INTRODUCTION

There are many areas in the tropics that do not have the right combination of resources (i.e., water supplies, soil type or topography) to culture tilapia by standard dug-pond techniques. The Lesser Antilles, a group of Eastern Caribbean Islands, is one such area. The relatively dry Leeward Islands have insufficient water for pond culture and their porous caliche soils do not retain water. The rugged Windward Islands generally lack suitable level terrain for a large expanse of dug ponds.

There is a need for cultured fish in the Lesser Antilles to offset declines in the fisheries sector (de Graaf and Moore 1987). To supply seafood to local and tourist markets, the Caribbean Community and Common Market (Antigua and Barbuda, Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Jamaica, Montserrat, St. Lucia, St. Kitts and Nevis, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago) imported US$84 million worth of fisheries products in 1996 (FAO 1998). Tilapia is the ideal culture fish to increase local supplies in the Lesser Antilles because it can be cultured at high densities in systems that are feasible with limited resources. Although West Indians traditionally consume only marine finfish, they will accept tilapia as a substitute. Moreover, there is large tourist market for tilapia because resort restaurants cannot depend on consistent supplies of marine finfish.

The University of the Virgin Islands (UVI) has developed three tilapia culture systems that are appropriate for the Lesser Antilles and other resource-limited, tropical areas. The systems are cage culture in small watershed ponds, greenwater tank culture and aquaponics, the combined culture of fish and hydroponic plants in recirculating systems. Research on the commercial development of the latter two systems is ongoing. Therefore, this paper will be a summary of the cage culture work and a progress report on the development of greenwater tank culture and aquaponic systems.

Cage Culture in Small Watershed Ponds

The Leeward Islands have no running water except for a few days after major rainstorm events, which occur about once a year. Many small watershed ponds have been constructed to
store runoff water for agricultural use and groundwater recharge. New ponds often have high seepage rates and dry quickly. Eroded clay and organic matter eventually seal the ponds, some of which hold sufficient water year round for cage culture while others retain water long enough for one cage crop.

Since the ponds range in size from 0.1 to 2 ha, small cages are required. All of the cage culture studies at UVI utilized 1-m$^3$ cylindrical cages constructed of semi-rigid plastic screen (1.9-cm mesh) tied onto steel hoops. This mesh size facilitated maximum water exchange between the cage and the pond. The cages were 1.22 m high and 1.06 m in diameter and floated with approximately 10 cm of freeboard. A feeding ring was suspended from the cage top to a depth of 51 cm (Figure 1).

![Figure 1.](image-url) Small cage (1 m$^3$) for tilapia culture showing demand feeder and feeding ring.

Cages were deployed in the deepest section of the pond in an area with the greatest exposure to wind and currents. Cages were individually anchored at least 2 m apart. Since smaller ponds could support only four to six cages, the twice-daily feeding became too time consuming for farmers with diversified operations. The farmer would have to deploy a small boat and row to the cage to administer floating feed. Following a fixed-rate feeding schedule was not practical for small operations and the fish were often overfed or underfed. Therefore, an inexpensive demand feeder was developed and tested (Hargreaves et al. 1988). The demand feeder consisted of an 18.9-L plastic bucket into which a polyethylene funnel was inserted (Figure 2). The feeder was mounted on the cage top and could be activated by a brass rod suspended from the funnel into the cage. When demand feeders were compared to a fixed-rate feeding schedule, there was no significant difference ($P > 0.1$) in growth rate, and in two out of three experiments marketable production was significantly higher and the feed conversion ratio (FCR) was significantly lower ($P < 0.1$) with demand feeders as compared to a fixed-rate feeding schedule. The most important finding was that demand feeders reduced labour by 88 to 94%. The demand feeders were filled on average every 4.3 days to 7 days in the three experiments. Reduction in labour made small operations feasible.
An experiment was conducted in a 2-ha pond to evaluate five species/strains of tilapia stocked at 300 fish/cage (1 m³) and fed with the demand feeders (Rakocy et al. 1993a) (Figure 2). The species/strains were *Oreochromis niloticus* (Ivory Coast strain), *Oreochromis aureus*, a modified Florida red tilapia from Jamaica, an Aurea red tilapia (95% *O. aureus* heritage bred into Florida red tilapia) and Taiwan red tilapia. Using sex-reversed male fingerlings, the fish were allowed to feed on nutritionally-complete floating pellets (36% protein) for 143 days. The best-performing species/strain was *O. niloticus*. It grew from 73 g to 616 g, a daily weight gain of 3.8 g/day. Final cage biomass, FCR, and survival were 182 kg, 1.30 and 97.7%, respectively. Among the red tilapia the modified Florida red and the Aurea red tilapia performed equally well with daily weight gain of 3.5 and 3.3 g/day, final cage biomass of 163 and 161 kg, FCR of 1.45 and 1.30, and survival of 93.3 and 98.3%, respectively. Since West Indians prefer colourful fish that resemble familiar marine species, the modified red tilapia was selected for future research. The Aurea red tilapia was discontinued due to the difficulty of maintaining this cross.

The next experiment evaluated the effects of four levels of diffused aeration (one air stone per cage activated for 0, 6, 12 or 24 hours/day) in the cages and two stocking densities (400 and 600 fish/1-m³ cage) on the culture performance of red tilapia (Hargreaves et al. 1991). Using demand feeders, a nutritionally-complete floating pellet was fed for 143 to 146 days. Diffused aeration had no significant (P > 0.05) effect on fish growth, survival, feed conversion and production in cages. Combined across all levels of diffused aeration, fish stocked at 400/cage had a significantly greater growth rate (2.21 vs. 1.97 g/day), larger final body weight (370 vs. 335 g) and lower feed conversion ratio (1.69 vs. 1.80) than fish stocked at 600/cage (P < 0.05). The final biomass of fish stocked at the higher density (181 kg/m³) was greater than that at the lower density (140 kg/m³). Increased water exchange rates by diffused aeration did not lead to increased tilapia growth or production.
Enterprise budgets were prepared from the growth and production data of red tilapia stocked in 1-m³ cages at three densities (300, 400 and 600 fish/m³) (Bailey et al. 1989). The previous experiments showed that fish growth rate, final body weight, survival rate and feed conversion efficiency were inversely related to stocking density. Therefore, annual return to risk for a hypothetical cage culture enterprise in a 2-ha watershed pond with production capacity assumed to be 3,000 kg/ha/crop was higher at 300 fish/m³ ($41,506) than at 400 fish/m³ ($35,439) or 600 fish/m³ ($30,745). High growth rates at low density and the use of less male fingerlings improved feed conversion efficiency, reduced cost and allowed the production of more large fish of higher value, thereby increasing revenue. Assumed value of red tilapia was $5.50/kg for fish > 454 g and $4.40/kg for fish <454 g. The breakeven price was $2.71/kg at a density of 300 fish/m³. Given the relatively minimal labour requirements of the production enterprise and the modest investment required ($125 per cage with demand feeder), a farmer can significantly increase farm revenues by adding cage culture to the farm business.

Using different assumptions, a second economic analysis was performed for the production of red tilapia on a staggered schedule in a 2-ha pond and in batches in a 0.4-ha pond that retains water intermittently (6 months per year) (Bailey and Rakocy 1992). All stages of production would occur in the 2-ha pond and would require nine hapas and 49 cages of variable mesh size for breeding, sex reversal, three stages of fingerling rearing and growout. The growth stages would require different feeds. Staggered production would involve considerably more labour than needed in the previous analysis, but it represents a more realistic production system for small islands where markets demand agricultural products on a consistent basis. Harvests of 545 kg would occur biweekly, and annual production would be 14,182 kg. Net cash flow would range from $27,780 in year 2 to a high of $29,852 in year 15 out of a 20-year projection. The net present value at 20% and internal rate of return would be $28,279 and 27%, respectively. In the 0.4-ha pond, annual production would be 1090 kg. The annual net cash flow would be $4,218 over a 5-year period. Net present value at 20% and internal rate of return would be $10,988 and 259%, respectively. With this scenario, the farmer would have to store the cages in a shelter during the dry season and purchase fingerlings when the pond fills. This analysis shows that even a small cage culture facility, operated during high water periods, can supplement a farmer’s income.

Implementation of cage culture in small watershed ponds would increase dramatically if a supply of tilapia fingerlings were available. If island governments choose to promote tilapia aquaculture, they may have to invest in a hatchery for the initial production of tilapia fingerlings, for sale to farmers. As an industry develops, fingerling production should eventually be transferred to the private sector. Jamaica followed this strategy in the development of their tilapia industry, which developed on a much larger scale than envisioned for the Lesser Antilles.

There are some important factors to consider in planning cage culture operations in small ponds. One factor is the production capacity of the ponds. Earthen ponds can generally assimilate the waste generated from a maximum feeding rate of approximately 50 kg/ha/day without the need for emergency aeration. With fish constricted to high densities in cages and more dependent on high dissolved oxygen (DO) levels than open-water fish, the maximum feeding should not exceed 25 kg/ha/day for extended periods to ensure adequate water quality. The pond will be most productive with a staggered production system whereby the feed is consistently administered near the maximum feeding rate.
Another factor to consider is the need for emergency aeration after major rainstorm events. Between major rainstorm events pond levels gradually decline and shoreline vegetation proliferates. Excessive rain and runoff will flush phytoplankton from the pond and submerge shoreline vegetation, which slowly decays and depletes DO by the ninth or tenth day after the storm. This phenomenon was observed repeatedly in St. Croix. An emergency aeration system is necessary for 3 to 4 weeks after ponds refill with runoff water.

A final factor to consider is the susceptibility of caged fish to theft. Cages deployed in isolated ponds often prove to be an irresistible temptation. Ponds should be secured to the greatest extent possible and cages should be situated in a manner that makes theft difficult. In St. Croix, cages were attached to yacht rigging, which cannot be cut with normal wire cutters, and anchored individually in the deepest water with two concrete blocks. Nevertheless, some theft occurred. Whatever makes cages easily accessible to farmers will also benefit thieves.

Greenwater Tank Culture

UVI initiated research on greenwater tank culture of tilapia because production levels are substantially higher than ponds, water seepage problems are avoided and commercial levels can be achieved with relatively limited water resources. Variations of greenwater tank culture are used in Israel (Avnimelech 1998), Louisiana (Lutz 1998) and California (Schroeder and Serfling 1989).

The process whereby metabolic waste products of fish are treated in greenwater tank culture, allowing productivity increase, is alternately referred to as a suspended growth process, an activated suspension process or a bioconversion process. Regardless of name, the principle is the same and involves the oxidation of toxic ammonia and nitrite to relatively non-toxic nitrate ions by nitrifying bacteria attached to suspended organic matter. Additional removal of ammonia occurs through direct uptake by phytoplankton. Organic wastes are incorporated into bacteria or respired as carbon dioxide. The rich microbial populations of greenwater tank systems provide nutrition to tilapia and improve feed conversion efficiency. Most greenwater systems remove settleable solid waste daily while some add a fixed-film nitrification unit to supplement the biofiltration that occurs in the water column. Greenwater tank systems must be aerated to sustain adequate DO levels in tanks with elevated organic loading and correspondingly higher biochemical oxygen demand (BOD).

A major advantage of greenwater tank systems is that water treatment is based primarily on bacteria. In ponds, water treatment is based mainly on phytoplankton. An algal die-off in ponds leads to oxygen depletion, necessitates emergency aeration and disrupts feeding and production. An algal die-off in greenwater tanks has relatively minor impact. Mechanical aeration continues to supply sufficient oxygen and bacteria continue to oxidize toxic waste metabolites. Dead algae settle to the tank bottom and are eliminated through daily sludge removal, thereby reducing BOD and avoiding secondary ammonia production.

Greenwater tank culture research at UVI is conducted in circular fiberglass tanks that are 6 m in diameter and 1.22 m in height. Water volume averages 30 m³. The tanks are continuously aerated by a 1/20-hp vertical lift pump and 13 air stones (7.6 cm x 3.8 cm x 3.8 cm). The rearing tank floor has a 3° degree slope to a central drain. Water is drawn from the rearing tank by an airlift pump into a 1.4-m³ cylindro-conical clarifier with a 45° bottom slope. Each clarifier is stocked with 10-15 male tilapia fingerlings to graze algal growth and facilitate the settling of solids. Two baffles are placed perpendicular to the water flow. The central baffle
extends the height of the cylinder. Flow rate is maintained at 20 L/min so that the entire rearing tank volume passes through the clarifier once every 24 hours. The clarifier residence time is 70 minutes. Concentrated solids (sludge) are removed and volumetrically measured twice daily from each clarifier.

Six experiments were conducted in greenwater tanks. All experiments except one included two treatments with three replications per treatment. In the first experiment, male red tilapia (mean wt. = 46 g) were stocked at 8 and 16 fish/m³ and cultured for 20 weeks using a 32% protein floating feed at 4% body weight initially, a rate that was gradually reduced (Cole et al. 1994). Mean fish growth rates of both treatments were 2.8 g/day. Mean yield, survival and feed conversion were 2.9 kg/m³, 93% and 1.7 at the low density (LD) and 5.9 kg/m³, 95% and 1.6 at the high density (HD). There were no significant differences (P > 0.05) and the production capacity of the system was not reached. The clarifiers were very effective at removing dead algal cells as indicated by substantially higher chlorophyll a concentrations in the sludge than in the water column. Substantial nitrification occurred in the water column as indicated by nitrate levels, which increased from 2.9 to 60.0 mg/L in the LD systems and 2.9 to 121.7 mg/L in the HD systems. The rearing water and sludge, which were used in an experiment to irrigate and fertilize bell peppers, compared favourably with inorganic fertilizers. Levels of total phosphorus at 20 weeks were 12.3 mg/L (LD), 21.5 mg/L (HD) and 90.0 mg/L (sludge).

A second experiment was conducted to determine the effect of a 5% daily water exchange and no water exchange on tilapia production (Cole et al. 1994). Male red tilapia (mean wt. = 94 g) were stocked at 12 fish/m³ and cultured for 24 weeks. Daily water exchange was initiated after week 8. Mean growth rates, yields, survival and feed conversion were 3.5 g/day, 6.8 kg/m³, 97% and 1.8 for water-exchange tanks and 3.4 g/day, 6.5 kg/m³, 95% and 1.9 for tanks without water exchange. Yields were larger than those in the first experiment due to the use of larger fingerlings and a longer culture period. A 5% daily water exchange did not significantly improve (P > 0.05) any of the production parameters. The sludge was used to irrigate bell peppers, which performed better with sludge (total fruit yield of 15.1 mt/ha) than with inorganic fertilizers applied at 100 kg/ha of P and K and 200 kg/ha of N in the irrigation water (10.5 mt/ha). The application of sludge resulted in the addition of 28 kg/ha of inorganic nitrogen, 913 kg/ha of organic nitrogen and 122 kg/ha of total phosphorus.

The stocking rate was increased in the third experiment to 24 fish/m³ (mean wt = 16.5 g) using male red tilapia (Cole et al. 1995). The fish were fed for 24 weeks. Sludge was removed twice daily from one set of tanks (SR). In another set of tanks the clarifier was disconnected and sludge was not removed (NSR). Growth rate, final weight and final biomass were significantly higher (P < 0.05) in the SR tanks (2.4 g/day, 422 g, 9.0 kg/m³) than in the NSR tanks (2.1 g/day, 364 g, 7.6 kg/m³). There were no significant differences in survival, feed conversion, DO, total ammonia-nitrogen (TAN) or nitrite-nitrogen. The final concentration of total suspended solids was significantly higher in the NSR tanks (1,250 mg/L) compared to the SR tanks (368 mg/L). Although mean chlorophyll a levels were significantly higher in the NSR tanks (1029 µg/L) than in the SR tanks (655 µg/L), phytoplankton appeared healthier in the SR treatment as dead or clumped algal masses were quickly removed. Two crops of pak choi were raised using rearing tank water, sludge and standard fertilization treatments. The culture water and sludge were comparable or better than standard fertilization techniques.
The third experiment was repeated using male *Oreochromis niloticus* (mean wt. = 71 g), stocked at 26 fish/m$^3$ and fed for 24 weeks (Cole et al. 1997). The treatments were solids removal (SR) twice daily and no solids removal (NSR). Growth rate, final weight, final biomass and feed conversion ratio were significantly better (P < 0.05) in the SR tanks (2.6 g/day, 514 g, 13.4 kg/m$^3$, 1.4) than in the NSR tanks (2.1 g/day, 417 g, 10.8 kg/m$^3$, 1.5). Solids removal did not affect survival (overall mean = 99.1%). Nile tilapia performed better in the system than the red tilapia in previous experiments. Solids removal did not significantly affect DO, temperature, TAN or nitrite-nitrogen. Combined treatment means were 6.5 mg/L, 25.7°C, 0.82 mg/L, and 2.99 mg/L. Nitrite-nitrogen removal is less efficient with a suspended growth process than TAN removal. However, any harmful effects of nitrite-nitrogen were mitigated by high levels of chloride ions (108 mg/L) in the groundwater source. If the source water has low chloride concentrations, a preventive treatment with calcium chloride is recommended. The amount of water required to produce 1 kg of tilapia was 0.2 m$^3$ in both treatments. Per 1 kg of feed input, the clarifiers removed 325 g of total solids, 38 g of BOD, 18 g of total nitrogen and 5 g of total phosphorus. The sludge, which was used to irrigate and fertilize guineagrass forage, performed significantly better than a standard inorganic fertilizer treatment. An advantage of the sludge is that it has a long (>1 year) residual fertilizer effect.

The fifth experiment (unpublished data) was a non-replicated preliminary trial to evaluate the effect of three levels of weekly alum (aluminium sulphate) addition on tilapia production. Male Nile tilapia (mean wt. = 197 g) were stocked at 17.8 fish/m$^3$ and fed *ad libitum* for 25.6 weeks. Weekly additions of alum were 25.8, 38.7 and 51.5 mg/L. Respective results were 4.35, 4.41 and 4.66 g/day for growth rate, 947, 954 and 1,002 g for final size, 16.0, 16.3 and 17.1 kg/m$^3$ for final biomass and 1.79, 1.86 and 1.87 for feed conversion ratio. Growth rate, final size and final biomass were substantially higher than results obtained in previous experiments due to a much larger fingerling size, a longer production period and modification of the feeding method to better reflect demand. It appeared that higher alum application led to higher production. The total amount of sludge generated was 11.6, 12.5 and 17.1 m$^3$ for weekly alum applications of 25.8, 38.7 and 51.5 mg/L.

The sixth experiment (unpublished data) employed replicated treatments to determine if weekly additions of 50 mg/L of alum affect tilapia production. Male Nile tilapia (mean wt. = 41.5 g) were stocked 24 fish/m$^3$ and fed *ad libitum* for 30 weeks. Growth rate, final weight, final biomass and feed conversion ratio were 3.4 g/day, 744 g, 17.0 kg/m$^3$ and 1.56 for the non-alum treatment and 2.8 g/day, 629 g, 14.5 kg/m$^3$ and 1.55 for the alum treatment, respectively. The results were not significantly different (P > 0.05). There was no significant difference in total sludge production, TAN and nitrite-nitrogen between the non-alum (12.7 m$^3$, 2.7 mg/L, 2.0 mg/L) and alum (13.8 m$^3$, 3.8 mg/L, 4.6 mg/L) treatment, respectively. Nitrate-nitrogen was significantly (P < 0.05) higher in the non-alum treatment (156.9 mg/L) than in the alum treatment (104.0 mg/L) while DO was significantly lower in the non-alum treatment (6.5 mg/L) than in the alum treatment (6.5 mg/L). It appears that the application of alum increased the removal of suspended organic matter and its associated nitrifying bacteria, which resulted in higher concentrations of TAN and nitrite-nitrogen and lower levels of nitrate-nitrogen. Lower nitrate-nitrogen levels indicate that there was less nitrification. By removing more organic matter and BOD, the alum treatment produced higher DO levels. Although the results were not significant, it appeared that alum decreased tilapia production.

With greenwater tank culture feeding response appears to fluctuate more than it does with pond culture. A practical method has been devised to feed at the correct rate. On Mondays,
Wednesdays and Fridays the fish are fed *ad libitum* for 30 minutes at 0900 and 1600 hours. The rate established on those days is used on the following day, or, in the case of Fridays, the next two days. This method has been successful in conforming to the feeding response as evidenced by a low feed conversion ratio of 1.56 for 744-g tilapia. The fish occasionally go off-feed for several days for unknown reasons. The off-feed response cannot be attributed to DO, TAN or nitrite, which are generally at acceptable levels. Off-feeding may be due to the temporary accumulation of some organic breakdown product that is detrimental to the fish. An experiment is now in progress to determine if one large dose of alum (100 mg/L) at the beginning of an off-feeding cycle can purge of system of the parent material from which the detrimental dissolved organic compound is derived, thereby shortening the cycle. The addition of 1 kg of alum will destroy 0.5 kg of alkalinity. Therefore, when adding alum to a greenwater system, it is important to monitor alkalinity and add base.

The greenwater tank has been scaled up to a commercial size for small islands. A 200-m$^3$ tank has been constructed using a block wall and a high-density polyethylene liner (Figure 3). The tank is 16 m in diameter and 1 m in depth. A 1-m$^3$ clarifier with a 45° slope has been incorporated in the centre of the tank floor, which has slope at 3° from the sidewall to the centre clarifier. A vertical-lift pump has been tilted on its side to establish a circular flow pattern, which moves settleable solids to the clarifier. Solids are removed by opening an external standpipe. If two crops per year can be produced at a final density of 17 kg/m$^3$, this tank will produce 6,800 kg of tilapia annually (Figure 4). Producing a comparable amount of tilapia by pond culture would require 25 to 30 times more water and land.

![Figure 3. Commercial-scale greenwater tank (200 m$^3$) at UVI (St. Groix).](image)
Aquaponic systems require very little water and land for the intensive production of tilapia, hydroponic vegetables and other crops such as culinary herbs, medicinal herbs and cut flowers. The fish provide adequate quantities of most of the nutrients required for plant growth. The nutrients are excreted directly by the fish or generated through the mineralization of organic waste. The plants utilize these nutrients to produce a valuable by-product and improve the system’s profit potential. The hydroponic component also serves as a biofilter, removing ammonia through direct uptake by plants and through oxidation of ammonia and nitrite by nitrifying bacteria that grow on the tank surface area. A very stable balance is reached between nutrient generation and water treatment, which eliminates the need for the intensive water quality monitoring required by non-integrated systems. By removing nutrients, hydroponic plants extend water use and reduce discharge to the environment.

Aquaponic research at UVI began with six replicated systems that consisted of a rearing tank (12.8 m³), a cylindro-conical clarifier (1.9 m³), two hydroponic tanks (13.8 m²) and a sump (1.4 m³) (Rakocy 1997). The hydroponic tanks (6.1 m long by 1.22 m wide by 28 cm deep) were initially filled with gravel supported by wire mesh above a false bottom (7.6 cm). The gravel bed, which served as a biofilter, was alternately flooded with culture water and drained. Due to the difficulty of working with gravel, the gravel was removed and a raft system, consisting of floating sheets (2.44 m long x 1.22 m wide x 3.8 cm thick) of polystyrene, was installed. A rotating biological contactor (RBC) was then used for nitrification. Effluent from the clarifier was split into two flows, one going to the hydroponic tanks and the other to the RBC. These flows merged in the sump, from which the treated water was pumped back to the rearing tank.
The rearing tank in this design proved to be too large relative to the plant growing surface area of the hydroponic tanks, or, conversely, the hydroponic tanks were too small relative to the size of the rearing tank. When the rearing tank was stocked with tilapia at commercial rates, nutrients rapidly accumulated to levels that exceeded the recommended upper limits for hydroponic nutrient solutions [2,000 mg/L as total dissolved solids (TDS)] (Rakocy et al. 1993b). Using Bibb lettuce, the optimum ratio between the fish feeding rate and plant growing area was determined (Rakocy 1989). At this ratio (57 g of feed/m² of plant growing area/day) the nutrient accumulation rate decreased and the hydroponic tanks were capable of providing sufficient nitrification. Therefore, the RBCs were removed and the fish stocking rates were reduced to levels that allowed feed to be administered near the optimum rate for good plant growth.

The experimental system has been scaled up three times. In the first scale-up, the length of each hydroponic tank was increased from 6.1 m to 29.6 m. The optimum design ratio was used to allow the rearing tank to be stocked with tilapia at commercial levels (for a diffused aeration system) without excessive nutrient accumulation. In the second scale-up, the number of hydroponic tanks (29.6 m in length) was increased to six; the number of fish rearing tanks was increased to four (each with a water volume of 4.4 m³); the number of clarifiers was increased to two; four filter tanks (0.7 m³ each) were added and the sump was reduced to 0.6 m³. This production unit, commercial aquaponics 1 (CA1), represented a realistic commercial scale, although there are many possible size options and tank configurations. The final scale-up, commercial aquaponics 2 (CA2), involved the enlargement of the four fish rearing tanks (each with a water volume of 7.8 m³) and the two clarifiers (each with a water volume of 3.8 m³) and the addition of a 0.7-m³ degassing tank (Figures 5 and 6). The commercial-scale units could be configured to occupy as little as 0.04 ha of land.

![Figure 5. Commercial-scale aquaponic system producing a crop of basil at UVI (St. Croix).](image)

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Figure 6. Commercial-scale aquaponic system at UVI (St. Croix) showing (counterclockwise) rearing tank (top right), clarifier, filter tanks, degassing tank and return sump.

The rearing tanks and water treatment tanks were situated under an opaque canopy. This inhibits algae growth, lowers water temperature, which is beneficial for hydroponic plant production, and creates more natural lighting conditions for the fish.

The system uses multiple fish rearing tanks to simplify stock management. Tilapia production is staggered in four rearing tanks so that one rearing tank is harvested every six weeks. The fish are not moved during their 24-week growout cycle. In a 2.5-year production trial in CA 1 using sex-reversed red tilapia, annual production was 3,096 kg, based on the last 11 harvests out of 19 harvests (Rakocy et al. 1997). Fingerlings, stocked at 182 fish/m³, grew at an average rate of 2.85 g/day to a size of 487 g. The final biomass averaged 81.1 kg/m³. This is equivalent to annual production of 175.7 kg/m³ of rearing tank space. The average feed conversion and survival were 1.76 and 91.6%.

The stocking density appeared to be too high for maximum growth and efficient feed conversion. Midway through each production cycle, *ad libitum* feeding levelled off at approximately 5 kg per rearing tank. As the fish grew in the last half of the production cycle, feed consumption did not increase. Therefore, more of the feed was used for maintenance and less was used for growth, leading to a relatively high feed conversion ratio for 487-g fish. In CA2 the stocking rate for red tilapia has been lowered by 15% to 154 fish/m³. The growth of Nile tilapia is being evaluated at a stocking rate of 77 fish/m³ with a goal of producing 1-kg fish for the fillet market. With larger rearing tanks and higher growth rates, it is anticipated that CA2 will produce 5 mt of tilapia annually.

The production trial employed two methods of *ad libitum* feeding. A demand feeder, used initially, was replaced by belt feeders, utilizing variable quantities of feed adjusted to meet the demand. Neither method proved to be entirely satisfactory. With demand feeders, high

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winds would shake the feeder, which then dispensed too much feed, or clumps of feed would block the funnel opening of the demand feeder, which then delivered too little feed. The belt feeders periodically failed, not delivering any of the day’s ration. Both devices are expensive and require support structures. In CA2 the fish are fed *ad libitum* by manual feeding three times daily.

In the production trial, DO levels were maintained at a mean of 6.2 mg/L by high DO in the incoming water and by diffused aeration with air delivered through 10 air stones (22.9 cm x 3.8 cm x 3.8 cm) around the perimeter of the tank. In the last 12 weeks of the growout period, a 1/20-hp vertical lift pump was placed in the centre of the tank for additional aeration. Vigorous aeration vented carbon dioxide gas into the atmosphere and prevented its buildup. A high water exchange rate quickly removed suspended solids and toxic waste metabolites (ammonia and nitrite) from the rearing tank. A 1/2-hp in-line pump moved water at an average rate of 378 L/min from the sump to the rearing tank (mean retention time, 0.8 h). Values of ammonia-nitrogen and nitrite-nitrogen in the rearing tanks averaged 1.47 and 0.52 mg/L, respectively. A pH of 7.2 was maintained by frequently adding equal amounts of calcium hydroxide and potassium hydroxide. Total alkalinity averaged 56.5 mg/L as calcium carbonate.

In CA2 the vertical lift pump was eliminated, and the number of air stones around the rearing tank perimeter was increased to 22 (15.2 cm x 3.8 cm x 3.8 cm). With larger water volumes, the retention time will increase to an average of 1.37 hours.

Effluent from the fish rearing tanks flowed into two 1.9-m³ clarifiers in the production trial. Separate drains from two of the rearing tanks were connected to each clarifier [see Rakocy (1997) for a detailed description]. The clarifiers removed settleable solids, but the production of solids was not as great with the 9.5-minute retention time in the production trial as it had been in previous trials with longer retention times (>20 minutes). Therefore, in CA2 the clarifiers were increased in size to 3.8 m³ and the retention time is 19 minutes. The bottom slope of the new clarifiers is 45° as compared to 60° slopes in the 1.9-m³ clarifiers. Sludge is removed from the clarifiers three times daily.

Suspended solids levels, which decline slightly on passage through the clarifier, must be reduced further before the effluent enters the hydroponic tanks. Excessive solids are detrimental to plant growth. Solids adhere to plant roots, create anaerobic conditions and block nutrient uptake. Two filter tanks in series, each with a volume of 0.7 m³ and filled with orchard netting, receive effluent from the clarifier and remove considerable amounts of suspended solids, which adhere to the orchard netting. In the production trial, total suspended solids averaged 9.0 mg/L in the rearing tanks, 8.2 mg/L in the effluent from the clarifiers (a 9% reduction) and 4.5 mg/L in the effluent from the filter tanks (a 45% reduction). The filter tanks were drained and the orchard netting was washed with a high-pressure sprayer once or twice per week. Solids from the filter tanks and clarifiers were discharged through drain lines into two 16-m³ lined ponds, which were continuously aerated using air stones. As one pond was being filled over a 2 to 4-week period, water from the other pond was used to irrigate and fertilize field crops.

The relatively slow removal of solids from the system (twice/day from the clarifiers and 1-2 times/week from the filter tanks) is an important design feature. While solids remain in the system, they are mineralized. The generation of dissolved inorganic nutrients promotes vigorous plant growth. In addition, filter-tank solids create anaerobic zones where
denitrification occurs. As water flows through the accumulated organic matter on the orchard netting, nitrate ions are reduced to nitrogen gas. Nitrate is the predominant nutrient in aquaponic systems. High nitrate levels promote vegetative growth but inhibit fruiting. With fruiting plants such as tomatoes, low nitrate concentrations maximize fruit production. Nitrate levels can be controlled by regulating the cleaning frequency of the filter tanks. If the filter tanks are cleaned twice per week, there is less solids accumulation, less denitrification and higher nitrate levels. If the filter tanks are cleaned once per week, there is more solids accumulation, more denitrification and lower nitrate levels.

Organic decomposition in the filter tanks produces carbon dioxide, methane, hydrogen sulphide and other gases. If filter-tank effluent enters the hydroponic tanks directly, it retards the growth of plants near the inlet. Therefore, a 0.7 m$^3$ degassing tank was added to the CA2 system. Filter-tank effluent enters the degassing tank and is vigorously aerated, venting potentially harmful gasses into the atmosphere. Degassing-tank effluent is split into three equal portions, each of which passes through a set of two hydroponic tanks. In each set of tanks, water flows 59.2 m before returning to the sump and being pumped back to the fish rearing tanks.

The hydroponic tanks retain the fish culture water for an average of three hours before it is returned to the fish rearing tanks. Each set of hydroponic tanks has 48 air stones (7.6 cm x 2.5 cm x 2.5 cm), located 1.22 m apart along the central axis of the tank, which re-aerate and mix the water, exposing it to a film of nitrifying bacteria that grows on the tank surface areas, especially the underside of the polystyrene sheets. In the production trial, DO increased from 4.0 to 6.9 mg/L on passage through the hydroponic tanks (Rakocy et al. 1997). Through direct nutrient uptake by plants or bacterial oxidation, Gloger et al. (1995) found that the UVI raft hydroponic tanks removed an average of 0.56 g of NH$_3$-N, 0.62 g of NO$_2$-N, 30.29 g of COD, 0.83 g of total nitrogen and 0.17 g of total phosphorous per m$^2$ of plant growing area per day using romaine lettuce. The maximum sustainable waste treatment capacity of raft hydroponics was found to be equivalent to a feeding rate of 180 g/m$^2$ of plant growing area/day. At the optimum design ratio of 57g of feed/m$^2$ of plant growing area/day needed to reduce nutrient accumulation, raft hydroponics has 200% excess waste treatment capacity. After an initial acclimation period of one month, it is not necessary to monitor ammonia or nitrite values in commercial-scale raft systems.

Several materials were used to construct the hydroponic tanks. The best construction materials consisted of poured concrete walls (40 cm high) and a 20-mil high-density polyethylene tank liner. The black liners used for CA1 absorbed considerable heat along the top of the tank walls. For CA2 the portion of the liners above the water level was painted white to reflect heat. A white liner that is resistant to UV light is also being tested. The polystyrene sheets were painted white with a potable grade latex paint to reflect heat and prevent the deterioration that results if it is exposed to direct sunlight.

There are several advantages to raft culture. There is no limitation on tank size. Rafts provide maximum exposure of the roots to the culture water and avoid clogging. The sheets shield the water from direct sunlight and maintain lower than ambient water temperatures, which is beneficial to plant growth. A disruption in pumping does not affect the plant’s water supply. The sheets are easily moved along the channel to a harvesting point, where they are lifted out of the water and placed on supports at an elevation that is comfortable for workers.
A disadvantage of raft culture is that the plant roots are vulnerable to damage caused by zooplankton, snails and other aquatic organisms. Biological methods have been successful in controlling these invasive organisms. Ornamental fish, particularly tetras (Gymnocorymbus ternetzi), are effective in controlling zooplankton, and red ear sunfish (shellcrackers, Lepomis microlophus) are effective in controlling snails.

During the 2.5-year production trial for tilapia and lettuce in CA1, total annual production averaged 1,248 cases (Rakocy et al 1997). In 112 lettuce harvests, marketable production averaged 27 cases per week and ranged from 13-38 cases (24-30 heads/cs). Average harvest weight was 269 g for Sierra (red leaf), 327 g for Parris Island (romaine), 314 g for Jerhico (romaine) and 265 g for Nevada (green leaf). The plants were weighed after the lower leaves were trimmed. Production was always greater during the cooler winter months when water temperature averaged 25.1°C than in the summer months when water temperature averaged 27.5°C.

Fish feed provided adequate levels of 10 of the 13 nutrients required for plant growth. The nutrients requiring supplementation were K, Ca and Fe. During the production trial, 168.48 kg of KOH, 34.48 kg of CaO, 142.9 kg of Ca(OH)$_2$ and 62.668 kg of iron chelate (10%) were added to the system, which was equivalent to the addition of 16.1, 3.3, 13.7 and 6.0 g, respectively, for every kilogram of feed added to the system. The amount of Ca and K added was the result of the quantity of base required to maintain pH at 7.2. Rainwater is used in all the aquaponic systems at UVI because the NaCl content of groundwater in the Virgin Islands is too high.

Two species of pathogenic root fungi (Pythium myriotylum and P. dissoticum) caused production to decline during the warmer months. Pythium myriotylum causes root death while P. dissoticum causes general retardation in the maturation rate of the plant. CA2 was designed to lower water temperature, through shading, reflective paint and heat dissipation manifolds (attached to the blowers), in an effort to minimize the effects of Pythium. A plant potting media containing coconut fibres (coir) is used to produce transplants for CA2 instead of the peat-based potting media used for CA1 because some peat products contain Pythium spores. A study is planned for the experimental systems to determine the effects of chillers and evaporative coolers on lettuce production, level of Pythium, water quality and system economics. The use of resistant varieties and antagonistic organisms also offer potential for Pythium control in aquaponic systems.

The only significant insect problem with lettuce was caused by caterpillars of the fall armyworm and corn earworm. These caterpillars were controlled by twice weekly sprays with Bacillus thuringiensis, a bacterial pathogen that is specific to caterpillars.

Hydroponic research in the CA2 system will evaluate production levels, planting densities, support structures and pest control techniques for a range of vegetable types, including cucumber, pole bean, snap pea, tomato, pepper, bush bean, squash, cantaloupe, watermelon, basil, pak choi and mustard green. Production output figures are needed to develop business plans. Research will also be conducted on the production of medicinal herbs and cut flowers.

Perspective

Cage culture in small watershed ponds, greenwater tank culture and aquaponics are intensive tilapia production systems that can be applied in areas that are not often considered as suitable for aquaculture development due to some resource limitation. The systems can be
applied on a hobby scale with experimental-sized units to supplement the family diet, or multiples of the larger units can be used to produce tilapia at commercial levels.

All of the systems developed at UVI represent appropriate or intermediate technology. The levels of complexity in constructing and operating these systems range from very simple for cage culture to moderately complex for aquaponics. A knowledge of dissolved oxygen, pH, alkalinity and nitrogen is important, but the greenwater tank and aquaponic systems can be operated by following a set a guidelines without a thorough understanding of the intricacies of water quality.

Capital input varies similarly. Small cages are inexpensive while aquaponic systems, even small ones, can be relatively expensive, considering the need for an assortment of tanks, a canopy, a water pump, an air blower, liners and floating sheets. The high output of fish and vegetables from aquaponic systems compensates for the cost.

One constraint in applying these systems in locations that are new to aquaculture is the availability of fingerlings. Adding a fingerling operation increases cost and complexity and may negatively impact the economics, especially for small-scale operations. The economies of scale of large commercial facilities will justify the addition of a fingerling production facility. The UVI research program is currently investigating the potential of small fingerling production facilities using small static tanks for breeding, a greenwater recirculating system for sex reversal and greenwater tank culture and clearwater recirculating systems for fingerling production.

Working on a dry and small Caribbean island in the Lesser Antilles, we are gratified at the enthusiasm and interest our research has generated, not only in the Virgin Islands but on several neighbouring islands as well. Many people are eager to raise fish for their local markets and are hungry for information. Most potential fish farmers do not have access to a pond for cage culture, so we generally recommend that they start with greenwater tank culture to gain experience, either on a hobby scale or a commercial size involving at least six tanks so that marketable fish are available monthly. We recommend small-scale aquaponics to those who are interested in fish and hydroponic plants, but we caution that large-scale aquaponics requires some preliminary experience or advanced technical training. We offer a short course annually on the UVI systems and plan to write detailed manuals for beginners. We are optimistic that tilapia culture will continue its phenomenal growth and that the concepts presented here will contribute to future expansion.

References


Rakocy, J.E. 1989. Hydroponic lettuce production in a recirculating fish culture system. University of the Virgin Islands, Agricultural Experiment Station, Island Perspectives 3:4-10.


Techniques for Modern Aquaculture. Aquacultural Engineering Group, American Society of Agricultural Engineers.


Table 1. Summary of six greenwater tank culture experiments giving tilapia species (modified Florida red or *Oreochromis niloticus*), experimental treatment, stocking rate, stocking size, final size, growth rate, final biomass, feed conversion ratio (FCR) and survival. Values within each column of an experiment followed by the same letter are not significantly different (P > 0.05).

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<th>Experiment</th>
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<th>Treatment</th>
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<th>Stocking Size (g)</th>
<th>Final Size (g)</th>
<th>Growth Rate (g/d)</th>
<th>Final Biomass (kg/m³)</th>
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¹ Yield