INNOVATIVE TECHNOLOGIES AND METHODOLOGIES FOR COMMERCIAL-SCALE POND AQUACULTURE

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PROJECT OBJECTIVES

1. Evaluate new or improved production systems for channel catfish.
   a. Continuous production and inventory control with the partitioned aquaculture system.
   b. Installation of low-cost, semi-confinement systems in commercial-scale, earthen ponds.
   c. Fry and food fish production using in-pond raceways with the option for culturing supplemental species in open-pond areas.
   d. High-intensity production in heterotrophic-based culture units.
2. Improve equipment to enhance culture.
   a. Motor-powered U-tube aerator for commercial-scale channel catfish ponds.
   b. Low-head, low-speed paddlewheel aerator for crawfish ponds.
   c. Low-power, electrically-enhanced seine to harvest market-sized channel catfish from commercial-scale ponds.
3. Assess energy, material, and economic efficiency of production systems.

a. Quantify energy, protein, and water use in traditional systems for channel catfish culture.

b. Develop and evaluate economic and financial models of existing and improved production practices and technologies.

ANTICIPATED BENEFITS

Aquaculture operations in the southeastern United States find it increasingly difficult to maintain profitability as production costs increase and farm gate prices remain relatively low. Solutions to the problem are complex and multifaceted, but improved production efficiency can decrease production costs and improve the prospects for profitability. This project will provide new technology for production systems, aeration and harvesting techniques, and use of energy, materials, and capital. These technologies will be valuable in improving the profitability of aquaculture in the southeast.

PROGRESS AND PRINCIPAL ACCOMPLISHMENTS

Objective 1. *Evaluate new or improved production systems for channel catfish.*

Objective 1a. *Continuous production and inventory control with the partitioned aquaculture system.*

Clemson University. The experimental trials in 2005 focused on 1) physical holding and handling of fry and fingerlings, 2) stocking density and required water flow rates, 3) feed presentation and food consumption, and 4) growth response under raceway culture conditions as opposed to an "accelerated" fingerling culture pond.

On 10 June 2005, channel catfish fry were stocked in six cells (1.83 m × 2.89 m × 1.22 m deep) located within the 0.81-ha PAS system (Figures 1, 2, and 3). Three cells were stocked with 5,000 fry and three cells with 10,000 fry. Fry were held in bins (46 cm × 76 cm × 30 cm deep) with 0.16-cm (1/16-inch) mesh screens for 1 week and then transferred to bins with 0.32-cm (1/8-inch) mesh screens for an additional week. After having reached an average size of 1.2 to 1.4 g, fingerlings were released into 0.63-cm (1/4-inch) mesh net-pens held within the 6.5-m^3 PAS cells. Each cell was supplied with water delivered by a 0.56-kW submerged aerator providing between 280 to 720 L/min to individual cells (Figures 2 and 3). After initial stocking, fish were fed starter feed of 52% to 56% protein supplied using automated feeders (Figure 4).

After 6 weeks, fingerlings had reached 11 to 14 g and hand feeding was initiated. At 7 weeks, fish in cells containing 10,000 fingerlings had reached 14 to 15 g, and were moved to grow-out raceways in the 0.1-ha PAS units (9.1 m × 2.1 m × 1.22 m deep). At the end of 8.5 weeks, fingerlings had reached 27 to 32 g in units stocked at 5,000 per cell, and 20 to 22 g in cells stocked at 10,000 per cell.

In addition to the fingerling culture trials conducted within cells and raceways, experiments were initiated to study the possibility of using PAS cells and raceways to provide a growth acceleration, or "boost" before stocking and grow-out in conventional fingerling ponds. A conventional, 0.20-ha fingerling culture pond was stocked with 34,000 fry (0.03 g/fish), while 17,000 fry of the same cohort were held in bins for 2 weeks with automated feeding until reaching 1.4 g. The "boosted" fry were stocked into a conventional, 0.12-ha fingerling culture pond. At

Figure 1. Overview of the 0.8-ha Clemson PAS unit with fingerling production cells.

Figure 2. Six, 4.5-m^2 fingerling production cell with aerator-driven water flow.

Figure 3. Individual fingerling production cell with aerator-driven water flow.

Figure 4. Automatic feeders used to feed fingerlings during initials stages of culture.

the end of culture trials fingerlings in both ponds were observed to be of similar size, reinforcing the importance of converting the boosted fry or fingerlings to floating feed as quickly as possible. Growth response in the "accelerated" pond was delayed as a result of slow initial response of the fish to hand feeding after being stocked in the pond.

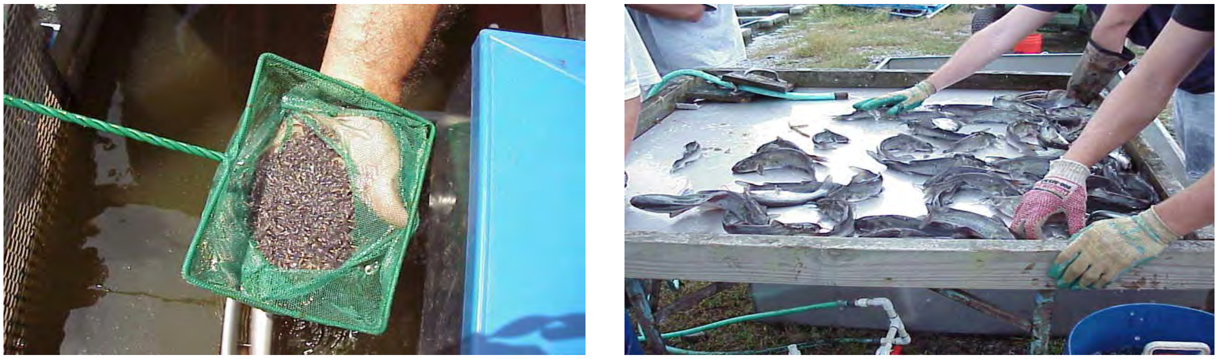
On 10 October 2005, fingerlings in the cells, raceways and control ponds were harvested, sorted, counted and weighed (Table 1; Figure 5). After 120 days of culture, the net-pen cultured fingerlings grew from an initial weight of 0.10 g/fish (3- to 7-days-old) to an average harvest weight of 122 to 158 g (Figure 6). Feed uptake for the pooled net-pen fingerlings was fit to a power law (Figure 7) yielding the relationship:

> Feed application rate (% body weight) = 0.3223 $X^{-0.551}$ where X = fish weight (g). The coefficient of determination (R^2) was 0.846.

Table 1. Average fingerling weight, density (in cells and ponds) and feed application rates in 2005.

Unit #	Size (g/fish)	Density (kg/m^3)	Loading/ feed(kg/ha)
Cell 1	122	112.9	2,576/63
Cell 2	139	136.7	2,576/63
Cell 3	124	111.3	2,576/63
Cell 4	158	47.7	2,576/63
Race 1	73	28.6	3,696/112
Race 2	77	28.6	9,072/215
Race 3	56	19.1	9,072/215
Pond 1	38	0.95	5,600/78
Pond 2	49	0.64	3,808/56

Figure 5. Fry stocking and fingerling harvest sizes.



On 1 June 2006, channel catfish fry were stocked into nine, 1.83 m × 2.89 m × 1.22 m deep cells located within the Clemson 0.8-ha PAS system. The experimental trials for 2006 focused on, 1) physical holding and handling of fry and fingerlings, 2) required water flow rates, 3) comparison of fingerling growth at base feed application rate (from 2005), +25% feed application, and at +50% feed application rate, 4) growth response under raceway culture conditions as compared to net-pen culture.

Figure 6. Final harvest fingerling size distribution in cell 2 (average wt = 139 gm) in 2005.

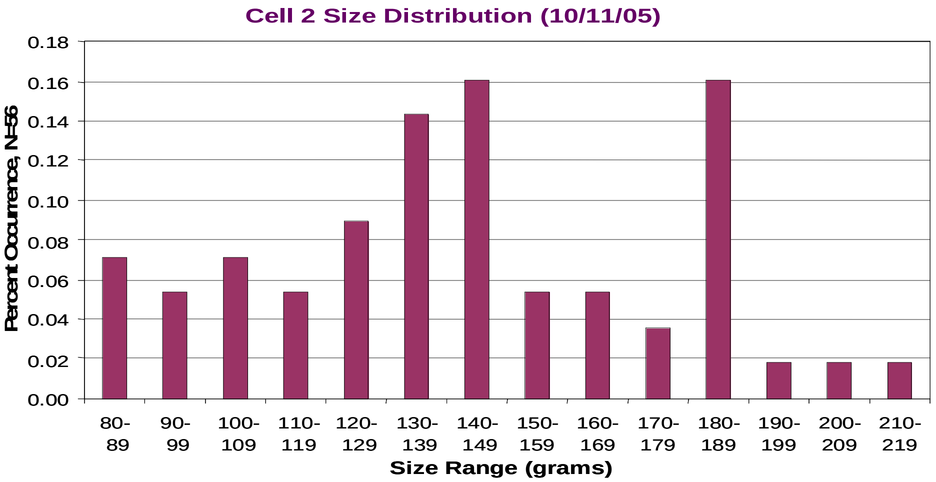
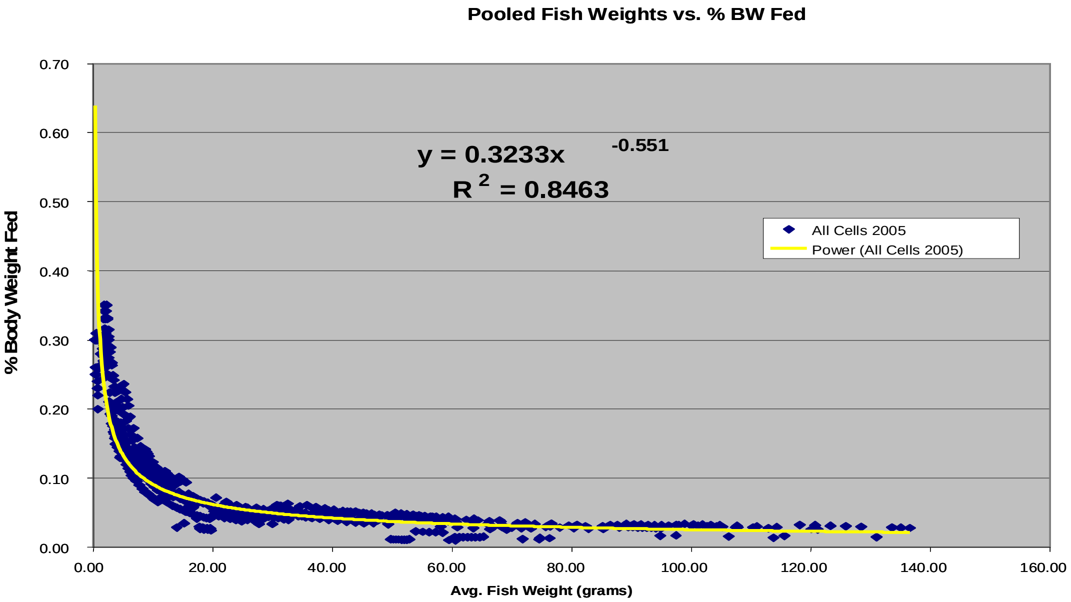


Figure 7. Observed, pooled fry/fingerling feed application rate vs fingerling wt. in 2005.



The nine, 6.5-m^3 cinder block cells were stocked with 3,000 fry in each cell (Figure 8). The fry were held in 1,050-cm^3 bins for 2 weeks, transferred to 3,710-cm^3 bins for two additional weeks, and after having reached 1.8 to 2.0 g in size, the fingerlings were released into a 0.63-cm (1/4-inch) mesh net-pens held within the cells. Each cell was supplied with water flow delivered from two 0.56-kW submerged aerators providing between 280 to 946 L/min flow to the individual cells. From the initial stocking, the fish were fed starter feed supplied with automatic feeders. After 8 weeks the fingerlings had reached 14 to 17 g in size. At 8 weeks, 14 to 15 g fingerlings were stocked into the 0.12-ha PAS raceways units (9.1 m × 2.1 m × 1.22 m deep) at a stocking rate of 74,130 fingerlings/ha.

Fish were harvested on 26 October 2006. End-of-season fingerling weight after 148 days of culture ranged from 126 to 133 gm/fish. Data suggested no statistical difference between fish harvest weight at base, +25, and +50% feed application rates. Overall food uptake rate and fish growth was pooled from the 2005 and 2006 fingerling culture trials and re-fit to a power law yielding the relationship:

> Feed application rate (% body weight) = $0.2855X^{0.4818}$ where X = fish weight in grams.

Results at a glance...

- *The Clemson University Partitioned Aquaculture System (PAS) is particularly well-suited for production of channel catfish fingerlings. Growth is excellent, with fingerlings reaching approximately 140 g/fish (300 pounds/1000 fish) in 4 months. The semi-confinement units tested at the University of Arkansas at Pine Bluff also increased the yield of fingerling catfish in ponds.*

In 2006 culture trials, system-wide feed application rate to the two acre PAS peaked at a maximum of 118 kg feed/ha per day. Overall survival of fingerlings averaged 90%. In all cases observed fingerling growth was significantly reduced in raceways as compared to net-pen culture.

Beginning 15 June 2007, channel catfish fry were stocked into nine, 1.83 m × 2.89 m × 1.22 m deep cinder-block cells located within the Clemson 0.8-ha PAS system. At this time each of the nine cells were stocked with 5,000 fry. The fry were initially stocked (at 0.04 g) in the smallest bins with 0.16-cm (1/16-inch) mesh screens for 9 days of growth (reaching

Figure 8. High density PAS catfish fingerling culture in 6.5 m^3 (1720 gallon) cells with 63-cm (1/4-inch) mesh net cages.

0.32 g), after which time, they were transferred to larger bins with 0.32-cm (1/8-inch) mesh screens for an additional week until reaching 0.9 gm when they were transferred to 0.48-cm (3/16-inch) mesh bin where they were cultured until reaching an average size of 3.2 g (at 34 days), at which point, the fingerlings were released into 0.63-cm (1/4-inch) mesh net-pens held within the PAS cell. Each cell was supplied with water flow delivered with either 5-cm airlift pumps, or with 0.56-kW submerged aerators providing an initial flow-rate of 150 L/minute, with increased flow (at 5 g fingerling weight) of 1,250 liters per minute to the individual cells (Figure 7). At initial stocking the fish were fed starter feed of 52-56% protein, supplied with automated feeders. After 6 weeks of culture the individual fingerling weight averaged 7.3 to 8.6 g. The fingerlings were harvested after 143 days of culture at an overall combined average fingerling weight of 114 g/fingerling.

In the 2007 season, stocking rates and cell number were adjusted to target a system-wide fingerling carrying capacity approaching expected commercial production levels. Final maximum daily feed application rates exceeded 135 kg/ha of 40% protein feed with maximum fingerling carrying capacity of 4,200 kg/ha. Fingerling feed uptake rates were pooled from all three seasons (2005, 2006 and 2007) suggesting a final feed application relationship of:

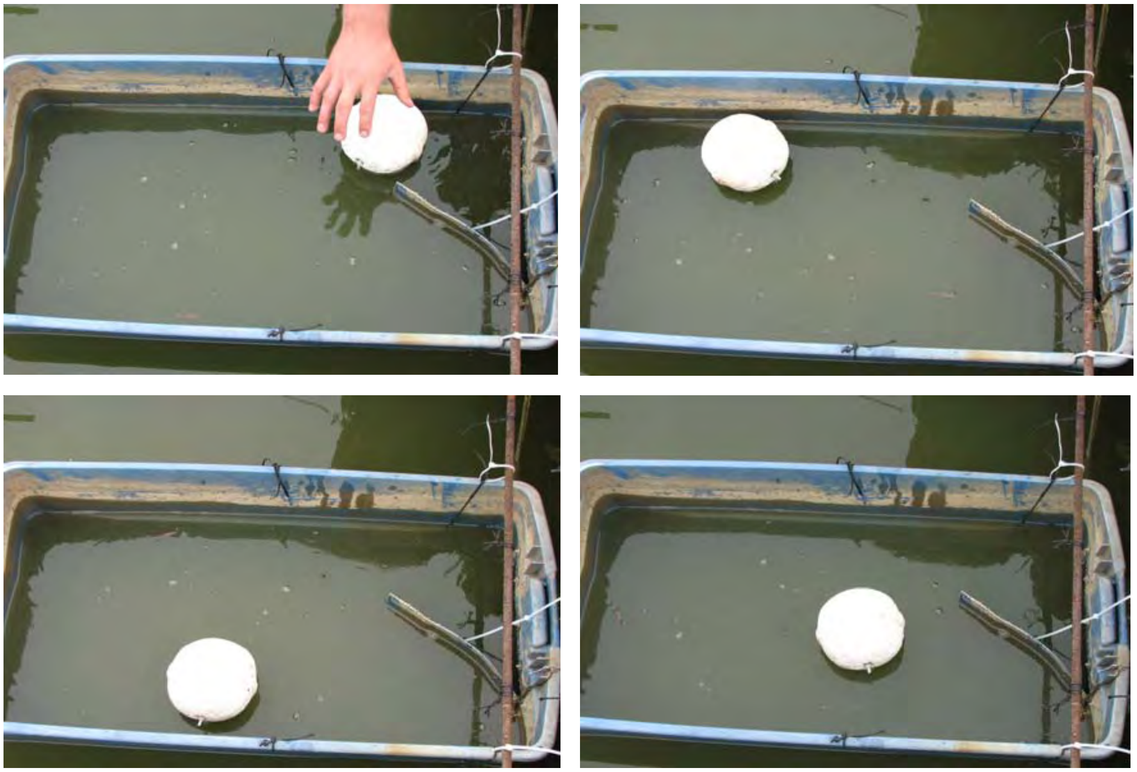
> Feed application rate (% body weight) = 0.3233X0.551 where X = fish weight in gms.

Results from the earlier 2005 and 2006 seasons suggested that fingerlings were extremely sensitive to variations in un-ionized ammonia concentrations resulting from water TAN concentration ranging between 1.0 to 2.0 mg/L at pH values ranging from 8.0-9.0. During 2007 trials, pH-values in four of the nine fingerling culture cells were continually suppressed 0.5 pH units with carbon dioxide supplemental to investigate the potential to increase fingerling feed uptake and growth through reduction in un-ionized ammonia concentrations. At the end of the season average fingerling sizes ranged from 96 to 126 g, and there was no statistically significant differences in fingerling growth attributable to pH adjustment.

In the 2008 season, three of the PAS fingerling growth cells were reconfigured to allow for passive water flow through the cell by utilizing the raceway-paddlewheel (Figure 9), in contrast to using airlifts or aerators to provide water flow as in the 2005, 2006 and 2007 seasons (Figure 8). The goal of these experimental trials was to investigate the possibility of using a lower cost system design, expected to be more economically viable for commercial application. The best configuration providing a controllable high flow rate through the cells consisted of combinations of baffles in the water delivery channel and "angled flaps" in the individual fry bins and fingerling net-pens directing water flow into a circular path within the fingerling cells and net pens (Figure 10). Maintaining a circular flow regime within the bins and net-pens was critical to keep feed from washing out at increased flow velocities. Fingerlings were placed into 0.16-cm (1/16-inch) mesh bins, 0.53 m × 0.46 m × 0.38 m at 5,000 fry/bin on June 2, 2008. On 13 June, fry were transferred to 0.32-cm (1/8-inch) mesh bins measuring 0.6 m × 0.53 m × 0.36 m. Finally on July 8 (36 days), fry were transferred to the 0.63-cm (1/4-inch) mesh net-pens, 2.74 m × 1.22 m × 0.91 m in size. Water velocities into bins and net pens ranged from 0.27 to 0.15 m/sec, yielding average water flow rates of 1,514 L/minute (400 gpm) in the bins (contrasted to 151 L/min using airlifts in 2007) and 7,570 L/min (2,000 gpm) in the net-pens (contrasted to 1,362 L/min using aerators in 2007). Bin and net-pen hydraulic detention times were reduced to 0.85 - 0.4 minutes using passive flow in 2008 as opposed to "pumped-flow" detention times of 2 to 5 minutes in the 2006/2007 growth trials. Water flow generated using airlifts and paddlewheels during the 2007 growing season for the entire 2-acre PAS system was 152% of the 2008 growing season. However,

Figure 9. 2008 PAS fingerling-cell configuration with paddle-wheel driven flow.

Figure 10. Demonstration of flap use to direct water flow into circular pattern in 2008 fry-bin providing capture zone for fine mesh fry-feed (0 sec, 2 sec, 8 sec, and 10 sec).



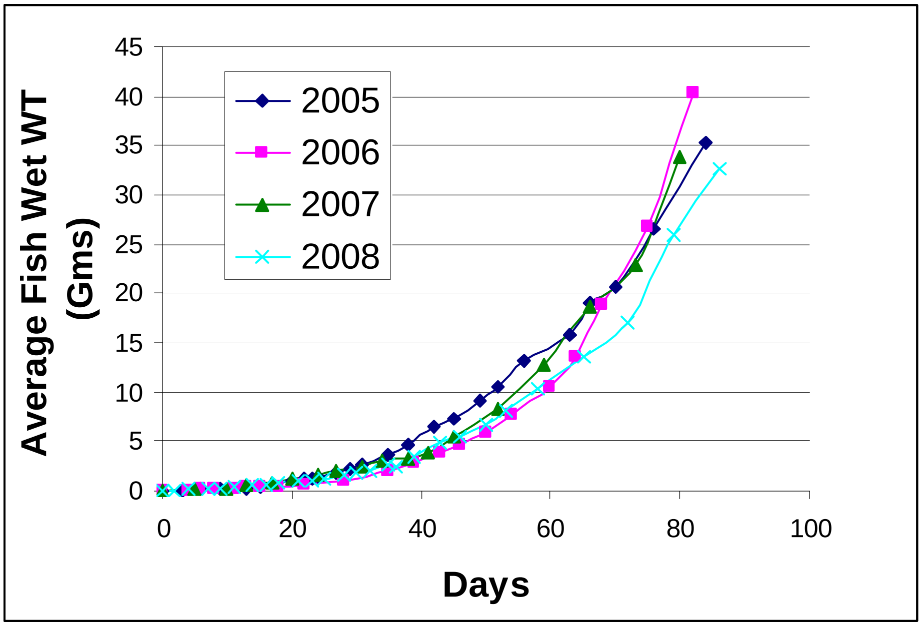
power requirements in 2008 were reduced by 58% by operating the system using passive flow rather than active flow.

The 2008 fingerlings were harvested after 65 days of growth. Growth to that point was compared to the previous three growing seasons (Figure 11) and was within one standard deviation of the average fingerling weight 65 days into the growing season. The 2008 growth rate follows the same trend over as earlier years using "active flow" water distribution. Water quality in the 2008 passive flow configuration was also similar to that in the active flow configuration used in previous years. Average dissolved oxygen concentration within the fish cohorts for the first 65 days during the 2005-2007 growing season was 5.3 mg/L with an average decrease in oxygen concentrations ("delta DO") within fish-holding units of 0.64 mg/L; average dissolved oxygen concentration for 2008 growing season was 4.5 mg/L with a "delta DO" of 0.25 mg/L. Average total ammonia-nitrogen concentration within the fish cohorts for the first 65 days during the 2005-2007 growing season was 0.50 mg/L with an increase in total ammonia-nitrogen concentration

Results at a glance...

- *In 2008 catfish fingerlings were grown at Clemson University in a "passive flow" PAS configuration. This modification reduced pumping energy use by 58% over previous "active flow" configurations. After two months of culture, fingerling weights (~30gms) were seen to be essentially the same as observed during earlier water distribution configurations.*

Figure 11. Comparison of average fry/fingerling size vs. time, from 2008 season using passive water flow distribution, as opposed to, previous years 1-3 using active water flow distribution.



("delta TAN") within a fish-holding unit of 0.38 mg/L; in 2008, the average TAN concentration was 1.08 mg/L, with a "delta TAN" of 0.02 mg/L.

Based on 4 years of growth data, the annual yield from a conventional fry/fingerling and foodfish production system was compared to 1) conventional fry/fingerling production followed by PAS grow-out and 2) PAS fry/fingerling production followed by PAS grow-out system. For this analysis we assumed a market channel catfish average weight of 1.63 pounds. For the conventional fry/fingerling ponds a carrying capacity of 2,100 pounds/acre was chosen, yielding an average 30-g fingerlings. Conventional foodfish production pond carrying capacity was projected at 5,000 pounds/acre. It was assumed that 70% of the stocked fingerling would be harvested after the first growing season and 30% would be carried over into a second growing season. The fingerling PAS carrying capacity was projected at 4,695 pounds/acre yielding an average 115-g fingerlings. PAS foodfish production carrying capacity of 18,000 pounds/acre was assumed. If stocked with conventional 30-g fingerlings, it is assumed that 70% of the stocked fingerlings would be harvested after the first growing season and 30% would be carried over into the second growing season. On the other hand if the system is stocked with 115-g fingerlings from the fry/fingerling PAS production, then 100% of the stocked fingerlings could be harvested in one growing season.

Projected yields showed that conventional fingerling production followed by foodfish growout in the PAS would produce a 300% increase in net fish yield per acre as compared to conventional pond fish production. The combination of fingerling PAS production followed by grow-out of foodfish in the PAS resulted in an additional 10% increase in annual harvest compared to conventionally grown fingerlings followed by PAS foodfish grow-out. The potential overall production increase from using fingerling PAS production is somewhat reduced by the large increase in PAS foodfish production compared to conventional pond foodfish production. Further, the much greater size "fingerling" produced in the PAS requires relatively a larger PAS area to produce a given number of fingerlings, which partially offsets the higher PAS fingerling carrying capacity. Nevertheless, fingerling production in the PAS offers a number of advantages over conventional production, including

- Potential for staged harvests during the growing season due to stocking with larger fingerling resulting in increased annual harvest without increasing carrying capacity;
- More control of over fingerling predation, disease treatment/vaccination, and harvest/inventory control in a PAS fingerling production system;
- Elimination or reduction in over-wintering requirements for food-fish reducing potential PGD mortality;
- Higher overall fingerling survival rate; and
- Reduced or eliminated water discharge

Mississippi State University. The PAS as currently configured in the Clemson system consists of an extensive, shallow algal growth basin (representing about 95% of the total system water surface area), and an intensive fish-confinement area in which fish are held at about 20 to 40 times the density of traditional ponds. In this objective, a modified PAS system, called the split-pond, was constructed that confines fish at a lower density than the Clemson system. The split-pond was built with a lower proportion of the total system area in the algal growth basin (about 80% of the total area) and a higher percentage of area in the fish-holding area (fish will be held at only 5 times the density of traditional ponds). The overall concept is to take advantage of the fish confinement benefits of the PAS (facilitation of inventory, harvest, feeding, health management, and protection against predation) while avoiding the need for intensive system management. A parallel goal of this objective is to design and evaluate a PAS-type system that can be constructed by retrofitting existing earthen ponds, rather than requiring new construction. This is accomplished by simply dividing an existing earthen pond into two sections with an earthen levee and then connecting the two sections with water flow induced by a slow-turning, energy-efficient paddlewheel.

In year 2004, one system was constructed in an existing 0.324-ha earthen pond at the National Warmwater Aquaculture Center, Stoneville, Mississippi (Figure 12). A 2-m-high earthen levee was constructed to separate the pond into two sections: a 0.227-ha algal basin and 0.073-ha fish-confinement area. Two, 3-m concrete-block sluiceways were constructed at either end of the cross-levee. One sluiceway was equipped with a six-bladed, 3-m long paddlewheel to induce water flow out of the fish confinement area and into the algal basin. The paddlewheel is 2 m in diameter and was installed to provide minimal clearance (less than 3 cm) with the sluiceway bottom and side walls. The paddlewheel can be operated at 1 to 6 rpm via a variable-speed, 3.7-kW hydraulic motor. The other sluiceway accommodates return flow from the algal basins into the fish confinement area. Both sluiceways were fitted with double barriers of 2.54-cm expanded metal to prevent fish escape out of the confinement area. Aeration in the fish confinement area is provided by eight, highly efficient deep-water release membrane diffusers. Air to the diffuser array will be provided by a 3.7-kW blower through a manifold of PVC pipe. The aeration system is designed to provide a field oxygen transfer rate of approximately 4.5 kg oxygen/hour at a water temperature of 30°C and 2 mg/L ambient dissolved oxygen. That rate should be adequate to meet the respiratory needs of at least 8,000 kg of fish.

Figure 12. The split-pond system at Stoneville, Mississippi. An existing 0.32-ha earthen pond was split into a waste-treatment basin (foreground) and a fish-holding section (barely visible over the dividing levee). The two basins are hydrologically connected by a low-speed paddlewheel (at the right) and a return-flow sluiceway (at the left).

The system was stocked with approximately 4,000 kg of catfish to optimize operating parameters. A paddlewheel speed of 1 rpm resulted in a water flow of 15.2 m3/minute through the fish-confinement basin. This flow rate was adequate to prevent accumulation of waste ammonia in the fish-confinement area at fish feeding rates of 150 kg/ha per day. At fish feeding rates of 175 to 200 kg/ha per day, total ammonia concentrations did not exceed 0.5 mg/L and dissolved oxygen concentrations remained above 3 mg/L.

In spring 2005, the system was stocked with 7,400 stocker-sized hybrid channel × blue catfish (24,710 fish/ha). Fish grew from an initial average weight of 0.08 kg/fish to an average of 0.78 kg/fish in a 6-month growing season. Total harvest weight was 5681 kg (18,940 kg/ha), for a net fish production of 5089 kg (16,960 kg/ha). Fish survival was 99% at a feed conversion efficiency of 1.87 kg of feed/kg of fish produced.

In spring 2006, the system was stocked with 11,100 hybrid channel × blue catfish (37,065 fish/ha at an average weight of 50 g/fish). As of August 23, 2006 fish averaged 0.43 kg/fish, giving a standing crop of approximately 16,000 kg/ha. In early September, a mechanical problem with the aeration system resulted in an acute nighttime dissolved oxygen depletion in the system and about half the fish standing crop was lost. The system was restocked with an equal number and weight of channel catfish to continue growout.

In spring 2007, the system was stocked with 9500 stocker-sized hybrid channel × blue catfish (29,320 fish/ha; average weight 80 g/fish). Fish were harvested in mid-November, 2007. Approximately 98% of the standing crop was harvested on the first seine haul. Total harvest weight was 7,275 kg (22,742 kg/ha) for a net fish production of 6,253 kg (19,479 kg/ha). Average fish weight at harvest was 0.91 kg/fish. Significant fish loss to *Edwardsiella tarda* infections in the last three weeks of growout reduced fish survival to 85% and feed conversion to 1.99. If those late-season losses are added to the final production (that is, if fish had been harvested 3 weeks earlier), net production would have been approximately 23,000 kg/ha with a feed conversion ratio of approximately 1.7. Maximum daily feeding rates averaged approximately 300 kg/ha in August and early September, yet total ammonia-nitrogen rarely exceeded 1.5 mg/L.

Results at a glance...

- *The Mississippi State University split-pond modification of the PAS can be constructed by modifying existing earthen fish ponds. Net annual catfish production has ranged from 17,000 to almost 20,000 kg/ha (15,000 to 18,000 pounds/acre) at feed conversion ratios less than 2.0. After successful scale-up in 2009, several catfish farmers are building split-ponds for commercial use in 2010.*

The system was renovated in winter 2008 to repair eroded embankments. The re-built system in 2008 consisted of a 0.065-ha fish confinement area and a 0.219-ha waste-treatment area, providing a total system area of 0.283 ha. In spring 2008, the system was stocked with 8750 stocker-sized hybrid channel × blue catfish (30,887 fish/ha; average weight 88 g/fish). Fish were offered feed to satiation daily starting 9 April. Fish were harvested 30 October 2008. Total harvest weight was 6,933 kg (24,432 kg/ha) with an average weight of 0.82 kg/fish. Net production was 6,153 kg (21,686 kg/ha). Survival was 97% with an feed conversion ratio of 1.90. Once again, maximum daily feeding rates averaged more than 300 kg/ha for several weeks in August and early September, yet total ammonia-nitrogen rarely exceeded 1.5 mg/L.

In April 2009, the system was stocked with 8750 stocker-sized hybrid channel × blue catfish (30,887 fish/ha; average weight 50 g/fish). Fish were harvested in late October, 2009. Total harvest weight was 20,160 kg/ha; net fish production was 18,620 kg/ha. Average harvest weight was 0.70 kg/fish. Harvested yield and net fish production were somewhat less than in previous years because smaller-sized stockers were used and a prolonged period of unseasonably cool, rainy weather in late August and September caused poor feeding conditions. Maximum daily feeding rates during that period averaged less than 250 kg/ha, whereas feed additions often exceeded 300 kg/ha per day during the same period in previous years.

A commercial-sized split-pond was constructed in 2008 and put into production in 2009. The large split-pond consists of a 1.42-ha algal basin and 0.40-ha fish-confinement area. Overall design was similar to the pilot-scale system used in previous years. Two, 3.7-m-wide concrete-block sluiceways were constructed at either end of an earthen cross-levee. Both sluiceways were fitted with double, expanded metal fish barriers to prevent fish movement between the two basins. Water was pumped from the fish-confinement area into the algal basin with a six-bladed, 3.66-m long, 2-m diameter paddlewheel installed in one sluiceway; the other sluiceway accommodated return water into the fish-confinement area. The paddlewheel was driven at 2.5 rpm with a 3.7-kW gearmotor, which induced a water flow of 60 m^3/minute. Aeration in the fish confinement area was provided by two, 7.5-kW paddlewheel aerators. Aeration and water flow was controlled by a set of remote-sensing dissolved oxygen probes. Aeration with one paddlewheel aerator was initiated when dissolved oxygen concentration fell below 5 mg/L in the fish confinement area; the second aerator was activated when dissolved oxygen concentration fell below 3 mg/L. The large paddlewheel pumped water between the two sections only when dissolved oxygen concentration was above 5 mg/L in the algal basin.

The large split-pond was stocked in April 2009 with 45,000 stocker-sized hybrid channel × blue catfish (24,700 fish/ha; average weight 54 g/fish). Fish were fed on 202 days until harvest in late October, 2009. Overall survival was 98% and total harvest weight was 19,210 kg/ha, giving a net fish production of 17,880 kg/ha. Average fish weight at harvest was 0.80 kg/fish. A total of 32,800 kg/ha of feed was offered to fish, resulting in a feed conversion ratio of 1.83. Average daily feeding rate over entire feeding period was 162 kg/ha, with maximum daily feeding rates averaging approximately 250 kg/ha in late August through September.

In addition to good fish production and few water-quality problems, the Stoneville "split-pond" system offers advantages related to confining the fish into a smaller area than in traditional ponds. Fish in the confinement area are easier to feed and harvest. The smaller area is also easier to protect from bird predation. Although not yet required in our studies, the fish-confinement area can be isolated from the rest of the pond, making it easier and far less expensive to use certain disease therapeutants because only about 15 to 20 percent of the total pond water volume is treated These attributes, combined with fish production characteristics that exceed those achieved in traditional ponds, make the split pond an attractive alternative for commercial catfish culture.

Objective 1b. *Installation of low-cost, semi-confinement systems in commercial-scale, earthen ponds.*

University of Arkansas at Pine Bluff. Five confinement systems were installed in research ponds at the UAPB Aquaculture Research facility to determine whether physically separating fish by size group with a pond confinement system would result in improved yield, survival, feed conversion ratio, and growth compared to normal multiple-batch culture. This study consisted of ten, 0.1-ha ponds; five were control ponds and did not have barriers. The five treatment ponds had a 1.27-cm × 2.54-cm PVC-coated wire mesh barrier that partitioned off a third of the pond. In the treatment ponds, fingerling catfish were reared in the smaller portion of the pond and larger carryover fish were stocked in the remaining larger portion of the pond. The fish in the control ponds were allowed to co-mingle as in traditional multiple-batch culture. Ponds were seined every 2 months during the growing season and average weights were calculated to estimate growth. After harvest, survival and FCR were calculated. The facility was stocked on April 28, 2005 and the study terminated on October 18, 2005.

Mean net yield of the fingerlings, total feed fed (kg/ha), and mean daily feeding rate (kg/ha/d) were greater in the confinement system than in the control ponds (Table 2). However, there were no differences in net yield of carryover fish, overall feed conversion ratio, or survival of either size of fish in the confinement system as compared to the control ponds. There were no significant differences in total ammonia, un-ionized ammonia, nitrite, nitrate, total nitrogen, and total phosphorus concentrations. The confinement system appears to offer potential to increase yield of fingerling catfish because of greater feed consumption in the system when the barrier is used to separate size classes. A partial budget analysis with price sensitivities was completed for the first study of raising fish in the confinement system. When fingerlings were physically separated from larger, carryover fish, significantly greater yields of fingerling (stocker) fish were achieved. There were no significant differences in survival, feed conversion ratio, or growth. The partial budget analysis revealed a positive net change of $367/ha or $38,125 for a 104-ha catfish farm at a market price of $1.54/kg of additional stockers produced (Table 3).

Another study was initiated in the spring of 2006 to compare production of catfish within the barrier system to open pond culture. This will help determine if there are any potential culture advantages to confining catfish to one-third of the total pond area. Stocker-sized catfish (136 g) were stocked into the smaller section of the confinement ponds and in the open ponds at a rate of 11,115 fish/ha. Yields, feed conversion ratios, and daily growth of food fish were significantly lower in the confinement system than in the open ponds, but there were no differences in survival (Table 4). However, seining efficiency was significantly greater for the confinement system.

Table 2. Selected data of fingerling and carryover fish in control and confinement ponds. Values with the same letter in the row are not significantly different. All values are mean ± SD.

	Control	Confinement
Net Yield (kg/ha)		
Fingerlings	1,788 ± 448a	2,391 ± 158b
Carryover	4,882 ± 490a	4,712 ± 679a
Total Feed Fed (kg/ha)	11,095 ± 541a	12,189 ± 579b
Mean Daily Feeding Rate (kg/ha/d)	62 ± 3a	67 ± 3b
Feed Conversion Ratio	1.67 ± 0.2a	1.68 ± 0.1a

Table 3. Partial budget analysis for the confinement system on a 104-hectare catfish farm, Study 1.

Parameter	Description	Unit Cost($)	Quantity	Benefit/Cost ($)/Farm	Benefit/Cost ($)/ha
Additional costs					
Variable Costs					
	Feed	250/ton	107	26,750	257
	Interest	0.10	1	2,675	26
Fixed Costs					
	Depreciation	179,336	10 yrs	17,934	172
	Interest			11,253[a]	108
Reduced revenue[b]				0	0
Total additional costs and reduced revenue				58,612	563
Additional revenue					
	Stockers	1.54/kg	62,816	96,737	930
Reduced costs[c]				0	0
Total additional revenue and reduced costs				96,737	930
Net change in profit				38,125	367

[a] Average annual interest based on a loan amortized for 10 years at 10% interest.

[b] There are no reduced costs from adopting the barrier system.

[c] There is no reduced revenue since there is an increase in yield resulting from the confinement system.

Table 4. Yield, survival, growth, mean weight and percent of the population that is sub-marketable at harvest of stocker catfish stocked in the confinement system and in open control ponds, Study 2. Values with the same letter in the row are not significantly different. All values are ± SD.

Production parameter	Unit	Confinement	Open
Gross yield	kg/ha	6,783 ± 345a	8,315 ± 254b
Net yield	kg/ha	5,274 ± 345a	6,806 ± 254b
Survival	%	80 ± 0.05a	85 ± 0.02a
Growth	g/d	3.69 ± 0.3a	4.29 ± 0.2b
Mean weight at harvest	g	759± 62a	884 ± 34b
Sub-marketable	%	22 ± 8a	13± 5a

The partial budget analysis (Table 5) showed a change in revenue of -$2,186/ha (-$227,334 across a 104-ha farm) at a food fish market price of $1.54/kg. Single-batch grow out of catfish stockers, under the conditions of this study, was not economically feasible in spite of the improved seining efficiency. Additional research is needed to determine whether refinements to the system can achieve yields similar to those in open ponds.

To evaluate scale-up issues, a commercial size barrier system was constructed on a catfish production facility in Chicot County, Arkansas (Figure 13). The barrier system was constructed in a 6-ha earthen

Table 5. Partial budget analysis for the confinement system on a 104-hectare catfish farm, Study 2.

Parameter	Description	Unit Cost($)	Quantity	Benefit/Cost ($)/Farm	Benefit/Cost ($)/ha
Additional costs					
Variable Costs		0	0	0	0
Fixed Costs					
	Depreciation	179,336	10 yrs	17,934	172
	Interest			11,253[a]	108
Reduced revenue	Foodfish	1.54/kg	159,328 kg	245,365	2,359
Total additional costs and reduced revenue				274,552	2,640
Additional revenue[b]		0	0	0	0
Reduced costs					
	Feed	250/ton	171.7	42,925	413
Interest			0.1	4,293	41
Total additional revenue and reduced costs				47,218	454
Net change in profit				-227,334	-2,186

[a] Average annual interest based on a loan amortized for 10 years at 10% interest.

[b] There is no additional revenue from adopting the barrier system.

Figure 13. Construction of a commercial-scale confinement system in a 6-ha earthen pond in Chicot County, Arkansas.

pond that was under renovation. Construction of the barrier system was completed by mid-October 2006. The barrier system was stocked with channel catfish on 21 March 2007. Approximately 2 weeks after stocking, it was evident that catfish were escaping from the barrier system. Within a month, the number of catfish outside the barrier had increased to a critical level and the farm manager had to start feeding fish on both sides of the barrier. We found a 5- to 7-cm gap between the barrier and the pond bottom along a deep depression about mid-way across the pond where the fish were congregating. This area was the deepest part of the pond along the transect where the barrier was constructed. Due to the escapement problem, the barrier was removed from the pond and the study was terminated.

Several factors may be responsible for barrier failure, and these factors may seriously affect the usefulness of this practice. First, poor compaction of the soil during pond renovation resulted in low spots being filled with loose fill material. Second, the barrier was not buried deep enough to get at least 15 cm below the hard-pan bottom of the deepest section of the pond. After all the loose fill material was swept clean from this area by fish activity, the bottom of the fence was exposed. In smaller research ponds over two separate seasons of production we never had a fish escape. However, because the fencing material was only 1.8 m, we had to decrease the height of the standpipe and thus the pond depth to keep fish from going over the top. If we would have buried the commercial pond barrier deep enough to prevent this problem, we would have had to drop the level of the standpipe by at least 0.3 m.

An alternative confinement system was designed and constructed in two, 0.1-ha research ponds during the spring and early summer of 2008 to address the escapement issue and to take advantage of the benefits related to segregating fish by size. The current design (Figure 14) includes two, 18-cm

Figure 14. Overview of the circular production units constructed in a 0.25 acre pond at the University of Arkansas at Pine Bluff, Aquaculture Research Facility.

(7-inch) diameter confinement systems constructed of 1.8-m-high PVC-coated wire mesh fastened to steel fence posts and imbedded in a circular concrete slab. Each production unit (pen) was fitted with a sliding gate mechanism that provides for the attachment of a standard harvesting sock for fish movements. Also, each pen includes a simple feeding tube to direct blown feed to the pen, a feed containment ring, and protective bird netting. Standard paddlewheel aeration was positioned so that aerated water would circulate through both the pens (Figure 14). Construction of the pens was completed in mid-July, 2008.

Channel catfish (1,500 fish, 69 g/fish) were stocked into one pen in each pond on 21 July 2008. This corresponds to a fish density of approximately 350 fish/m3 (10 fish per cubic foot) and a stocking density of 13,400/ha of pond. These fish have responded well to the system and production data is currently being collected. The second pen in each pond was stocked with larger channel catfish (1,500 fish weighing 350 g/fish) on 21 August 2008. These fish have also responded well to the system. Production data will be collected through the remainder of the 2008 growing season.

Objective 1c. *Fry and food fish production using in-pond raceways with the option for culturing supplemental species in open-pond areas.*

Louisiana State University. As part of an effort to improve the efficiency of intensive pond aquaculture systems, the potential for double-cropping freshwater prawns in Louisiana was evaluated. Juvenile prawns were stocked into twelve, 400-m2 ponds at a nominal density of 2.5/m2 on 7 May and fed a 32%-protein sinking feed at a daily rate of 25 kg/ha. Vertical substrate at 25% of pond surface area was installed in each pond. Ponds were aerated nightly. Prawns in six ponds were harvested between 3-4 August (after 88-89 d) and subsequently re-stocked with prawn juveniles that were cultured until November 7-9 (91-93 d); prawns in six ponds were cultured from early May until early November (184-186 d). Prawns harvested in the single-crop treatment were 55 g each, whereas prawns harvested from the first (early) crop were 24 g each and the prawns from the second (late) crop were 29 g each. In aggregate, production from double-cropped ponds was 822 kg/ha and production from single-cropped ponds was 568 kg/ha. An economic evaluation of the two cropping systems is being conducted. More prawns were produced in the double-crop treatment, but the prawns were of lower average weight than the prawns produced in the single-crop treatment. The additional biomass in the single-crop treatment will be evaluated relative to the price premium that can be obtained for larger animals. Also during 2007, development of the Partitioned Aquaculture System (PAS) continued, including automation of data acquisition. In particular, development of a cost effective system to monitor and manage critical water quality parameters, including dissolved oxygen, pH, and nitrite nitrogen continued. Development of linkage between this project and a related project in which autonomous vehicles were used to capture water quality in ponds and natural water bodies is in progress.

A 0.3-ha (0.75-acre) Partitioned Aquaculture System, with three fish-culture raceways, were stocked with channel catfish, blue catfish, and channel × blue catfish hybrid fingerlings in separate raceways between 29 June and 19 July. Average stocking size and density were as follows: channel catfish, 29 g and 5,000 fish/raceway; channel × blue catfish hybrids, 32 g at 5,000 fish/raceway; and blue catfish, 36 g and 4,683 fish/raceway. The collective stocking density of catfish was 14,683 fish (48,300/ha). Catfish were fed daily, generally as much as they would consume. In July 1,396 Nile tilapia weighing 391 kg (average weight = 272 g) were stocked into the open pond area of the system for algal control. After 533 days of culture, catfish were harvested.

Production of blue catfish and channel × blue hybrids were 2.4 times higher than for channel catfish (Table 6). Total catfish production of 4,570 kg equated to a yield of 15,014 kg/ha. Recovery rates of channel catfish from the PAS were low compared to blue catfish and channel × blue hybrids. No disease-related mortality was observed although wading birds were able to predate on some catfish. Feed consumption and subsequent growth of blue catfish and channel × blue catfish hybrids were 2 to 3 times higher than channel catfish which verifies finding from other studies that blue catfish and channel × blue hybrids appear to be better suited for high density cultivation. Feed conversion ratio of the system as a whole was 1.59. The presence of tilapia as biological filter-feeders in the open area of the PAS stabilized oxygen concentrations, and odiferous species of blue-green algae were rarely observed in the PAS. All tilapia died from cold water temperatures in January indicating that probably Nile tilapia overwintering in south-central Louisiana is remote.

Table 6. Recovery, size, and yield of channel, blue, and channel × blue catfish hybrids in three raceways in a 0.75-acre (0.3 ha) partitioned aquaculture system (PAS), Aquaculture Research Station, LSU AgCenter, Baton Rouge, LA.

Species	Number Stocked	Number Recovered	% Recovered	Total Weight of Fish (kg)	Average Size after 533 days (g)
Channel Catfish	5,000	2,126	43	783	368
Blue Catfish	4,683	3,088	66	1,824	590
C × B Hybrids	5,000	3,482	70	1.963	563
Total	14,683	8,696	59	4,570	

Objective 1d. *High intensity production in heterotrophic-based culture units.*

Louisiana State University. The performance of a heterotropic-based "biofloc" system consisting of eight 1.5-m3 tank mesocosms stocked with tilapia (3.0 kg/m3, 41 g/fish) was investigated in an indoor wet laboratory. Vigorous diffused aeration was provided to maintain solids in suspension, provide oxygen, and remove carbon dioxide. Settleable solids concentration was measured daily in each tank and maintained at eight different nominal concentrations (5, 10, 15, 20, 25, 50, 75, 100 mL/L) through intermittent operation of 80-L settling columns and removal of solids. The range of settleable solids concentration was equivalent to a range of total suspended solids concentration of about 250 to 1,000 mg/L. Daily feeding rate was increased weekly by 25 g/m3 and water quality was measured weekly before feeding rate adjustments. The biofloc system operated effectively within arbitrarily established water quality limits for ammonia, nitrite, carbon dioxide, and dissolved oxygen concentrations across a broad range of solids concentration and feed loading. After 11 weeks and a daily feeding rate of 275 g/m3, total ammonia concentration exceeded the pre-established criterion of 2 mg N/L in all tanks. For these indoor tank mesocosms, the sustainable maximum daily feeding rate is about 200 g/m3. At daily feeding rates greater than 200 g/m3, control of solids concentration became more difficult and water quality became more variable. Process instability was related to the development of filamentous bacteria that produced severe foaming associated with flocs with poor settling characteristics. As solids concentration increased, water respiration rate, nitrification rate, and solids retention time increased, and hydraulic retention time decreased. Increases in water respiration and nitrification rates were also related to increases in daily feeding rate. There was no effect of solids concentration on specific growth rate (1.27 %/day), final biomass density (9.8 kg/m3), and feed conversion ratio (1.83). After a cumulative feed loading of about 12 kg/m3 and a cumulative feed burden of about 130 kg/m3, tilapia in all tanks displayed signs of respiratory distress and stopped feeding. All tilapia in one tank died. This loading limit was independent of solids concentration. Hypotheses offered to explain this effect include combined metal toxicity related to low hardness, nitrate toxicity, or some factor associated with the accumulation of dissolved organic matter. Within three days of a 50% dilution of tank volume, fish resumed feeding, indicating that dilution sufficiently reduced the concentration of the factor that caused cessation of feeding.

Based on the findings of 2006 biofloc study, the effect of cumulative feed burden (CFB) on the performance of a recirculating biofloc (a combination of suspended solids and attached microorganisms) tilapia system was investigated in eight 1.5-m3 indoor tanks stocked with tilapia (5.1 kg fish/m3, 183 g/fish) and cultured for 21 weeks. All tanks were vigorously aerated to provide oxygen (DO, 6.4-6.8 mg/L), homogeneous mixing of solids, and CO_2 stripping. Each tank was managed at one of eight CFBs. CFB is a measure of water use intensity and is calculated as the daily feeding rate (g/day) divided by daily effluent (water replacement) rate (L/day). Culture tanks were managed with a CFB of 1, 2.5, 5, 10, 15, 25, 50, or 100 g/L. CFB was managed by increasing the daily water exchange rate with the increase in daily feeding rate. The daily feeding rate was initially 85 g/m3, increased weekly by 15 g/m3, and ended at 325 g/m3. Water quality (TAN, NO_2-N, NO_3-N, TSS, pH, total alkalinity, CO2, water respiration, temperature and DO) was measured weekly. Settleable solids were controlled at concentrations less than 100 mL/L by intermittent operation of an 80-L settling column. Alkalinity was maintained near a targeted level of 150 mg/L as $CaCO_3$ by weekly additions of $NaHCO_3$.

The NO_2-N, pH, and alkalinity increased with a decrease in CFB, and NO_3-N, TSS, water respiration, and CO_2 decreased. Higher mean NO_2-N concentrations were observed in tanks with CFBs of 2.5 and 1. Nitrite concentration was negatively correlated with a decrease in TSS. The increased water exchange rate (i.e. shorter solids retention time, SRT), associated with low CFBs, likely resulted in a loss of nitrifying bacteria in the effluent that exceeded the ability of remaining nitrifying bacteria to process substrate inorganic nitrogen, thus resulting in significant accumulation of nitrite in tanks with a CFB of 2.5 and 1. Findings of this study indicated that a CFB of 5 or higher was needed to maintain satisfactory water quality conducive to fish production in biofloc recirculating systems.

United States Department of Agriculture-Stuttgart (formerly at Pine Bluff). An intensively-managed, microbial-based production system has been used successfully to culture penaeid shrimp and tilapia, and appears to have potential application in growing catfish. When used for penaeid shrimp or tilapia production, the microbial floc that develops in the culture unit serves as a sink for ammonia-nitrogen and as a supplemental food source for the culture species. While it is unlikely that catfish will derive nutritional benefit from the microbial floc, bacterial control of ammonia-nitrogen may permit increased catfish stocking and feeding rates.

Nine tanks (4.6 m × 9.2 m × 0.9-m water depth) with semi-circular ends that are equipped with a center divider and lined with HDPE were filled with well water on 6 April 2005 and each fertilized with

0.32 kg 18-46-0 fertilizer. Stock salt (5 kg/tank) was added on 12 April 2005 and 12 August 2005. Each tank was equipped with a 0.37-kW electric paddlewheel aerator that operated continuously. Well water was added periodically to replace evaporative losses.

In 2004, stocker channel catfish (un-vaccinated) stocked in the tanks suffered high mortality from ESC (Edwardsiella ictaluri). Channel × blue hybrid catfish were stocked in 2005 because they appear more resistant to ESC. Hybrid catfish (mean weight 0.085 kg/fish), obtained from the ARS Catfish Genetics Research Unit, Stoneville, Mississippi, were stocked on 13 April 2005 at 25, 50, 75, 100, 125, 150, 175, 200, or 225 fish/tank. A stocking error was detected for the 125-fish treatment, so that treatment was excluded. Fish were fed a 32% protein floating feed daily to apparent satiation. Beginning on 14 July 2005, white flour (0.7 kg/kg feed), as a flour-water slurry, was added daily as an additional source of carbon to tanks. Agricultural limestone (250 mesh) was added to tanks as needed beginning in mid-August to mitigate low water pH. All tanks were harvested by draining on 17 October 2005.

Hybrid catfish survival after 188 days ranged from 61.3 to 79.1%, with an average of 71.0% (Table 7). Mean individual weight at harvest appeared independent of stocking rate up to a stocking rate of 100 fish/tank (2.4 fish/m2), and decreased linearly (y = 0.0017x + 0.6988; R2 = 0.9835) at stocking rates of 100 to 225 fish/tank (2.4 to 5.5 fish/m2) (Table 7; Figure 15). Fish biomass at harvest increased linearly with stocking rate (Figure 16). Feed conversion was variable, ranging from 1.8 to 6.3, and averaged 2.8. Daily feed rates ranged from 13 to 331 kg/ha. The feeding response by hybrid catfish in the tanks was variable and appeared unpredictable.

Mean weekly nitrite-nitrogen concentrations were low and independent of fish stocking rate (or the total amount of feed fed; Table 8). Nitrite-nitrogen concentrations remained low throughout the experiment except between days 60-80 when concentrations spiked as high as 5.78 mg/L NO_2-N. Mean weekly nitrate-nitrogen concentrations were high and increased as fish stocking rate increased (Table 8). Concentrations of NO_3-N were 0.30 mg/L or less through about day 60, after which concentrations increased. Mean weekly total ammonia-nitrogen (NH_3-N) concentrations were

Table 7. Mean weight at harvest, gross and net yields, and survival of channel × blue hybrid catfish after 188 days. At stocking, mean fish weight was 0.085 kg/fish.

Fish/Raceway	Mean Weight (kg/fish)	Yield (kg/m^3) Gross	Net	Survival (%)
25	0.53	0.22	0.18	64.0
50	0.50	0.47	0.38	78.0
75	0.54	0.66	0.52	61.3
100	0.54	0.86	0.67	77.0
150	0.44	0.94	0.66	70.7
175	0.40	1.16	0.84	73.7
200	0.35	1.08	0.69	64.0
225	0.34	1.34	0.86	79.1

Figure 15. Mean individual weight at harvest of channel × blue hybrid catfish stocked at 25 to 225 fish in 41-m² raceways.

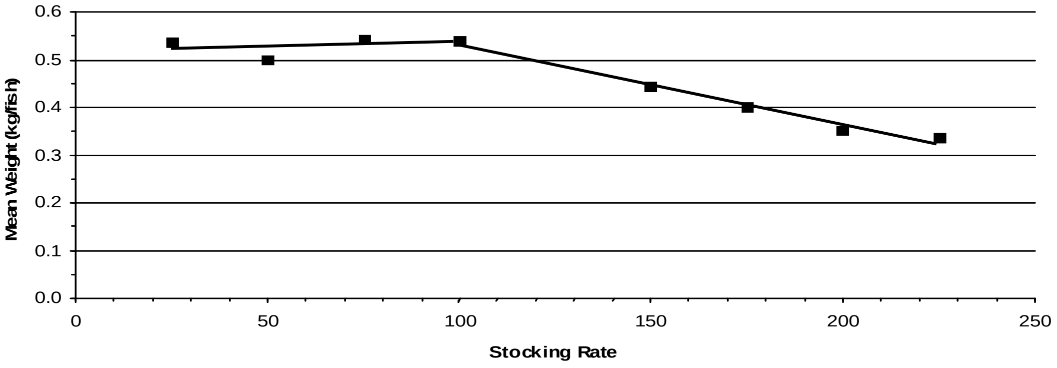
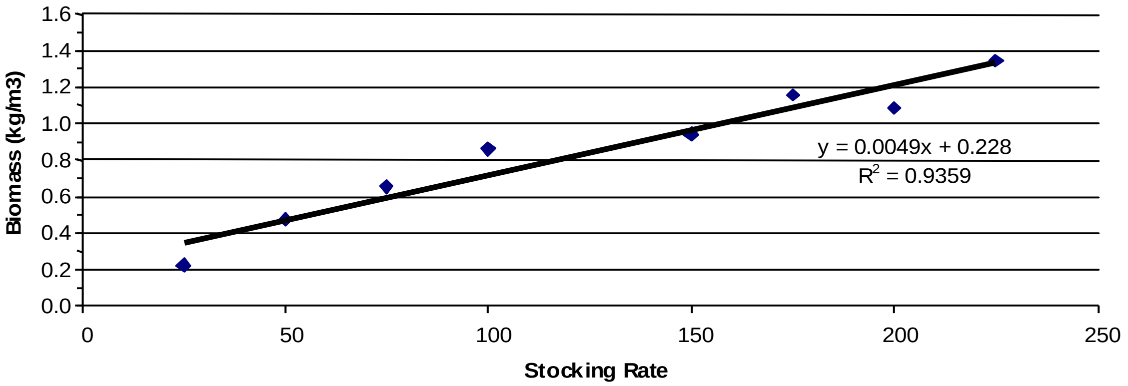


Figure 16. Relationship between final biomass and stocking rate of channel × blue hybrid catfish in 41-m² raceways.



low and independent of fish stocking rate (Table 8). There were several spikes in total NH_3-N concentration, generally in the tanks stocked with greater than 150 fish. The concentration spikes were short-lived and likely inconsequential to stocked fish because pH values were less than 7.9, and often less than 7.0. A maximum of about 5% of the total NH_3-N would be present as un-ionized ammonia at the water temperatures when the concentration spikes were observed. Mean weekly total nitrogen (N) and organic N concentrations were high and each increased linearly as fish stocking rate increased ($R^2 = 0.855$ and $R^2 = 0.909$, respectively; Table 8). Total N and organic N concentrations increased throughout the experiment. Organic N was, on average, 59% of the total N concentration.

Mean, weekly soluble reactive phosphorus was low and independent of fish stocking rate (or total amount of feed fed) below about 150 to 175 fish/

Table 8. Mean weekly concentrations of dissolved inorganic nitrogen and phosphorus, total nitrogen and phosphorus, organic nitrogen, pH, and chlorophyll *a* in raceways stocked with 25 to 225 channel × blue hybrid catfish.

Fish/ Raceway	NO_2-N	NO_3-N	NH_3-N	Total N	Organic N	PO_4-P	Total P	pH	Chlorophyll *a*
				mg/L					mg/m^3
25	0.390	13.88	0.03	30.91	16.60	0.26	1.07	7.30	1,241.6
50	0.056	7.19	0.29	22.57	15.03	0.16	0.93	7.50	908.1
75	0.197	9.66	0.01	25.77	15.90	0.08	0.74	7.29	1,264.4
100	0.108	12.31	0.01	32.08	19.65	0.24	1.03	7.28	803.2
150	0.225	16.83	0.02	43.13	26.06	0.27	1.38	7.07	1,223.8
175	0.289	18.75	0.03	45.23	26.15	0.15	1.11	7.01	1,126.8
200	0.106	21.60	0.35	53.08	31.04	0.57	1.50	6.74	1,461.0
225	0.205	28.82	0.38	67.43	38.02	0.76	2.00	6.64	1,454.5

raceway. Mean weekly concentrations increased linearly with increased fish stocking rate. Total phosphorus mean weekly concentrations ranged from 0.93 to 2.00 mg/L PO_4-P and increased linearly as stocking rate increased ($R^2 = 0.809$; Table 8).

Mean weekly early morning pH was 7.50 or less and decreased linearly as fish stocking rate increased ($R^2 = 0.869$; Table 8). During the first 100 days, mean, weekly early morning pH values were similar among tanks, and ranged from pH 7 to 8. After day 100, weekly early morning means became more variable and trended lower at stocking rates 150 fish/tank and greater. Afternoon pH generally was 0.5 to 1.0 pH units greater than the morning pH.

Mean, weekly chlorophyll *a* concentrations were high and increased linearly ($R^2 = 0.425$; Table 8). Chlorophyll *a* concentrations increased throughout the experiment in all tanks, attaining concentrations of 1,000 to 2,500 mg/m3 at the end of the experiment. A combined photoautotrophic-autotrophic bacteria system appeared to control tank water quality. Phytoplankton (photoautrotrophic) removed dissolved inorganic nitrogen and inorganic carbon as alkalinity or carbon dioxide. Autotrophic bacteria involved in nitrification oxidize ammonia to nitrate in a two-step process mediated by bacteria of two distinct genera. The populations of nitrifying bacteria appear to have become established in two stages beginning with increasing populations of ammonia oxidizing bacteria around days 60 to 80 that produced a spike in nitrite-nitrogen concentrations. Populations of nitrite oxidizing bacteria lagged slightly, with concentrations of nitrate beginning to increase around day 80. Total ammonia-nitrogen remained low throughout the experiment.

Nitrification results in decreased pH values, which were more apparent in tanks with the higher stocking rates. Applications of agricultural limestone were necessary in all tanks to mitigate the decrease in pH.

The 2006-2007 trial continued to investigate the effect of stocking rate on production of catfish in heterotrophic-based tank units. Three stocking rates were selected based on the 2005-2006 results.

On 28 March 2006, tanks were stocked with stocker hybrid channel × blue hybrid catfish obtained from the ARS Catfish Genetics Research Unit, Stoneville, Mississippi. Stocking rate was 100, 300, or 500 fish/tank (2.6, 7.9, or 13.1 fish/m3). Treatments were assigned randomly to tanks. There were three replicates per treatment. At stocking, fish averaged 0.069 kg/fish. Fish were fed daily to apparent satiation (20 min.) with a 32% protein floating extruded feed. Fish that died during the first 6 weeks were replaced from excess fish from the original population that were held in a hoop net in a pond. Dead fish were counted and, if intact, weighed. Gross feed conversion was calculated as the total quantity of feed divided by the total weight of fish harvested plus mortalities. All tanks were harvested by draining on 30 October 2006, 216 days after stocking. Specific growth rate (SGR) was calculated using the formula: SGR = 100(ln Wf – ln Wi)/t, where ln Wf is the natural log of the final individual weight, ln Wi is the natural log of the initial individual weight, and t is the duration in days.

Hybrid catfish survival and performance was poor (Table 9). Survival did not differ significantly among treatments and averaged 26.7%. Mean individual weight at harvest was independent of stocking rate over the range tested. Gross yield ranged from 0-0.96 kg/m3, did not differ among treatments, and averaged 0.48 kg/m3. Gross feed conversions ranged from 0.6-4.7, and did not differ significantly among treatments, and averaged 2.15. There was a curvilinear decline in feed conversion ratio with increased survival. Higher FCR was observed with lower fish survival. It was difficult to track low-level, chronic mortality accurately to use for adjusting feeding rates. The feeding response by hybrid catfish in the tanks was variable and appeared unpredictable and not as vigorous as with channel catfish. Maximum daily feed consumption (0.2-1.5 kg/tank) was observed from early June in seven tanks to early July in two tanks. Daily feed consumption decreased thereafter and oscillated between 3-50% of the maximum. The reduction in feed consumption was attributed to reduction in fish biomass caused by mortality and the apparent inability of the channel × blue hybrid to adapt to the tank environment.

Dissolved oxygen concentrations exceeded 40% of saturation throughout the experiment. Mean water quality variable concentrations (Table 10) did not differ significantly among stocking rates and were independent of feed and flour inputs. The absence of treatment effects on water quality variables was attributed to the lack of significant differences among treatment total feed input.

The high mortality of the channel × blue hybrid catfish combined with their variable and unpredictable feeding behavior indicates that a tank production system environment is inappropriate for the channel × blue hybrid catfish. Thus, treatment effects were unable to be expressed. Consequently, fish production characteristics and water quality variable responses were similar among treatments. The high chlorophyll *a* and nitrate concentrations observed in all tanks indicated that a combined

Table 9. Specific growth rate, mean weight at harvest, gross and net yields, and survival of channel × blue hybrid catfish after 216 days. Fish were stocked into raceways at 100, 300, or 500 fish/raceway (2.6, 7.9, or 13.1 fish/m^3). At stocking, mean fish weight was 0.069 kg/fish.

Treatment (fish/m^3)	SGR (%)	Mean Weight (kg/fish)	Yield (kg/m^3) Gross	Yield (kg/m^3) Net	Survival (%)
2.6	0.60	0.33	0.30	- 0.06	26.7
7.9	0.58	0.24	0.60	0.06	33.2
13.1	0.61	0.27	0.55	- 0.12	20.2

Table 10. Mean weekly concentrations of dissolved inorganic nitrogen and phosphorus, total nitrogen and phosphorus, total settleable solids, pH, and chlorophyll *a* in raceways stocked with 2.6, 7.9, or 13.1 channel × blue hybrid catfish/m^3. Means did not vary among treatments ($P > 0.05$).

	Fish/m^3		
Variable	2.6	7.9	13.1
Ammonia (mg NH_4-N/L)	1.36	0.57	1.25
Nitrite (mg NO_2-N/L)	2.74	1.81	2.51
Nitrate (mg NO_3-N/L)	12.75	13.21	11.49
Soluble Reactive Phosphorus (mg PO_4-P/L)	3.37	3.15	1.18
Total Nitrogen (mg/L)	36.20	37.80	36.20
Total Phosphorus (mg PO_4-P/L)	6.97	7.64	4.58
Total Settleable Solids (mL/L)	33.7	44.1	52.4
pH	7.39	7.41	7.43
Chlorophyll *a* (mg/m^3)	1733.50	2421.20	1663.40

photoautotrophic-autotrophic bacteria system controlled tank water quality. Phytoplankton removed dissolved inorganic nitrogen and inorganic carbon. Autotrophic, nitrifying bacteria oxidize ammonia to nitrate in a two-step process mediated by bacteria of two distinct genera. The populations of nitrifying bacteria appeared to have become established contemporaneously between days 21-49 that produced a transitory spike in nitrite-nitrogen concentration and increased nitrate-nitrogen concentration. Total ammonia-nitrogen generally remained low throughout the experiment, with the exception of several transitory spikes in concentration.

The 2007-2008 trial continued to investigate the effect of channel catfish stocking rate on production and water quality in mixed suspended growth (biofloc) tank culture units. Three stocking rates were selected based on the 2005-2007 results.

Nine tanks (35.1 m^2; 28.1 m^3) that have semi-circular ends, are equipped with a center divider, and are lined with HDPE, were filled with well water on 17 March 2007. On 19 March, each tank was fertilized with 0.32 kg 18-46-0 fertilizer. Salt was added to each tank to ensure chloride concentration exceeded 100 mg/L. A continuously operating blower system was installed to aerate tanks instead of an electric paddlewheel aerator. One 1.87-kW blower per three tanks provided air through a diffuser grid on the bottom of each tank. Well water was added only periodically to replace evaporative losses.

On 22 March 2007, tanks were stocked with fingerling

Results at a glance...

- *A zero-exchange, mixed suspended growth (biofloc) system capable of producing up to 4.8 kg of fish/m^2 was developed at the ARS Aquaculture Systems Research Unit. This production is more than 10 times that possible per unit volume of water in traditional channel catfish ponds.*

NWAC 103 strain channel catfish (*Ictalurus punctatus*) that had been vaccinated against *Edwardsiella ictaluri*. Stocking rate was 100, 200, or 300 fish/tank (2.9, 5.7, or 8.5 fish/m^2). Treatments were assigned randomly to tanks. There were three replicates per treatment. At stocking, fish averaged 0.013 kg/fish. Fish were fed daily to apparent satiation with a 32% protein floating extruded feed. Dissolved oxygen and temperature were measured daily, and water quality variables (pH, TAN, NO_2, NO_3, SRP, total settleable solids, and chlorophyll *a*) were measured on a weekly basis. In mid-June, most of the fish in one replicate of the 5.7 fish/m^2 treatment died overnight; an undiagnosed disease was the suspected cause as dissolved oxygen and water quality variable concentrations were within acceptable limits. Data from this replicate were excluded from analyses and reporting.

At harvest, 238 d after stocking, catfish net yield increased linearly from a mean of 1.0 to 3.7 kg/m^3 as stocking rate increased from 2.9 to 8.5 fish/m^2 (Figure 17). Mean final individual weight (semi-log transformed) decreased linearly from a mean of 0.57 to 0.50 kg/fish with increased stocking rate (Table 11). However, specific growth rate of fish did not differ among treatments. Fish survival varied among tanks and ranged from 48 to 73%, but did not differ significantly among treatments. Net fish yield was affected by fish survival, increasing linearly as final fish density increased from 0.9 to 6.7 fish/m^2.

Tank water quality was impacted significantly by channel catfish stocking rate, primarily because feed application increased linearly with stocking rate (Table 12). However, concentrations of water quality variables were within acceptable limits throughout the trial and did not appear to inhibit fish growth. Chlorophyll *a* and total settleable solids mean concentrations did not differ among treatments. Mean nitrite- and total ammonia-nitrogen concentrations did not differ significantly among treatments. Mean nitrate-nitrogen and soluble reactive

Figure 17. Relationship between net yield and stocking rate of channel catfish (*Ictalurus punctatus*) grown in a mixed-suspended growth (bio-floc) system in nine HDPE-lined raceways (35.1 m^2; 28.1 m^3) for 238 days.

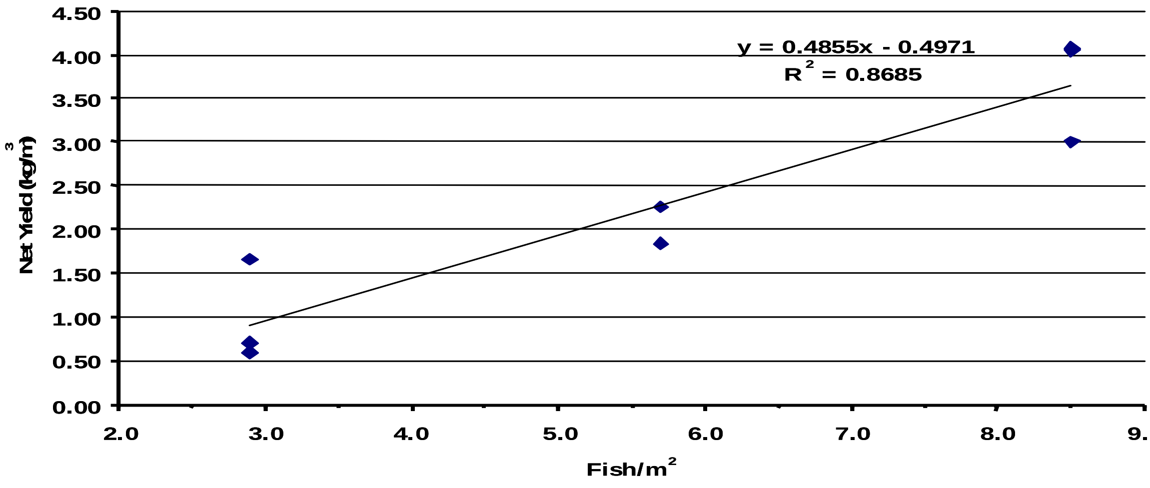


Table 11. Specific growth rate, mean weight at harvest, gross and net yields, and survival of channel catfish after 238 days. Fish were stocked into raceways at 100, 300, or 500 fish/raceway (2.9, 5.7, or 8.5 fish/m^3). At stocking, mean fish weight was 0.013 kg/fish.

Treatment (fish/m^2)	SGR (%)	Mean Weight (kg/fish)	Net Yield (kg/m^3)	FCR	Survival (%)
2.9	1.58	0.57	1.0	2.2	48.2
5.7	1.50	0.47	2.0	1.8	65.9
8.5	1.52	0.50	3.7	1.7	72.7

Table 12. Least squares mean weekly concentrations of dissolved inorganic nitrogen and phosphorus, total settleable solids, pH, and chlorophyll *a* in raceways stocked with 2.9-8.5 channel catfish/m^2.

	Fish/m^2		
Variable	2.9	5.7	8.5
Ammonia (mg NH_4-N/L)	0.30	0.25	0.49
Nitrite (mg NO_2-N/L)	0.25	0.23	0.42
Nitrate (mg NO_3-N/L)	5.98	7.59	19.20
Soluble Reactive Phosphorus (mg PO_4-P/L)	3.10	4.08	5.65
Total Settleable Solids (mL/L)	20.4	31.6	34.2
pH	7.77	7.72	7.51
Chlorophyll *a* (mg/m^3)	690.8	1,014.5	1,047.2

phosphorus increased with increasing stocking rate because of increasing amounts of feed fed. Nitrate-nitrogen began to accumulate in tanks beginning in mid-June in response to nitrification. Increased nitrification was inversely related to mean water pH. Fine-mesh agricultural limestone was added to tanks as needed to maintain pH.

In March 2008, the ARS Aquaculture Systems Research Unit, Pine Bluff, AR, was redirected to the Harry K. Dupree Stuttgart National Aquaculture Research Center, Stuttgart, AR. During April and May, nine HDPE-lined, 18.6-m^2 (15.5 m^3) tanks were constructed to further investigate the effect of channel catfish stocking rate on production and water quality in an intensive mixed-suspended growth system. One 1.87-kW blower per three tanks provided air continuously through a diffuser grid on the bottom of each tank. Tanks were filled on 11-12 June. Tanks were stocked on 18 June 2008 with fingerling NWAC 103 strain channel catfish (*Ictalurus punctatus*) vaccinated against *Edwardsiella ictaluri*. Fingerlings (47 g/fish average weight) were stocked in triplicate tanks at 7.5, 12.5, or 17.5 fish/m^2. Fish are fed daily to apparent satiation with a 32% protein floating extruded feed. Dissolved oxygen and temperature were measured on a daily basis, and water quality variables (pH, TAN, NO_2, NO_3, SRP, settleable solids, total suspended solids, and chlorophyll *a*) were measured weekly. Well water was added periodically to replace evaporative losses. In late July, fish were diagnosed with *Edwardsiella ictaluri*; fish in all tanks were fed for 10 days with medicated feed. Observed mortality from this disease outbreak was low. Beginning in September, sodium bicarbonate was added to tanks as needed to ameliorate decreased water pH. All tanks were harvested by draining on 3 November 2008, 138 d after stocking. All fish in each tank were weighed individually at harvest. Feed conversion ratio was calculated for each replicate as the net yield divided by the total quantity of feed fed.

The net yield of increased linearly from 3.1 to 4.8 kg/m^3 as stocking rate increased from 7.5 to 17.5 fish/m^2 (Figure 18). Mean individual weight at harvest did not differ significantly among treatments and averaged 0.36 kg/fish (Table 13). No significant difference in specific growth rate was detected among treatments (Table 13). Fish survival in the 17.5 fish/m^2 treatment

Figure 18. Relationship between net yield and stocking rate of channel catfish (*Ictalurus punctatus*) grown in a mixed-suspended growth (biofloc) system in nine HDPE-lined tanks (18.6-m^2, 15.5 m^3) for 138 days. At stocking, fingerlings averaged 47 g/fish.

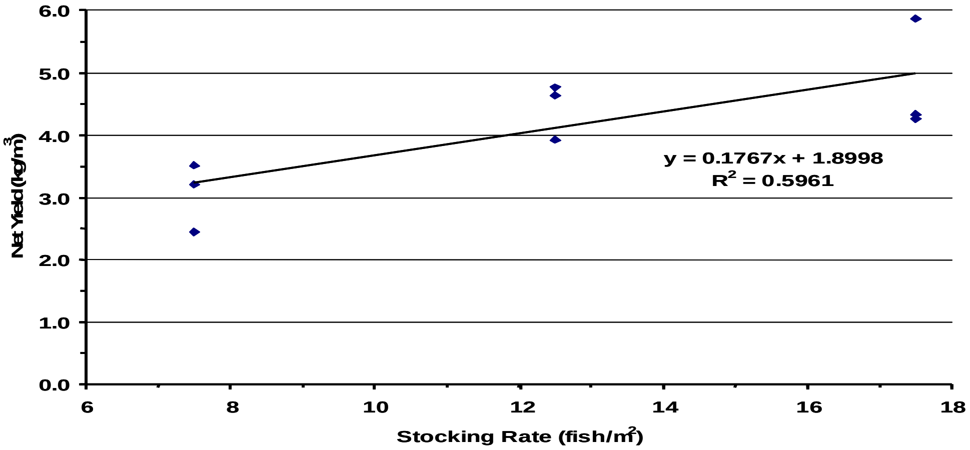


Table 13. Specific growth rate (SGR), mean weight at harvest, net yield, net daily yield, feed conversion ratio (FCR), and survival of channel catfish after 138 days. Fish were stocked into tanks at 7.5, 12.5, or 17.5 fish/m^2. Mean initial fingerling weight = 47 g/fish.

Treatment (fish/m^2)	SGR (%)	Mean Weight (kg/fish)	Net Yield (kg/m^3)	Net Daily Yield (g/m^3/d)	FCR	Survival (%)
7.5	1.56	0.40	3.1	22.2	1.58	96.4
12.5	1.47	0.36	4.4	32.2	1.47	96.3
17.5	1.36	0.31	4.8	35.0	1.63	88.9

averaged 88.9%, significantly lower than the 96.4% and 96.3% survival in the 7.5 and 12.5 fish/m^2 treatments, respectively. Fish survival was consistent among replicates within treatment. Mean daily feed consumption by fish at the 12.5 and 17.5 fish/m^2 stocking rates was 52.8 and 58.5 g/m^3/d, respectively, significantly greater than the 36.1 g/m^3/d of feed consumed by fish at the 7.5 fish/m^2. High feeding rates were sustained from late August through mid-October and averaged 51.4, 79.9, and 79.1 g/m^3/d, for the 7.5, 12.5, and 17.5 fish/m^2 treatments, respectively. Feed conversion ratio and specific growth rate did not differ significantly among treatments.

Mean nitrite- and total ammonia-nitrogen, settleable solids, and total suspended solids concentrations, and pH did not differ significantly among treatments. Cumulative feed addition increased linearly as stocking rate increased. Tank water quality variables were impacted differentially by cumulative feed addition. Mean total suspended solids, nitrate-nitrogen, and soluble reactive phosphorus concentrations increased linearly with increased cumulative feed addition. Mean chlorophyll *a* concentration decreased linearly with increased cumulative feed addition. Nitrate-nitrogen concentration began to increase in early July, indicating the onset of nitrification, and continued to increase throughout the remainder of the experiment. Sodium bicarbonate was added to tanks to mitigate the decreased pH that resulted from nitrification.

Objective 2. *Improve equipment to enhance culture.*

Objective 2a. *Motor-powered U-tube aerator for commercial-scale channel catfish ponds.*

United States Department of Agriculture-Stoneville. A prototype U-tube (Figures 19 and 20) was constructed and installed in a 0.4-ha pond at the National Warmwater Aquaculture Center, Stoneville, Mississippi. The U-tube was fabricated from a 91-cm-diameter, corrugated, galvanized culvert that was installed vertically in a 6-m deep bore hole made in the pond bottom. The unit was powered by a 240-volt, 3-phase, 3.72-kW, helical-geared Flender motor. The motor was vertically mounted on a 91-cm-diameter culvert elbow that was attached to the tube with a 25-cm band clamp. The motor turned a three-vane impeller attached to a 61-cm long × 5-cm diameter unsupported, steel shaft. Water level was maintained at the top of the elbow. The impeller speed was controlled by an in-line, general purpose, open-loop vector, AC-drive (Safetronics Model GP10). With an impeller speed of 150 rpm at 60 Hz, the motor drew 12.7 amps and produced 3.99 kW with a water output of 30.6 m3/min (Table 14).

Pump efficiency increased as impeller speed decreased, but both total output and water velocity decreased. It was determined that the higher velocity was necessary to entrain the volume of air needed to optimize performance. Air was provided by a 3.7-kW, 3-phase blower to diffusers located at or below the mouth of the "down-leg" of the U-tube, which was level with the pond bottom and approximately 1.5 m below the water surface.

Oxygen transfer efficiency tests were conducted using a variety of diffuser types and configurations. The optimum conditions produced an increase in dissolved oxygen of 2.3 mg/L (outflow DO minus inflow DO) and a standard aeration efficiency of 1.01 kg O2/kW·hr. These results were encouraging but less than desired for commercial application.

Two problems were noted during testing of the initial prototype during Year 1. First, it was desired to eliminate obstructions in the tube to enhance water flow. Thus, the impeller shaft was kept relatively short because it had no lateral support near

Figure 19. Prototype U-Tube with pond empty.

Figure 20. Prototype U-Tube with pond full. Discharge can be seen.

Table 14. Operational data for a prototype motor-powered U-tube aerator.

Impeller (rpm)	Motor Amperage	Volts	kW	Water Velocity (m/sec)	Water Output (m^3/min)	Pump Efficiency (m^3/kW · hr)
150	12.7	230	4.00	0.78	30.6	459
125	10.6	205	2.55	0.60	23.8	560
100	8.1	148	1.43	0.45	18.1	759

the end. This resulted in the impeller being located slightly above the bottom of the horizontal (discharge) end of the elbow. As the air:water ratio increased, back-flow from the pond through the mouth of the discharge was observed. This decreased water flow through the tube, and at higher air:water ratios, flow through the tube ceased entirely. Second, using this design, the water level is critical. If the water level dropped below the top of the discharge elbow, flow rate decreased. If the water level rose more than 15 cm above the top of the elbow, the motor could be damaged. For commercial application, the unit should have at least a 60 cm "freeboard" to allow for normal variations in pond water level.

During Year 2 (1 August 2005 – 31 August 2006), two major design modifications were introduced to eliminate the problems identified in Year 1. First, the shaft length was increased to 91 cm. The only concern was the potential for instability with a longer, unsupported shaft. This was not observed. The longer shaft was stable and apparently eliminated the "backflow" problem seen with the shorter shaft. Second, a 60 cm diameter × 41 cm insert was built and installed in the "down" leg of the tube. This did provide a faster water velocity in the "down" leg, allowing for a greater input of air into the system. Tests are now underway to quantify the impact of these modifications. While funding through SRAC ended in July 2006, work on this project is continuing under USDA/ARS funding.

In addition to further testing of the completed modifications, three additional design changes are being considered. First, a submersible motor placed in the mouth of the "down" tube would allow for larger pond water level fluctuations. This would be desirable in commercial applications. Suitable motors are being examined. Second, a venturi will be examined as a means of introducing gas into the water, eliminating the need for a blower. This would both reduce the overall horsepower requirements (increasing efficiency) and eliminate a motor that is a potential cause of failure. Third, the use of pure oxygen (instead of air) will be examined. While the economics may not justify this for routine aeration, the use of pure oxygen in an emergency situation could eliminate the need for a tractor-powered aerator.

Objective 2b. *Low-head, low-speed paddlewheel aerator for crawfish ponds.*

Louisiana State University. A low-speed paddlewheel mixer is being designed and a horizontal circulator/aeration unit was acquired for evaluation in two 1.5 to 2 ha (4 to 5 acre) experimental crawfish ponds at the Aquaculture Research Station in Baton Rouge. Baffle levees are being constructed to configure the ponds so that water can be recirculated. Mixing patterns and water quality will be monitored during the 2006-2007 crawfish production cycle.

Because of rainfall during the summer of 2006 ponds would not sufficiently dry to support heavy equipment required to laser-level ponds and construct internal baffles necessary install paddlewheel mixers. Weather conditions were more favorable in during summer 2007, and baffles were constructed in two large experimental crawfish ponds to accommodate a paddlewheel mixer and a submersible turbine mixer, respectively, in each pond. Mixing patterns, water quality and nutrient budgets will be determined in the mixed and non-mixed control pond during 2007-2008 crawfish production season.

Paddlewheel mixer/blending units were installed in three large experimental crawfish ponds at the Aquaculture Research Station each pond containing earthen baffles to re-circulate and mix water throughout each pond. Spatial distribution of dissolved oxygen (DO) in morning and afternoon was evaluated in March, May and June at 18 sampling stations in each pond. Mixers were operated continuously and DO were measured at each station in the morning and afternoon. Spatial variability in DO concentration throughout the ponds provided an index of the degree of water mixing. In March when significant amounts of cultivated rice forage was present and phtyoplankton density was low, oxygen concentration was more evenly distributed in mixed ponds (coefficient of variation, CV, associated with mean DO = 11%) than in non-mixed ponds (CV = 29%). However, in May and June when rice forage had been depleted and phytoplankton biomass increased, the variability of DO in mixed ponds (CV = 23%) was high as in non-mixed ponds (CV = 25%).

Objective 2c. *Low-power, electrically-enhanced seine to harvest market-sized channel catfish from commercial-scale ponds.*

Mississippi State University. The primary objectives for the first year of research were to design, manufacture, and test the electrical components required to build the individual modules that will power the electrically-enhanced seine. Three models of the power supply and electrical circuitry were designed, manufactured, and tested during this year. Through this process, the total weight of the electrical components needed to build an electrical module has been reduced over 60%. The power supply and electrical circuitry were miniaturized to fit on a 7.6 cm × 12.7 cm circuit board. A safety circuit designed to switch off the electrical power to a panel as it comes out of the water was added to the circuit board of the latest model of the system. The results of tests conducted in concrete vats indicate that the low powered electrical system (electrodes with no net) will repel adult catfish away from the attached electrodes. However, the system currently appears to be underpowered.

The miniature fish stimulator and power supply module was redesigned based on results of the first year. The system was further reduced in weight while maintaining the developed safety features. The output transformer was redesigned to operate at a higher frequency. In addition, the operating power was reduced from 60 to 10 watts. The results of vat tests using production-sized catfish indicated that the unit is only moderately effective as constructed. It was recently determined that the redesigned output transformer had a lower voltage than specified because of a tooling error by the manufacturer. Efforts are currently underway to get the manufacturer to correct this problem. The power supply and electrical circuitry will be re-tested once properly manufactured parts are obtained.

During the fall of 2006, efforts to eliminate manufacturing design flaws in the miniature transformer were unsuccessful; consequently, further development of the miniature transformer has been abandoned. During 2007, two new designs for a miniature fish stimulator were completed and the prototype units are currently being tested. Prototype-I operates without a transformer thus is the lightweight design. It is designed to stimulate catfish using a low voltage current produced by two AA-batteries. Prototype-II uses a power transformer to generate a high voltage AC pulse to stimulate catfish. The strength of the output current produced by both units can be controlled. The objectives of the new designs are to determine the efficacy of low-voltage system and to investigate the extent of the capabilities of the traditional transformer design. The ultimate goal is to develop an optimal design that is both lightweight and effective.

Problems were identified with both Prototype-I and Prototype-II fish stimulators when they were tested in concrete vats stocked with varying numbers of adult-sized catfish. Prototype-I (no transformer, low voltage, and light-weight) was not effective. Fish appeared to sense the presences of the electrodes but were able to easily swim past them. The design of this unit is being reevaluated; it will likely be abandoned. Prototype-II (high voltage with a transformer) was only moderately effect in repelling approaching fish. Also, durability issues with the unit must be resolved.

Modifications to Prototype-I and Prototype-II fish stimulators were unsuccessful in improving their effectiveness in repelling adult catfish away from the energized electrodes. Consequently, we have concluded that we will abandon our efforts to reduce the complexity, size, and weight of the electrical components needed to build an electrically enhanced seine.

Objective 3. *Assess energy, material, and economic efficiency of production systems.*

Objective 3a. *Quantify energy, protein, and water use in traditional systems for channel catfish culture.*

Auburn University. During 2005, data on electricity and fuel use were obtained monthly from four catfish farmers. However, in early 2006, the graduate student unintentionally caused slight, cosmetic damage to some equipment on one of the farms. All four farmers subsequently refused to cooperate further.

Data on the cost of electricity and fuel used on catfish farms are now being sought by other means. Twelve farmers, two hatchery owner-operators, one processing manager, and one seining crew manager agreed to participate in the study. In early summer of 2006, questionnaires about energy use were sent to the new cooperators. We have received full responses from four farmers, one seining crew manager, one processor, and no hatchery operators. Data collection was delayed by the onset of the peak of the farming season, and will continue again in the fall when people are more accessible. We anticipate full participation except for the two farmers that have been unresponsive.

The questionnaires include items on total use of electrical power and petroleum specific to each aspect of raising channel catfish. The questionnaires

Results at a glance...

- *Indicators of the efficiency of resource use in aquaculture have been developed and are being used by several environmental advocacy groups in assessing the sustainability of aquacultural production. Direct energy use for production of channel catfish in Alabama was 3.059 kW · hr/kg with 44% of energy used on farms.*

make sure that the respondent lists only energy use for catfish. The questionnaires also include items on fish survival, food use, and yields where appropriate.

During late 2006 and early 2007, we obtained the responses to the questionnaire mentioned above. In all, we obtained amounts of gasoline, diesel fuel, natural gas, propane, and electricity used and production achieved over a 12-month period for one pond construction firm, two hatcheries, four farms, a feed mill, a custom harvesting crew, and a processing plant. These data were incomplete and we had to visit the respondents and interview them to obtain sufficient information.

Energy for pond construction was from diesel fuel. The contractor provided data on fuel used and area of ponds constructed in one year. This allowed the calculation of energy use per hectare of pond construction, and the energy expenditure was amortized over 20 years, the estimated service life of a pond. Hatchery operations used only electricity. The feed mill used mainly natural gas as an energy source. About 80% of energy used on farms was from electricity and about 20% from diesel, gasoline, and propane. The harvesting operation relied on vehicles and other machines powered by diesel fuel. Electricity was the sole energy source for the processing plant. The kilocalories of hydrocarbon fuels used were converted to kilowatt · hours (kW · hr) so that these inputs could be easily combined with electrical energy.

The energy use estimates allowed calculation of energy expenditures (Table 15) incurred at each stage in the production chain for one kilogram of live catfish (completely processed). The greatest proportion of energy was used on farms and mainly for feeding fish and applying aeration to ponds by mechanical means. Manufacturing enough feed to produce 1 kg of fish required about 62% as much energy as used on farms to grow out 1 kg of fish. Processing required about half as much energy as feed manufacturing. The smallest amount of energy was used for harvesting. Pond construction required a large quantity of energy, but ponds last a long time. Thus, when energy for pond construction was spread over 20 years, it was only slightly greater than the energy used for harvesting. Hatchery operation was similar to pond construction with respect to energy use per kilogram of catfish. Estimation of the energy expended in shipping processed fish and maintaining them in refrigerated storage until used by consumers was not attempted. Moreover, energy consumed indirectly for producing feed ingredients, and for producing machines and fuel used in catfish production was not considered in this study.

Table 15. Direct energy use in channel catfish farming in Alabama.

Activity	Energy use (kW · h/kg)	Percentage
Pond construction	0.154	5.03
Hatchery	0.185	6.05
Feed	0.843	27.56
Grow-out	1.362	44.52
Harvest	0.092	3.01
Processing	0.423	13.83
Total	3.059	100.0

One kilogram of live catfish, the production of which required 2,630 kilocalories of energy directly, provides about 600 g or edible meat containing about 912 kilocalories (or 912 calories as referred to in human diets). This is an energy in:energy out ratio of about 3:1. Of course the ratio would be much greater if all indirect energy costs mentioned above were included.

At the farm level, the energy to produce 1 kg of fish costs about \$0.127. This is a substantial expense considering the farm gate price of catfish is only \$1.30 to \$1.60 per kilogram. The total cost of energy for producing and processing 1 kg of live catfish was about \$0.251.

It is doubtful that it would be possible to greatly reduce energy use for feed manufacturing or fish processing. About half of the energy use was on farms, and most of this energy went to power aerators. Improvement in the efficiency of aeration appears to be an opportunity for reducing energy use on farms. Moreover, improvement in the feed conversion ratio (FCR) in grow-out ponds could reduce the contribution of feed manufacturing to energy use/kg fish.

Investigations of water use require definitions of water use terminology. Total water use should refer to the amount of water applied to an aquaculture system in rainfall, runoff, and other natural processes and by management intervention, such as water added by pumping or other mechanical means.

Consumptive water use should represent the reduction in surface runoff caused by an aquaculture facility on a watershed. Less runoff equates to less stream flow for downstream water users. In addition, all freshwater withdrawn from aquifers by wells should be included as a consumptive use, because this water would not be available to other users of ground water in the area. Although ground water is re-charged by infiltration, it sometimes is removed by wells at a rate exceeding recharge. This diminishes the amount of water available from wells in the area. Ground water depletion usually is more serious in arid than in humid climates, but even in humid climates, availability of water from wells may be reduced during the dry season and especially during droughts. Consumptive water could be determined as follows:

Consumptive water use = Reduction in stream flow + Water withdrawn from wells

The amount of ground water pumped or derived by artesian flow from wells should be indicated as a separate variable for ground water use. This is a major issue in many regions. Spring flow should not be included, for springs discharge onto the land surface naturally.

Non-consumptive water use should refer to water that passes through aquaculture facilities and is still available to other users downstream. It could be calculated as follows:

Non-consumptive water use = Total water use – Consumptive water use

A water use index relating the amount of water used in an aquaculture facility to production could be useful. Although this index could be calculated for both total and consumptive water use, the consumptive water use index would be most meaningful. The index could be calculated as shown below (mt = metric tons):

Water use index (m^3/mt) = consumptive water use (m^3) ÷ production (mt)

An index of the economic value of water used in aquaculture should be available. This variable could be determined with the following equation:

Water value index (\$/m^3) = [production (mt) × crop value (\$/mt)] ÷ consumptive water use (m^3)

Studies of protein use in catfish farming also will require some indices of protein and fish meal use. The following indices have been developed based upon the feed conversion ratio (FCR):

> Protein conversion ratio (PCR), an index of the amount of feed protein needed per unit of production: PCR = FCR × [feed protein (%) ÷ 100]
>
> Protein equivalence (PE), the ratio of feed protein to aquaculture protein produced: PE = FCR × [Feed protein (%) ÷ protein concentration in live culture species (%)]
>
> Fish meal conversion ratio (FMCR), the ratio of fish meal in feed to aquacultural production: FMCR = FCR × [fish meal in feed (%) ÷ 100]
>
> Live fish equivalence of fish meal (LFE), the ratio of live fish needed for the fish meal in feed to aquacultural production: LFE = FMCR × 4.5

The Auburn University component of this project was completed in 2007. However, during 2008, two manuscripts were written and published, and a paper describing the results of the energy study was presented at a scientific meeting.

Objective 3b. *Develop and evaluate economic and financial models of existing and improved production practices and technologies.*

University of Arkansas at Pine Bluff. Cash flow budgets were developed for five farm sizes: 24 ha, 103 ha, 147 ha, and 407 ha. Validation tests were conducted against cash flow budgets of commercial catfish farms. The effect of varying equity levels, from 0% to 100% was measured across the five farm sizes (Figures 21 and 22). Schedules of cash flow and cash flow risk were developed in 10% increments from 0% to 100% equity for each farm size. With 100% equity, monthly cash flows were positive for all months except February for all farm sizes. Cash flow risk ranged from 0.28 to 0.31 when compared with total cash inflow and from 0.39 to 0.44 when compared against operating expenses. With 100% financing, only the larger farm sizes cash flowed, but at very high levels of risk (0.0008 compared to cash inflow and 0.0012 compared against operating expenses).

A survey was conducted to gather data from lenders with portfolios in catfish, row crop, and livestock loans. A total of 80 banks (6 in Alabama, 23 in Arkansas, 36 in Mississippi, and 15 in Louisiana) have been included in the sample. Of these, 32 have catfish loans and 48 have agriculture, but not catfish loans. Data obtained from the survey was used to identify the range of lending programs, structures, and repayment plans commonly used for catfish,

Results at a glance...

- *Detailed cash flow budgets were developed for existing and new startup catfish farms under a variety of equity positions. Budgets measure cash flow risk for varying farm sizes with different levels of financing and different management strategies.*
- *Current cash flow budgets showed a much longer time period to develop positive cash flow than for budgets developed more than 20 years ago. This finding explains financial difficulties for farms that entered catfish production in the 1990s. Startup catfish farms require a 4-year cash flow planning period. Purchasing stockers in the first year alleviates cash flow problems. This study identified sizes and stocking densities of stockers that result in positive cash flow in the early years of a catfish farm.*

Figure 21. Cash flow coverage ratio across farm sizes with 30%, 60%, and 90% financing.

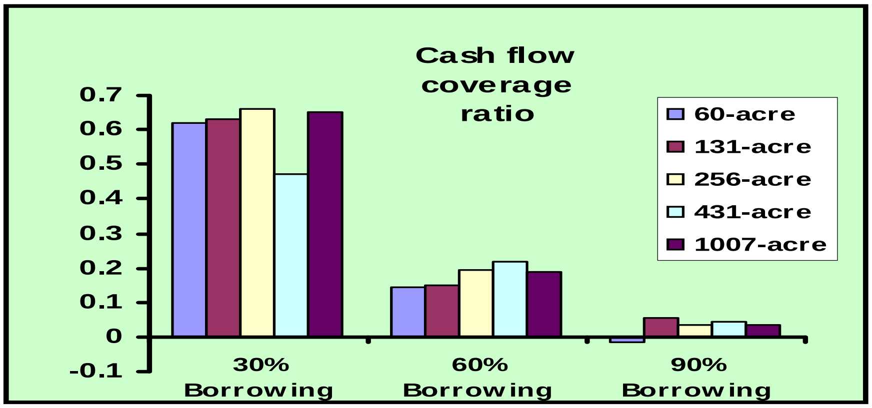
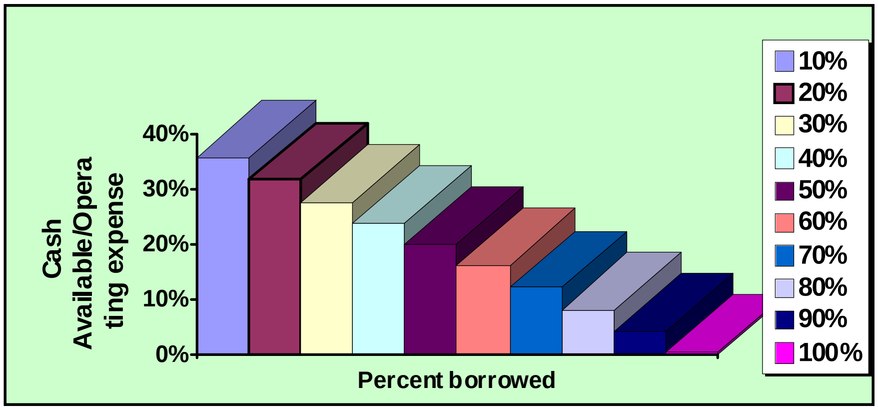


Figure 22. Cash availability compared to operating expenses on a 256-acre farm with levels of financing from 10% to 100%.



loans as well as those commonly used in other types of agriculture. These financial lending scenarios will then be applied sequentially to the cash flow budgets to assess the effects on cash flow and repayment capacity.

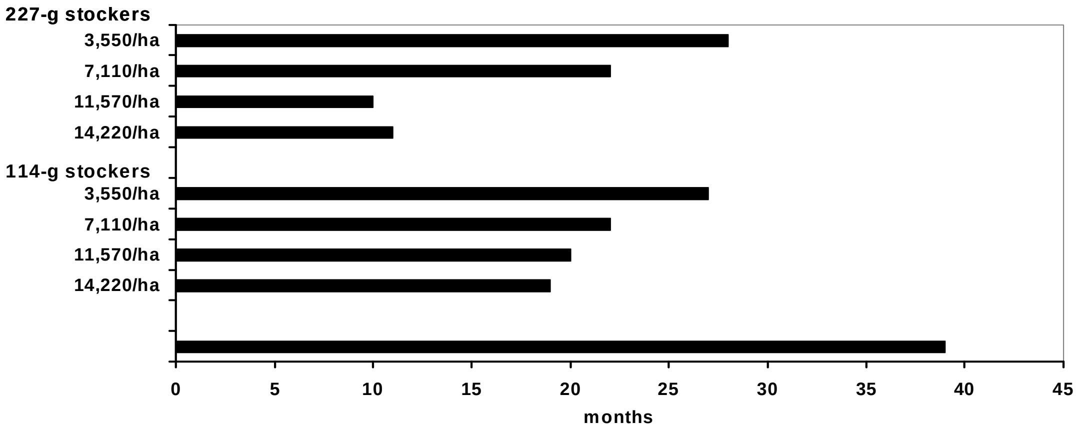
The initial cash flow budgets were developed for existing farm situations, farms that had been in business for a number of years. However, startup catfish farms require four years to build production to levels that generate adequate cash flow, if initial stockings are based on 12.7-cm fingerlings. Additional cash flow budgets were constructed to measure effects of the use of varying percentages and sizes of stockers on cash flow. The cash flow budgets developed for the 24 ha, 103 ha, 147 ha, and 407 ha catfish farms were further modified to reflect cash flow for startup catfish businesses. The effect of equity position was varied from 0% to 100% in 10% increments to evaluate its effect on startup catfish businesses.

These budgets are multi-year budgets with no revenue in Year 1 because a startup farm that stocks fingerlings will have no revenue in Year 1. These budgets showed that, for all five farm sizes, cash flow did not become positive until Year 4. These results, based on current cash flow conditions, showed a much longer time period to develop positive cash flow than previous cash flow budgets (that are more than 20 years old). This finding explains financial difficulties of farms that entered catfish production in the 1990s. Startup catfish farms require a 4-year cash flow planning period.

Use of stockers improved cash flow and reduced the number of years required to reach adequate cash flow coverage, with the degree of the effect varying with the size of stockers used and the percentage of total stocking devoted to stockers. A startup catfish farm requires 39 months to achieve a positive cash flow (Figure 23). Stocking ponds with 114-g catfish stockers reduces the number of months to achieve positive cash flow to 19-27 months. Stocking 14,220 stockers/ha achieved the shortest time, 19 months. Stocking at lower rates lengthens this time to 20 (11,570/ha), 22 (7,110/ha), and 27 (3,550/ha). Stocking 227-g stockers at the higher rates (14,220/ha and 11,570/ha) resulted in positive cash flow in the first year (10 and 11 months). However, the lower stocking rates of 7,110/ha and 3,550/ha did not improve the time to achieve positive cash flow over that of 114-g stockers, but would be more costly. Thus, if a farm must generate positive net cash flow in the first year, 227-g stockers should be used at 11,570/ha. If a positive cash flow is not needed until the second year, 114-g stockers can be used at either 11,570/ha or 14,220/ha. These results were robust across the five farm sizes modeled.

Two mathematical programming economics models have been developed that incorporate grow-out and fingerling production activities. The models maximized net farm income subject to constraints that include: quantity of operating capital, the number of ponds available, farm size, appropriate balance and transfer rows, and non-negativity conditions. Fingerlings were produced either with or without thinning at different stocking densities. Results showed that the optimal size of fingerling to under-stock was 12.7 cm. On-farm production of fingerlings was selected across all farm sizes but the fingerling production technique selected varied with farm size. Models of larger farm sizes began to thin fingerling production ponds, while models of smaller farm sizes produced fingerlings only without thinning.

Figure 23. Length of time (months) required to achieve positive cash flow with no stockers and various stocker options.



When farm size was treated as endogenous, the optimal size of a catfish farm was 404-water ha. Sensitivity analyses suggested that net returns were sensitive to changes in the key parameters of the model, whereas the optimal size of fingerling to under-stock was robust to variations in the model's parameters. In multiple-batch production, profits were maximized with on-farm production of 12.7-cm fingerlings.

We developed a second multi-period mixed integer-programming model that included six different types of stockers (stockers produced from 6.7-cm fingerlings stocked at 50,000, 100,000, and 150,000/ha, and from 9-cm, 11-cm and 13-cm fingerlings stocked at 100,000/ha) and three different sizes of fingerlings (7.6-cm, 12.7-cm, and 17.8-cm). The results revealed that nearly one-third of the area available for catfish grow-out production should be allocated to foodfish production from fingerlings and two-thirds from stockers. Profits were maximized with on-farm production of 12.7-cm fingerlings, and stockers produced from 9-cm and 11-cm fingerlings stocked at 100,000/ha (Table 16). Sensitivity analyses suggested that the results were sensitive to varying levels of operating capital in that a decrease in the availability of operating capital would result in an increase of foodfish production from fingerlings and a decrease in foodfish production from stockers. Increased availability of operating capital increased on-farm production of stockers for subsequent use in foodfish grow-out. Results of this analysis provide guidelines for farmers related to trade-offs between the use of fingerlings and stocker catfish on farms.

The mathematical programming models of fingerling and stocker production were extended to incorporate the cash flows required as indicated by the cash flow budgets for the various farm sizes and equity positions. Results show that cash flow position affects the selection of optimal management strategies.

The models demonstrated that, when lenders restrict access to operating capital (for example, when lending limits decrease as the price of fish decreases and the value of assets on the balance sheet falls), and there are cash shortfalls, farms are forced to take ponds out of production. The effect is more pronounced on smaller farms. Across all farm sizes, the financial

Table 16. Results of simulations of farm size and pond allocation to stockers and fingerlings.

				Fry Stocking Rates Stockers (fry/ha)			
	Pond Allocation			No Thinning		Fingerlings Stocking Rate (100,000/ha)	
Farm Size	Stockers	Fingerlings	Fingerlings Stocked	543,334	1,398,990	9-cm	11-cm
(ha)	(%)	(%)	(cm)	(%)	(%)	(%)	(%)
40	71	29	12.7	0	100	96	4
80	71	29	12.7	0	100	100	0
120	71	29	12.7	0	100	99	1
160	70	30	12.7	0	100	95	5
200	66	34	12.7	1	100	81	19
240	62	38	12.7	25	75	70	30

condition of farms became particularly acute at cash flow restrictions greater than about 30%.

Cash flow problems when total operating capital was not restricted resulted in changes to the management plan on the farm. The optimal strategies in the base models prior to imposing cash flow restrictions, were foodfish production from fingerlings on the smaller farms and foodfish production from stockers on the larger farms. As cash flow was restricted, the smaller farms switched to stocking smaller fingerlings and the larger farms switched to stocking fingerlings instead of stockers. Thus, the feasibility of a stocker phase on catfish farms is affected by both the overall level of operating capital and cash flow limitations.

Results at a glance...

- *Cash flow budgets developed in this project were used extensively in 2009 to 1) update cash flow simulator-spreadsheet models available online; 2) conduct financial management workshops state-wide in Arkansas; and 3) provide one-on-one financial assistance to catfish farmers from late 2008 through 2009. These budgets and models were used extensively by Arkansas catfish farmers to plan management strategies to attempt to survive the extremely high feed prices of 2008-2009. Farmers have reported that these models were helpful in decision-making through 2009.*

Additional sets of mathematical programming models were developed that incorporated a variety of lending strategies along with various production and marketing strategies. The models were most sensitive to the availability of credit in the first quarter of the year, typically a quarter with fewer sales, but increased costs of purchasing fingerlings. However, restricted market access results in increased borrowing in subsequent quarters, decreasing net returns. These models can be used to provide guidance to farmers on terms of lending that are best suited for their financial situation.

A Just-Pope catfish production function was used to estimate minimum catfish prices and maximum feed prices at which various feeding rates would be economically efficient. Optimal stocking and feeding rates were estimated for very low catfish price levels. Low catfish prices require lower stocking and feeding rates to operate at profit-maximizing levels. Stocking rates below 10,000/ha will not generate adequate revenue to cover debt-servicing requirements for long-term capital investment loans. Thus, farmers must adopt management strategies that will satisfy the multiple business requirements of servicing debt and meeting fish delivery schedules. The results of this analysis provide guidance on the relationships among prices of catfish and feed, with stocking and feeding rates, to provide a basis for these decisions.

IMPACTS

Studies of Partitioned Aquaculture Systems developed at Clemson University revealed that channel catfish fingerling growth can be significantly intensified and accelerated in these systems, yielding fingerlings in excess of 100 gm in size within a 120 to 140 day growing season at demonstrated carrying capacities of 4200 kg/ha. The "split-pond" modification of the PAS systems used at Mississippi State University also allowed excellent grow-out of stocker-sized fish to harvestable size. Several commercial catfish farmers are currently building split-ponds for commercial use in the 2010 production year.

Net yield of channel catfish in intensively managed earthen ponds ranges from 0.4-0.7 kg/m^3, but more intensive production systems are required to increase catfish net yields further. A zero exchange, mixed suspended growth (biofloc) production system was used to investigate the effect of channel catfish stocking rate on production. Channel catfish net yield increased curvilinearly from 1.0 to 4.8 kg/m^3 as the stocking rate increased from 2.9 to 17.5 fish/m^2. High feeding rates (24.2 to 79.9 g/m^3/d) were sustained without impacting water quality negatively. This research demonstrated that channel catfish yield could be increased by using the zero exchange, mixed suspended growth (biofloc) system.

The prototype, motor-powered, U-tube aerator being developed by United States Department of Agriculture-Stoneville can move up to 759 m^3/water/kW · hr, but the oxygen transfer efficiency must be improved for commercial application.

Studies at Auburn University have resulted in a number of indicators of sustainable aquaculture that are already being used by the Global Aquaculture Alliance and the World Wildlife Fund in evaluating the ecological efficiency of different production systems. Studies of energy use indicated that a total of 3.059 kW · hr energy is used to produce and process 1 kg of live catfish. Grow-out of fish on farms account for nearly half of energy use and feed production accounts for another 30% of energy use.

The semi-confinement units tested at the University of Arkansas at Pine Bluff increased the yield of fingerling catfish in ponds and has commercial potential. A similar system is being tested at a commercial facility for grow-out of fingerlings.

Economic analyses done at University of Arkansas at Pine Bluff revealed that the optimum size of a catfish pond was about 400 ha of water surface area. Cash flow budgets have been developed for five farm sizes, for existing and startup farming operations with no stockers, 114-g and 227-g stockers, stocked at four different rates for 11 different financing options, for a total of 550 budgets. These spreadsheet model budgets have been used extensively to provide direct financial assistance to catfish farmers through the difficult financial times of recent years. A number of workshops on cash-flow based management have been held to aid farmers to make decisions related to survival of their farm businesses. The cash flow budgets developed in this project were used extensively in 2009 to: 1) update cash flow simulator-spreadsheet models available online; 2) conduct financial management workshops statewide in 2009; and 3) provide one-on-one financial assistance to catfish farmers from late 2008 through 2009. These budgets and models are in use in Arkansas by catfish farmers to plan management strategies to attempt to survive the extremely high feed prices of 2008-2009. Farmers have reported that these models were helpful in decision-making through 2009.

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