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Efficiency of Water Use of an Integrated Fish/Vegetable Co-Culture System

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Abstract.—Fish and vegetable production were linked in a recirculating water system designed to achieve a high degree of efficiency of water use for food production in addition to functional and technological simplicity. Hybrid tilapia *Oreochromis mossambicus* × *O. niloticus* L. were grown in tanks associated with biofilters (sand beds) in which tomatoes *Lycopersicon esculentum* were grown. The effect of four biofilter volume (BFV)/fish rearing tank volume ratios (0.67/1, 1.00/1, 1.50/1, 2.25/1) on water use efficiency was evaluated. 'Laura' (first experiment) or 'Kewalo' tomatoes were grown 4/m^2 in biofilters of four different sizes and surface-irrigated 8 times daily with water from the associated fish tanks. Daily water consumption increased with BFV/tank ratios and with time. Fish production rates increased with biofilter volume in the first experiment, but were not significantly different in the second experiment. Total tomato fruit yield per plot increased from 13.7 to 31.7 kg (Experiment 1) and from 19.9 to 33.1 kg (Experiment 2) with increasing BFV/tank ratio. For fish plus fruit, total energy production increased from 4,950 to 8,963 kcal/plot and from 4,804 to 7,424 kcal/plot in Experiments 1 and 2, respectively, and protein production increased from 536 to 794 and from 352 to 483 g/plot in Experiments 1 and 2, respectively, with increasing BFV/tank ratio. Trends in water use efficiency for production of food energy (kcal/L) and of protein (g/L) in tomatoes and fish were complex. Water use efficiency for total energy production (fish plus fruit) did not significantly differ with biofilter volume. Economy of water use for total protein production (fish plus fruit) decreased significantly with increasing BFV/tank ratio. The component ratios of the system may be manipulated to favor fish or vegetable production according to local market trends or dietary needs, and thus may have economic potential in areas of limited water supply and high demand for quality food.

Developing nations, many of which are in arid and semiarid climates, will be most affected by the sharp increase in population facing us today (International Arid Lands Consortium 1996). These regions are suffering from desertification and famine, and research is needed on ways to make them more habitable and productive. Of particular value are techniques for increasing the efficiency of water use for the production of high quality food.

The aquaculture industry largely has developed without regard to the increasing scarcity of water. Traditional intensive (high production per unit area) aquaculture systems require more water than less intensive pond systems, being dependent on high volumes of fresh water flowing through fish-

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rearing tanks to supply dissolved oxygen and remove deleterious metabolites. Both have very high water demand compared with other competing industries, arguing strongly for the integration of aquaculture with other industries or with agriculture (Phillips et al. 1991).

Integration of aquaculture with agriculture can reduce the water requirement for the production of quality protein and fresh vegetable products relative to both culture systems operated independently. Innovative fish/vegetable co-culture systems use the nutrient by-products of fish culture as direct inputs for vegetable production, constantly recycling the same water. While pond or cage aquaculture in arid environments is limited by the constraints of water supply and soil type, recirculating systems are unaffected by soil type, use less than 1% of the water required by pond culture for the same yields and are efficient in terms of land utilization (Rakocy 1989) like the high-volume, flow-through systems.

Water from fish rearing tanks in recirculating systems is usually treated for removal of solids and BOD (biochemical oxygen demand) and passed through a biofilter for oxidation of reduced nitrogen compounds before being returned to the fish tank. High levels of phosphates and nitrates have been controlled by exchange of large amounts of effluent water for fresh water and further purification by microbial denitrification. The potential for recovery of nitrate and phosphate was introduced with the incorporation of hydroponic plant culture (Naegel 1977). Although nutrient recovery by plants reduced the need for high rates of water exchange and produced a second crop (Lewis et al. 1978; Watten and Busch 1984; Rakocy and Hargreaves 1993), if the ratio of plants to fish is low the nutrient recovery will be inefficient (Rakocy et al. 1993).

Previous integrated fish/vegetable systems have also removed suspended solids from water by sedimentation prior to plant application. Acceptable fruit yields in such systems have been achieved with substantial supplementation of plant nutrients (Lewis et al. 1978, 1981; Rakocy 1989). The introduction of the reciprocating biofilter, in which filter beds are alternately flooded and drained, has reduced problems of clogging, channelization and low oxygen (Lewis et al. 1978; Paller and Lewis 1982), opening the possibility of retaining the solids as nutrient resource for plant growth (McMurtry et al. 1997).

The purpose of this work was to design and test a recirculating fish/vegetable co-culture system with high efficiency of water use in production of quality food as well as high functional and technological simplicity. The main features were a greatly increased hydroponic plant culture/biofilter capacity relative to the fish rearing capacity compared with previous systems (Rakocy and Hargreaves 1993); also, the fish effluent, including solids, was pumped directly onto sand beds. The sand beds served as: 1) biofilters operating in the reciprocating mode; 2) hydroponic plant growth substrate; and 3) the locus for oxidation of organic solids. We have examined the water quality and general dynamics of the system as a function of the ratio of plant growth/biofilter capacity to fish rearing capacity (McMurtry et al. 1997). In this paper we consider the effects of these four ratios of biofilter volume (BFV) to fish rearing tank volume (0.67/1, 1.00/1, 1.50/1 and 2.25/1) on the efficiency of water use in production of protein and food calories, and on the economic productivity of the system.

Materials and Methods

System. Experiments were conducted in a greenhouse in Raleigh, North Carolina, USA. All-male (sex-reversed) hybrid tilapia *Oreochromis mossambicus* × *O. niloticus* were cultured. One system was comprised of a rearing tank coupled to a biofilter (Fig. 1). The rectangular fish tanks were formed with plywood, the bottom sloped to 45° and lined with 0.50-mm (2 @ 10 mil) black polyethylene. Biofilters were 1.2-m wide × 0.33-m deep and 0.86-, 1.25-, 1.90- or 2.90-

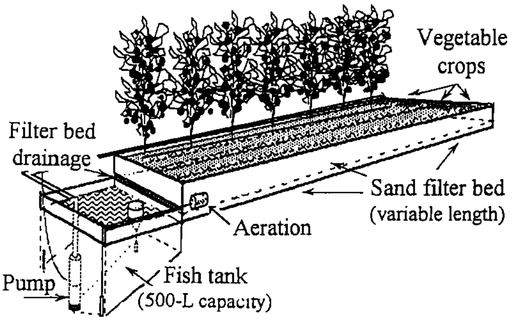

FIGURE 1. *Schematic diagram of the integrated fish/vegetable co-culture system.*

m long to achieve 4 ratios (0.67:1, 1.00:1, 1.50:1, 2.25:1) by volume (v/v) to the fish tanks (Table 1). Four blocks were arranged down the length of the 6 × 14-m greenhouse with the four ratio treatment systems randomly arranged within each block. Aeration in the tanks was provided by regenerative blowers at 0.7 L/sec through two (3.8 × 3.8 × 15 cm) airstones per tank. Water temperatures were maintained above 25 C by two 250-W thermostatic aquarium heaters (Visitherm, Mentor, Ohio, USA) per tank. Biofilters were lined with 0.45-mm (three @ 6 mil) polyethylene plastic and the bottom sloped 1/200 along the length to direct drainage for return to the associated tank. Builder's grade sand was employed as substrate. Sand composition, which was critical to avoiding clogging, was 99.25% quartz sand, 0.75% clay, 0.0% silt. The sand fractionation was: very fine sand (0.10–0.05 mm), 2.2%; fine sand (0.25–0.10 mm), 5.2%; medium sand (0.50–0.25 mm), 21.0%; coarse sand (1.00–0.50 mm), 38.8%; and very coarse sand or fine gravel (2.00–1.00 mm), 33.3% (USDA particle size system; Brady 1990).

The fish were fed a diet of modified Purina Fish Chow 5140, with a minimum analysis of 32% crude protein, 3.5% crude fat, and not more than 7.0% crude fiber. The vitamin/trace element package was not added to the feed to avoid buildup of trace elements to levels toxic for the plants. Adjustment of fish biomass to uniform levels (± 2.5%) among replicates and treatments was performed monthly so that all nutrient inputs were constant across treatments. The adjustments among tanks were made with fish from this study (no new fish were introduced). The daily ration was divided equally into two feedings administered at 0800 and 1300 h. Feed was consumed within 15 min of application. The fish also grazed algae *Oscillatoria* spp. and *Ulothrix* spp. which grew in the water and on the tank sides.

Irrigation water was drawn from the bottom of the fish tanks at evenly spaced intervals 8 times daily between dawn and sunset and applied to the biofilter surface at 500 L/m^2 per d. Each square meter of sand bed received equal irrigation volume and frequency. Evapotranspiration losses were replaced with city water when tank volumes were 75% of capacity, about once weekly. Deep sampling of the sand substrate resulted in the development of leaks in the plastic liners which became obvious as replacement water volume increased over time.

Fish standing biomass was determined after removal of all fish from each tank. Fish were sedated with 20-ppm Quinaldine (Aquacenter, Leland, Mississippi, USA), blotted dry, and weighed individually. Fish biomass increase was calculated by subtraction.

Before fish stocking, the sand beds were fumigated with methyl bromide-chloropicrin (98-2) at the rate of 250 kg/ha. Each

TABLE 1. *Physical parameters of the biofilters.*[a]

BFV/ tank vol. ratio	Biofilter plot area (m^2)	Plants per plot	Biofilter volume (m^3)	Water moved per d[b] (L)	Tank exchanges per d[c]
0.67/1	1.00	4	0.33	500	1.00
1.00/1	1.50	6	0.50	750	1.50
1.50/1	2.25	9	0.75	1,125	2.25
2.25/1	3.40	14	1.14	1,700	3.40

[a] Tank volume = 0.5 m^3 (or 500 L). Biofilters are 0.33 m deep.

[b] Water moved/d = (500 L/m^2)·(m^2/plot).

[c] Tank exchanges/d = (L water moved/d)/500.

biofilter was inoculated with 1.0 L of Fritzzyme #7 (a suspension of *Nitrosomonas* spp. and *Nitrobacter* spp.; Aquacenter, Leland, Mississippi), and irrigated with aquaculture effluents for 9 d prior to planting.

Insect pests were controlled principally through the use of beneficial insects including *Encarsia formosa* and Lacewings *Chrysopa carnea* for greenhouse whitefly *Trialeurodes vaporariorum*, and Ladybugs *Hippodamia convergens* for potato aphid *Macrosiphum euphorbiae*. All were used in accordance with product directions. Insecticidal Soap (Safer Inc., Newton, Massachusetts, USA) was applied as necessary to control sweetpotato whitefly *Bemisia tabaci* populations below threshold levels. An inground subsonic alarm was effective against shrews *Balarina* spp.

Protocol. For Experiment. 1, fish were stocked on 5 May 1988 at a uniform stocking density of (mean ± s.e.m.) 77 ± 4/m^3, with 1.14 ± 0.07 kg/m^3 density and 14.8 ± 0.67 g mean individual weight. The initial daily feeding rate was 4.3% of the initial biomass. Feed was adjusted upward based on feeding response. At the end of Experiment 1, daily feeding rate was 2.2% of final biomass, or 0.35 kg/m^3. Tomato *Lycopersicon esculentum* 'Laura' seedlings were transplanted into each biofilter at 4/m^2 resulting in 4, 6, 9 or 14 plants per biofilter. This indeterminate greenhouse variety was grown as a single stem. Because of excessive heat (>40 C) and some bacterial wilt, fruit set occurred only on the first 4 trusses. These fruit were harvested at the incipient color stage and weighed and graded according to U.S. grade standards (McMurtry et al. 1993). The experiment was terminated at 95 d after planting the tomatoes, 103 d after stocking the fish.

For Experiment 2, fish were restocked on December 22 at a uniform density (mean ± s.e.m.) of 20.1 ± 0.6/m^3, with 8.7 ± 0.1 kg/m^3 biomass and 434 ± 10 g mean individual weight. Initial daily feed was 1.8% of initial biomass and final feeding rate was 0.6% of final biomass, or 0.083 kg/m^3. The semi-determinate, bacterial wilt-resistant tomato 'Kewalo' was planted 23 December, and grown as a single stem at the same density as Experiment 1. Fruit were harvested, weighed and graded as for Experiment 1. Fish were harvested and the experiment was terminated 132 d from stocking, on 2 May 1989.

TABLE 2. *Influence of BFV/tank volume ratio on fresh weight, energy and protein production in a fish/vegetable co-culture system.*

	Total production			
BFV/tank vol. ratio	Fish (kg fresh wt/plot)	Fruit	Energy[a] (kcal/plot)	Protein[b] (g/plot)
	Experiment 1, 'Laura' tomato			
0.67/1	6.67	13.7	4,950	536
1.00/1	7.87	17.0	6,013	641
1.50/1	7.29	21.0	6,608	646
2.25/1	8.01	31.6	8,963	794
$\text{LSD}_{(0.05)}$	1.18	4.2	1,232	113
	Experiment 2, 'Kewalo' tomato			
0.67/1	2.580	19.9	4,804	352
1.00/1	2.785	22.1	5,307	386
1.50/1	2.675	27.3	6,308	431
2.25/1	2.580	33.1	7,424	483
$\text{LSD}_{(0.05)}$	NS	8.4	1,674	90

[a,b] Sum of fish and fruit.

Food value was considered as protein content or food energy (g or kcal, respectively; Table 2). Efficiency of water use in food production was expressed as fish, fruit, energy or protein production per L of water used (Table 3). Each experiment was conducted as a randomized complete block design with four independent replicate systems per BFV/rearing tank ratio treatment. Analyses of variance for variables in Tables 2–4 were made with Statview 512+ software (Abacus Concepts, Berkeley, California, USA). F-tests were performed, and where $P \leq 0.05$, least significant differences (LSDs) were included in the tables.

Assumptions for nutritional and economic analyses. Edible fish biomass production was assumed to be 33% of the increase in live weight (Losordo, personal communication). Caloric content of the edible fish

TABLE 3. *Influence of BFV/tank volume ratio on efficiency of water use in the production of fish and tomato fresh weight, energy and protein in a recirculating fish/vegetable co-culture system.*

BFV/tank vol.ratio	Efficiency of water use							
	Yield (g fresh wt/L)		Energy (kcal/L)			Protein (g/L)		
	Fish	Fruit	Fish	Fruit	Total	Fish	Fruit	Total
Experiment 1, 'Laura' tomato								
0.67/1	8.2	16.4	2.76	3.27	6.03	0.49	0.16	0.65
1.00/1	7.4	16.1	2.48	3.19	5.68	0.44	0.16	0.60
1.50/1	6.0	17.9	2.02	3.54	5.56	0.36	0.18	0.54
2.25/1	4.8	19.5	1.61	3.86	5.47	0.29	0.19	0.48
$LSD_{(0.05)}$	1.5	3.2	0.50	0.63	NS	0.09	0.03	0.09
Experiment 2, 'Kewalo' tomato								
0.67/1	1.45	11.8	0.49	2.33	2.82	0.09	0.12	0.20
1.00/1	1.39	12.0	0.47	2.39	2.86	0.08	0.12	0.20
1.50/1	1.18	12.6	0.40	2.49	2.89	0.07	0.12	0.20
2.25/1	0.91	10.8	0.31	2.14	2.45	0.05	0.11	0.16
$LSD_{(0.05)}$	0.30	NS	0.04	NS	NS	0.01	NS	0.03

biomass was assumed to be 1.02 kcal/g, and the protein fraction 18.2% of the edible portion (USDA 1975). The edible portion of tomato fruit was assumed to be 100% of the Grade No. 1 and Grade No. 2 yields. Caloric content of tomato fruit was assumed to be 0.22 kcal/g and the protein fraction 1.1% of the edible yield (Lorenz and Maynard 1980).

TABLE 4. *Parameters of water use in the production of fish and vegetables as influenced by BFV/tank volume ratio.*

BFV/tank vol. ratio	Liters of replacement water		Tank exchanges per crop[b]	Total crop applications per L used[c]
	per crop interval[a]	per d		
Experiment 1, 'Laura' tomato (103 d)				
0.67/1	832	8.1	103	124
1.00/1	1,058	10.3	155	146
1.50/1	1,222	11.9	232	190
2.25/1	1,619	15.7	350	215
$LSD_{(0.05)}$	52	0.5	—	7
Experiment 2, 'Kewalo' tomato (132 d)				
0.67/1	1,682	12.7	132	79
1.00/1	1,833	13.9	198	108
1.50/1	2,174	16.5	297	137
2.25/1	3,062	23.2	449	146
$LSD_{(0.05)}$	59	0.5	—	3

[a] Replacement water/crop = sum of weekly replacements for evapotranspiration and leakage losses.

[b] Tank exchanges/crop = d/crop·tank exchanges/d (from Table 1).

[c] Total crop applications/L used = [(L water moved/d)·2 crops·(d/crop interval)]/L replacement water.

Yearly gross income from tilapia and tomatoes was estimated. The growth interval for the tilapia was estimated from linear regressions of mean individual increases in fish weight from 14 g to 442 g. Economic yields were based on an assumed market value ranging from \$2–3.30/kg, average \$2.64/kg whole fish (local market estimates, Raleigh, North Carolina, USA). Projected yearly yield of 'Kewalo' tomato in each treatment ratio was estimated for 3 crops grown per year. Fruit quality grade distribution was assumed to be 60% Grade No. 1, 30% Grade No. 2 and 10% defective as was found in Experiment 2. Market values of grades 1 and 2 were \$2.20 and \$1.32/kg, respectively (Sanders, unpublished observation). Disposal costs of defective fruit was estimated at \$0.05/kg.

Results and Discussion

Water use. The quantity of replacement water per system per crop interval for evapotranspiration and leakage increased with increasing BFV/tank ratio in both experiments (Table 4). Daily replacement also increased with BFV/tank ratio and ranged from 1.2% to 4.7% of system capacity. Water replacement in the largest BFV/tank ratio treatment was approximately double that of the smallest, though the surface area and number of plants per plot more than tripled (Table 1). Leakage losses were greater in Experiment 2 than in Experiment 1, and in the 2.25/1 treatment ratio were disproportionately large. The number of complete tank volume exchanges of recycled water also increased with increasing BFV/tank ratio in both experiments (Table 4). Likewise, total crop applications per L of water used significantly increased with increasing BFV/tank ratio. These are both measures of how often each unit volume of water was used in the production of the crops.

Daily water exchange of the system was low, ranging from 1.2% to 4.7% of system capacity (Table 4), or, in Experiment 1, 125-202 L/kg fish produced. Rakocy (1989) reports a water consumption figure of 87 L/kg fish produced. The main factors contributing to this difference are: 1) that the ratio of vegetable culture area (potential evapotranspiration) to rearing tank volume in the system considered here is 3–10 times higher than that used by Rakocy; and 2) the stocking density was much lower. The higher daily water replacement in Experiment 2 (winter) compared with Experiment 1 (summer; Table 4) occurred in spite of this seasonal difference and is attributed to leakage. The biofilter liners would probably be sufficient for normal operating procedures but did not hold up to the rigors of experimental sampling of the sand medium.

Production. In Experiment 1, fish production increased as BFV/tank ratio increased. Production in the largest BFV/tank ratio treatment was improved by about 20% compared with the smallest ratio treatment (Table 2). Production of tomato fruit also increased with BFV/tank ratio. However, yield per biofilter of 'Laura' tomatoes was not proportional to the number of plants. There were 3.5 times as many plants in the largest biofilters compared with the smallest ones, yet yield was only 2.5 times greater. Therefore yield per unit area decreased. Both total energy and total protein production per plot increased with BFV/tank ratio.

In Experiment 2, fish production was unrelated to BFV/tank ratio treatment (Table 2). Tomato yield per plot increased about 1.5 times between the smallest and the largest BFV/tank ratios (Table 2). As for Experiment 1, however, production decreased with increasing BFV/tank ratio if calculated on an area basis. Dominated by the contribution of the tomatoes, the energy and protein production per plot increased significantly with increasing biofilter size.

In Experiment 1 an average of 15 kg/m^3 of fish were produced in 103 d, or 146 g/m^3 per d (calculated from Table 2). Individual fish growth rate was consistently about 1.9 g/d, with no elaborate filtration device. This compares with 3 g/d obtained in the system used by Rakocy (1989), 2.5 g/d (Watten and Busch 1984) and 1.6 g/d (Nair et al. 1985). In Experiment 2, individual fish growth rate was about 1.95 and production was 39 g/m^3 per d. The reason for this lower rate is unknown, though it could be related to the small size of the fish rearing tanks relative to the fish themselves. It was certainly lower than expected since all water quality measurements were good (McMurtry et al. 1997).

Although productivity for the cultivar 'Laura' is potentially higher than that of 'Kewalo', there were low, unrepresentative yields for 'Laura' in Experiment 1. A bacterial wilt in the sand and excessive summer heat caused abortion of flowers and fruit above the 4th truss. 'Kewalo' tomato yields were 5.0, 3.7, 3.0 and 2.4 kg/plant, and 13.7, 11.3, 9.7 and 9.3 kg/m^2, as BFV/tank ratio increased from 0.67/1 to 2.5/1. These data are consistent with increasing nutrient limitation with increasing BFV/tank volume ratio. They fall within a range of tomato yields obtained in a number of other temperate zone greenhouse or outside recirculating fish culture systems (Rakocy and Hargreaves 1993). Crop plants grow well on low concentrations of nutrients if these nutrients are constantly replenished in the root zone (Winsor et al. 1985). Replenishment of nutrients as well as oxygen in the root zone resulted from the alternating flooding and draining of the sand beds (McMurtry et al. 1997).

Water use efficiency. For Experiment 1, fish production per L of water used (i.e., replacement water) decreased significantly as BFV/tank ratio increased (Table 3). However, fruit yield per L of water used increased. Expressed in terms of food energy (kcal/L), production from fish likewise decreased and that of tomato fruit tended to increase with increasing BFV/tank ratio. The trends were thus reciprocal and since they contributed about equally to the total, there was no significant response of total energy production efficiency to biofilter/tank ratio. For protein, however, the greater magnitude of the fish component caused the total protein production per L of water to decrease as BFV/tank ratio increased.

In Experiment 2, as in Experiment 1, fish production per L of water used decreased as BFV/tank ratio increased. This decrease was accentuated by the disproportionate leakage in the 2.25/1 ratio treatment tanks (Table 4). A trend towards increasing efficiency of water use for fruit production with increasing BFV/tank ratio for 'Kewalo' tomatoes similar to that of 'Laura' in Experiment 1 was weakened by this same leakage. Thus, the decreases in the efficiency of water use for production of fish and fish energy and protein were statistically significant, whereas there was no significant response for tomato fruit, energy, or protein.

Food production in Experiment 1, before development of the leaks, averaged 24.1 g/L and did not vary with BFV/tank ratio (combining fish and fruit yields, Table 3). Sanders et al. (1989) reports a water use efficiency for tomato production of 23.9 g/L using advanced traveling trickle irrigation systems in the San Joaquin Valley of California. Both of these represent an enormous advance over, for instance, the average water use efficiency reported for tomato production in Egypt (Strategies for Accelerating Agricultural Development 1982) of 1.19 g/L, and the food produced is of much higher protein content.

TABLE 5. *Influence of BFV/tank volume ratio on projected annual yields and economic returns*[a] *for tilapia and 'Kewalo' tomatoes, raised in a recirculating fish/vegetable co-culture system.*

	Projected annual yield		Projected gross annual returns	
BFV/tank vol. ratio	Tilapia (kg/m^3)	Tomatoes (kg/m^2)	Tilapia (US\$/m^3)	Tomatoes (US\$/m^2)
0.67/1	41.5	59.6	109.56	102.04
1.00/1	47.6	44.1	125.66	75.49
1.50/1	49.3	36.4	130.15	62.37
2.25/1	54.0	29.2	142.56	49.98

[a] See Materials and Methods for quality distribution and market value assumptions.

This value of water use efficiency, 24.1 g/L, expressed as the water requirement for food production, corresponds to 41.5 m^3/mt. Even calculated on the basis of the fish alone, this is 1–3 orders of magnitude more efficient than all of the aquaculture production systems around the world tabulated by Phillips et al. (1991) except for the farming of air breathing walking catfish *Clarias batrachus* in Thailand. This fish has low water requirements because it can tolerate poor water quality in anaerobic culture conditions.

Projected returns. Projected annualized yield for the tilapia increased with increasing BFV/tank ratio (Table 5). Corresponding gross returns were estimated to range from \$110 to \$143/m^3 per yr. Projected tomato yields per m^2, based on the performance of 'Kewalo', decreased with BFV/tank ratio treatment. Projected annual gross returns on the tomatoes ranged from \$50 to \$102/m^2.

The projected economic returns analysis was based on these experimental results and current, local North Carolina (USA) market values for tilapia and greenhouse tomatoes (Table 5). It shows that gross returns from this co-culture system, conservatively evaluated and still experimental, are on a par with traditional commercial greenhouse tomato production. Mickey et al. (1989) estimate such returns in North Carolina to fall in a range from \$77 to \$157 with an average of \$114/m^2 annually (3 crops).

Conclusions

The first goal of this work was to implement a recirculating fish/vegetable co-culture system which would operate with high efficiency of water use and with low chemical, technological and labor inputs. The expanded ratios of plant growth capacity to fish rearing capacity relative to other systems (Rakocy and Hargreaves 1993) permitted recovery of nutrients in the fish waste by the vegetable crop. This resulted in suitable water quality (McMurtry et al. 1997) and good fish production without the exchange of large quantities of water or complex biofiltration devices. The solid waste was held in the sand beds and good crop growth was achieved without supplemental fertilizer.

Our second goal was to investigate how different component ratios of the system affect fish vs. vegetable productivity. In terms of water use, vegetable production was more efficient with larger plant populations. Both fruit production per L (Table 3) and crop applications per L of water used (Table 4) were greatest at the largest biofilter size. In addition, larger biofilters provided better filtration, resulting in better fish production in the first experiment, while the fish were still growing rapidly (Table 2). However, fish production per L of water was higher at low BFV (Table 3). The upper limit of fish production was not clearly established by the range of BFV/tank ratios used here. If efficient protein production per unit volume of water is high priority, then a relatively smaller BFV, larger rearing tank, or increased stocking density might be in order. The "optimum" ratio of biofilter to fish rearing capacity would depend on regional conditions and goals.

The aspect of this system which is novel is the high ratio of biofilter/plant production capacity to fish rearing capacity, compared with previous systems. This factor is largely responsible for its efficiency of water use in food production. The absence of high tech biofilters and use of the sand beds to perform several operations (plant support, biofilter, particulate removal and nutrient transfer to plants) account for its functional simplicity. Future work indicated by these results is to optimize production of the fish or vegetables while maintaining this functional balance.

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