EVALUATION OF A RECIRCULATING AQUACULTURE - HYDROPONICS SYSTEM

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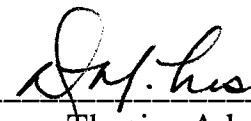

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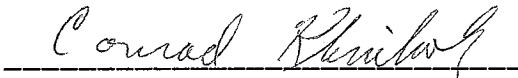

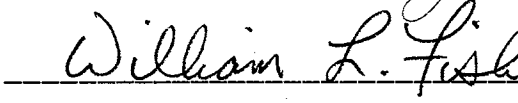

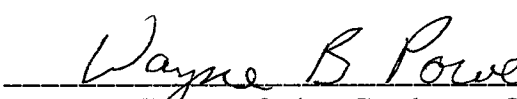

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Aquaculture is the rearing of aquatic organisms under controlled conditions. Pond culture can be traced to fifth-century China where carp and goldfish were kept for their aesthetic appeal (McLarney 1984). Aquaculture spread from China to Korea, then to Japan and Southeast Asia (McLarney 1984). Japan's extensive coastline allowed aquaculture to expand to include mariculture. Estuarine and cage culture were contributions of Southeast Asia to aquaculture

Aquaculture in Europe developed in the Middle Ages, probably independently of Asia (Huet 1970). Contributions of European aquaculture included controlled spawning, application of the scientific method to fish-culture research, and culture of salmonids. The latter developed in response to concerns of sportfishermen that natural trout populations were declining. Aquaculture was introduced to the United States in the mid-nineteenth century, also in response to the perceived depletion of game fish stocks (McLarney 1984).

Interest in freshwater fish farming in the United States has grown tremendously during the last four decades. This is due, in part, to greater demands for animal protein and the inability of livestock husbandrymen and commercial fishermen to keep pace with this increase (Smitherman et al. 1978). For example, in 1963

only 960 hectares were devoted to production of channel catfish, *Ictalurus punctatus*, (Meyer et al. 1973). That figure had grown to 29,895 hectares by 1982 (USDA 1982) and >60,729 hectares in 1990 (McCall 1990).

The majority of aquaculture throughout the world is conducted in ponds (Stickney 1979). Requirements for pond culture are soil with good water-holding capacity and an abundant and readily available water supply of suitable quality to support aquacultural species of choice. If either of those requirements can not be met or the regional climate is such that pond aquaculture is not feasible, a closed, recirculating, water-reuse system may be a viable and energy efficient alternative (Lucchetti and Gray 1988; Muir 1982 Stickney 1979).

CHAPTER II

LITERATURE REVIEW

Collins (1976) characterized intensive aquaculture as culture in a system that required some environmental control, where fish were stocked at densities higher than the natural carrying capacity of the system and where all feed was provided from an outside source. One of the problems inherent with intensive aquacultural systems is accumulation of organic wastes (Bardach et al. 1972), particularly by-products of nitrogen metabolism (Martin 1978). Ammonia is the principal excretory product of fish that affects health, growth, and the number of fish that can be cultured in a recirculating or water-reuse system (Lucchetti and Gray 1988). Unionized ammonia (NH_3) is highly toxic to fish and must be removed from the system. Sublethal concentrations of ammonia and nitrite can reduce growth, damage gills, and increase susceptibility of fish to disease (Lucchetti and Gray 1988).

Nitrification oxidizes ammonia, first to nitrite, which is highly toxic to fish, then to nitrate, which is relatively harmless (Knepp and Arkin 1973). The nitrifying bacteria Nitrosomonas oxidize ammonia to nitrite, and Nitrobacter oxidize nitrite to nitrate. Uncertainty in establishing and maintaining colonies of nitrifying bacteria are major problems in aquaria (Spotte 1979). The oxidation process usually involves a lag time of 33-56 days for nitrifying bacteria to reach equilibrium (Lucchetti and Gray 1988, Spotte 1979). Denitrification, usually by volatilization, removes nitrates from the system (Spotte

1979). Nitrate removal is necessary because "nitrate respiration," or dissimilation, can reduce nitrates to lower oxidation states; i.e., nitrite and gaseous nitrogen (Spotte 1979) in localized anaerobic areas of the filtering system (Muir 1982).

Hydroponics is the cultivation of plants, including normally terrestrial forms, in an aqueous nutrient solution rather than soil. Hydroponics apparently developed at about the same time as aquaculture. The "Hanging Gardens" of Babylon and the "Floating Gardens" of the Aztecs and Chinese were examples of early hydroponic culture (Resh 1985). Modern hydroponics developed in Europe from experiments to determine composition of plants and plant growth substances (Laurie 1940). By the mid-nineteenth century, researchers had demonstrated that plants could be grown in an inert medium moistened with a water solution containing certain minerals (Matlin 1940).

In 1929, W.F. Gericke conducted experiments with vegetables grown in nutrient solutions without soil. Because nutrients in the growth solutions could be controlled closely and plant roots were in constant contact with the nutrient solution, he experienced unusually high yields of vegetables (Turner and Henry 1939). Application of Gericke's findings led to food production for troops stationed on nonarable islands in the Pacific during World War II, to greenhouse culture, and to highly specialized culture in atomic submarines (Resh 1985).

Cultivation of plants in nutrient solutions is more efficient than soil culture (Douglas 1975). Labor, equipment, and energy requirements for soil preparation are either eliminated or drastically

reduced with a hydroponic system. Its principal advantages, however, are high yields of crops, utility in all climates, and suitability on nonarable lands (Douglas 1975). Many countries have developed large, automated, hydroponic greenhouses to produce vegetables throughout the year. The majority of hydroponics systems today use inorganic fertilizers in their nutrient solutions. However, use of organic nutrient solutions is possible when hydroponics is combined with aquaculture (McLarney 1984).

The few joint aquaculture-hydroponics ventures to date were attempted primarily to determine if hydroponics could act as a filter for a closed, recirculating aquacultural system. Lewis et al. (1978), McLarney (1984), and Rakocy (1984) used aggregate culture, settling basins (for solid waste removal), and biological filters. Aggregate culture uses gravel of different sizes as the growing medium. Gravel is usually arranged in layers in a tank or trough with the larger particles on the bottom and smaller ones on top. Lewis et al. (1978) and Rakocy (1984) found that the hydroponic component effectively filtered enough nutrients from the aquaculture component to maintain water quality and promote good fish growth.

For optimum growth, channel catfish require a nutritionally complete ration, water temperature close to 30 C and dissolved oxygen levels >5 mg/L (Dupree and Huner 1984). Water volumes to adequately maintain organic waste concentrations below toxic levels also are essential. Alternatives to the volumetric water requirement are flushing with fresh water and filtering. In a closed system, filtering is preferred because it is usually more economical than using pumped water for flushing, depending on the source of the

pumped water (Stickney 1979). As an added benefit, fish wastes can supply the majority of nutrients required for plant growth (McLarney 1984). Plants require conditions for growth comparable with those for channel catfish. Tomatoes, peppers, lettuce, spinach, and mint grow well in a closed aquaculture system (Kleinholz et al. 1985).

Nutrient-film hydroponics use plants grown directly on an impermeable surface to which a thin film of water and plant nutrients is continuously applied. Root production on this impermeable surface results in a large mass of roots and accumulated matter that act as a filter. Plant top-growth also results in nutrient uptake. Increased root growth accompanying plant top-growth and accumulation of suspended solids in the roots should cause a gradual expansion of the filter (Jewell et al 1983).

Kleinholz et al. (1985) devised a closed aquaculture-hydroponics system that maximized functions of each of the components of the system and thereby reduced the number of components needed, which made it more economically feasible than previous versions. The system (referred to here as the "Kleinholz system") combines nutrient-film hydroponics with intensive tank culture. This design solved the problem of a build-up of organic solids and also eliminated the need for separate biofiltration. The prototype for the Kleinholz system consisted of a 1.7-m^2 hydroponic rack mounted over a 1,400-l fiberglass tank. Nutrient solution was provided to the hydroponic rack by airlift and returned to the fish culture tank by gravity. The airlift and increased surface area of the hydroponic rack eliminated the need for additional aeration. The

thin (1.3 cm) layer of water on the hydroponic rack adequately supplied water to the plant roots, prevented any anaerobic areas from forming in root masses, and allowed roots to trap organic solids.

Kleinholz et al. (1985) conducted experiments with treatments of 50 channel catfish and 5 tilapia Oreochromis aurea, 50 catfish, 5 tilapia, and 48 pepper plants, and 150 catfish, 15 tilapia, and 48 pepper plants. Those experiments suggested that the hydroponic component needed to be larger with more plants to allow higher stocking rates of fish. Higher densities of fish were necessary in this system to break down territorial behavior (Stickney 1979) and offset high costs of construction and energy use (Muir 1982).

Several questions have to be answered to fully evaluate the Kleinholz system. How will the controlled environment in the greenhouse affect growth of the fish? Will fish grow at the same rate in the system as they would in a pond? Will the feed conversion ratio be the same in the system as in a pond? How many fish can be reared in the system without plants? Do fish wastes contain enough essential plant nutrients to adequately sustain plant growth? Will enough ammonia be converted to nitrate and subsequently be removed from the system to increase carrying capacity of fish in the system? How many fish and plants can be cultured in the system before overloading it?

My study examined components and configuration of the Kleinholz system with the intent of identifying critical parameters and procedures, and developing a model, with which a recirculating aquaculture-hydroponics system can be evaluated. This study was designed to: (1) quantify fish production and determine if production

rates were enhanced by the hydroponic component; (2) assess effect of the hydroponic component on water quality; (3) determine if nitrification and nitrogen removal were adequate to permit stocking rates high enough to make this system a viable production venture for fish farmers; and (4) determine optimum ratios of plants to fish in the system.

My study consisted of two experiments. In the first experiment, numbers of fish were kept constant and the number of plants were varied among treatments. In the second experiment, numbers of fish were varied and numbers of plants were kept constant. Analysis of data from those experiments should suggest an optimum ratio of fish and plants that the system could support. Null hypotheses were: (1) there were no differences in fish production among treatments with varying plant densities; (2) there were no differences in water quality among treatments with varying plant densities; (3) ammonia removal through nitrification and subsequent uptake by plants were not sufficient to allow higher stocking rates of fish in treatments with higher numbers of plants; and (4) there was no relationship between numbers of fish and plants that the system can sustain.

CHAPTER III

METHODS

Each experiment was comprised of three treatments. Effects of different stocking rates of channel catfish and plants in the system were determined by comparing mean weight gain of the fish in grams/fish/120 days. Concentrations of dissolved oxygen (DO), ammonia, and nitrite, which are affected by the density of fish in the system and are critical to survival and growth of catfish, were monitored. Comparison of plant and fruit production, turbidity, and chemical oxygen demand were used to test effects of different fish to plant ratios. Temperature, pH, and chlorine were monitored because of their potentially limiting effects on fish growth. Effects of the plants were determined by comparing differences in nitrate, phosphorus, and potassium levels. Iron, zinc, manganese, copper, boron, and molybdenum, all of which are essential for plant growth, were monitored to determine their availability to plants. Alkalinity, hardness, and calcium were used to monitor buffering capacity of the system.

Nine experimental aquaculture-hydroponics units were used to evaluate effects of the different treatments. The nine experimental units were grouped in three complete blocks (Figure 1). Each block contained one replicate of each of three treatments. Positions of the treatments in the blocks were selected randomly. Each experimental unit consisted of a 1,400-l tank (3 m x 0.6 m x 0.9 m, water depth 0.8 m) with a 3.7-m^2 hydroponic rack (2.4 m x 1.5 m) mounted 15

cm above it (Figure 2). The nutrient-film technique was used in the hydroponic component. Water containing plant nutrients (fish wastes) was supplied to the hydroponic rack from the tank by a 5-cm airlift and was returned to the tank by gravity.

I conducted two experiments. Stocking rates of catfish and plants in experiment I were: low density - 100 fish, 40 plants (treatment 1); high density - 100 fish, 80 plants (treatment 2); control - 100 fish, no plants (treatment 3). In experiment II, each replicate contained 40 plants; stocking rates of catfish were: control - 100 fish (the link with experiment I, treatment 1), low density - 200 fish (treatment 2), and high density - 300 fish (treatment 3). Catfish used in these experiments were graded to ensure uniformity of size and averaged about 28 g (SE = 0.625) at stocking.

The growth period was 120 days in each experiment. Catfish were fed a 36% protein complete catfish ration at 2% of the total weight of catfish, estimated weekly, for the 120-day growth period. Individual weights were recorded for all fish at the beginning and end of each growth period but fish were not tagged and weights were not linked. Weight gained and feed conversion ratios (FCR: weight of feed offered/weight gained) were determined at the end of each experiment.

Bell peppers (Capsicum annuum) were used in the hydroponic component. Bell peppers have been successfully grown hydroponically (Kleinholz et al. 1985). Plants were started 3-4 weeks before use in the system to ensure that they were a minimum of 8 cm tall and capable of absorbing nutrients. Equal plant numbers were maintained on all hydroponics racks in each treatment that

required plants. Bell peppers, fruit from the plants, were harvested once each month during the experiment (30, 60, 90, and 120 days), and mean fruit weight of the combined harvests was calculated. Weights of all plants were recorded at the end of each experiment.

Concentrations of dissolved oxygen and water temperatures were monitored daily during each trial with a YSI model 57 dissolved oxygen and temperature meter. Water quality parameters were monitored with HACH reagents and standards (HACH Incorporated, Loveland, Colorado). The nitrogen complex (NH_3, NO_2 and NO_3) and pH were monitored by colorimetric analysis twice each week with a HACH DREL 3 Spectrophotometer until the systems were conditioned (NO3≈0.01 mg/1, from Lewis et al. 1976 reporting molecular ammonia typically in the range of 0.005 to 0.015 ppm) and then weekly for the remainder of each experiment. Potassium, phosphorus, chlorine, sulfate, turbidity (NTU - the spectrophotometric equivalent of secchi disc transparency), and chemical oxygen demand were monitored weekly through the trials. The metals iron, zinc, maganese, copper, boron, and molybdenum were monitored bi-weekly. Alkalinity, hardness and calcium were measured titrimetrically.

Critical parameters for fish in this study were dissolved oxygen, temperature, the nitrogen complex, pH, and chlorine (all water was from a municipal system) (Reynolds, 1982) Those parameters were monitored to determine if they contributed to mortality of catfish. Potassium, phosphorus, and metals were measured to determine their availability to the plants.

Differences in stocking weights of fish among treatments were tested using analysis of variance (ANOVA, Steel and Torrie 1960). Because no significant differences in stocking weights existed, harvest weights and mean weight gain were analyzed by ANOVA. Differences in water quality parameters were determined by nested ANOVA (SYSTAT 1992) and by analyzing treatment means with simple ANOVA (Steel and Torrie 1960). Mean plant weights also were analyzed by ANOVA. Means were compared using Fisher's Least Significant Differences (LSD) (SYSTAT 1992). In addition to statistical analyses, biological observation (visual, comparative) of data recorded daily was used to explain fluctuations in water quality parameters and fish mortality.

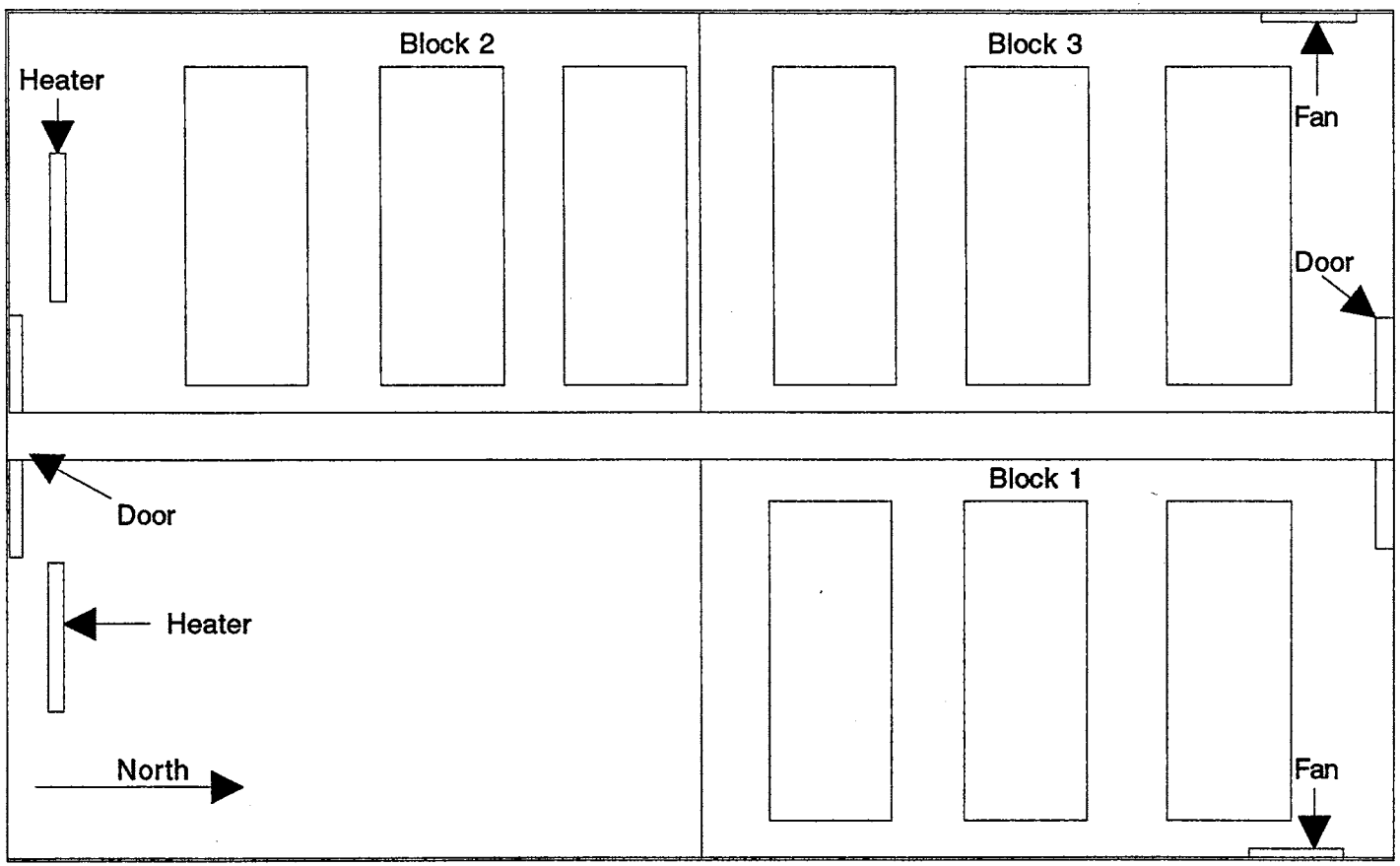

Figure 1. Greenhouse floor plan. Location of blocks, tanks, doors, heaters and exaust fans.

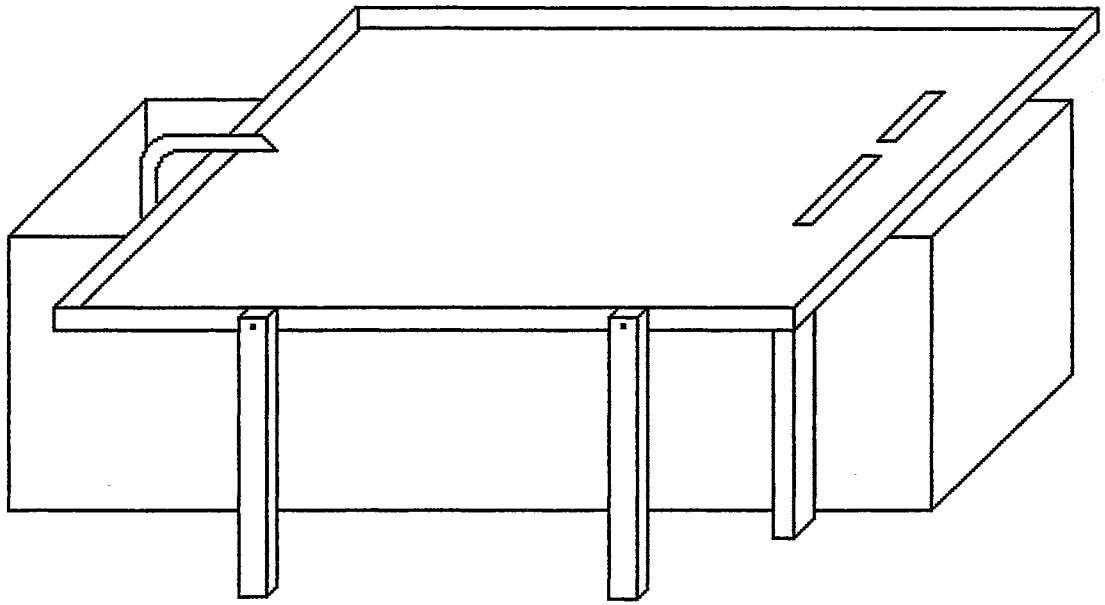

Figure 2. Diagram of an aquaculture tank with a nutrient-film hydroponic rack mounted above. Water is moved up to the hydroponic component by air-lift and drains back to the aquaculture tank by gravity. Scale: 1 cm = 0.24 m.

CHAPTER IV

RESULTS

EXPERIMENT I

Experiment I was conducted during summer 1989 and was terminated after 120 days. Catfish in treatment 3, block 2 were lost during week 13 of the experiment. Low dissolved oxygen ≤3.0 mg/l and water temperature fluctuations that week contributed to the mortality.

Mean catfish gain showed treatment and block differences ($p = 0.01$). Treatment 2 performed best at 80.4 grams of gain/fish with treatment 1 and 3 yielding 75.2 and 77.7 g, respectively. Mean catfish gain by block was: block 1- 83.6 g, block 2- 78.6 g and block 3- 71.1 g (Figure 3). Survival ranged from 89% to 97% and was not significant among treatments (Figure 3). Feed conversion ratio ranged from 1.0:1 to 1.3:1 but did not differ significantly between treatments (Figure 3). Mean plant growth was 131.6 g in treatment 1 (low density) and 85.5 g in treatment 2 (high density) but was not significant among treatments (Figure 3). Mean fruit weight was 19.9 g (mean fruit count = 210) in treatment 1 and 18.5 g (mean fruit count = 200) in treatment 2 and did not differ significantly among treatments. Average fruit weight per plant was 109.5 g in treatment 1 (40 plants) and 49.8 g in treatment 2 (80 plants) and did not differ significantly among treatments.

Mean dissolved oxygen in treatment 3 (7.0 mg/l) differed significantly ($p < 0.01$) from treatments 1 (6.5 mg/l) and 2 (6.5 mg/l). Mean dissolved oxygen did not differ among blocks but did show a significant treatment by block interaction ($p = 0.01$) (Figure 4). Mean temperature of block 2, 23.4 C, differed from block 1, 22.8 °C ($p = 0.06$) and from block 3, 22.9 C ($p < 0.01$), but there were no among-treatment differences or block by treatment interaction (Figure 4).

Ammonia did not differ significantly among treatments or blocks (Figure 5). Mean nitrite in treatment 3 was significantly higher than either treatment 1 or 2 at $p < 0.03$ (Figure 5). Mean nitrate was similar and ranged from 7.74 mg/l in treatment 1 to 13.16 mg/l in treatment 3 ($p = 0.01$) (Figure 5). There were no among block differences in nitrite or nitrate.

Alkalinity differed ($p = 0.01$) among treatments but not blocks (Figure 6). Hardness was similar with only treatments differing significantly ($p = 0.01$) (Figure 6). The pH in tanks ranged from 6.5 to 8.9 but did not differ significantly among treatments or blocks (Figure 6). Calcium differed ($p < 0.01$) among blocks but not treatments (Figure 6).

Phosphorus was higher in treatment 3 with a mean of 7.66 mg/l, which was significantly different from treatments 1 and 2 ($p = 0.01$) (Figure 7). Potassium also showed a significant treatment difference ($p = 0.01$) with treatment 3 having the highest mean of 14.39 mg/l. There was a significant treatment by block interaction ($p = 0.03$) (Figure 7).

Chemical oxygen demand was different among treatments ($p = 0.01$) and blocks ($p = 0.03$), but there was no interaction between the

two (Table 1). Turbidity differed among treatments ($p = 0.01$) with treatment 3 having the highest mean of 51.11 NTU (Table 1). Chlorine differed among treatments ($p = 0.02$) (Table 1). Sulfate differed among treatments ($p = 0.01$) and blocks ($p = 0.02$), and it exhibited treatment by block interaction ($p = 0.01$) (Table 1). Boron, molybdenum, iron, zinc, manganese, and copper were available in minute quantities ($\leq$ 0.1 mg/l), and none differed among treatments or blocks (Appendix A).

EXPERIMENT II

Experiment II was conducted during summer 1990. Catfish in treatment 1 block 3 and treatment 3 block 2 were lost during week 13 of the experiment. As in experiment I, low dissolved oxygen $\leq$3.0 mg/l and water temperature fluctuations contributed to mortality of catfish. Mean catfish gain showed no significant treatment or block differences (Figure 8). Survival ranged from 92% to 99% and did not differ among treatments (Figure 8). Feed conversion ratios ranged from 1.1:1 to 1.3:1 but did not differ significantly among treatments or blocks (Figure 8). Mean plant growth days was not significantly different among treatments but block effects were greater than treatment effects (Figure 8). Mean fruit weight of treatment 3, 46.8 g (mean fruit count = 67), was different from treatments 1, 42.1 (mean fruit count = 67) and 2, 43.7 (mean fruit count = 89), respectively ($p = 0.03$) (Figure 8). Average fruit weight per plant was 75.5 g in treatment 1, 87,1 g in treatment 2, and 76.1 g in treatment 3 and did not differ significantly.

Mean dissolved oxygen of 7.3 mg/l in treatment I differed from treatment 2 ($p < 0.01$) (6.6 mg/l), and treatment 2 differed from treatment 3 (5.1 mg/l) at $p = 0.01$ (Figure 9). Dissolved oxygen in block 1 (6.7 mg/l) was different ($p < 0.01$) from blocks 2 (6.0), and 3 (5.8 mg/l) (Figure 9). Dissolved oxygen also showed significant treatment by block interaction ($p \leq 0.01$) (Figure 9). There was a significant difference in mean temperature among treatments ($p \leq 0.04$) and blocks ($p \leq 0.01$). Treatment 3 and block 3 were highest at 25.5 C and 25.0 C, respectively (Figure 9). Temperature also showed significant treatment by block interaction ($p < 0.01$).

Ammonia differed significantly ($p < 0.01$) among treatments and showed treatment by block interaction ($p < 0.01$) (Figure 10). Nitrite was significant among treatments ($p < 0.01$), and treatment 3 had the highest mean (Figure 10). Mean nitrate also was significant among treatments and blocks and showed treatment block interaction ($p < 0.01$) (Figure 10).

Alkalinity and hardness both differed significantly among treatments and blocks ($p < 0.01$) (Figure 11). Treatment by block interaction also was significant at $p < 0.01$ (Figure 11). The pH differed by treatment and block, and the treatment by block interaction was significant at $p < 0.01$ (Figure 12). Calcium differed among treatments and blocks, and the treatment by block interaction also was significant at $p < 0.01$ (Figure 12).

Phosphorus was higher in treatment 3 (3.95 mg/l), which was significantly different at $p < 0.1$, and the treatment by block interaction was significant at $p < 0.01$ (Figure 13). Potassium showed a significant block difference ($p < 0.01$) (Figure 13). Chlorine differed

among treatments ($p < 0.01$) (Table 2). Sulfate differed among treatments and blocks, and it exhibited a treatment by block interaction ($p < 0.01$) (Table 2).

Chemical oxygen demand differed among treatments and blocks with a treatment by block interaction $p < 0.01$ (Table 2). Turbidity differed among blocks ($p < 0.01$) with block 2 having the highest mean of 33.6 NTU, and the treatment by block interaction was significant at $p < 0.01$ (Table 2). Boron, molybdenum, iron, zinc, manganese, and copper were present in trace amounts and were not significantly different among treatments or blocks (Appendix B).

Table I. Mean chlorine, sulfate, chemical oxygen demand, and turbidity - Experiment I. Chlorine (mg/l), sulfate (mg/l), chemical oxygen demand (mg/l), and turbidity (NTU) by treatment and block. Treatment 3 block 2 perished week 13. Numbers with common or no letter following are not significantly different.

Treatment	Block	Chlorine	SE	Sulfate	SE	COD	SE	Turbidity	SE
Raw Data									
1	1	0.05	0.01	24.1	1.37	65.9	10.2	23.2	6.07
1	2	0.06	0.01	23.5	1.37	62.2	10.2	21.7	6.07
1	3	0.06	0.01	19.3	1.37	67.3	10.2	16.5	6.07
2	1	0.07	0.01	22.7	1.37	62.3	10.2	20.7	6.07
2	2	0.07	0.01	21.9	1.37	55.7	10.2	17.8	6.07
2	3	0.08	0.01	16.3	1.37	57.1	10.2	17.3	6.07
3	1	0.09	0.01	29.8	1.37	154.5	10.2	55.2	6.07
3	2								
3	3	0.09	0.01	31.3	1.37	141.7	10.2	55.5	6.07
Means									
1		0.06a	0.01	22.28	0.79	65.12a	5.89	20.43a	3.50
2		0.07b	0.01	20.27	0.79	58.35a	5.89	18.61a	3.50
3		0.09c	0.01	29.24	0.83	131.10b	6.26	51.11b	3.68
	1	0.07	0.01	25.54a	0.79	94.26a	5.89	3302	3.50
	2	0.07	0.01	23.97b	0.83	71.68b	6.26	27.39	3.68
	3	0.08	0.01	22.27c	0.79	88.70a	5.89	29.45	3.50

Table II. Mean chlorine, sulfate, chemical oxygen demand, and turbidity - Experiment II. Chlorine (mg/l), sulfate (mg/l), chemical oxygen demand (mg/l), and turbidity (NTU) by treatment and block. Treatment 1 block 3 and treatment 3 block 2 perished week 13. Numbers with common or no letter following are not significantly different.

Treatment	Block	Chlorine	SE	Sulfate	SE	COD	SE	Turbidity	SE
Raw Data									
1	1	0.07	0.01	74.3	2.54	38.1	3.6	16.9.	2.90
1	2	0.07	0.01	63.9	2.54	74.7	3.6	42.1	2.90
1	3								
2	1	0.08	0.01	100.9	2.54	81.4	3.6	35.1	2.90
2	2	0.09	0.01	87.6	2.54	67.1	3.6	28.9	2.90
2	3	0.10	0.01	78.5	2.54	51.4	3.6	24.8	2.90
3	1	0.10	0.01	90.2	2.54	61.4	3.6	27.6	2.90
3	2								
3	3	0.12	0.01	92.4	2.54	53.2	3.6	22.9	2.90
Means									
1		0.07a	0.01	76.56a	1.56	50.97a	2.13	27.28	1.74
2		0.09b	0.01	89.02b	1.50	66.67b	2.05	29.58	1.67
3		0.11c	0.01	90.56b	1.56	59.60c	2.13	26.78	1.74
	1	0.08	0.01	88.46a	1.50	60.29a	2.05	26.53a	1.67
	2	0.09	0.01	80.17b	1.56	68.69b	2.13	33.62b	1.74
	3	0.10	0.01	87.57a	1.56	48.26c	2.13	23.47a	1.74

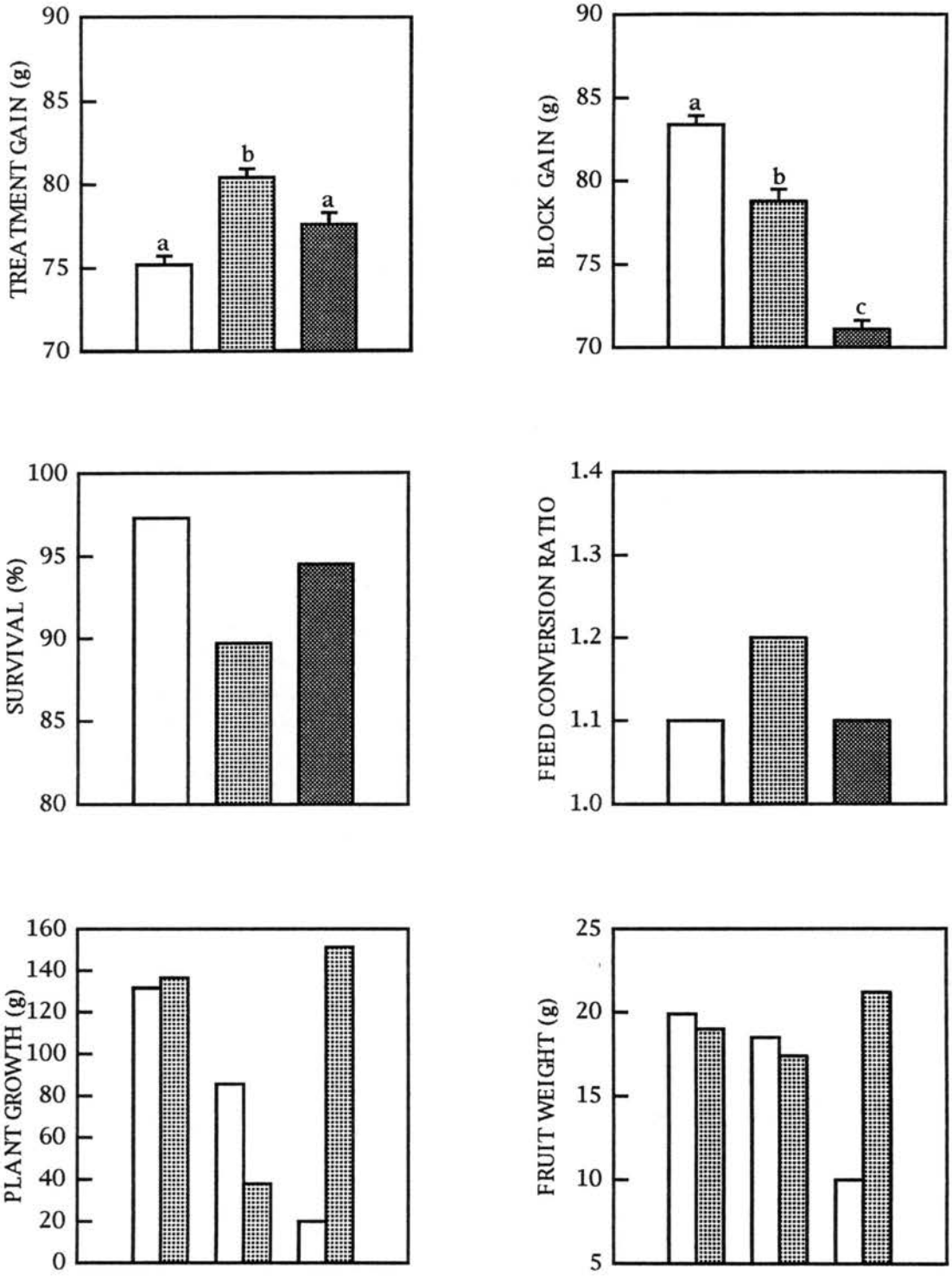

Figure 3. Mean catfish gain (SE) by treatment and block, survival, feed conversion ratio by treatment, plant growth and fruit weight grouped by treatment and block - experiment I. Open bars are treatment or block 1, medium shaded bars are treatment or block 2, dark shaded bars are treatment or block 3 in gain, survival, and feed conversion ratio. Adjoining bars are treatment and block grouped 1 - left, 2 - center, and 3 - right. Bars with similar letters or no letters are not significantly different.

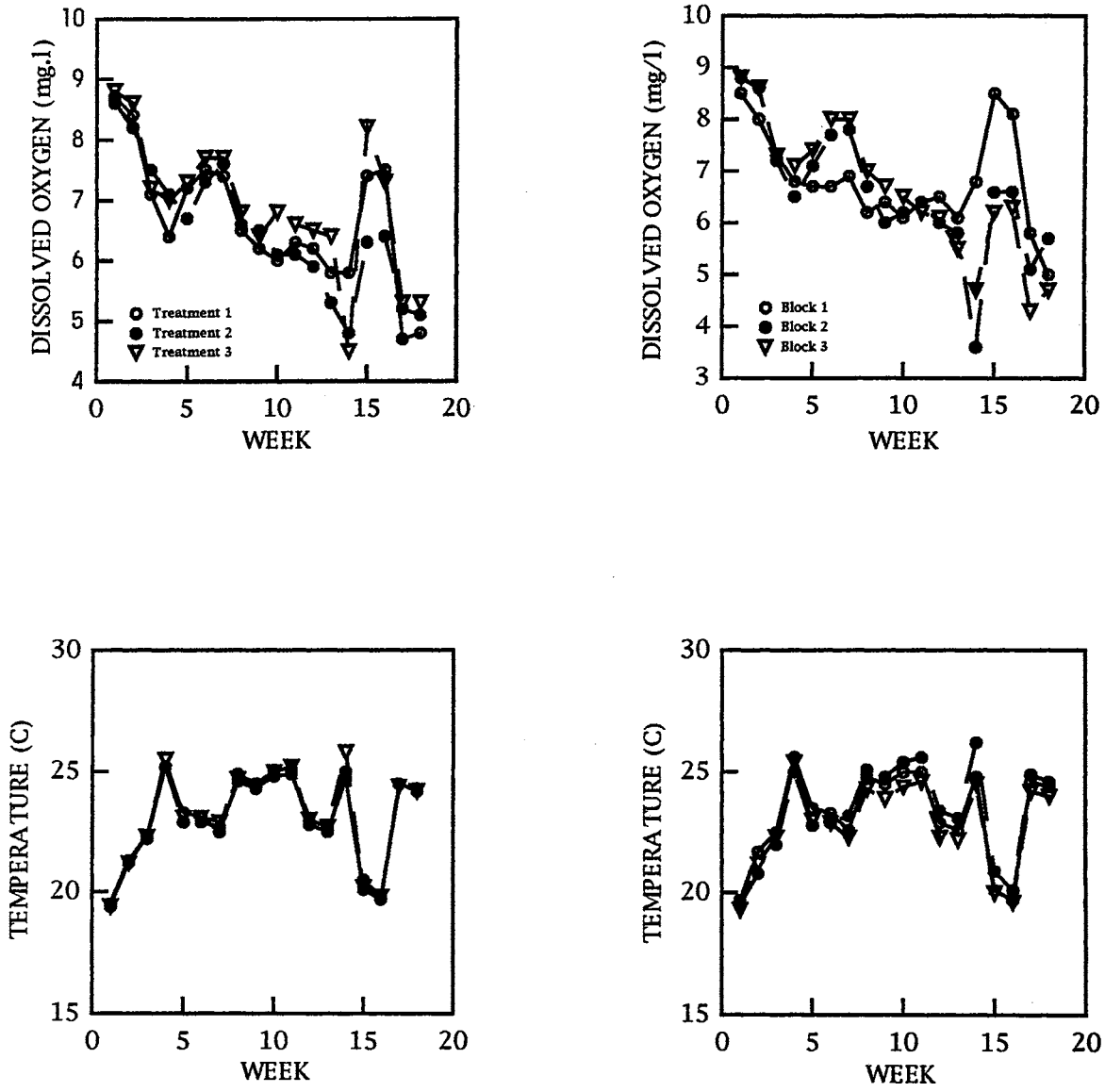

Figure 4. Mean dissolved oxygen and temperature by treatment and block - experiment I. Open circles are treatment or block 1, closed circles are treatment or block 2, and triangles are treatment or block 3. Treatments - left, blocks - right.

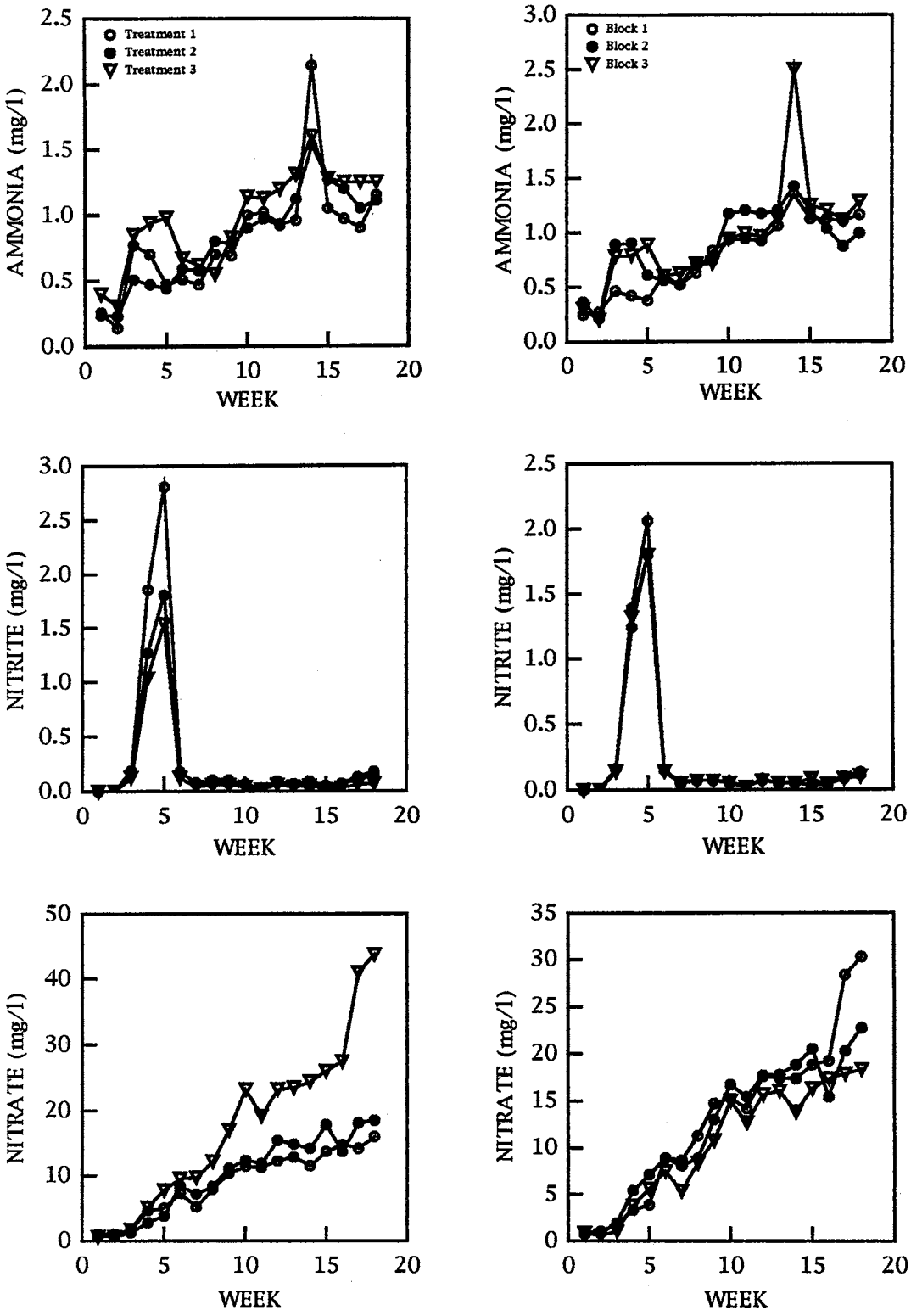

Figure 5. Mean ammonia, nitrite, and nitrate - experiment I. Open circles are treatment or block 1, closed circles are treatment or block 2, and triangles are treatment or block 3. Treatments - left, blocks - right.

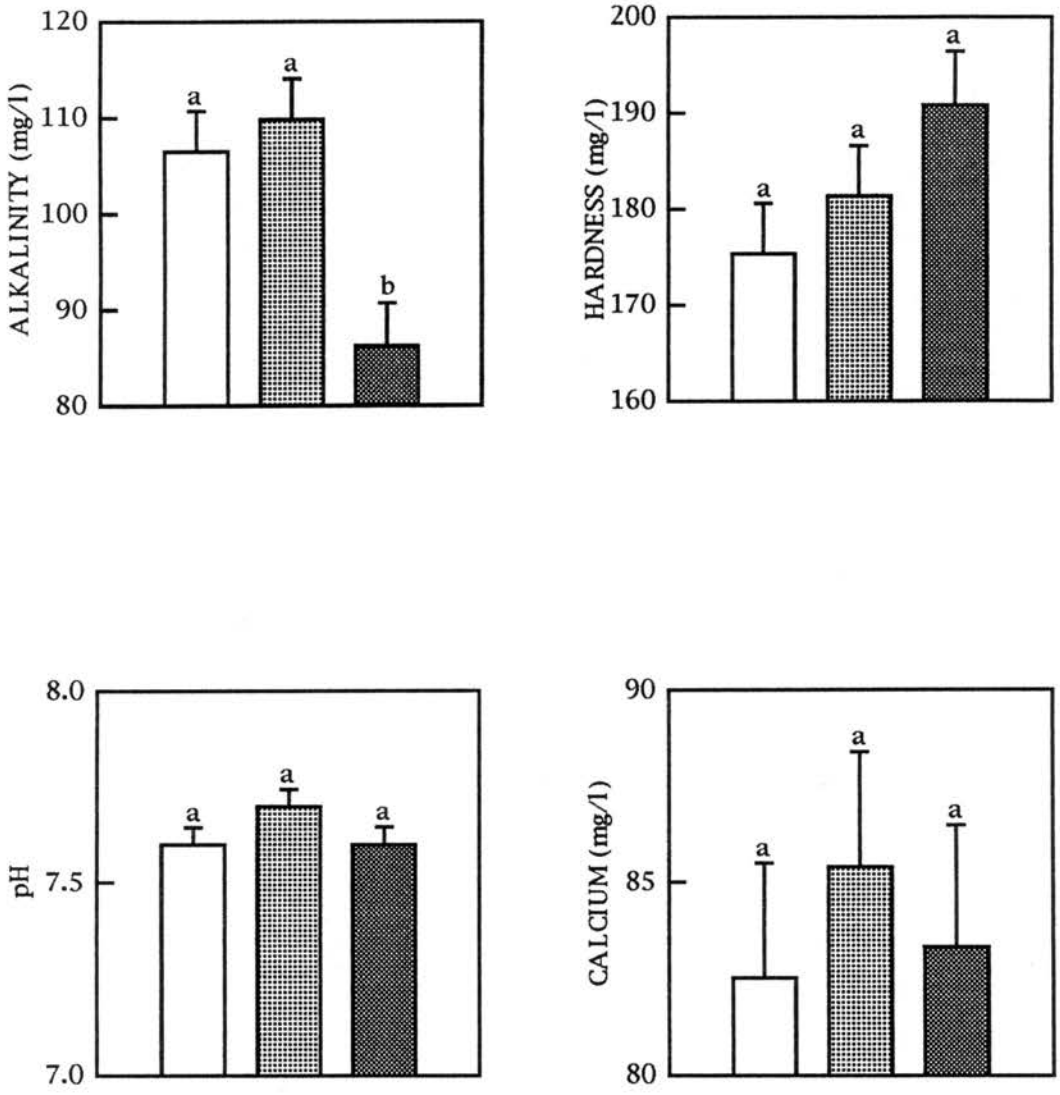

Figure 6. Treatment means (SE) of alkalinity, hardness, pH, and calcium - experiment I. Open bars are treatment 1, medium shaded bars are treatment 2, and dark shaded bars are treatment 3. Bars with a common letter or no letter above are not significantly different.

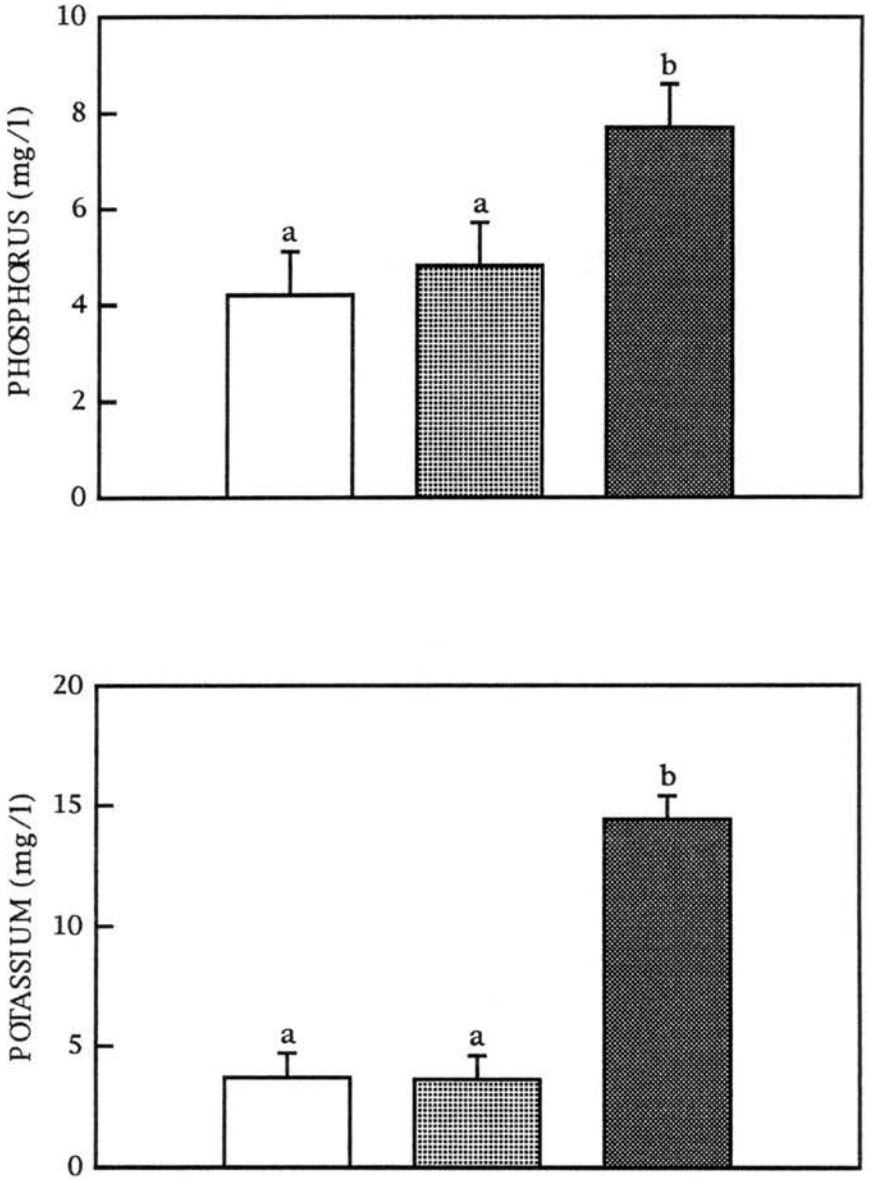

Figure 7. Treatment means (SE) of phosphorus and potassium - experiment I. Open bars are treatment 1, medium shaded bars are treatment 2, and dark bars are treatment 3. Bars with a common letter are not significantly different.

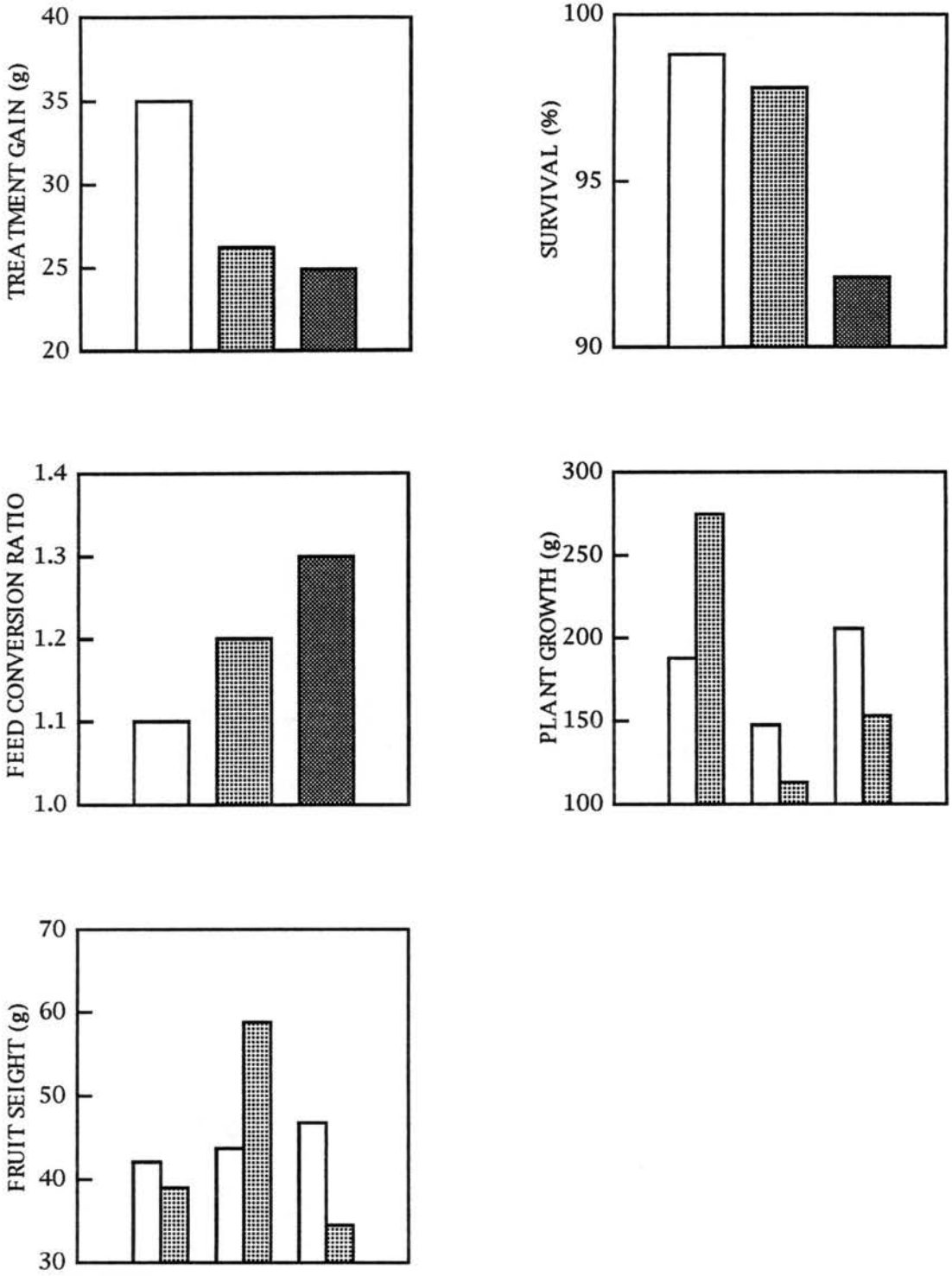

Figure 8. Treatment means of catfish gain, survival, feed conversion ratio, and grouped treatment and block means of plant growth and fruit weight - experiment II. Open bars are treatment 1, medium shaded bars are treatment 2, and dark bars are treatment 3 in gain survival, and feed conversion ratio. Open bars are treatment and shaded bars are block in plant growth and fruit weight. Treatment and block 1 - left, treatment and block - 2 center, and treatment and block 3 - right.

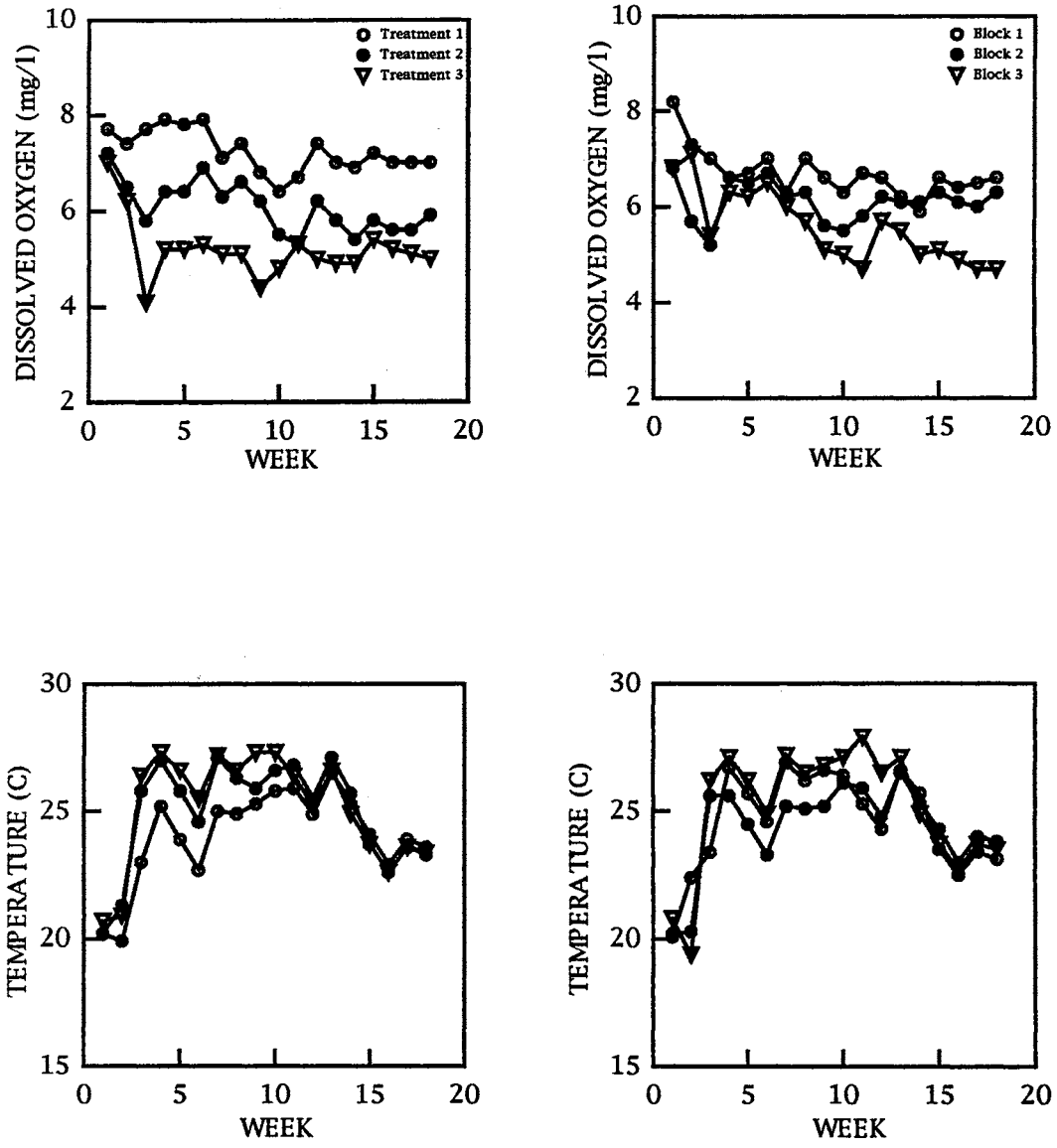

Figure 9. Mean dissolved oxygen and temperature by treatment and block - experiment II. Open circles are treatment or block 1, closed circles are treatment or block 2, and triangles are treatment or block 3. Treatments - left, blocks - right.

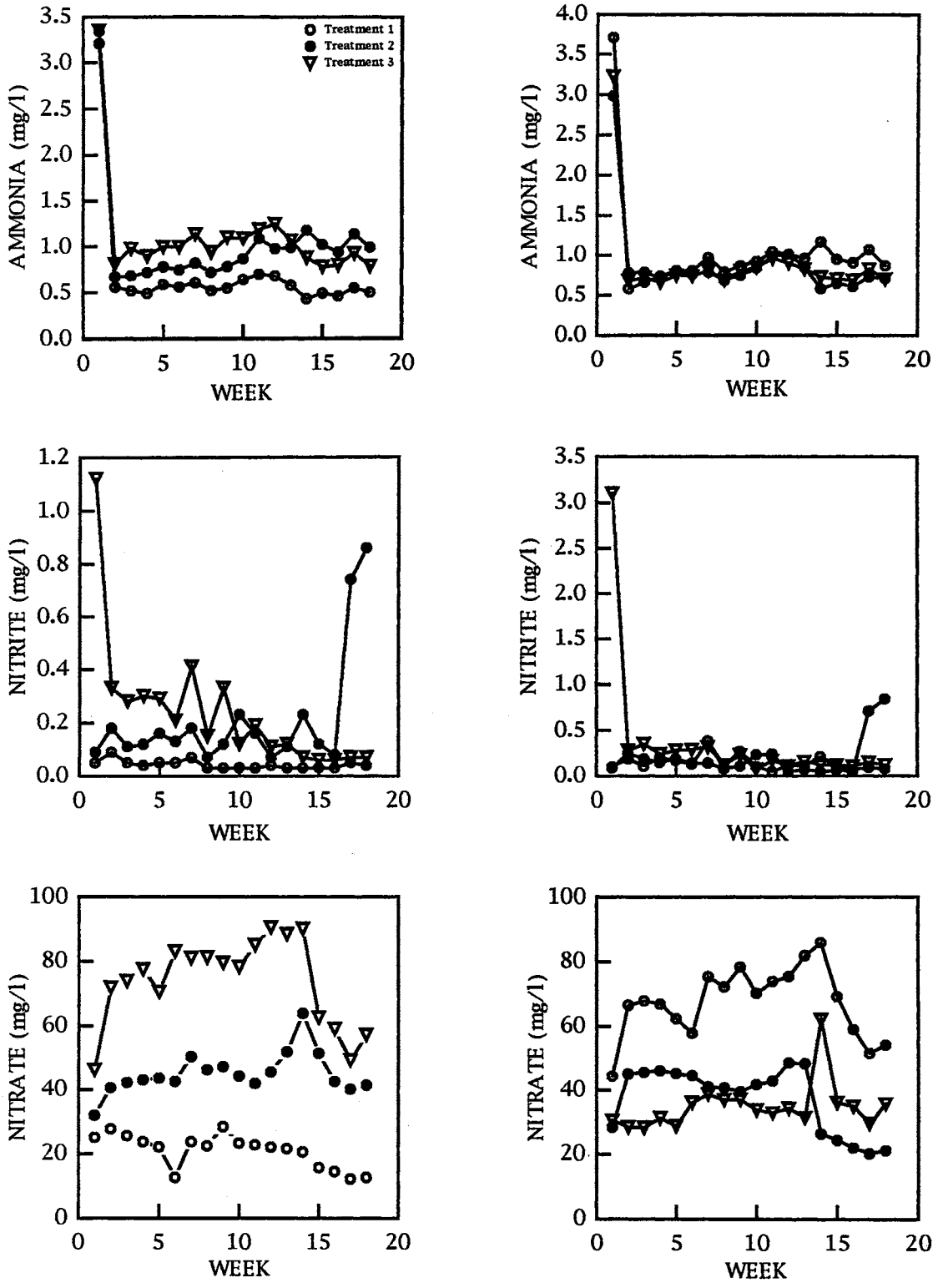

Figure 10. Mean ammonia, nitrite, and nitrate by treatment and block - experiment II. Open circles are treatment or block 1, filled circles are treatment or block 2, and triangles are treatment or block 3.

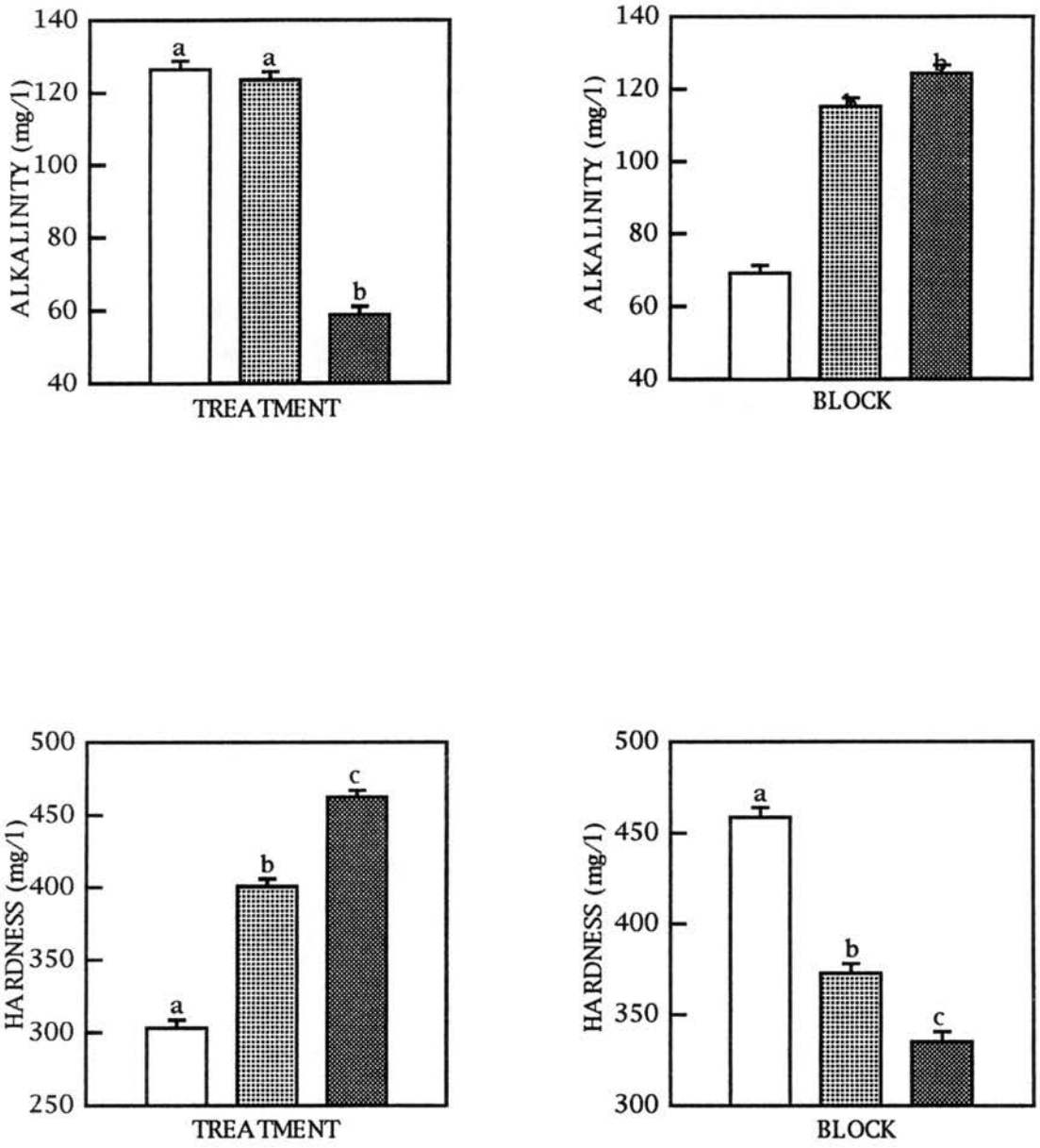

Figure 11. Mean alkalinity and hardness by treatment and block - experiment II. Open bars are treatment or block 1, medium shaded bars are treatment or block 2, and dark bars are treatment or block 3. Bars with a common letter or no letter above are not significantly different.

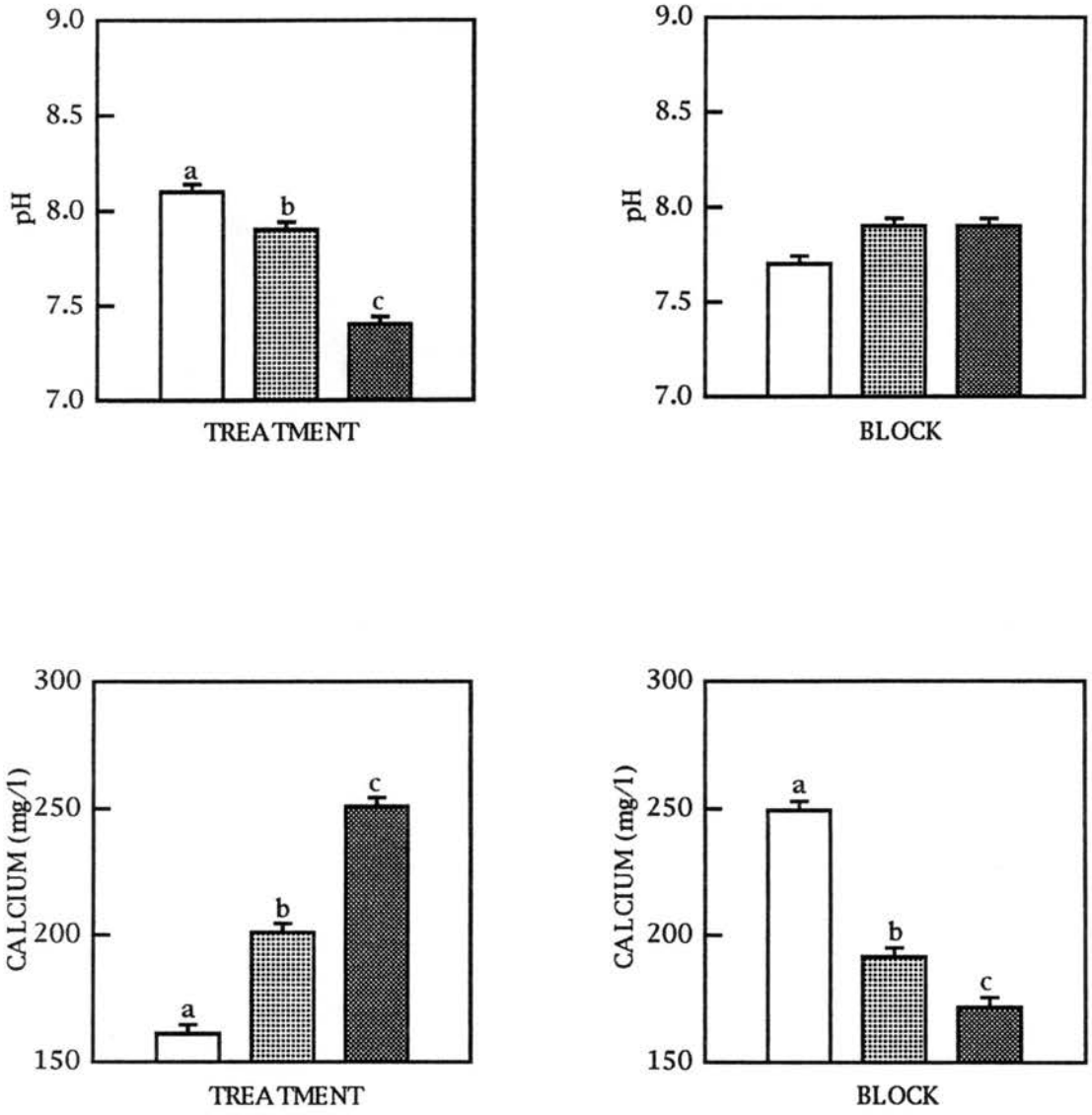

Figure 12. Means and SE of pH and calcium - experiment II. Open bars are treatment or block 1, medium shaded bars are treatment or block 2, and dark bars are treatment or block 3. Bars with a common letter or no letter above are not significantly different.

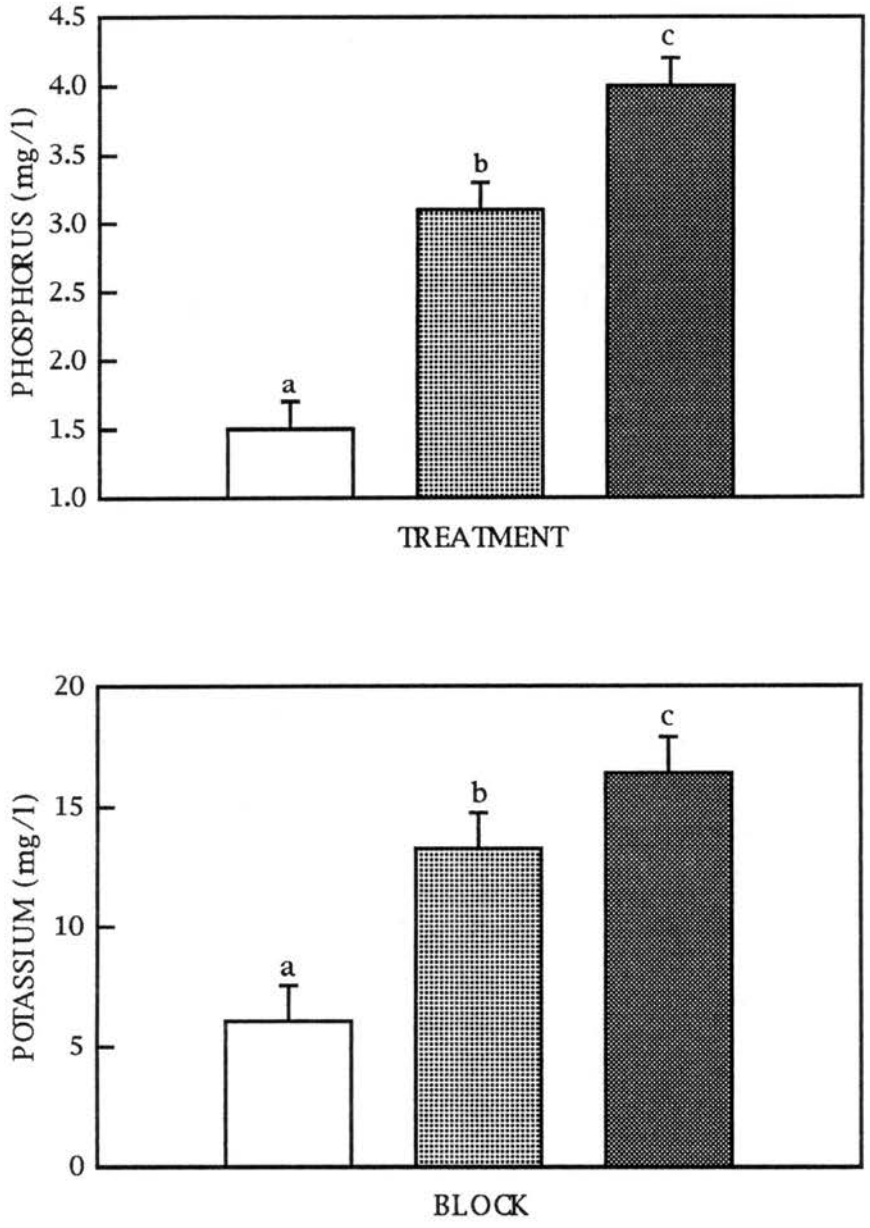

Figure 13. Treatment mean and SE of phosphorus and block mean and SE of potassium - experiment II. Open bars are treatment or block 1, medium shaded bars are treatment or block 2, and dark bars are treatment or block 3. Bars with a common letter or no letter above are not significantly different.

Chapter IV

Discussion

EXPERIMENT I

The first experiment was designed to answer the following questions. (1) How would the controlled environment in the greenhouse affect the growth of the fish? (2) Would fish grow at the same rate in the system as they would in a pond? (3) Would the feed conversion ratio be the same in the system as in a pond? (4) How many fish could be reared in the system without plants? (5) Did fish wastes contain enough essential plant nutrients to adequately sustain plant growth? (6) Would enough ammonia be converted to nitrate and be subsequently removed from the system to increase carrying capacity of fish in the system before overloading it?

We were concerned primarily with the growth of catfish in this system. The value of plant growth was its ability to act as a biofilter in this system and as a secondary crop. Water quality parameters determine health and productivity of a system. Beem (1986) stated that an aggregate of water quality parameters determine the amount and rate of growth of any organism in such a system. This study was not designed to study cumulative effects of those water quality parameters, but they were grouped as parameters essential for, or detrimental to, growth of catfish and peppers.

The high density treatment (100 catfish: 80 plants) gained an average of 3 g/fish more than the low density treatment (100

catfish: 40 plants) and 5 g/fish more than the control (40 catfish: no plants) which suggested that may have been the best ratio of fish to plants. That small difference in catfish growth, although significant, would suggest that culture conditions for the fish were consistent throughout experiment I despite differences in plant densities. Catfish growth was about 80 g/120 days, a growth rate of 375%, which is less than the 688% seasonal gain for fish of this size in cage culture reported by Beem (1986). That gain is an average of 0.67 g/day/fish, which is also less than the mean of 2.05 g/day/fish reported by Lewis et al. (1978).

The catfish were fed a 36% protein, nutritionally complete catfish ration daily at 2% of their estimated total weight, which was increased weekly. The feed conversion ratios were all uniform and between 1.0:1 and 1.3:1. The implication here is that the 2% feeding rate may not have been enough for maximum growth under those culture conditions. The only feed available to the catfish was that offered once a day six days a week. However, the amount of feed offered did not cause extreme deterioration of water quality as was reflected by levels of dissolved oxygen, ammonia, and nitrite through the duration of experiment I.

Dissolved oxygen remained at acceptable levels through the majority of the experiment I. That implied that the system was not overloaded. Dissolved oxygen dropped to 1.5 mg/l in treatment 2 block 3 during week 13 and was associated with a temperature increase. The catfish in that replicate survived.

Water temperature for the most of the 120 days was below the 28 to 30 C required for maximum growth (Lewis et al. 1978). It

fluctuated continually throughout the experiment. A 5 C drop in temperature overnight contributed to the stress in treatment 3 block 2 that led to total mortality in that tank. Although the growing season was only 120 days long, the lower temperatures may account for the less than ideal growth of catfish in this study.

Unionized ammonia (NH_3) was below the 96 hour LC50 of 3.1 mg/l (Robinette 1983) throughout experiment I. Treatment 1 block 2 reached a maximum of 2.9 mg/l in week 4 but was quickly converted to nitrite and then nitrate by bacteria in the system. The conditioning of experimental units before stocking allowed bacterial populations to increase to proportions that could nitrify excess ammonia that was produced as a result of handling during stocking.

Nitrite levels were low to moderately high compared with the 96-hour LC50 of 7.5 mg/l (Robinette 1983). Treatment 3 with no plants showed a peak level of 5.8 mg/l nitrite, which may be explained in part by the lack of plants in that treatment. Treatment 2 with 80 plants had the lowest nitrite levels throughout experiment I, which could have been the result of the increased surface area of the plant roots providing more surface area for nitrifying bacteria.

Vegetative growth (g/120 days) was sparse in all treatments. There was more mean plant top growth in treatment 1 than treatment 2. Blocks 1 and 3 produced 100 g more plant growth than block 2. Treatment 1 produced a higher mean fruit weight than treatment 2. Apparent treatment differences in mean fruit weight and number of peppers per plant were not statistically significant. That lack of significance was due to a limited number of degrees of freedom (W. Warde pers. commun.). The mean weight of peppers

was similar for all blocks. All peppers were small and irregularly formed, which suggested that plant nutrients were the limiting factor in plant growth and pepper production by treatment. Low and fluctuating temperature was the probable cause of the block effect on plant growth and pepper production.

Nitrate, phosphorus, and potassium, which are all essential plant nutrients, were low in experiment I. Smith (1979) suggested a nutrient solution for peppers hydroponically grown in rockwool that included concentrations of nitrate - 172 mg/l, phosphorus - 39 mg/l, and potassium - 234 mg/l (Appendix III). Nitrate the end product of nitrification was below the tolerance limit of 80 ppm noted in Lewis et. al. 1978. Phosphorus was lower in treatment 1 than treatment 2, but potassium was lower in treatment 2 than treatment 1. The nitrogen-phosphorus ratio may have been the limiting factor, but further investigation is needed (S Burks, 1991, pers. commun., Wetzel 1983).

The pH remained constant and the same as the input water through experiment I. The catfish and bacteria in the system did not produce enough carbon dioxide to lower the pH, another indication that the system was buffered well and not over stocked. Mean alkalinity was lower than the input water, which suggested that nitrifying bacteria were consuming CO_2 from alkalinity, expressed as $CaCO_3$ (Loyless and Malone, 1997; Sawyer and McCarty, 1978). Hardness, also expressed as $CaCO_3$, and calcium increased by a small amount in conjunction with the decrease in alkalinity (Wetzel 1983).

The difference in chlorine levels was the result of having to add more make-up water to some tanks as a result of leakage from

the hydroponics racks. Chlorine was low enough not to have been toxic in this experiment. Chlorine was not toxic to guinea pigs at 0.07 mg/l but caused deterioration in the nutritional state and blood alterations at 1.7 mg/l. However, repeated exposure of rabbits to concentrations of 0.7 - 1.7 mg/l over periods up to 9 months caused weight loss and increased incidence of respiratory disease (Smith et al. 1976).

Turbidity is an indication of the particulate matter available to form sediment in the system. COD is a measurement of organic matter in the system terms of the total quantity of oxygen required for oxidation to carbon dioxide and water (Sawyer and McCarty 1978). COD is an indication of anaerobic respiration occurring in the sediments (Wetzel 1983). Sulfate is a measure of the amount of sulfur released by decay in the sediment. Sulfur when released in the sediment is in the form of hydrogen sulfide which is toxic to fish, but it is quickly converted to sulfate if the system is well oxygenated (Wetzel, 1983). Increases in turbidity, COD, and sulfate indicated that all systems were well oxygenated and vigorous throughout experiment I.

Boron, molybdenum, iron, zinc, manganese, and copper were present in negligible quantities in experiment I. All concentrations were below levels suggested for a nutrient solution to grow peppers hydroponically in rockwool (Appendix C). Their availability is required by both fish and plants in minute quantities. If available along with all other required nutrients, all organisms grow well. If not, despite other nutrient levels, organisms grow poorly.

Ambient conditions were very difficult to control in experiment I. Air temperature, although not considered in this experiment, fluctuated more than 10 C during daylight hours. Although water temperature changes more slowly than air, evaporative cooling, exposure of the water on the hydroponics racks, and recirculation times caused fluctuation in water temperature that limited catfish growth. Growth rate of catfish was less in this system than in pond or cage culture. High air temperature and extreme fluctuations along with limited nutrients were the possible cause of poor plant growth. The feed conversion ratio in experiment I was less than that experienced in pond catfish culture (Stickney 1979). The combined water quality parameters indicated that the systems were not over stocked with catfish. The biological comparison of the means of catfish growth, feed conversion ratios, ammonia, nitrite, and pH indicated that this system supported 100 catfish equally well with and without plants and suggested that this number could possibly be increased if temperature could be controlled better. Poor plant growth is an indication that plant nutrients were a limiting factor. Nitrification was very effective in converting ammonia to nitrate, and the stocking rate of fish could be increased without overloading.

EXPERIMENT II

Examination of data from the first experiment suggested that plant growth was limited by levels of plant nutrients. The decision was made at that time to use the lowest number of plants and to increase the number of fish by 100 and 200 in treatments 2 and 3, respectively. Treatment 1 (100 catfish, 40 plants) was the control,

and the link between the two experiments. Treatment 2 (low density) had 200 catfish, 40 plants and treatment 3 (high density) had 300 catfish, 40 plants.

Experiment II was designed to answer the following questions. (1) Would enough ammonia be converted to nitrate and be subsequently removed from the system to support an increase in stocking rate of fish in the system before overloading it and (2) did wastes from increased numbers of fish contain enough essential plant nutrients to adequately sustain plant growth?

Extremely low gain and no variation among treatments or blocks indicate that all catfish in experiment II were severely stressed. Catfish growth was about 35 g/120 days in all treatments. That gain was an average of < 0.3 g/day/fish, which was far less than the mean of 2.05 g/day/fish reported by Lewis et al. (1978).

The catfish were fed a 36% protein, nutritionally complete catfish ration daily at 2% of their estimated total weight, which was increased weekly. The feed conversion ratios were all uniform and between 1.1:1 and 1.3:1. The 2% feeding rate combined with poor environmental control was not adequate for maximum growth. The feeding regime was the same as in experiment I. However, the amount of feed offered caused some deterioration of water quality as reflected by levels of dissolved oxygen, ammonia, and nitrite through the duration of experiment II. That deterioration in water quality may also be an indication of the presence of uneaten feed, and its subsequent decomposition.

Dissolved oxygen remained at acceptable levels through the majority of experiment II. That again implied that the system was

not overloaded. Water temperature for the most of the 120 days was below the 28 to 30 C required for maximum growth (Lewis et. al 1976). It fluctuated continually throughout the experiment. A 5 C drop in temperature overnight contributed to the stress in treatment 1 block 3 and treatment 3 block 2 that led to total mortality in those tanks. Although the growing season was only 120 days long, the lower and sporadic temperatures may have accounted for the less than ideal growth of catfish in experiment II.

Levels of unionized ammonia (NH_3) were very similar to those in experiment I. Nitrite levels were once more low to moderately high compared with the 96-hour LC50 of 7.5 mg/l mentioned by Robinette (1983). Treatment 1 with 100 catfish had the lowest mean nitrite levels throughout experiment II and treatment 3 with 300 catfish had the highest. Mean nitrite levels increased threefold for each 100 catfish increase in stocking rate.

Vegetative growth in experiment II was more profuse and luxuriant in all treatments than in experiment I. There was more mean plant top growth in treatment 3 than treatments 1 or 2. Mean plant growth was a minimum of 60 g higher than experiment I. Again, blocks 1 and 3 produced a higher mean plant growth than block 2, but the difference in experiment II was not significant. Mean fruit weight (bell peppers) in experiment II was similar for all treatments but was double the fruit production in experiment I. Again, all peppers were irregularly formed. These factors suggested that temperature and nutrients ratios were the limiting factor in pepper production in experiment II as well.

Nitrate levels in experiment II were all higher than experiment I. Treatment 1, which was the same as treatment 1 in experiment I, had a mean nitrate level 10 mg/l higher. Nitrate levels in experiment II were 3 times higher in treatment 1 than experiment I, 6 times higher in treatment 2, and 10 times higher in treatment 3. That combined with mean nitrite levels was an indication that the catfish were under stress that caused them to produce more ammonia during experiment II than during experiment I. Phosphorus and potassium, both essential plant nutrients, were low in experiment II. Phosphorus was lower in treatment 1 than treatment 2, but potassium was lower in treatment 2 than treatment 1. That also suggested that the nitrogen-phosphorus ratio may have been the limiting factor for plant growth and fruit production in experiment II.

The pH increased in experiment II which was partially caused by a profuse filamentous algae growth on the hydroponics racks during the second half of the experiment. The catfish and bacteria in the system did not produce enough carbon dioxide to support photosynthesis (Stickney 1979), consequently the algae used CO_2 from $CaCO_3$, which left free oxygen to combine with hydrogen ions to form water molecules, therefore raising the pH (Sawyer and McCarty 1978). Mean alkalinity was lower than the replacement water which suggested that nitrifying bacteria were also consuming CO_2 from alkalinity, expressed as $CaCO_3$ (Loyless and Malone, 1997). Hardness, also expressed as $CaCO_3$, and calcium increased 2 to 3 times the amount in the replacement water as a result of the decrease in

alkalinity (Kleinholz, pers. commun.). Algae also competed with the bell peppers for nutrients.

The difference in chlorine levels in experiment II was again the result of having to add more make-up water to some tanks as a result of leakage from the hydroponics racks. Turbidity was not as high in experiment II, compared with experiment I, showing the effectiveness of the increased root systems and the algae as a particulate filter. Levels of COD were the same in all treatments, which was more evidence of the filtering capability of the root systems. All sulfates in experiment II were 3 times higher than in experiment I, which indicated the presence of more decaying organic matter, but sufficient oxygen was available to convert the hydrogen sulfide produced to sulfate.

Ambient conditions were very difficult to control in experiment II. The combined water quality parameters indicated that the systems were not overstocked with catfish. Nitrification was very effective in converting ammonia to nitrate and would support this level of stocking if temperature could be controlled. Wastes from increased numbers of fish contained enough essential plant nutrients to adequately sustain plant growth but not fruit production. Poor fruit production in experiment II was an indication that plant nutrients and fluctuating temperature were limiting factors.

CHAPTER V

CONCLUSIONS

My study examined components and configuration of the Kleinholz system with the intent of developing an instrument and protocol with which a closed aquaculture-hydroponics system could be evaluated. The inability to control ambient conditions combined with the small size of the fish culture units resulted in temperature fluctuations that were problematic in both experiments. Despite the difficulty of keeping the catfish alive, I was able to determine that production rates were enhanced by the hydroponic component. The hydroponic component effectively aided in the removal of nitrogen from the fish culture systems. The increased surface area provided ample substrate for nitrifying bacteria, which was shown by the rapid lowering of nitrogen levels after the catfish were stocked and by the low levels of ammonia and nitrite throughout both experiments. With adequate environmental control, I can conceive of stocking rates high enough to make this system a viable production venture for small scale fish farmers or backyard ventures.

Catfish mortalities in week 13 of both experiments is an anomaly that requires elucidation. I can not completely explain those mishaps. I surmise here that large temperature, and associated dissolved oxygen fluctuations during weeks 11, 12, and 13 caused additional stress for catfish in those tanks that were already stressed by the synergistic effects of low dissolved oxygen and sublethal levels of ammonia and nitrite. Individual parameters

here were sub-lethal, but their cumulative effects may have been lethal to catfish in those tanks. Those effects also may have been intensified by the location of those tanks in the greenhouse and by the addition of chlorinated replacement water, made necessary by leakage from the hydroponics racks.

Catfish gain in experiment I was greater than in experiment I. Feed conversion ratios were similar in both experiments despite different numbers of fish and different amounts of feed offered. Uneaten feed particles impinged in the airlift and were carried up to the hydroponic racks with the water. Nutrients from the uneaten feed particles supplemented the nutrients available to the plants in the fish waste. Those supplemental nutrients are partially responsible for the lush growth of vegetation in experiment II

Analysis of data from the experiments should have suggested an optimum ratio of fish and plants that the system could support. However, difficulties encountered with the system, the result of a lack of control of ambient conditions, prevented me from determining an optimum ratio of plants to fish in the system. Null hypotheses (H_O) were as follows. (1) There were no differences in fish production among treatments with varying plant densities. I reject hypothesis 1 because catfish production in experiment I was significantly greater in treatment 2 with 80 plants. (2) There were no differences in water quality among treatments with varying plant densities. Hypothesis 2 was rejected because parameters crucial for fish growth, dissolved oxygen, ammonia, and nitrite were moderated in treatments with plants. (3) There were no differences in plant production among

treatments with varying catfish numbers. Treatment 3, experiment II with 300 catfish produced more vegetative growth than treatments 1 and 2. Treatments 2 and 3 produced more fruit than treatment 1 in the same experiment. The differences were not significant, therefore the null hypothesis is supported. (4) There were no differences in water quality among treatments with varying catfish densities. Significant differences in dissolved oxygen, ammonia, nitrite, and nitrate suggest that hypothesis 4 should be rejected. (5) Ammonia removal through nitrification and subsequent uptake by plants was not sufficient to allow higher stocking rates of fish in treatments with higher numbers of plants. Significantly lower levels of nitrite and nitrate in treatments 1 and 2 of experiment I suggest that hypothesis 5 should be rejected. (6) There was no relationship between numbers of fish and plants that the system can sustain. I did not find the sustainable fish to plant ratio for this system The statistically significant differences in a number of crucial parameters and the biological examination of the data from the two experiments were sufficient to reject 4 of the 6 null hypotheses.

The ability to better manage ambient conditions in the green house and better control of leakage and algae growth are of utmost importance in any future endeavors. Investigation of sustainable ratios of fish to plants in this system should be extended. The synergistic effects of nutrients in this system should also be investigated.

LITERATURE CITED

Beem, M. D. 1986. Water quality and water exchange time in caged channel catfish culture. Ph. D. dissertation, Oklahoma State University, Stillwater, Oklahoma, 69 pp.

Bardach, J. E., J. H. Ryther, and W. O. McLarney. 1972. Aquaculture, the farming and husbandry of freshwater and marine organisms. Wiley Interscience, New York, 868 pp.

Collins, R. A. 1976. Comparative economics of aquaculture in cages, raceways and enclosures. Pages 472-477 in Advances in Aquaculture. T.V.R. Pillay and W. A. Dill, eds. F A O Technical Conference. Kyoto, Japan.

Crop Reporting Board. 1982. Statistical Reporting Service. U.S. Department of Agriculture, Sp Cr. 8(2):28.

Douglas, J. S. 1975. Hydroponics. Oxford University Press. London,

Dupree, H. K. and J. V. Huner, editors. 1984. Third report to the fish farmers. The status of warm water fish farming and progress in fish farming research. U. S. Department of the Interior, U. S. Fish and Wildlife Service (S/N 024/-10-00654-4).

Hicks, C. R. 1982. Fundamental concepts in the design of experiments. Holt, Rinehart, and Winston. New York, 425 pp.

Huet, M. 1970. Textbook of fish culture: Breeding and cultivation of fish. Surrey and London, England: Fishing News (Books), 436 pp.

Jewell, W. J., J. J. Madras, W.W. Clarkson, H. Delancey-Pompe, and R. M. Kabrick. 1983. Wastewater treatment with plants in nutrient films. U.S. Environmental Protection Agency Report No. EPA-600/2-83-067.

Kleinholz, C., G. Gebhart, and O. E. Maughan. 1985. Integrated hydroponic-aquaculture systems utilizing fish waste for plant fertilization. Project report. OKLX-8388-15-0089771.

Knepp, G. L., and G. F. Arkin. 1973. Ammonia toxicity levels and nitrite tolerance of channel catfish. Progressive Fish-Culturist, 35:221-224.

Laurie, A. 1940. Soilless culture simplified. McGraw-Hill Book Company, Inc. 201 pp.

Lewis, W., J. Yopp, H. Schramm, Jr., and A. Brandenburg. 1978. Use of hydroponics to maintain quality of recirculated water in a fish culture system. Transactions of the American Fisheries Society, 107(1):92-99.

Loyless, J. C. and R. E. Malone. 1997. A sodium bicarbonate dosing methodology for pH management in freshwater-recirculating aquaculture systems. Progressive Fish-Culturist, 59:198-205.

Lucchetti, G.L. and G. A. Gray. 1988. Water reuse systems: A review of principal components. The Progressive Fish-Culturist, 50(1):1-6.

Martin, M. 1978. Abundant supply of clean water is absolutely essential for commercial fish farming. The Commercial Fish Farmer, 4(4): 15-18.

Matlin, D. R. 1940. Growing plants without soil. Chemical Publishing Company, Inc. New York, New York, 137 pp.

McCall, M. 1990. The Catfish Journal. The Catfish Farmers of America. 4(7):1.

McLarney, W. O. 1984. The freshwater aquaculture book: a handbook for small scale fish culture in North America. Hartley and Marks, Point Roberts, Washington, 583 pp.

Meske, Ch. 1976. Fish culture in a recirculating system with water treatment by activated sludge. Pages 527-530 in Advances in Aquaculture, T.V.R. Pillay and W.A. Dill, eds. F A O Technical Conference. Kyoto, Japan.

Meyer, F. P., K.E. Sneed, and P.T. Eschemeyer. 1973. The status of warm water fish farming and progress in fish farming research, Second report to the fish farmers. Bureau of Sport Fisheries and Wildlife Research. Publication 113, 123 pp.

Muir, J. F. 1982. Recirculated water systems in aquaculture. Pages 357-456 in Recent Advances in Aquaculture. J. F. Muir and R. J. Roberts. Westview Press. Boulder, Colorado.

Neal, R. A. and C. R. Mock. 1976. A model closed system for aquaculture incorporating the recycling of wastes. Pages 521-523 in Advances in Aquaculture, T.V.R. Pillay and W. A. Dill, eds., F A O Technical Conference. Kyoto, Japan.

Rakocy, J.E. 1984. A recirculating system for tilapia culture and vegetable hydroponics in the Caribbean. Presented at the Auburn Fisheries and Aquaculture Symposium, September 20-22, 1984. Auburn University, Alabama.

Resh, H.M. 1985. Hydroponic food production. Third edition. Woodbridge Press, Santa Barbara, California, 384 pp.

Reynolds, T. D. 1982. Unit operations and processes in environmental engineering. PWS-Kent Publishing Company. Boston, Massachusetts, 576 pp.

Robinette, H. R. 1983. Ammonia, Nitrite and Nitrate. Pages 28 to 34 in Water quality in Channel Catfish Ponds, C. S. Tucker, Editor. Southern Cooperative Series Bulletin 290.

Sawyer, C. N. and P. L. McCarty. 1978. Chemistry for environmental engineering. McGraw-Hill, Inc. New York, New York, 532 pp.

Smith, R. G., M. C. Battegelli, R. R. Cook, W. S. Ferguson, N. Lacasse, and W. D. Shults. 1976. Chlorine and Hydrogen Chloride. National Research Council. Committee on Medical and Biologic Effects of Environmental Pollutants. Printing and Publishing Office, National Academy of Sciences, Washington, D. C., 282 pp.

Smitherman, R. O., H. El-Ibiary, and R. E. Regan., eds. 1978. Genetics and Breeding of Channel Catfish. Southern Cooperative Series. Bulletin 223, 34 pp.

Spotte, S. H. 1979. Fish and invertebrate culture: Water management in closed systems. John Wiley and Sons, Inc. New York, New York, 145 pp.

SYSTAT, Inc. 1992. Systat: Statistics, Version 5.2. Edition. Evanston, Illinois, 724 pp.

Steele, R. G. D and J. H. Torrie. 1960. Principles and Procedures of Statistics. McGraw-Hill Book Company, Inc. 481 pp.

Stickney, R. R. 1979. Principles of Warmwater Aquaculture. John Wiley and Sons, Inc. New York, New York, 375 pp.

Turner, W. I. and V. M. Henry. 1939. Growing plants in nutrient solutions. John Wiley and Sons, Inc. New York, New York, 154 pp.

Wetzel, R. G. 1983. Limnology. W. B. Saunders Company. New York, New York, 858 pp.

APPENDICES

APPENDIX A

SUMMARIES OF CHANNEL CATFISH GAIN, PLANT GROWTH AND SELECTED WATER QUALITY PARAMETERS - EXPERIMENT I

APPENDIX A.1

Means of catfish gain (g), survival (%), and feed conversion ratio by treatment and block - experiment I.

Treatment	Block	Gain	SE	Survival	SE	FCR	SE
Raw Data							
1	1	80.6		97		1.1	
1	2	77.0		100		1.0	
1	3	68.0		95		1.3	
2	1	86.0		97		1.0	
2	2	80.7		95		1.1	
2	3	74.6		77		1.6	
3	1	83.6		90		1.2	
3	2						
3	3	70.6		95		1.0	
Means							
1		75.2	0.52	97	4.4	1.1	0.13
2		80.4	0.52	90	4.4	1.2	0.13
3		77.6	0.69	95	5.8	1.0	0.18
	1	93.4	0.52	95	4.4	1.1	0.13
	2	78.8	0.69	98	5.8	1.0	0.18
	3	71.1	0.52	89	4.4	1.3	0.13

APPENDIX A.2

Mean plant growth (g), fruit weight (g), dissolved oxygen (mg/l DO), and temperature by treatment and block - experiment I.

Treatment	Block	Plant growth	SE	Fruit Wt.	SE	DO	SE	Temperature	SE
Raw Data									
1	1	216.0		22.9		6.5		23.3	
1	2	57.0		16.5		7.2		23.3	
1	3	122.0		20.2		6.2		23.8	
2	1	57.0		15.1		6.4		23.3	
2	2	19.0		18.3		6.5		23.4	
2	3	181.0		22.2		6.6		22.8	
3	1					7.5		23.2	
3	2								
3	3					7.0		23.0	
Means									
1		131.6	44.6	19.9	2.3	6.6	0.08	0.13	
2		85.4	44.6	18.5	2.3	6.5	0.08	0.13	
3						7.0	0.08	0.14	
	1	136.5	54.6	19.0	2.8	6.8	0.08	0.03	
	2	37.0	54.6	17.4	2.8	6.7	0.08	0.14	
	3	151.3	54.6	21.2	2.8	6.6	0.08	0.13	

APPENDIX A.3

Means of ammonia (mg/l), nitrite (mg/l), and nitrate (mg/l) by treatment and block - experiment I.

Treatment	Block	Ammonia	SE	Nitrite	SE	Nitrate	SE
Raw Data							
1	1	0.63		0.11		7.9	
1	2	0.82		0.58		9.0	
1	3	0.79		0.12		6.4	
2	1	0.71		0.24		7.7	
2	2	0.71		0.18		9.5	
2	3	0.76		0.27		8.2	
3	1	0.75		0.29		16.9	
3	2						
3	3	1.01		0.85		11.6	
Means							
1		0.75	0.056	0.27	0.097	7.74	1.05
2		0.73	0.056	0.23	0.097	8.48	1.05
3		0.88	0.058	0.57	0.100	13.16	1.08
	1	0.70	0.056	0.21	0.097	10.81	1.05
	2	0.80	0.058	0.45	0.100	9.84	1.08
	3	0.86	0.056	0.41	0.097	8.73	1.05

APPENDIX A.4

Means of pH, alkalinity (mg/l), and hardness (mg/l) by treatment and block - experiment I.

Treatment	Block	pH	SE	Alkalinity	SE	Hardness	SE
Raw Data							
1	1	7.6		100.2		180.8	
1	2	7.7		99.2		179.3	
1	3	7.7		112.2		165.9	
2	1	7.7		118.9		180.8	
2	2	7.7		114.8		195.2	
2	3	7.6		95.7		167.9	
3	1	7.5		74.1		213.6	
3	2						
3	3	7.7		90.1		179.1	
Means							
1		7.6	0.08	106.5	4.19	175.3	5.29
2		7.7	0.08	109.8	4.19	181.3	5.29
3		7.6	0.08	86.2	4.46	190.8	5.62
	1	7.6	0.08	100.4	4.19	191.7	5.29
	2	7.6	0.08	102.8	4.46	184.7	5.62
	3	7.7	0.08	99.3	4.19	171.0	5.29

APPENDIX A.5

Means of calcium (mg/l), phosphorus (mg/l), and potassium (mg/l) by treatment and block - experiment I.

Treatment	Block	Calcium	SE	Phosphorus	SE	Potassium	SE
Raw Data							
1	1	91.2		2.30		3.61	
1	2	78.2		6.85		4.76	
1	3	78.1		1.93		4.34	
2	1	86.8		5.17		5.52	
2	2	86.3		4.46		3.78	
2	3	83.2		1.12		5.02	
3	1	101.6		16.96		8.90	
3	2						
3	3	75.4		16.59		8.91	
Means							
1		82.5	3.03	3.69	0.98	4.25	0.87
2		85.4	3.03	3.58	0.98	4.77	0.87
3		86.3	3.24	14.40	1.04	7.66	0.91
	1	93.2	3.03	8.14	0.98	6.01	0.87
	2	82.1	3.24	6.97	1.04	4.57	0.91
	3	78.9	3.03	6.54	0.98	6.10	0.87

APPENDIX A.6

Means of boron (mg/l), molylbdenum (mg/l), and iron (mg/l) by treatment and block - experiment I.

Treatment	Block	Boron	SE	Molybdenum	SE	Iron	SE
Raw Data							
1	1	0.10	0.07	0.03	0.04	0.04	0.01
1	2	0.10	0.07	0.04	0.04	0.04	0.01
1	3	0.07	0.08	0.00	0.04	0.06	0.01
2	1	0.10	0.07	0.00	0.04	0.04	0.01
2	2	0.10	0.07	0.00	0.04	0.03	0.01
2	3	0.10	0.07	0.00	0.04	0.04	0.01
3	1	0.08	0.07	0.07	0.04	0.04	0.01
3	2						
3	3	0.09	0.07	0.00	0.04	0.03	0.01
Means							
1		0.09	0.04	0.02	0.02	0.05	0.01
2		0.10	0.04	0.00	0.02	0.04	0.01
3		0.09	0.04	0.05	0.02	0.04	0.01
	1	0.10	0.04	0.03	0.02	0.04	0.01
	2	0.10	0.04	0.04	0.02	0.04	0.01
	3	0.10	0.04	0.00	0.02	0.04	0.01

APPENDIX A.7

Means of Zinc (mg/l), manganese and copper (mg/l) by treatment and block - experiment I.

Treatment	Block	Zinc	SE	Manganese	SE	Copper	SE
Raw data							
1	1	0.11	0.09	0.10	0.04	0.10	0.05
1	2	0.12	0.09	0.06	0.04	0.07	0.05
1	3	0.11	0.10	0.08	0.04	0.10	0.06
2	1	0.13	0.08	0.08	0.04	0.07	0.04
2	2	0.11	0.08	0.10	0.04	0.07	0.04
2	3	0.10	0.08	0.10	0.04	0.04	0.04
3	1	0.10	0.08	0.11	0.04	0.05	0.04
3	2						
3	3	0.14	0.08	0.08	0.04	0.07	0.04
Means							
1		0.11	0.05	0.09	0.02	0.09	0.02
2		0.12	0.05	0.10	0.02	0.06	0.03
3		0.12	0.05	0.09	0.02	0.06	0.03
	1	0.12	0.05	0.10	0.02	0.10	0.02
	2	0.12	0.05	0.08	0.02	0.07	0.03
	3	0.12	0.05	0.10	0.02	0.07	0.03

APPENDIX B

SUMMARIES OF CHANNEL CATFISH GAIN, PLANT GROWTH AND SELECTED WATER QUALITY PARAMETERS - EXPERIMENT II

APPENDIX B.1

Means of catfish gain (g), survival (%), and feed conversion ratio by treatment and block - experiment II.

Treatment	Block	Gain	SE	Survival	SE	FCR	SE
Raw Data							
1	1	36.4		97		1.1	
1	2	33.0		98		1.2	
1	3						
2	1	23.1		98		1.3	
2	2	25.0		99		1.2	
2	3	30.7		98		1.2	
3	1	29.7		87		1.3	
3	2						
3	3	21.8		98		1.3	
Means							
1		35.0	4.26	98.8	3.11	1.1	0.06
2		26.3	3.18	97.8	2.32	1.2	0.04
3		24.9	4.26	92.1	3.11	1.3	0.06
	1	29.7	3.17	93.7	2.32	1.2	0.04
	2	27.1	4.26	96.2	3.11	1.2	0.06
	3	29.4	4.26	98.8	3.11	1.2	0.04

APPENDIX B.2

Mean plant growth (g), fruit weight (g), dissolved oxygen (mg/l DO), and temperature by treatment and block - experiment II.

Treatment	Block	Plant growth	SE	Fruit Wt.	SE	DO	SE	Temperature	SE
Raw Data									
1	1	260.9		34.2		7.7		23.7	
1	2	141.5		50.0		6.9		23.0	
1	3								
2	1	214.9		31.0		6.4		25.9	
2	2	59.3		51.0		6.2		23.9	
2	3	168.1		45.0		5.5		25.1	
3	1	347.8		54.0		6.0		24.5	
3	2								
3	3	130.1		39.8		4.6		25.0	
Means									
1		187.5	51.9	42.1	12.8	7.3	0.07	24.3	0.17
2		147.4	38.7	43.7	9.5	6.1	0.06	25.0	0.16
3		205.4	51.9	46.8	12.8	5.1	0.07	25.5	0.07
	1	274.5	38.7	39.3	9.5	6.7	0.06	24.7	0.16
	2	113.0	51.9	58.8	12.8	6.0	0.07	24.7	0.17
	3	152.8	51.9	34.5	12.8	5.8	0.07	25.4	0.17

APPENDIX B.3

Means of ammonia (mg/l), nitrite (mg/l), and nitrate (mg/l) by treatment and block - experiment II.

Treatment	Block	Ammonia	SE	Nitrite	SE	Nitrate	SE
Raw Data							
1	1	0.57		0.05		50.49	
1	2	0.69		0.53		5.45	
1	3						
2	1	0.90		0.20		71.54	
2	2	0.80		0.29		46.57	
2	3	0.80		0.06		13.71	
3	1	1.07		0.23		78.54	
3	2						
3	3	1.05		0.23		79.35	
Means							
1		0.58	0.022	0.05	0.051	22.48	1.57
2		0.83	0.021	0.18	0.049	43.93	1.51
3		1.03	0.022	0.30	0.051	78.48	1.57
	1	0.84	0.021	0.16	0.049	66.86	1.51
	2	0.82	0.022	0.20	0.051	43.19	1.57
	3	0.78	0.022	0.18	0.051	34.86	1.57

APPENDIX B.4

Means of pH, alkalinity (mg/l), and hardness (mg/l) by treatment and block - experiment II.

Treatment	Block	pH	SE	Alkalinity	SE	Hardness	SE
Raw Data							
1	1	7.9		73.9		395.4	
1	2	8.2		176.5		255.8	
1	3						
2	1	7.8		79.6		496.6	
2	2	7.9		107.6		402.1	
2	3	8.1		183.4		302.8	
3	1	7.5		53.8		482.5	
3	2						
3	3	7.4		60.5		444.7	
Means							
1		8.1	0.038	126.5	2.25	303.2	5.55
2		7.9	0.036	123.5	2.19	400.5	5.40
3		7.5	0.038	68.7	2.27	462.4	5.55
	1	7.7	0.036	69.1	2.19	458.5	5.40
	2	7.9	0.038	115.3	2.25	372.7	5.55
	3	7.9	0.038	124.3	2.27	335.0	5.55

APPENDIX B.5

Means of calcium (mg/l), phosphorus (mg/l), and potassium (mg/l) by treatment and block - experiment II.

Treatment	Block	Calcium	SE	Phosphorus	SE	Potassium	SE
Raw Data							
1	1	225.8		0.64		1.18	
1	2	117.4		2.95		11.94	
1	3						
2	1	268.3		2.67		8.17	
2	2	198.6		3.03		17.11	
2	3	135.9		3.66		15.76	
3	1	253.9		5.31		10.44	
3	2						
3	3	239.5		3.92		14.49	
Means							
1		161.0	3.69	1.53	0.213	10.70	1.55
2		200.9	3.59	3.12	0.203	13.69	1.49
3		250.5	3.69	3.95	0.213	11.89	1.55
	1	249.3	3.59	2.87	0.203	6.60	1.49
	2	191.3	3.69	2.87	0.213	13.26	1.55
	3	171.7	3.69	2.86	0.213	16.41	1.55

APPENDIX B.6

Means of boron (mg/l), molylbdenum (mg/l), and iron (mg/l) by treatment and block - experiment II.

Treatment	Block	Boron	SE	Molybdenum	SE	Iron	SE
Raw Data							
1	1	0.11		0.03		0.04	
1	2	0.10		0.00		0.07	
1	3						
2	1	0.12		0.00		0.06	
2	2	0.12		0.00		0.06	
2	3	0.16		0.00		0.03	
3	1	0.08		0.07		0.04	
3	2						
3	3	0.09		0.00		0.03	
Means							
1		0.09	0.042	0. 24	0.022	0.06	0.007
2		0.13	0.039	0.000	0.022	0.04	0.006
3		0.09	0.042	0.048	0.022	0.04	0.006
	1	0.10	0.039	0.033	0.022	0.05	0.006
	2	0.11	0.042	0.038	0.022	0.05	0.007
	3	0.11	0.042	0.000	0.022	0.05	0.007

APPENDIX B.7

Means of Zinc (mg/l), manganese and copper (mg/l) by treatment and block - experiment II.

Treatment	Block	Zinc	SE	Manganese	SE	Copper	SE
Raw data							
1	1	0.17		0.13		0.18	
1	2	0.19		0.06		0.07	
1	3						
2	1	0.16		0.09		0.07	
2	2	0.23		0.10		0.07	
2	3	0.10		0.15		0.04	
3	1	0.11		0.13		0.05	
3	2						
3	3	0.20		0.08		0.07	
Means							
1		0.19	0.054	0.09	0.025	0.12	0.028
2		0.16	0.048	0.11	0.022	0.06	0.025
3		0.13	0.050	0.09	0.023	0.06	0.026
	1	0.15	0.050	0.11	0.022	0.10	0.025
	2	0.16	0.051	0.08	0.023	0.07	0.027
	3	0.17	0.051	0.10	0.024	0.07	0.027

APPENDIX C

NUTRIENT SOLUTION FORMULA FOR PEPPERS GROWN IN ROCKWOOL

APPENDIX C.1

Nutrient Solution formula for peppers grown in rockwool.

Nitrate-N	172 ppm
Phosphate (P)	39 ppm
Sulfate-S	40 ppm
Ammonium-N	nil
Potassium (K)	324 ppm
Calcium (Ca)	150 ppm
Magnesium (Mg)	30 ppm
Iron (Fe)	0.56 ppm
Copper (Cu)	0.03 ppm
Zinc (Zn)	0.25 ppm
Manganese (Mn)	0.55 ppm
Boron (B)	0.38 ppm
Molybdenum (Mo)	0.05 ppm
pH	5.8
Bicarbonate (HCO_3)	50 ppm

Note: 1ppm = 1mg/l

Smith, D. 1979.

VITA

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