0.10$) of chlorophytes (Fig. 4) and significantly higher percentage ($P \le 0.10$) of cyanoprokaryophyta than the polyculture treatments, but no significant differences ($P > 0.10$) between polyculture treatments for chlorophytes or cyanoprokaryophyta. On sample dates 8 July and 24 July, ponds without tilapia had a greater number ($P \le 0.10$) of bacillariophytes than the HDP (Fig. 4); however, there was no significant difference ($P > 0.10$) between the polyculture treatments. On dates when percent contribution of algal divisions were significantly different ($P \le 0.10$), biovolume was calculated for frequently encountered species in the CTL and HDP treatments (Table 2). As a result of low occurrence of the flagellates and euglenoids, further analyses were not done on these groups.

Prawn

Average harvest weights of prawn in the polyculture treatments (43.2 g) were significantly greater ($P \le 0.05$) than in the prawn monoculture treatment (36.4 g), but not significantly different ($P > 0.05$) from each other (Table 3). Prawn production in the HDP (2720 kg/ha) was significantly greater than ($P \le 0.01$) in the LDP treatment (2368 kg/ha), which was greater than ($P \le 0.01$) in the CTL ponds (2125 kg/ha). There were no significant differences ($P > 0.05$) in survival among prawns in the three treatments, which averaged 85% overall. The prawn FCR in the HDP (1.9) was significantly lower than ($P \le 0.01$) in the LDP (2.2), which was lower than ($P \le 0.01$) in the CTL (2.4). The SGR (g/d) for prawns in both polyculture treatments (0.37 g) were significantly higher ($P \le 0.05$) than in CTL ponds (0.31 g). The PSI was not significantly different ($P > 0.05$) between polyculture treatments (123), but both were significantly higher than ($P \le 0.05$) in CTL ponds (79). There was no significant difference ($P > 0.05$) in the percent marketable prawns ($\ge$ 20 g) between treatments, with an overall average of 93.3%; however, both polyculture treatments had a significantly higher percentage ($P \le 0.05$) of premium prawns ($\ge$ 30 g) (83.0%) than CTL ponds (70.4%).

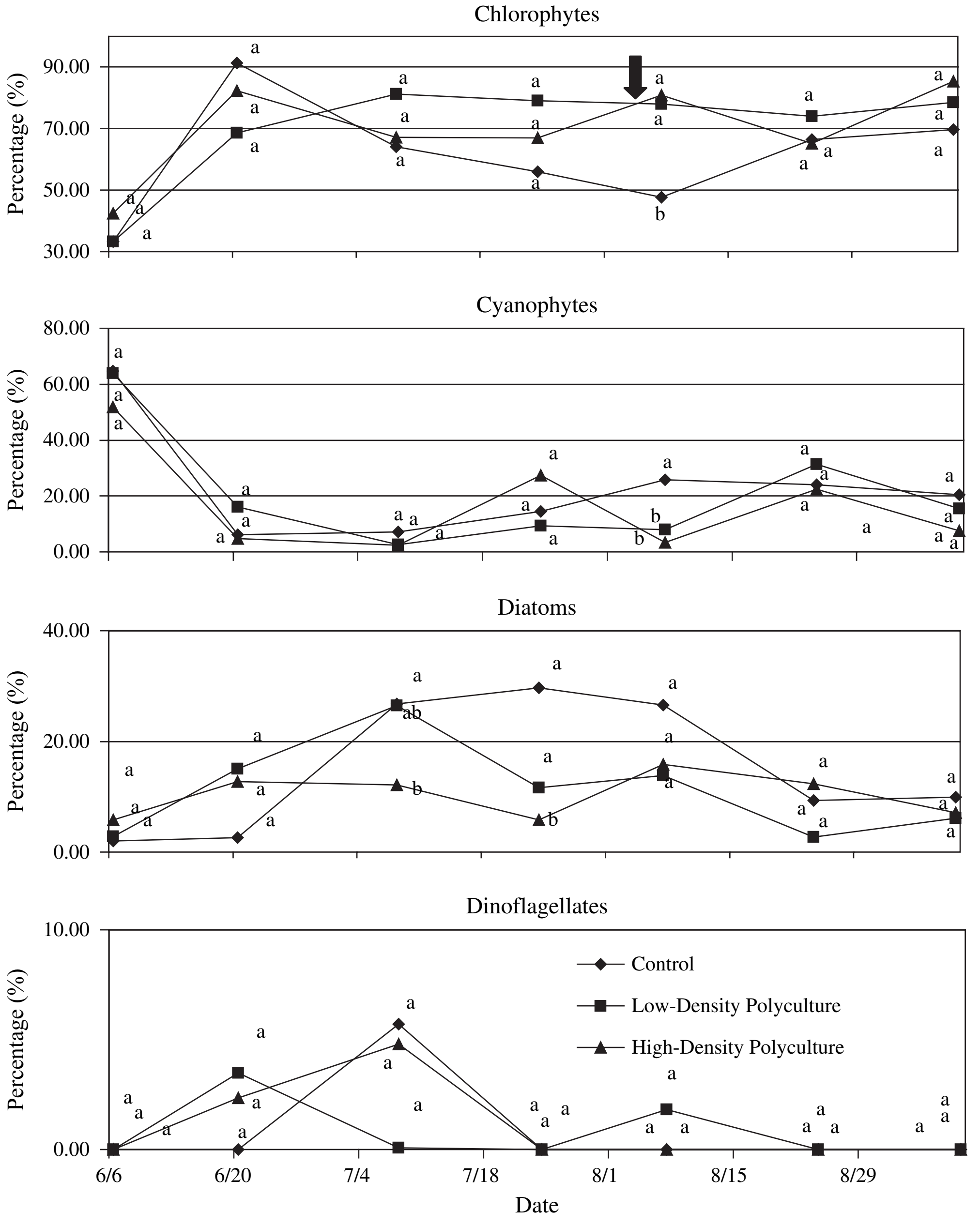

FIGURE 4. *Percent distribution of algal groups on individual sampling dates. Treatment means designated by a different letter are significantly different (*P ≤ 0.05*) using an ANOVA. The arrow indicates when the circulators were discontinued in all experimental ponds.*

Total prawn yields increased 12% in the LDP and 28% in the HDP, compared with the CTL.

The three treatments had no significant impact ($P > 0.05$) on prawn population structure in terms of numbers of each sexual morphotype (analyzed as a percentage of sex) (Table 4). The average weight of blue claw males (BC) was significantly greater ($P \leq 0.05$) in the HDP (71.9 g), and the average weight in the LDP treatment (66.7 g) was significantly higher

TABLE 2. *Direct comparison of mean biovolumes (µm³/mL) of algal taxa in production ponds for dates when differences in algal abundance occurred.*[1]

Variable		Species		
Date	Treatment	*Aulacoseira granulate* var. *angustissima*	*Scenedesmus quadricauda* var. *maxima*	*Dactylococcopsis rhaphidiodes*
September 8	Control	1468.5 ± 626.6[a]	—	—
	High-density polyculture	1024.8 ± 502.2[b]	—	—
September 24	Control	1233.6 ± 608.9[a]	—	—
	High-density polyculture	1004.6 ± 827.8[a]	—	—
August 7	Control	—	316.3 ± 233.6[a]	102.7 ± 72.9[a]
	High-density polyculture	—	220.2 ± 168.0[b]	74.9 ± 48.0[b]

[1] Those taxa means on the same sample date followed by a different superscript are significantly different ($P \leq 0.10$) by *t*-tests.

($P \leq 0.05$) than in the CTL (52.7 g) (Table 5). There was no significant difference ($P > 0.05$) in average weight of orange claw males (OC) between polyculture treatments (51.5 g); however, both polyculture treatments had a significantly higher ($P \leq 0.05$) weight than the CTL (44.0 g). There was no significant difference ($P > 0.05$) among treatments in mean weight of small males (SM). The average weight of reproductive females (RF) was not significantly different ($P > 0.05$) between polyculture treatments (38.8 g), but both were significantly higher than ($P \leq 0.05$) in ponds without tilapia (32.7 g). The average weight of virgin females (VF) was not significantly different ($P > 0.05$) between polyculture treatments (29.5 g), but both were significantly higher ($P \leq 0.05$) than in ponds without tilapia (26.0 g).

Tilapia

The average harvest weight of tilapia in the LDP treatment (853 6 g) was significantly higher ($P \leq 0.05$) than in the HDP treatment (810.5 g) (Table 6). Tilapia density did not affect ($P > 0.05$) tilapia survival (96%, overall) or FCR (1.5, overall) in polyculture treatments. The total daily feeding rate for prawn and tilapia reached 67, 142, and 204 kg/ha/d in the CTL, LDP, and HDP, respectively. The LDP treatment resulted in a significantly higher ($P \leq 0.05$) SGR (7.0 g/d) than the HDP treatment (6.6 g/d). At harvest, there were no significant differences between treatments in terms of percent dress out of whole dressed fish (68%) or fillets (40%).

Economic Analysis

Table 7 reports total revenue, operational costs, fixed costs, and total profit for the three

TABLE 3. *Prawn result — mean (±SD) harvest weight, production, survival, FCR, SGR, PSI, percent marketable prawn, and percent premium prawn cultured in ponds with and without tilapia.*[1]

	Treatment		
Variable	Control	Low-density polyculture	High-density polyculture
Harvest weight (g)	36.4 ± 1.9[b]	43.3 ± 3.8[a]	43.0 ± 1.5[a]
Production (kg/ha)	2,124.5 ± 68.0[c]	2,368.3 ± 116.7[b]	2,720.4 ± 109.4[a]
Survival (%)	84.6 ± 4.0[a]	79.8 ± 7.0[a]	91.8 ± 2.8[a]
FCR	2.4 ± 0.1[a]	2.2 ± 0.1[b]	1.9 ± 0.1[c]
SGR (g/d)	0.3 ± 0.0[b]	0.4 ± 0.0[a]	0.4 ± 0.0[a]
SGR (%/d)	3.2 ± 0.0[b]	3.4 ± 0.0[a]	3.4 ± 0.0[a]
PSI	78.7 ± 6.1[b]	104.2 ± 11.9[a]	141.3 ± 7.5[a]
% Marketable (>20 g)	93.7 ± 0.4[a]	92.5 ± 0.9[a]	94.1 ± 1.3[a]
% Premium (>30 g)	70.4 ± 4.4[b]	82.4 ± 5.3[a]	83.4 ± 3.4[a]

FCR = food conversion ratio; PSI = production–size index; SGR = standard growth rate.

[1] Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$) by ANOVA.

TABLE 4. *Mean (±SD) number of prawns classified into one of five sexual morphotypes at harvest.*[1]

	Treatment		
	Control	Low-density polyculture	High-density polyculture
Blue claw males	11.5 ± 4.1[a]	10.4 ± 1.8[a]	14.3 ± 3.1[a]
Orange claw males	77.0 ± 3.3[a]	75.3 ± 4.7[a]	75.7 ± 3.1[a]
Small males	11.5 ± 1.1[a]	14.3 ± 4.7[a]	10.0 ± 1.6[a]
Reproductive females	84.2 ± 10.1[a]	79.7 ± 6.6[a]	73.3 ± 9.1[a]
Virgin females	15.8 ± 10.2[a]	20.3 ± 6.6[a]	26.6 ± 9.1[a]

[1] Means within a row followed by different superscript are significantly different ($P \leq 0.05$).

TABLE 5. *Mean (±SD) weight of prawns classified into one of five sexual morphotypes at harvest.*[1]

	Treatment		
	Control	Low-density polyculture	High-density polyculture
Blue claw males	52.7 ± 1.7[c]	66.7 ± 0.8[b]	71.9 ± 3.5[a]
Orange claw males	44.0 ± 1.0[b]	50.9 ± 3.8[a]	52.0 ± 1.5[a]
Small males	10.5 ± 1.7[a]	11.0 ± 1.3[a]	10.3 ± 1.6[a]
Reproductive females	32.7 ± 0.2[b]	38.6 ± 2.7[a]	39.0 ± 1.0[a]
Virgin females	26.0 ± 1.7[b]	29.1 ± 1.0[a]	29.8 ± 1.9[a]

[1] Means within a row followed by different superscript are significantly different ($P \leq 0.05$).

technologies. Total revenue for the CTL, LDP, and HDP treatments were $10,433.14, $18,864.99, and $27,210.65, respectively. Total variable costs for the CTL, LDP, and HDP treatments were $6156.73, $10,504.33, and $14,906.51, with fixed costs totaling $2498.67, $2678.17, and $2982.67, respectively. Profit associated with each technology increased as production intensified with the CTL earning $1572.52, LDP earning $5332.35, and the HDP earning $8824.59 per 0.4-ha pond. The three technologies differed primarily in the stocking costs, feed costs, and fixed costs. Stocking costs were noticeably higher than the feed costs for all technologies. Besides the additional stocking and feeding costs associated with polyculture, the LDP required the addition of twenty 1-m^3 cages and a 300% increase in the quantity of ice needed at harvest. The HDP treatment required forty cages, a 493% increase in the quantity of ice, a PTO aerator for emergency aeration, and the additional fuel.

TABLE 6. *Tilapia results – mean (±SD) harvest weight, production, survival, FCR, SGR, and percent dress out of caged tilapia cultured in freshwater prawn ponds.*[1]

	Treatment	
Variable	Low-density polyculture	High-density polyculture
Harvest weight (g)	853.6 ± 34.4[a]	810.5 ± 37.3[b]
Production (kg/ha)	4010.5 ± 164.7[b]	7735.3 ± 267.8[a]
Survival (%)	95.3 ± 1.9[a]	97.0 ± 0.8[a]
FCR	1.5 ± 0.1[a]	1.5 ± 0.1[a]
SGR (g/d)	7.0 ± 0.4[a]	6.6 ± 0.4[b]
SGR (%/d)	1.9 ± 0.0[a]	1.8 ± 0.0[b]
Whole dressed (%)	68.5 ± 0.0[a]	67.7 ± 0.1[a]
Fillet (%)	39.5 ± 0.0[a]	39.5 ± 0.0[a]

FCR = food conversion ratio; SGR = standard growth rate.
[1] Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$) using a two-sample *t*-test.

Discussion

Water Quality

The presence of caged tilapia stocked at rates ≥ 5000 fish/ha resulted in lower afternoon bottom pH levels in polyculture treatments. However, the actual ranges of pH were relatively small. These research ponds were largely dominated by chlorophytes through the production period. Cyanoprokaryophyta-dominated

TABLE 7. *Annual costs and profit for prawn monoculture and polyculture in a 0.4-ha pond.*[1]

		Control		Low-density polyculture		High-density polyculture	
Item (unit)	Value, $/unit	Quantity	Value, $/pond	Quantity	Value, $/pond	Quantity	Value, $/pond
Yield (kg)							
Prawn	12.10	862.24	10,433.14	967.49	11,706.63	1105.3	13,373.79
Tilapia	4.40	0	0	1626.9	7158.36	3144.7	13,836.86
Total revenue			10,433.14		18,864.99		27,210.65
Variable costs							
Juveniles (each)	0.08	28,000	2240.00	28,000	2240.00	28,000	2240.00
Fingerlings (each)	1.00	0	0	2000	2000	4000	4000.00
Prawn feed (mt)	396.00	2.08	823.68	2.08	823.68	2.08	823.68
Fingerling feed (mt)	484.00	0	0	2.38	1152.92	4.65	2250.60
Chemicals	5.00	0	0	0.04	5	0.04	5.00
Water quality reagents (refill)	1.00	1	30	1	30	1	30
Electricity (kWh)	0.07	3775.68	264.30	3775.68	264.30	3775.68	264.30
Pumping costs/fuel (no. of times)	20.00	2	40.00	2	40.00	10	200.00
Labor and management (h)	8.00	214	1712.00	214	1712.00	214	1712.00
Accounting/legal fees ($)	100.00	1	100.00	1	100.00	1	100.00
Maintenance ($)	0.02	13,642	272.84	13,642	272.84	13,642	272.84
Ice (kg)	0.68	862.24	588.05	2594.39	1769.37	4250.12	2898.51
Packaging ($)	100.00	1	100.00	1	100.00	1	100.00
Interest on variable cost			205.22		350.14		496.88
Total variable cost	6156.73		10,504.33		14,906.51		
Fixed costs							
Total depreciation			1489.97		1633.57		1877.17
Interest on fixed cost ($)	10%		1000.2		1036.1		1097.00
Tax			8.50		8.50		8.50
Total fixed cost			2498.67		2678.17		2982.67
Profit (S)			1572.52		5332.35		8824.59

[1] All price/costs are reported in US dollars for the year 2003. Assume a 106-d growing season for tilapia and 114-d season for prawn.

systems may show greater dynamics and greater differences.

The circulators used would likely need to be modified to create a more beneficial mixing pattern along a more horizontal axis rather than washing the pond bottom (Sukenik et al. 1991; Paerl and Tucker 1995; Tucker and Steeby 1995; Boyd 1997). When circulators were removed and constant aeration was supplied, oxygen concentrations were maintained at optimal levels in CTL and LDP treatments; however, emergency aeration was required periodically for the HDP treatment. Periods of low nighttime oxygen concentrations ($\leq$2 mg/L) occurred in polyculture ponds during the month of August but not in the CTL ponds. Future studies should monitor aeration requirements to more precisely determine the effects of increased stocking densities on oxygen budgets.

Tilapia did not create a consistent long-term shift in the percent contribution of algal groups during the duration of the experiment. Detailed phytoplankton counts were made for sampling dates previously identified as important time periods regarding changes in phytoplankton population. Phytoplankton samples were analyzed to detect changes in species composition and biomass to clarify reasons for these differences in physical and chemical variables (Zimba et al. 2002).

Chlorophytes were the dominant group in all treatments throughout the majority of the experiment. The major difference occurred after circulators were removed on 5 August. The CTL ponds had an increase in cyanoprokaryophyta abundance, but cyanoprokaryophyta did not become dominant in polyculture treatments (Fig. 4), possibly as a result of tilapia grazing. Perschbacher and Lorio (1993) found caged tilapia very effective in controlling cyanoprokaryophyta when stocked at pond surface area densities of $0.5/m^2$, and Turker et al. (2003b) found tilapia feeding habits more effective against cyanoprokaryota than against chlorophytes.

As tilapia density increased, their ability to control the abundance of bacillariophytes present in the pond also increased; however, after the removal of circulators, the ability of the tilapia to reduce bacillariophytes abundance decreased. It is presumed that circulators made these tychoplanktonic diatoms more accessible to tilapia by keeping them in suspension throughout the water column, and after mechanical mixing was stopped, diatoms settled out of the water column as has been previously documented (Sukenik et al. 1991). Results show that feeding habits of Nile tilapia stocked at rates $\geq$5000 fish/ha were effective in reducing phytoplankton cell size on certain sample dates (Table 2). Small cell size can prevent gill lesions (Landsberg 2002) and can also be beneficial to water quality through higher growth rates and increased assimilation rates of nutrients via increased cell surface area (Turker et al. 2003a).

Polyculture treatments had higher overall TAN and nitrite levels than CTL ponds probably in response to greater total nutrient inputs for the direct feeding of both species. However, there were no significant differences in TAN concentrations during August when treatments were receiving their highest daily feeding rates. With a three-fold increase in feeding rates in polyculture, higher unionized ammonia and pH levels would be expected; however, unionized ammonia levels did not differ among treatments (Fig. 2). All were within acceptable limits recommended by Straus et al. (1991). This study suggests that grazed phytoplankton populations effectively assimilated increased TAN concentrations, thus keeping water quality parameters within acceptable ranges. Yi and Fitzsimmons (2004) found that the presence of tilapia did not affect phytoplankton biomass, but their presence did stabilize water quality in tilapia–shrimp polyculture.

Feeding rates could be responsible for some effect on pH levels measured during the experiment. Intensification can result in increased respiration rates and carbon dioxide concentrations from the increase of biological activity (Boyd and Tucker 1998). Although carbon dioxide levels were not monitored during the experiment, possible increases in carbon dioxide concentrations may have also contributed to lower pH levels in intensified treatments. Future experiments should consider monitoring this additional parameter.

Prawn Production

In the present study, survival of freshwater prawn (85%) was within the range, or better than, reported in other polyculture studies with tilapia (Cohen and Ra'anan 1983; Garcia-Perez and Alston 2000; Tidwell et al. 2000a; Dos Santos and Valenti 2002) and other prawn monoculture studies (Daniels and D'Abramo 1994; Daniels et al. 1995; Tidwell et al. 2004). Miltner et al. (1983) and Cohen and Ra'anan (1983) found that prawn population structure was independent of free-swimming tilapia. This also appears to be true for tilapia grown in cages, as indicated in the present study.

Competition for feed has been a problem in polyculture systems using free-swimming fish (Garcia-Perez et al. 2000; Dos Santos and Valenti 2002) and can result in a change in prawn population structure (Garcia-Perez and Alston 2000). Garcia-Perez and Alston (2000) found a higher frequency of SM in their polyculture treatment (22%) using free-swimming tilapia compared with their prawn monoculture treatment (5%) and concluded this was probably because of prawn being outcompeted for feed. In the present study, the fraction of SM was similar in all treatments and made up only a small percentage (4–6%). In this study, tilapia were grown in cages so competition for feed was not a problem. Also, both species were fed separately with no reduction in allocations. Extra food available to the prawns from uneaten fish feed, fish feces, and increased natural productivity must not have been above prawn demands as prawn FCR actually improved in the polyculture treatments.

The additional nutrient input in the polyculture ponds appeared to have the most impact on prawn late in the production season. No differences were found in average weights of prawn during interim sampling. Larger prawn (>40 g) have been found to benefit from increased feed quality late in the production season (Tidwell et al. 2000b, 2004). As natural productivity becomes depleted, larger individuals (BC, OC, RF) require alternative food sources or greater nutrient density, whereas smaller individuals (SM) appear less affected.

Both polyculture treatments produced a significantly higher percentage of premium prawns (≥ 30 g) compared with the CTL. Garcia-Perez et al. (2000) found that 78% of the prawn weighed more than 20 g, 25% weighed more than 30 g, and 19% weighed more than 40 g in the polyculture treatment with prawns stocked at 7/m^2. In the present study, despite the same stocking density, polyculture treatments resulted in 93% of the prawns weighing more than 20 g, 83% weighing more than 30 g, and 48% weighing more than 40 g, indicating that caged tilapia may be preferred over free-roaming tilapia for markets requiring large-sized prawn. As was the case in our study for LDP and HDP, Wang et al. (1998) found increased yields of shrimp with increased tilapia stocking density in net cages. They determined that tilapia densities of 3200 fish/ha and 400 kg/ha positively affected production of shrimp stocked at 6/m^2. Our findings suggest that even greater tilapia densities can have a positive effect on prawn yield, survival, and total pond production.

Tilapia Production

Both polyculture treatments produced marketable-size tilapia and increased total pond production (tilapia and prawn) by 300 and 492% in the LDP and HDP, respectively, compared with prawn monoculture. Tilapia survival averaged 96% and no tilapia recruitment was observed in drained ponds. These data do not clearly indicate a reason for the slightly reduced growth rates of tilapia in the HDP treatment, but lower nighttime DO levels may have been the cause. DO levels below 2 mg/L sometimes occurred in the HDP treatment during nighttime monitoring (2300 h) after the removal of circulators. The HDP treatment may have been approaching carrying capacity of the pond for this level of aeration (Carro-Anzalotta and McGinty 1986). However, other water quality variables remained acceptable.

Clearly, intensification rewards a producer with higher profit although more capital is necessary as production intensifies. This also translates to a producer having greater flexibility in future price competition in different market channels. This study indicates that LDP could greatly increase pond profit (339%) over prawn monoculture. HDP increased pond profit over the LDP management practice and prawn monoculture by 165 and 561%, respectively. However, HDP management would probably be a much higher risk for the farmer. Garcia-Perez et al. (2000) found that the addition of tilapia to prawn ponds increased economic returns by 21% and the addition of prawn to tilapia ponds increased return by 112%. These data indicate that polyculture of Nile tilapia in cages with freshwater prawn actually improves prawn production and greatly increases total pond production.

Stocking and feeding rates, at least to LDP levels, for the two species appear to be essentially independent.

Future studies should analyze the polyculture of the freshwater prawn and free-roaming Nile tilapia in temperate ponds. There may be benefits from free-swimming tilapia through better algae grazing, feeding habits (Cohen et al. 1983; Costa-Pierce et al. 1987), improved water quality (Rouse et al. 1987; Azim et al. 2003), and increased production (Dos Santos and Valenti 2002; Garcia-Perez et al. 2000).

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