Intensive Culture of Channel Catfish *Ictalurus punctatus* and Hybrid Catfish *Ictalurus punctatus x Ictalurus furcatus* in a Commercial-Scale, In-pond Raceway System

by

Travis Waldemar Brown

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 09, 2010

Key words: In-pond, raceway, system,
catfish, production, economics

Approved by

Claude E. Boyd, Co-chair, Professor of Fisheries and Allied Aquacultures
Jesse A. Chappell, Co-chair, Associate Professor of Fisheries and Allied Aquacultures
Terrill R. Hanson, Associate Professor of Fisheries and Allied Aquacultures
Yifen Wang, Associate Professor of Biosystems Engineering

Abstract

An experiment was conducted utilizing a highly intensive fish production system in the Black Belt region of western Alabama. Three main objectives were addressed in this study. The first was based primarily on channel and hybrid catfish production and performance capabilities. The second objective dealt with detailed water chemistry and nutrient budgeting, while the third and final objective involved an economic analysis to determine the feasibility and commercial possibilities of the system.

The goal of this project was to improve the profitably of commercial catfish aquaculture by demonstrating methods to enhance feed efficiency and survivorship. A commercial size In-pond Raceway System (IPRS) was constructed in 2007 and installed in a 2.43-ha, traditional, earthen pond on a 170-ha catfish farm in Dallas County, Alabama. The IPRS consisted of six, individual raceways that share common walls. Each raceway has the capacity of water exchange every 4.9 minutes (≈12X/hr). Mean water velocity was determined to be 0.026 m/sec - equivalent to a flow rate of 8,853 l/min/raceway.

Individual raceways were stocked with 12,000 to 30,000 channel and hybrid catfish with average weights of 59.1 to 418.2 g, respectively. A total of 49,913 kg of catfish was harvested throughout an 8-month production season. An additional 6,365 kg of paddlefish and tilapia were harvested at the end of the study. The feed conversion ratio (FCR) for catfish ranged from 1.16 – 2.11 and mean survival was 83.7%. Catfish growth rates ranged from 1.1 to 2.2 g/fish/day. The results signify a high potential for efficient production of catfish along with other co-cultured species.

Water, nitrogen, phosphorous, chemical oxygen demand (organic matter), and dissolved oxygen (DO) budgets were estimated over the fish production season for the IPRS. Even with the addition supply of water from rainfall and runoff, 70 cm of well water were applied to the pond to offset evaporation and seepage. For each 1.49 kg of feed fed to the fish, there was one kilogram of weight gain. However, 51.7 g of nitrogen, 13.4 g of phosphorous, and 0.41 kg of chemical oxygen demand (COD) were released into the environment. The catfish harvested accounted for 33.9 % of nitrogen, 13.1 % of phosphorous, and 28.3 % of organic matter (COD) that was applied as feed. Large amounts of nitrogen and organic matter were lost from the system, although there was significant accumulation in pond mud. Organic matter was consumed in respiration while nitrogen was lost through denitrification and ammonia volatilization. Phosphorous was harvested in fish and absorbed in pond mud. Diffusion and mechanical aeration assured proper DO levels for fish production because the total respiration exceeded the levels produced by photosynthesis.

The economic analysis provides evidence that the IPRS may be more efficient for producing food-sized catfish as compared to traditional farming methods. The IPRS was more efficient at producing catfish as compared to the whole farm in 2008 and about as efficient as the average 4-year performance of the whole farm over the course of the study. Continual food fish production while utilizing the additional production from co-cultured species would be the most feasible for the IPRS. The cost of production for food fish was $1.565/kg with a total cost of production of $1.904/kg. With the addition of co-cultured fish (paddlefish and tilapia), the overall cost of production and total cost is reduced to \$1.388/kg and 1.689/kg, respectively. The electrical efficiency of the IPRS with and without the co-cultured species is 0.639 and 0.535 kg of fish produced per kW·h used, respectively.

Acknowledgments

This study was funded by the Alabama Catfish Producers, Dean Wilson Farms, Alabama Agriculture Experiment Station, and the Alabama Cooperative Extension System. First, I wish to extend a special thanks to my parents (Gerald and Joyce Brown) and sister (Charlotte Brown) for their encouragement for the pursuit of my dreams. I am deeply indebted to Dr. Luke Roy for his technical expertise, manuscript editing, and general advice such as keeping me cool, calm, and collective during intense times throughout the experiment. I would like to extend my gratitude to the Wilson Family in Browns, AL, specifically Butch Wilson, Travis Wilson, and Willard Poe. I'd like to acknowledge my academic mentors, Jesse A. Chappell and Claude E. Boyd for their guidance and direction. Without their assistance, I would not have been able to completely finish this degree in a timely fashion. I wish to thank Harvey Pine, Rawee Viriyatum, Naparat Prapaiwong, Suthira "Noi" Soongsawang, and Puttitorn Saengrungruang for their technical assistance and advice in the Lab. I would like to further thank Dr. Allen Davis and Jamie Yeager for general assistance.

Table of Contents

IV. Develpoment, Evaluation, and Economic Feasibility of an In-pond Raceway System for Fish Production

List of Tables

List of Figures

Chapter I

Introduction

The true definition of aquaculture depends upon the person you inquire or the book you read. I prefer to use two definitions that were passed down to me from authority figures and true aquaculture production and extension specialists:

Aquaculture - The rearing of aquatic organisms in a totally unnatural environment for a profit (Schmittou, 2008).

Aquaculture – Farming of plants and/or animals using an aquatic environment or medium. Commercial aquaculture is doing the above and with the objective of being able to sell it and make a profit (Chappell, 2010).

Although, there are other definitions such as:

Aquaculture - The rearing of aquatic organisms in controlled and semi-controlled environments or commonly called fish farming (Holland, 1999).

Aquaculture – "understood to mean the farming of aquatic organisms including fish, mollusks, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding and protection from predators. Farming also implies individual or corporate ownership of the stock being cultivated. " (FAO, 2007).

I believe that aquaculture is an art form that requires constant attention and dedication and once in your blood stream, probably will never leave.

Aquaculture is almost as old as human culture and in some cases may be. Historically, fish culture is believed to have began in China around 3,500 B.C. with the culture of common carp *Cyprinus carpio*, although many scientists believe that culturing fish wasn't common place until around 2,000 B.C. in Egypt and Assyria (Mesopotamia). Egyptian aquaculture focused on tilapia (*Oreochromis spp.)*, and its development seems consistent with that of carp in China (Parker, 2002). The first written documents describing early Chinese aquaculture were discovered to be from 500 B.C., *Classic of Fish Culture* written by Fan Lei, a Chinese politician turned fish-culturist, although drawings of tilapia in Egyptian tombs have been dated as far back as 2,500 B.C. (Pillay and Kutty, 2005). Many other early civilizations focused on different types of fish culture such as the Romans, Bohemians, Germans, Russians, and even French Monks. Native Americans knew a great deal about fish culture, unfortunately much of what they knew was not recorded and we must rely on artifacts left behind to understand their methods (Parker, 2002).

The total global production of fish and shellfish both from capture fisheries and aquaculture has continued to rise and reached 140 million metric tons (mt) in 2007. Capture fisheries leveled out in 2001 at around 90 million mt while aquaculture production has continued to increase at an annual rate of 6.5% from 2002 (36.8 million mt) to 2007 (50.3 million mt) which was valued at $87 billion (FAO, 2007). As of January 2010, world aquaculture production contributes to roughly half of the world's fish and shellfish consumed (FAO, 2010). This is due to the fact that capture fisheries appears to have reached a maximum limit and the demand for a protein source increases daily due to increasing human population growth and per capita consumption.

China contributed to over 62% of the world's aquaculture production of fish and shellfish in 2007 which is equivalent to 31.4 million mt or a value of approximately $40 billion. China also leads the world in seafood exports and in 2007 exported $ 9.2 billion alone. The U.S. produced approximately 526 thousand mt of fish and shellfish that same year valued at approximately $945 million (FAO, 2007). Ironically, the U.S. was the world's largest importer of seafood products that same year ($13.6 billion).

Channel catfish *Ictalurus punctatus* is the most important aquaculture species in the United States and probably will be for years to come. In 2003, approximately 300 thousand mt of channel catfish were harvested and processed which represented about half of the total aquaculture production in the U.S. (Hargreaves and Tucker 2004). By the end of 2009, only about 216 thousand mt of channel catfish were harvested with an overall value of approximately $352 million (USDA, 2010). There were over 1,161 commercial farm operations in the U.S. in 2003 with over 75-thousand ha of water (USDA, 2004). By January 2010, only 994 of the original farms still existed with a total of approximately 46-thousand ha of water. Mississippi, Alabama, Arkansas, and Texas produce greater than 90% of the cultured catfish produced in the U.S (USDA, 2010).

Channel catfish farming is the dominant form of aquaculture in Alabama and is one of largest sources of employment and income in west Alabama. Hale, Greene, Sumter, Marengo, Dallas, and Perry Counties within the Black Belt region of west Alabama are among the most economically depressed in the state. In addition to having median family incomes below state and national averages, west Alabama also suffers from low job availability and the potential for gainful employment. Approximately 3,000 Alabamians rely on jobs directly engaged in the catfish industry (Chappell and Crews,

2006) including jobs on farms, processing plants, feed mills, harvest crews, or provide other goods and services necessary to the catfish industry. Future job losses are predicted as competition from foreign markets, which supply alternatives to catfish to consumers (shrimp and tilapia), continues to take a toll on the west Alabama economy.

Due to increased operating costs and foreign competition, catfish farmers are constantly seeking ways to improve the efficiency and profitability of their operations. Traditionally, all phases of commercial catfish aquaculture have been conducted in ponds. While farm production has been profitable for farmers in the past, increased production costs are making it less sustainable each year. Most traditional pond based catfish systems have a production rate ranging from 4,500 to 7,000 kg/ha/yr (Brune, 1991; USDA 2006) although production rates have been as high as 13,000 kg/ha/yr under highly controlled conditions (Avault, 1980).

New, more efficient techniques for raising channel catfish are needed and dedicated research on intensive culture methods began in the 1960's but is more applicable today. Cages, raceways, and tanks have been utilized in the pursuit of greater aquaculture production efficiency (Schmitou, 1969; Andrews et al., 1971; Hill et al., 1974). Research evaluating the development of fixed and floating raceways started in the 1970's (Brown et al., 1971; Fremont, 1972; Hill et al., 1974; USEPA, 1974; Fast, 1977), although the floating raceway idea can be tracked back to the 1920's (Masser. 2004). Long (1990), Fast (1991) and Hawcroft (1994) brought back the idea of a floating raceway in the 1990's.

The design and use of an In-pond Raceway System (IPRS) has been one successful means whereby production efficiency and profitability has been improved for the production of food fish (Brown et al., 2010). A number of recent studies have evaluated new alternative production strategies that utilize high rate photosynthetic systems such as the Partitioned Aquaculture System (PAS) at Clemson University (Brune et al., 2004), or the split-pond system at Mississippi State University (Tucker and Kingsburg, 2009) and in west Alabama (Whitis, 2010). These systems have the potential to be more controllable and efficient at producing catfish than traditional farming methods due to the use of an efficient combination of biological, chemical, and physical intensification techniques.

Problems associated with traditional approaches to catfish aquaculture include but are not limited to: poor survival; high feed conversion ratio's (FCR); over feeding; variable growth rates; invalid inventory records; difficulty in properly treating diseases; and the tendency of "boom and bust" phytoplankton blooms which can cause severe fish stress and complete mortality. By using the IPRS approach, many of these challenges can be minimized or solved, allowing for more efficient and sustainable culture of catfish.

Research on fixed and floating raceways is an idea that was pioneered by Auburn University researchers (Hawcroft, 1994; Bernardez, 1995). In the previous studies the catfish were stocked into the newly-constructed systems in which water was circulated with an airlift pump. Solid fish waste settled toward the far side of the raceway which was then removed via a centrifugal pump. This system had many disadvantages such as poor fish waste removal technology, uneven water flow throughout the culture unit, and problematic disease occurrences. The in-pond raceway has been modified and upgraded to a commercial scale IPRS design and new equipment has been developed to deal with many of the original raceway problems.

The aquaculture industry is limited by resources such as land, water, and fishmeal that its future development depends upon (Naylor et al., 2000; Westers, 2000). However, developments with plant based proteins (e.g. soy beans) have reduced the dependency of wild caught fish to be used as a protein source in fish feed (Chappell, 2010). Nutrients such as nitrogen and phosphorous released from aquaculture operations can pollute the local environment and contribute negatively to natural ecosystem health if not managed correctly (Hakanson et al., 1998; Lemarie et al., 1998). Management practices which utilize and/or recycle parts of un-assimilated nutrients are a more efficient means and environmentally friendly form of aquaculture production. Integrated pond systems which utilize an IPRS, similar to a large scale outdoor recirculating aquaculture system (RAS), emphasizes nutrient reduction either through the immobilization of bacterial biomass, volatilization to the atmosphere, or conversion into harvestable products (Schneider et al., 2005). Ideally, converting the highest percentage of nutrients into a harvestable product would be most desirable as long as it is also the most economically feasible.

Fertilizers and feeds are usually the largest source of nitrogen and phosphorous inputs into fish ponds, although nutrients are also derived from rainfall, runoff, and regulated inflow (Green, 1993). Chemical budgets are designed to precisely account for nutrients entering aquatic ecosystems and terrestrial environments and to ultimately assist with the understanding of different nutrient sources. Rudimentary knowledge of nutrient budgets is available for integrated pond production systems (Krom and Neori, 1989; Brune et al., 2003; Yi et al, 2003; Schneider et al., 2005; Nhan et al., 2006), although chemical budgets for traditional channel catfish ponds have been calculated (Boyd, 1985; Gross et al., 2000).

Production technology as well as the species selected for culture should be socially acceptable and capable of generating a profit without negatively affecting the environment (Shang and Tisdell, 1997; Bardach, 1997). New technologies in aquaculture need to provide a profitable and efficient production model while allowing the industry to grow to meet the increasing demand (Shang and Tisdell, 1997; Williams, 1997).

This study describes the IPRS from a dimensional standpoint and elaborates on the techniques utilized for the successful production of channel catfish *Ictalurus punctatus* and hybrid catfish *Ictalurus punctatus* x *Ictalurus furcatus* as the primary culture species and paddlefish *Polyodon spathula* and tilapia *Oreochromis niloticus* as co-cultured species. The investigation focuses on concentrations of various water quality variables along with a water and partial nutrient budget. The final element in this study focuses on economic analysis and feasibility as it applies to the commercial catfish industry. All research was conducted over an 8-month period (March 13 – November 18, 2008).

Chapter II

Effects of a Commercial-Scale In-pond Raceway Syatem on Channel Catfish (*Ictalurus punctatus*) and Hybrid Catfish (*Ictalurus punctatus x Ictalurus furcatus*) Production and Performance

Abstract

The aim of this project was to improve profitability by demonstrating methods to achieve high levels of feed performance, survival, and efficiency in a commercial farm setting. A commercial-scale, modified In-Pond Raceway System (IPRS) was deployed in 2007 on a commercial catfish fish farm in west Alabama. The IPRS was developed and installed in a 2.43-ha earthen pond with an average depth of 1.67 m. The average water velocity in each raceway supplied by a slow rotating paddlewheel rotating at 1.2 revolutions per minute (rpm) was determined to be 0.026 meters per second (0.15 m^3/sec) which is equal to a water flow rate of 8,853-l/min. This flow rate would be equivalent to an average water exchange for each raceway every 4.9 minutes (≈12X/hr). Each raceway was originally stocked with 12,000 to 30,000 advanced channel and hybrid fingerlings that weighted between 59.1 and 418.2 g to simulate a staggered stocking and harvest production approach. During the 2008 production season, mean survival was 83.7% across all raceways. The average feed conversion ratio (FCR) for channel catfish and hybrid catfish was 1.74 and 1.36, respectively (range from 1.16 - 2.11) and 49,913 kg (20,540 kg/ha) of catfish were harvested. An additional 6,365 kg (2,619 kg/ha) of tilapia

and paddlefish were harvested as co-cultured species. Growth rates ranged from 1.1-1.8 g/fish/day for the channel catfish and 1.6 – 2.2 g/fish/day for the hybrid catfish. The results observed thus far indicate a high level of potential for more efficient production of catfish along with other co-cultured species compared to traditional catfish culture practices in ponds. Design and engineering modifications will need to be addressed in the future to future improve the IPRS.

Introduction

The largest segment of the U.S. aquaculture industry is the production of catfish. Two hundred and thirty-two thousand metric tons (509,597,000 lb) of food size channel catfish, *Ictalurus punctatus*, were produced in 2008 with an overall estimated value of $410 million (USDA 2009). Additionally in 2008, 1,617 operations existed in the U.S. with a total of 66,005-water ha (163,100 water acres) (USDA, 2009). As of January 2009, only 1,306 of the original farms still operated on a total of 59,450-water ha (146,900-water acres). This decreased the number of operations and total area by 19.2% and 9.9% respectively. About 92% of U.S. total sales was produced in Mississippi, Alabama, Arkansas, and Texas.

Channel catfish farming is the dominant form of aquaculture in Alabama. In 2008, there were 252 farms in Alabama that utilized 8,984-water ha (22,200-water acres) which produced 59,693 mt (131,600,000 lb) of product (USDA, 2009). The economic impact on Alabama is very impressive with approximately 3,000 Alabamians relying on jobs directly engaged in the catfish industry (Chappell and Crews, 2006).

Most catfish are commonly cultured in levee ponds or hillside watershed ponds and are harvested by seine. This technique requires a massive amount of land and labor associated with the overall yield. Despite being relatively labor intensive, Boyd and Tucker (1998) remind us that although open pond aquaculture may appear to be an archaic method for growing aquatic animals, it is one that has been consistently profitable when the pond is managed correctly. A traditional pond system yields a net annual production of about 4,500 to 5,500 kg/ha (4,000 to 5,000 lb/acre) with a maximum annual production of around 7,000 kg/ha (6,200 lb/acre) (Brune, 1991; USDA, 2006). On occasion, production in excess of 13,000 kg/ha (11,600 lb/acre) has been achieved under experimental conditions (Avault, 1980).

The demand for new, more efficient production techniques for raising channel catfish is increasing rapidly, although intensive production methods have been of interest in the U.S. since the 1960's (Schmittou, 1969). Early attempts at intensifying culture practices for warm water fish were applied to cages, raceways and tanks (Schmittou, 1969; Andrews et al., 1971; Hill et al., 1974). The concept of floating in-pond raceways can be traced back to the 1920's (Masser, 2004). Other research on development of raceways to culture fish occurred in the 1970's (Brown et al., 1971; USEPA, 1974; Hill et al., 1974) while the floating in-pond raceway concept also was drawing interest (Fremont, 1972; Fast, 1977, 1991; Hawcroft, 1994; Long, 1990).

Recent studies have demonstrated new production practices that utilize high rate photosynthetic systems such as the Partitioned Aquaculture System (PAS) at Clemson University (Brune et al., 2004) or the split-pond system at Mississippi State (Tucker and Kingsburg, 2009). These systems combine a number of biological, chemical, and physical intensification elements into a single integrated system. This technology is believed to be more controllable and efficient at producing catfish than traditional pond culture.

The Department Fisheries and Allied Aquacultures at Auburn University has utilized fixed and floating in-pond raceways for both research and intensive production of fish for many years. The basic, floating in-pond raceway and procedures utilized for the production of catfish were originally developed by Hawcroft (1994) and Bernardez (1995), respectively. These systems utilized direct stocking of small fingerlings into the raceway culture unit. Airlift pumps circulated pond water through the culture unit and a waste removal system was utilized to capture solid fish waste toward the end of the raceways. Although this system was successful, it had several disadvantages including uneven water flow throughout the raceways and poor efficiency at removing solid fish waste from collection areas. Results also indicated poor survival caused by disease outbreaks. Consequently, several alterations have been made in system design and operational procedures to increase the uniformity and volume of water flow and maximize the opportunity for biomass loading.

This study reports the methodologies deployed for the production of channel catfish (*Ictalurus punctatus*) and hybrid catfish (*Ictalurus punctatus* x *Ictalurus furcatus*) as primary species and tilapia (*Oreochromis niloticus*) and paddlefish (*Polyodon spathula*) as co-cultured species in a fixed In-pond Raceway System (IPRS) and typical results observed over an 8-month period.

Materials & Methods

System Layout

This study was conducted on a 174-water ha (430-water acre) commercial catfish farm in Browns, Alabama. A 2.43-ha traditional, earthen pond supplied by both well water and watershed runoff was utilized for the deployment of the In-pond Raceway System (IPRS). The IPRS consists of six individual raceways that share common walls which are attached to a permanent concrete foundation (overall length, width and height of 30.48 × 13.72 × 1.42 m) (Figure 1). Each raceway (13.71 × 4.88 × 1.22 m) consisted of three separate components: slow rotating paddle wheel area (3.11 ×4.88 × 1.22m); fish culture area (7.71 × 4.88 × 1.22 m); and waste settling zone (2.89 × 4.88 × 1.22m). The walls were constructed of standard cinder blocks (0.46 × 0.20 × 0.20 m) filled with concrete and supported with 1.3 cm reinforcing bar. The fish were confined in the culture unit by an end partition barrier that spans the width of each raceway unit (4.88 m). Each partition has a frame constructed of 3.8 cm^2 aluminum tubing (wall thickness of 0.32 cm). PVC-coated, steel-mesh wire (0.15 cm diameter) was attached to the frame by means of 0.6-cm, flat-bar aluminum, 10.0-mm, zinc-plated, self-taping screws, and 5.0-mm aluminum rivets. Three different mesh sizes were utilized throughout the experiment (12.7 × 25.4 mm, 25.4 × 25.4 mm, and 25.4 × 50.8 mm) depending on the initial stocking size of the fish. Two walkways (length and width of 30.48 × 0.76 m) were utilized to access individual raceways and the systems components with the first walkway located directly above the water inflow to the fish culture unit and the second 7.71 m down stream.

Each slow rotating paddlewheel (SRP) was constructed of six pieces of plywood (length, width, and depth of 2.44 × 1.22 × 0.02 m) which are evenly distributed around a central shaft (5.87 cm diameter) circling 360 degrees. The plywood was mounted on a steel frame attached to the central shaft with angle iron (5.08 cm at 90 degrees) and 6.4-mm, carriage-bolts. The SRP had an overall diameter of 2.50 m. Each individual SRP was powered by a 0.37-kW 3-phase, electric motor (Blador, Fort Smith, AZ) that rotates at 1,750 rpm. The motor was attached to a gear box (Iron Man, Cleveland, OH) that reduced the electric motor shaft speed by a factor of 7.5:1. The gear box was attached to a speed reducer (SHIMPO CIRCULATE, Itaska, IL) to further reduces the rpm by a factor of 233:1. An 11-tooth sprocket is attached to the output end of the speed reducer, and a chain connects the sprocket of the speed reducer to the 33-tooth sprocket of the central shaft of the SRP. The combination of the electric motor, gear box, speed reducer, and sprockets with chain equates to an overall rpm of 1.17 at 70 Hz for the SRP. The SRP allows for an even distribution of water flow through the culture unit to continually supply fresh water and to flush out waste material.

Water flow through a random raceway was measured before fish were stocked using a flow meter (Marsh-McBirney, Inc., Model-2000, Frederick, MD). A total of 100 measurements were made at various points throughout the culture unit. Five points at the water inflow and five at the water outflow were selected to make measurements. At each selection point, five measurements were made at 20 % and 80 % of the water depth, respectively (Bankston and Baker, 1995). A total of 100 measurements were recorded, and average velocity was calculated. The average velocity was multiplied by the cross sectional area of the raceway to determine the volume of water exchanged in a given amount of time. The water flows away from the raceways out into the north side of the pond, counterclockwise to the south side of the pond, and returns to the water inflow side of the raceways. A central divider known as a baffle is attached to the outside wall of raceway 6 and extends 122 m out into the pond (Figure 2). The divider prevents water flow short circuiting by forcing the water flow to the end of the pond before returning to the raceways.

Each raceway utilized for supplemental and emergency aeration a 1.12-kW regenerative blower (Sweetwater, Aquatic Eco-Systems, Inc., Apopka, FL) that is capable of delivering 2.4 - 2.6 cubic meters per minute (1.4 - 1.5 cfs) of air flow directly into the water column via a diffuser grid that is located between the SRP and the first partition barrier in the SRP area. The diffuser grid (length, and width of 2.59 × 0.76 m) was constructed of schedule 80 PVC (5.08-cm diameter), barbed fittings (1.27-cm diameter), and 2.54-cm diameter diffuser tubing (Colorite Plastics Company, Ridgefield, NJ). Barbed fittings were plumped into the PVC frame of the grid every 6.65 cm. The diffuser tubing (a total of 52.89 m per grid) was attached to the barbed fittings to allow for even distribution of air flow throughout the grid.

A feed delivery system was implemented to assist with feed management and allows a more controlled feed application process. The feed delivery system consisted of three main components: 10-mt bulk feed bin; 7.62-cm diameter feed auger; and 80-kg capacity feed hoppers. The bulk feed bin was plumped into a delivery auger that extends to the exterior wall of the last raceway. The auger was powered by an electric motor (BROCK Grain Systems, Milford, IN) and manual/automatic switch with sensor to allow the operator to continually monitor and maintain desired feed delivery levels throughout the system. Each raceway has its own individual feed hopper (Sweeney Enterprises Inc., Boerne, TX) where feed is delivered from the main auger line. The hoppers are located at the water inflow and directly in the center of each raceway. Each feed hopper was powered by a 12-volt electric motor (Sweeney Enterprises Inc., Boerne, TX) that was wired into a main control box for user friendly management. With a flip of a switch from a single location, feed could be delivered to any of the six raceway units.

An electrical service monitoring system was installed shortly after the initial fish were stocked into the raceways. The system consisted of three main components: an autodialer (Sensaphone Model 400); recirculating system monitor (YSI 5200); and computer aided management program (YSI Aquamanager). The autodialer (Sensaphone, Aston, PA) was programed to call the manager during emergency conditions such as a power failure or low dissolved oxygen (DO) levels.

Seven recirculating system monitors (YSI Incorporated, Yellow Springs, OH) were installed to monitor both DO and temperature. Each monitor had a single probe secured at the tail end of each raceway to monitor the culture environment (e.g. DO & temperature) for the fish (i.e. monitor 1 for raceway 1, monitor 2 for raceway 2, etc.). The seventh monitors probe was placed in the water inflow channel. This was employed as an aid in overall system management. The computer aided management program was used to oversee all measurements for the entire system. It also allows for complete data collection and parameter control for certain set points such as DO. Each of the monitors had four relays capable of controling many parameters. In this study, only two relays were used. The first relay was utilized to control the blower of each raceway. The parameter set point for relay 1 was to engage the relay and turn the blower on if the DO dropped below 4.0 mg/L and to turn the blower off once the DO rose above an acceptable level (5.0 mg/L). Relay 2 was installed and tested but never was used in this study. The responsibility of relay 2 would have been to control the automated feed delivery system utilizing the Aquamanager software. Relay 3 was connected to each individual DO monitor/probe, and the parameter set point alerts the Sensaphone if the DO dropped below 2.0 mg/L. The manager would then receive a call from the autodialer notifying him about the details provided by the sensors in place.

Culture Conditions

Fingerlings *Ictalurus punctatus* and *Ictalurus punctatus* × *Ictalurus furcatus* were obtained throughout the experiment from commercial suppliers (Eagle Aquaculture, Indianola, MS and Aquacenter, Leland, MS) with a history of providing high health fish. A portion of the system contained fish before the start of the study, so an initial complete inventory was conducted. Existing fish were crowded, harvested, weighted, sampled, and restocked into designated raceways. Upon arrival, new fingerlings were sampled to screen for disease and estimation of initial mean weights. Fingerlings were then acclimated to the culture conditions using partial water exchanges (a rate no faster than 5^{o} C per hour) to equalize environmental parameters. Once the initial inventory and fingerling acclimation was complete, fish were then stocked into the raceways at densities ranging from 17.7 - 118.3 kg/m^3 (Table 1).

The growout phase ran for 89 - 250 days depending on the size of fish initially stocked. The catfish were offered a commercial feed (Alabama Feed Mill, Uniontown, AL) 2 - 4 times per day based on the biomass, water temperature and fish size. The experiment was conducted in six, 43,660-L fixed raceways (previously described) with a continual water flow of 8,853-L/min. Dissolved oxygen, pH, temperature, and salinity were measured at dawn and dusk daily, whereas total ammonia nitrogen, nitrite nitrogen (Clesceri et al., 1998), alkalinity, and chloride (Boyd and Tucker, 1992) were measured weekly. Water quality parameters were maintained within acceptable limits for catfish production throughout the experiment (Table 2).

A variety of fish were stocked in the pond outside of the raceways to assist with water quality management issues and to aid with co-production of other marketable fish. Paddlefish (*Polyodon spathula*) with an average individual weight of 328 g were originally stocked at a rate of 288 per hectare. Tilapia (*Oreochromis niloticus*) brood fish with an average weight of 232 g were sexed and stocked at a rate of 12 breeding pairs per hectare (Dean Wilson Farms, Browns, AL). Two other species of fish were stocked outside of the raceways as preventative measures for diseases that may have affected the primary species. Fathead minnows (*Pimephales promelas*) were stocked at a rate of 11.2 kg/ha to reduce the chance of hamburger gill while redear sunfish (*Lepomis microlophus*) were stocked at a rate of 37.2 kg/ha to assist with the management of gastropods (Clary Seining, Greensboro, AL).

System maintenance such as recording of collected daily data, cleaning the probe membranes of the monitoring system (daily), feed delivery system cleaning and calibration (weekly), calibration of D.O. probes (biweekly), chemical treatment of fish (weekly - monthly depending on water temperature) and lubrication of sprockets and chains (monthly) were carried out on a regular basis. Mortalities were checked and recorded daily.

The estimated biomass in each raceway was adjusted daily by subtracting mortalities from the number of fish stocked. Catfish were sampled monthly to determine average size and total biomass in each raceway. A sample of at least 100 fish from each raceway were weighed and counted to determine individual average weight. Average weight (to the nearest 1.0 g) was calculated for each sub-group by dividing the sample weight by the total number of fish in the sample. Individual length and weight measurements were taken on approximately 75 fish from each raceway and used to determine average total length and size distribution for each sub-group. Length measurements were made to the nearest centimeter (Figures 3 and 4).

Total production (harvest weight - stocking weight) was calculated for each cohort of fish as the amount of total weight gained. Feed conversion ratios (FCR) for each cohort of fish were calculated by dividing the amount of feed consumed per amount of weight gained. Average, daily, weight gain per fish was calculated by dividing the total production weight of each cohort of fish by the number of days in the culture period and dividing that value by the total number of fish harvested. The fish were crowded in the raceway and a boom truck equipped with a hoist net was used to weigh and load the fish onto a haul unit for transport to the processing plant. Catfish were harvested throughout the study as they reached a marketable size.

Results and Discussion

The average water velocity in each raceway was determined to be 0.026 m/sec (0.15 m^3/sec) which equates to a water flow of 8,853-l/min. Maintaining this flow rate would yield an average water exchange every 4.9 minutes or ≈12 times per hour for each raceway culture unit. Brune et al., (2003) observed water exchange rates ranging from 0.226 - 0.988 times per hour within individual culture units of the partitioned aquaculture system, while Hawcroft (1994) observed water exchange rates as frequent as once every 3.8 minutes (≈16X/hr). The increase in flow and water exchange is beneficial at high fish densities because low DO levels may result in stress especially during the warmer part of the production season and at heavy feed rates. A total water flow of 53,118-l/min for the IPRS was determined by multiplying the individual flow rate for a single raceway by six (i.e. six raceways). With the estimated water exchange rate, the entire water volume in the pond theoretically flows through the raceways every 12.74 hours (40,594,125 l of total pond volume ÷ 53,118 l/min ÷ 60 min/hr).

The feed delivery system was inefficient at delivering feed to individual raceways, so a new design was researched. The main problem with the initial delivery system was that the feed delivery lines were not sealed, and rain-water flowed in to contaminate the feed on a regular basis especially after a rain event. This was corrected by re-plumbing the delivery lines and sealing them with silicon.

The next hurdle was to investigate the amount of feed delivered by individual feed hoppers. There was clearly a misdistribution of feed per raceway and a protocol was needed to correctly deliver the appropriate amount of feed to the fish. The “fowling” effect would take place when feed fines accumulated at the funnel section of the hopper and water splashed by the feeding action of the fish created a paste. This paste would eventually clog the delivery funnel of the feed hopper and restrict feed delivery. This problem was corrected by cleaning and calibrating the feed hoppers on a weekly basis. A 20-l bucket was attached to the bottom of each hopper, power was applied to the feed broadcaster, and the amount of time was recorded for each feeding event. After weighing the amount of feed from each hopper in a given amount of time, a calibration factor was calculated for each feed hopper.

The total weight harvested of all catfish was 49,913 kg for the IPRS or 20,540 kg/ha. The total weight harvested for the channel catfish and hybrid catfish was 18,240 and 31,673 kg respectively while overall production for the channel and hybrid catfish was 11,116 and 20,291 kg respectively (Table 3). This fits within the range of Brunes' (2004) production rates of 3,456 - 19,382 kg/ha/yr in the PAS. The growing period for the catfish in the IPRS ranged from 96 – 250 days depending on the initial fish size at stocking and optimal harvest size required by the processing plant. In general, catfish greater than 0.454 kg were considered market size and on several occasions were actually preferred over larger fish for marketability.

A total of 2,406 kg (990 kg/ha) of paddlefish and 3,959 kg (1,629 kg/ha) of tilapia were harvested as co-cultured fish from the pond (Table 4). Brune et al., (2004) harvested an additional co-culture of tilapia on a yearly basis with a range of 2,284 – 5,034 kg/ha. The additional production for all studies was based on initial stocking of breeding pairs of tilapia, allowing them to spawn throughout the production season, and harvesting the offspring of the spawns close to the end of the season. The offspring fed on the natural primary productivity of the pond. The lower production values of tilapia in the IPRS was more than likely because fewer breeding pairs were stocked as compared to the research with the PAS.

Overall survival for all catfish was 83.7%. Channel catfish had a lower average survival rate (78.0 %) as compared to hybrid catfish (89.1 %). This is probably the result of channel catfish contracting enteric septicemia of catfish (ESC) on several occasions across this study. However, medicated feed (Aquaflor) was utilized to avoid mass mortality. Hawcroft (1994) observed average survival rates of 75% for channel catfish in floating raceways, while Brune (2004) had excellent survival rates with the catfish that were harvested the same year. However, he expected a 25 - 100% mortality for fish that were unmarketable and had to be carried over to the next season (over-wintered). This mass mortality event was caused primarily by proliferative gill disease (PGD), although *Columnaris* was the most significant disease problem typically in the PAS.

Depending on water temperature, fish cultured in the IPRS were periodically treated with potassium permanganate baths as a preventative measure against diseases such as *Costia* and monogenetic trematodes (Table 5). The IPRS allows for ease of advanced treatment as compared to traditional catfish pond aquaculture methods. The fish can be observed for diseases and treated periodically without having to treat the entire pond or water body. This is not only more economical, but can save the production manager time.

The average feed conversion ratio (FCR) for the channel and hybrid catfish was 1.74 and 1.36, respectively. This is similar to the observed FCRs of both Brune (2004) and Hawcroft (1994) and suggests that catfish can be grown to food fish size on a commercial scale with efficient growth rates at FCRs less than 1.8:1. Ruane et al., (1977) and Lewis and Wehr (1976) observed FCR’s much higher than that would be expected in heated, concrete raceways and cages respectively. The lower FCR observed in the IPRS, PAS, and floating raceways can be contributed to the fact that the operator/manager watches the fish feed and doesn’t allow the fish to consume more than can be efficiently assimilated.

On commercial catfish farms, feed is blown into the production pond and “the feeder” continues on to another pond in hopes to finish feeding in a timely manner. There is no way to verify if all the feed delivered to the pond was consumed by the fish. This, along with poor survival, contributes to the higher than normal FCRs that are seen on commercial farms. Another factor reducing the FCRs of raceway type systems is that fish of uniform size are stocked into individual raceways. This eliminates cannibalism that frequently occurs under multi-batch type aquaculture practices. In turn, the average FCR is reduced (improved) and survival is increased utilizing the single batch method. With the utilization of raceways, we are allowed the advantage of both single batch and multi-batch aquaculture, because uniform-sized fish are stocked in individual raceways (single batch), while utilizing a stair step stocking and harvest regime. This allows the producer to stock varied sizes of catfish segregated by size, throughout the raceways. The obvious benefits from this method are continual harvest allowing for year-round cash flow and a reduction of the chances of exceeding the maximum carrying capacity such as what typically occurs in ponds. If all the catfish were stocked at once, the overall fish biomass would increase and feed rates would increase along with water quality deterioration (e.g. low dissolved oxygen, elevated ammonia, etc.).

Length-weight measurements were found to have a logarithmic pattern as observed in past studies (Steeby, 1995). The R^2 value for the channel and hybrid catfish was 0.901 and 0.902 respectively. With the close length-weight association, predicted values can be calculated in the field utilizing a simple formulation. The relationship between length and weight for the channel catfish and hybrid catfish, respectively, are depicted in the equations below:

$$Y = 11.076e^{0.0998X}$$

$$Y = 15.559e^{0.0922X}$$

Where: Y = Weight of fish (g)

X = Length of fish (cm)

Growth rates ranged from 1.1-1.8 g/fish/day for the channel catfish and 1.6-2.2 g/fish/day for the hybrid catfish. This is slightly lower than the growth rates of 2.5 g/fish/day observed in cages by Masser and Duarte (1994) and Hawcroft (1994). The slower growth rates observed in the IPRS likely result from fish not being fed to satiation and the fish with faster growth rates may have been overfed. Fish fed to satiation undoubtedly will have a fast growth rate, but the trade off is a higher FCR and less profit opportunity. Depending on the overall biomass of the fish and the total feed fed, a reduction in water quality of the system is imminent (Chappell, 2008).

The IPRS has demonstrated an efficient means of producing both channel catfish and hybrid catfish along with the co-culture of several other species. This benefit can be emphasized to justify some of the production costs associated with the initial construction of the system. The overall survival, feed conversion ratio, and production improved in a commercial setting as compared to traditional catfish food fish production methods. Fish inventory also is more controllable and “user friendly” because the animals are confined and easily monitored. This improvement in production has not only drawn interest from other researchers, but from fish farmers from west Alabama and east Mississippi. With additional support and continued production, we will be able to verify our initial research findings and adapt new technologies to help further improve the production capabilities of the IPRS.

References

Andrews, J.W., L.H. Knight., K.W. Page, Y. Matsuda, and E.E. Brown. 1971. Interactions of stocking density and water turnover on growth and food conversion of channel catfish reared in intensively stocked tanks. Progressive Fish-Culturist 33, 197-203.

Avault, J.W. 1980. Six tons of catfish with aeration in one acre of water. Aquaculture Magazine 7, 44.

Bankston, J.D. and F.E. Baker. 1995. Open Channel Flow in Aquaculture. SRAC Publication No. 374.

Bernardez, R.G. 1995. Evaluation of an In-pond Raceway System and its Economic Feasibility for Fish Production. M.S. Thesis. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Boyd, C.E. and C.S. Tucker. 1992. Water Quality and Pond Soil Analysis for Aquaculture. Alabama Agriculture Experiment Station, Auburn, AL.

Boyd, C.E. and C.S. Tucker. 1998. Pond Aquaculture Water Quality Management. Kluwer Academic Publishers, MA, 701 pp.

Brown, E.E., J.L. Chesness, and S.R. Chapman. 1971. Raceway and Pond Economics. Producing and marketing catfish in the Tennessee Valley. Tennessee Valley Authority, Tennessee, 90-93 pp.

Brune, D.E., 1991. Pond aquaculture. Timmons, M.B. (Editor): Engineering Aspects of Intensive Aquaculture. Natural Resources, Agriculture, and Engineering Service Publication NRAES-49, Natural Resources, Agriculture, and Engineering Service, New York, 118-130 pp.

Brune, D.E., 2003. Intensification of pond aquaculture and high rate photosynthetic Systems. Aquaculture Engineering 28: 65-86.

Brune, D.E., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and Hargreaves, J.A., (editors): Partioned Aquaculture Systems. Elsevier, New York, 561-562 pp.

Brune, D.E., G. Schwartz, A.G. Eversole, J.A. Collier. and T.E. Schwedler. 2004. Partitioned Aquaculture Systems. SRAC Publication No. 4500.

Chappell, J.A. and J.R. Crews. 2006. 2005 Alabama Aquaculture Factsheet. Agriculture Economics and Rural Sociology, Auburn University, Auburn, Alabama.

Chappell, J.A. 2008. Personal Communication. Fisheries and Allied Aquacultures, Auburn University, AL.

Clesceri, L.S., A.E. Greenberg, and A.D. Eaton. 1998. Standard Methods for the Examination of Water and Waste Water, 20th edn. American Public Health Association, Washington, DC, USA.

Fast, A.W. 1977. Floating fish rearing system. U.S. Patent No. 4,044,720.

Fast, A.W. 1991. A floating fish cage with solid plastic membrane and pumped water exchange. J. of Applied Aquacult. 1, 99-110.

Fremont, H.J., 1972. Floating fish growing tank. U.S. Patent No. 3,653,358.

Hawcfoft, B.A., 1994. Development and evaluation of an in-pond raceway and waste removal system.. M.S. Thesis. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Hill, T.K., J.L. Chesness. and E.E. Brown. 1974. Growing channel catfish, *Ictalurus punctatus*, in raceways. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28, 488-499.

Lewis, W.M., and L.W. Wehr. 1976. A fish rearing system incorporating cages, water Circulation, and sewage removal. Progressive Fish-Culturists. 38: 78-81.

Long, C.E., 1990. Raceway culturing of fish. U.S. Patent No. 4,915,059.

Masser, M.P., and S. Duarte. 1994. The Alabama Piedmont catfish cage farming industry. World Aquaculture 25(4): 26-29.

Masser, M.P. 1995. Intensive Catfish Systems. World Aquaculture 26(3): 60-64.

Masser, M.P., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and Hargreaves, J.A., (editors): Cages and In-pond Raceways. Elsevier, New York, 532 pp.

Ruane, R.J., T.Y.J Chu, and V.E. Vandergriff. 1977. Characterization and treatment Of waste discharge from high-density catfish cultures. Water Research 2: 789-800.

Schmittou, H.R., 1969. Intensive culture of channel catfish, *Ictalurus punctatus* (Rafinesque), in cages suspended in ponds. Doctoral Dissertation. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Steeby, J.A., 1995. A Commercial-Based Length-Weight Relationship for Channel Catfish Fingerlings Grown under Commercial Conditions in Mississippi. The Progressive Fish-Culturist 57: 161-163.

Tucker, C.S., and S. Kingsburg. 2009. A Split-pond Aquaculture System for Growing

Catfish. Presentation. Catfish Farmers of America Meeting, Natchez, MS.

United States Department of Agriculture (USDA). 2006. 2005 Census of Agriculture. Washington DC.

United States Department of Agriculture/National Agricultural Statistics Service USDA/NASS). 2009. Production and Inventory of Channel Catfish. Washington DC. http://usda.mannlib.cornell.edu/usda/nass/CatfProd//2000s/2009/CatfProd-01-30-2009_revision.pdf. April, 2008.

United States Environmental Protection Agency (USEPA). 1974. Pollution aspects of catfish production-review and projection. EPA, Report 660/2-74-064. Washington DC.

Table 1. Channel catfish and hybrid catfish stocking and harvest densities for the In-pond Raceway System in Browns, AL.

Fish species and rearing location	Stocking density (kg/m²)	Stocking density (kg/m³)	Harvest Density (kg/m²)	Harvest Density (kg/m³)
Channel catfish				
Raceway 1b	21.6	17.7	66.9	54.9
Raceway 2	55.4	45.4	175.5	143.9
Raceway 5	112.5	92.3	242.6	199.0
Hybrid catfish				
Raceway 1a	128.8	105.7	193.3	158.6
Raceway 3 (split into 3 & 4)[a]				
Raceway 3a	142.6	117.0	172.5	141.5
Raceway 4	144.2	118.3	214.7	176.1
Raceway 6	42.4	34.8	261.8	214.7

[a] Raceway 3 reached maximum density and the decision was made to partial harvest 50% of the biomass and stock into the neighboring raceway #4. Total weight of raceway 4 was known at the time of harvest, but assumptions from fish samples could only be made for the remaining fish in raceway 3.

Table 2. Water quality variables measured in pond water samples collected from an In-pond Raceway System (IPRS) in Browns, AL. Values represent the mean and standard deviation.

Water Quality Variable	IPRS		
Dissolved oxygen (mg/l)	6.38	±	3.62
Temperature (C^o)	25.15	±	5.12
pH	7.74	±	0.48
TAN (mg/l)	1.45	±	1.15
Nitrite-N (mg/l)	0.17	±	0.19
Total alkalinity (mg/l)	164.60	±	16.40
Total hardness (mg/l)	140.10	±	8.60
Chloride (mg/l)	705.30	±	75.60
Salinity (g/l)	1.24	±	0.12

Table 3. Summary of production of channel catfish and hybrid catfish utilizing an In-pond Raceway System during an 8-month period in Browns, AL.

Fish species and rearing location	Average stocking size (g)	Total Weight Stocked (kg)	Number of fish stocked	Average Harvest Weight (g)	Total Weight Harvested (kg)	Growing Period (days)	Production (g/fish/day)	Survival (%)	FCR
Channel catfish									
Raceway 1b	59.09	812	13,742	277.27	2,515	147	1.3	66.0	1.21
Raceway 2	177.27	2,082	11,745	590.91	6,600	220	1.8	95.1	1.54
Raceway 5	140.91	4,230	30,019	395.45	9,125	193	1.1	76.9	2.11
		7,124			18,240				
Hybrid catfish									
Raceway 1a	418.18	4,845	11,587	640.91	7,270	96	2.2	97.9	1.78
Raceway 3 (split into 3 & 4)[a]	240.91	4,943	20,517	768.18	14,559	239	2.1	92.4	1.43
Raceway 6	61.58	1,594	25,500	468.18	9,844	250	1.6	82.5	1.16
		11,382			31,673				
Total weight stocked (kg)		18,506	Total weight harvested (kg)		49,913				
			Total production (kg)		31,407				

[a] Raceway 3 reached maximum density and the decision was made to partial harvest 50% of the biomass and stock into the neighboring raceway #4. Total weight of raceway 4 was known at the time of harvest, but assumptions from fish samples could only be made for the remaining fish in raceway 3.

Table 4. Summary of paddlefish and tilapia production as co-cultured species utilizing an In-pond Raceway System in Browns, AL.

Species	Average stocking size (kg)	Total weight stocked (kg)	Number of fish stocked	Average harvest weight (kg)	Total weight harvested (kg)	Growing period (days)	Survival (%)
Paddlefish	0.328	229.3	700	4.00	2,406	675	85.9
Tilapia[a]	0.232	13.55	58	0.22	3,959	203	-

[a] Tilapia survival was not calculated as males and females continued to spawn throughout the production season (i.e. larger number of fish at harvest).

Table 5. Preventative measure schedule for potassium permanganate treatment of catfish cultured in the In-pond Raceway System in Browns, AL.

Temperature (C^o)	Average Secchi disk visibility (cm)	Concentration (mg/l)	Time (mins)
15	30.2	2	45
17	22.8	4	45
19	24.5	3	30
21	19.0	5	30
23	22.5	5	30
25	25.1	5	30
27	25.6	4	30
29	25.5	4	20
31	20.9	5	15
33	16.3	6	15

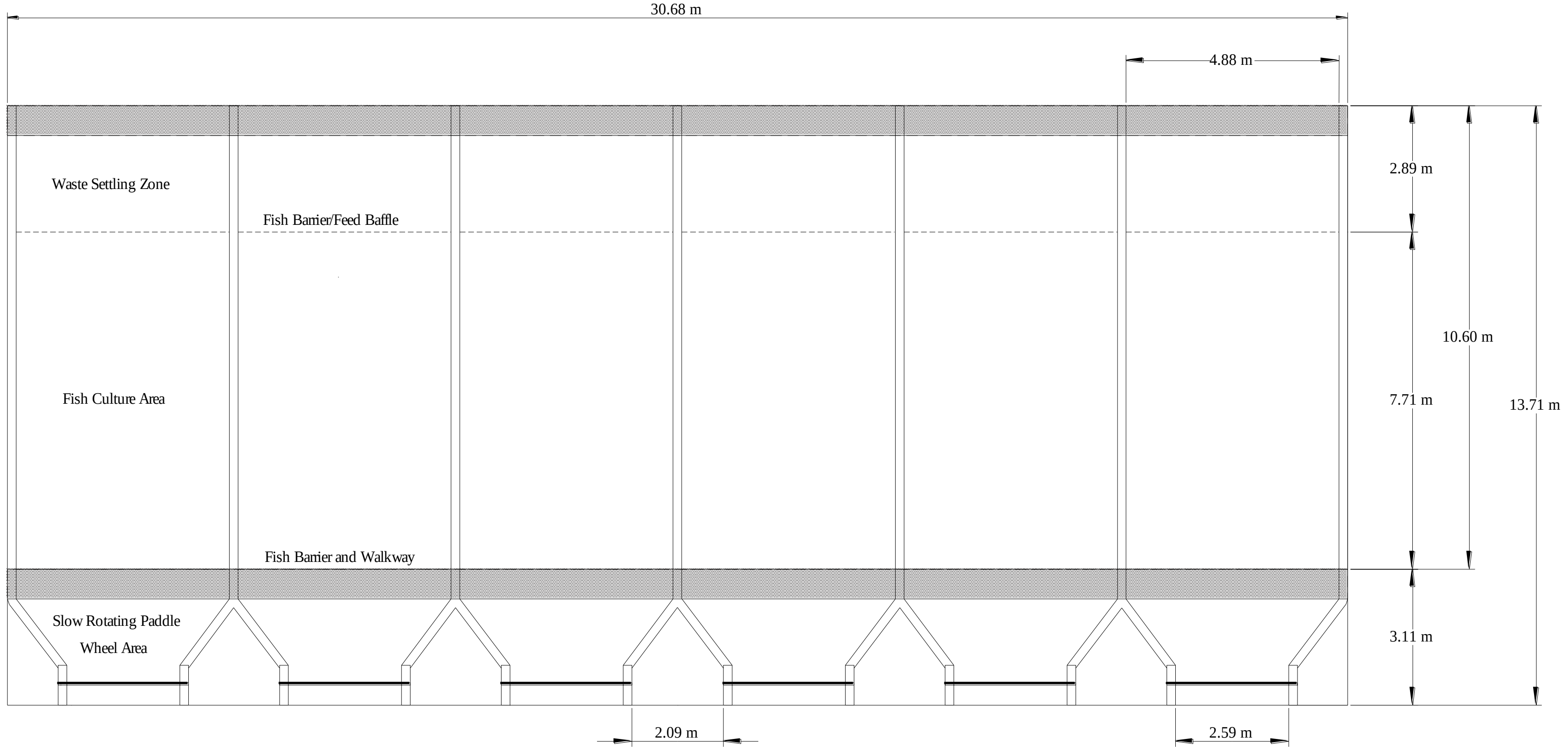

Figure 1. Aerial view of In-pond Raceway System design.

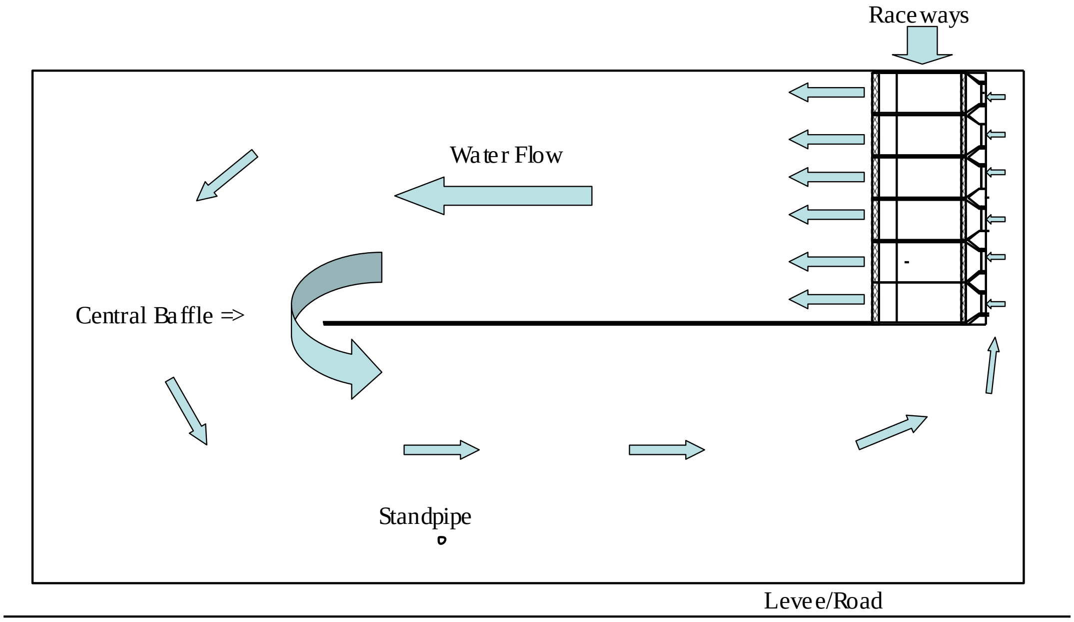

Figure 2. Aerial view of the In-pond Raceway System showing the direction of water flow throughout the pond and the raceways (not to scale).

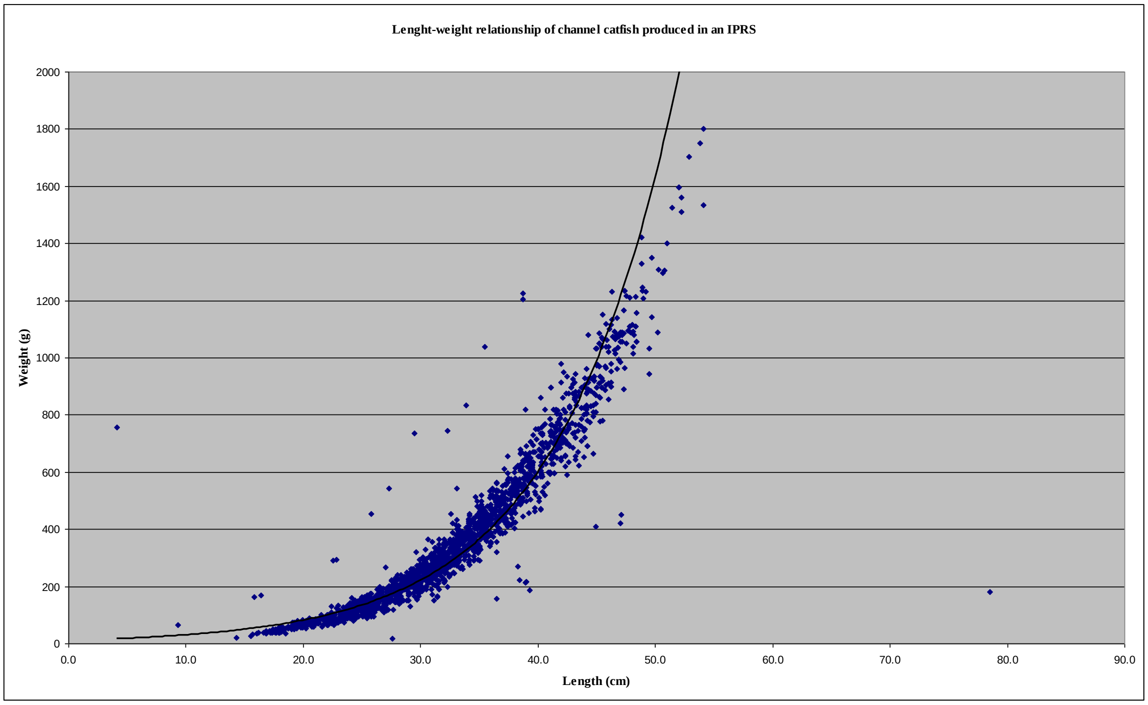

Figure 3. Length-weight relationship for channel catfish produced in an In-pond Raceway System in Browns, AL.

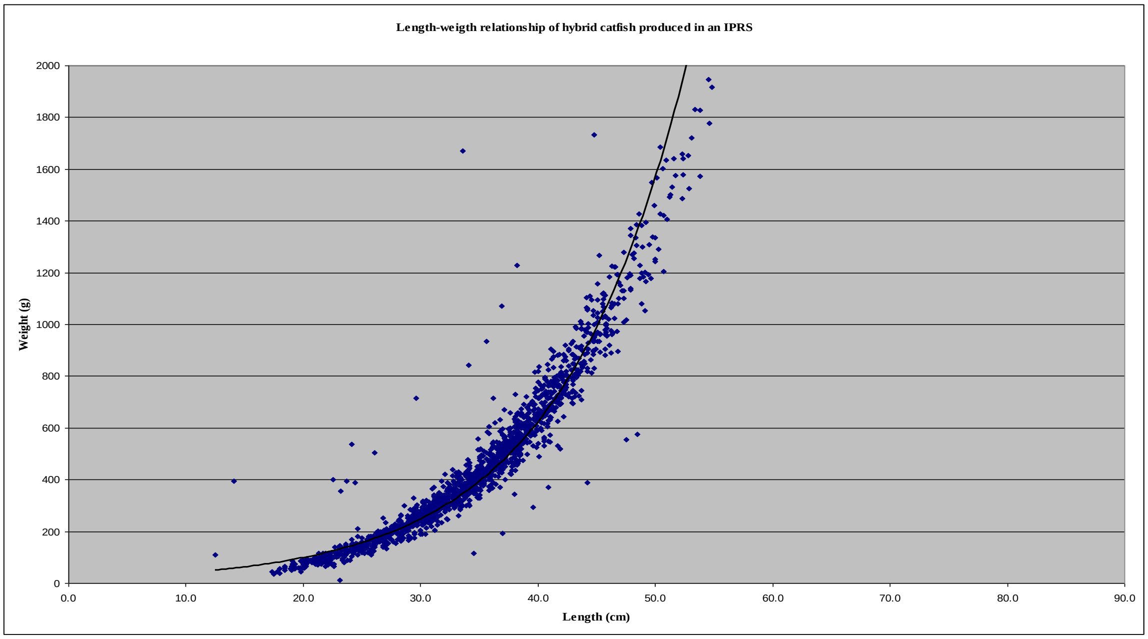

Figure 4. Length-weight relationship for hybrid catfish produced in an In-pond Raceway System in Browns, AL.

Chapter III

A Partial Chemical Budget for an Experimental In-pond Raceway System with Circularly Moving Water

Abstract

Budgets for water, nitrogen, phosphorous, chemical oxygen demand (organic matter), and dissolved oxygen (DO) were estimated over a production season (March-November) for an In-pond Raceway System (IPRS) used to culture channel catfish *Ictalurus punctatus*, hybrid catfish *Ictalurus furcatus*, paddlefish *Polyodon spathula*, and Nile tilapia *Oreochromis niloticus*. In addition to rainfall and runoff, 70 cm of water were applied from a nearby well to offset evaporation and seepage. Production of each kilogram of live catfish required 1.49 kg of feed and released 51.7 g nitrogen, 13.4 g phosphorous, and 0.41 kg chemical oxygen demand (COD). Metabolic wastes resulting from the production of 1 kg of catfish led to the synthesis of an additional 1.74 kg of COD in photosynthesis. Consequently, 1 kg of live catfish resulted in 2.06 kg COD. Harvest of catfish accounted for 33.9 % of nitrogen, 13.1 % of phosphorous, and 28.3 % of organic matter (COD) applied in feed. There was some accumulation of nitrogen and organic matter in pond sediment, but a large amount was lost from the system. Denitrification and ammonia volatilization probably removed large amounts of nitrogen while organic matter was consumed in respiration. Phosphorous was harvested in fish and

absorbed in pond sediment. Seepage and overflow removed only small portions of nitrogen, phosphorous, and organic matter. Total respiration within the system exceeded the DO produced by photosynthesis while diffusion and mechanical aeration aided in maintaining appropriate DO levels for fish production. Utilizing circulatory flowing water in an IPRS is an effective tool in destratification that improves DO concentration throughout the pond and increases aerobic oxidation of organic matter by microorganisms.

Introduction

The future development of the aquaculture industry may be limited by resources, such as land, water, and fishmeal (Naylor et al., 2000; Westers, 2000). Environmental pollution (mainly nitrogen and phosphorus) are other factors that can limit the growth of aquaculture and negatively impact natural ecosystems (Hakanson et al., 1998; Lemarie et al., 1998). Integrated pond systems, similar to recirculating aquaculture systems, utilize management practices to partially recycle nutrients that would normally be lost to the water column. These practices focus on nutrient reduction through immobilization in bacterial biomass, volatilization to the atmosphere, and conversion into harvestable products (Schneider et al., 2005). The use of these practices reduces waste discharge to the environment and fosters more efficient use of resources as compared to open raceways, cage culture, and ponds that are drained on a regular basis.

Catfish farming is the leading form of aquaculture in the U.S. with over 231,215 mt of food-sized channel catfish produced in 2008 (USDA, 2009). Most catfish are cultured in levee type ponds, watershed ponds, or a combination of both. The main water supply is from rainfall, runoff, or wells. A traditional pond system has a production rate of 4,500 - 5,500 kg/ha/yr with maximum annual production rates around 7,000 kg/ha/yr (Brune, 1991; USDA, 2006). Avault (1980) found that under experimental conditions, 13,000 kg/ha/yr was attainable with adequate management practices.

New and more efficient production methods for raising catfish have been of interest in the U.S. since the 1960's (Schmittou, 1969). Cages, raceways, and tanks were originally utilized to intensify culture practices (Schmittou, 1969; Andrews et al., 1971; Hill et al., 1974). Masser (2004) reports that the concept of floating raceways can be traced back to the early 1920's, while most of the research was performed during the 1970's (Brown et al., 1971; Fremont, 1972; Hill et al., 1974, USEPA, 1974; and Fast, 1977) and 1990's (Long, 1990, Fast, 1991, Hawcroft, 1994, Masser et al., 1994, and Masser, 1995).

Recent studies have demonstrated new production systems that utilize high rate photosynthetic systems such as the partitioned aquaculture system (Brune et al., 2004) or the split-pond system (Tucker and Kingsburg, 2009). These systems are believed to be more controllable and efficient at producing catfish than traditional farming methods because they combine a number of biological, chemical, and physical intensification practices into a single, integrated system.

Chemical and nutrient budgets can accurately account for the sources and fates of nutrients entering ecosystems and improve understanding of nutrient use. Green (1993) reported that fertilizers and feeds are generally the largest source of nitrogen and phosphorous inputs into fish ponds, albeit ponds also receive nutrients from rainfall, surface runoff, and regulated water inflow.

Nutrient budgets for traditional channel catfish ponds have been calculated (Boyd, 1985a; Gross et al., 2000), however minimal knowledge is available for integrated pond production systems (Krom and Neori, 1989; Brune et al., 2003; Yi, Y. et al., 2003; Schneider et al., 2005; Nhan et al., 2006). This study reports concentrations and various water quality variables and provides a complete water budget and partial nutrient budgets of an In-pond Raceway System (IPRS) for the production of catfish over an 8-month period.

Materials and Methods

In 2007, an intensive IPRS was constructed in a traditional 2.43 ha earthen pond of 1.67 m average depth supplied by well water and watershed runoff in west Alabama. The IPRS consists of six individual raceways that share common walls and attached to a permanent concrete foundation (overall length, width and height of 30.48 × 13.72 × 1.42 m). The fish are confined in the culture unit by an end partition barrier that spans the width (4.88 m) of each raceway unit. Water flows into the raceways via a slow rotating paddlewheel which rotates at 1.2 revolutions per minute and is capable of exchanging water in each raceway at a rate of once ever 4.9 minutes. The water flows away from the raceways out into the north side of the pond, counterclockwise to the south side of the pond, and returns to the water inflow side of the raceways as illustrated in Figure 1. A 1.12-kW regenerative blower with diffuser grid was operated whenever DO concentration fell below 3.0 mg/L. In addition, a 7.46-kW, paddlewheel aerator was installed near the water inflow channel and was utilized when the blower system could not maintain appropriate DO levels for fish production.

Fingerlings *Ictalurus punctatus* and *Ictalurus punctatus* × *Ictalurus furcatus* were obtained throughout the experiment from commercial suppliers (Eagle Aquaculture, Indianola, MS and Aquacenter, Leland, MS) with a history of providing high health fish. Once the initial inventory and fingerling acclimation was complete, the fish (59.1 – 418.2 g/fish) were then stocked into the raceways at densities ranging from 12,000 – 30,000 fish per raceway. The growout phase ran for 89 - 250 days depending on the size of fish initially stocked. Fish were offered a commercial feed (32% protein, 3.53% lipid, floating) (Alabama Feed Mill, Uniontown, AL) 2 - 4 times per day based on the biomass, water temperature and fish size. Catfish were harvested throughout the study as they reached a marketable size. Feed conversion ratios (FCR) for each cohort of fish were calculated by dividing the amount of feed consumed per amount of weight gained. Paddlefish (*Polyodon spathula*) with an average individual weight of 326 g were originally stocked into the pond at a rate of 288 per hectare while Nile tilapia (*Oreochromis niloticus*) brood fish with an average weight of 233g were sexed and stocked at a rate of 12 breeding pairs per hectare.

A water budget for the IPRS was calculated utilizing the hydrologic equation given by Yoo and Boyd (1994):

$$\text{Inflow} = \text{Outflow} \pm \Delta \text{ in storage},$$

where Inflow = rainfall, runoff, well water; Outflow = evaporation, seepage, overflow; and Δ in storage = pond water level at time 1 minus water level at time 2. Seepage was determined by adding the difference of all inflows and outflows to the change in storage. On average, pond water levels were maintained approximately 11.0-cm below the standpipe. This practice allowed the storage capacity to be adequate to avoid overflow after most rain events. However, pond overflow did occur on one occasion for a 3-day period during tropical storm Fay (August 25 – 27, 2008). The total amount of overflow was estimated according to Boyd (1982).

A metric staff gauge was installed in the IPRS to allow water level measurements to the nearest 0.3 cm. Water was usually added to replace evaporation and seepage losses after the pond water level had dropped about 9.0-cm. All regulated water inflow was timed and calculated utilizing the coordinate method for a horizontal pipe (Yoo and Boyd, 1994).

A Class A evaporation pan and standard rain gauge were placed on a foundation 50 meters from the IPRS. The evaporation pan was filled with well water, and water levels in the pan were measured with a hook gauge. Pond evaporation was estimated at 0.81 times pan evaporation (Boyd, 1985b). Measurements of rainfall, evaporation and pond water level were measured daily between 0600 and 0700 h.

Storm runoff (overland flow) was estimated by the curve number technique of the United States Soil Conservation Service (1972). Watershed soil was classified according to its soil use-vegetative-cover complex and hydrologic group. This information was utilized to select a runoff curve number for estimating the equivalent depth of runoff expected for a given rainfall event. The soil in the pond’s watershed was assigned to hydrologic soil group D, because the soil was mainly comprised of alkaline Selma chalk (Sumter soils). The vegetation cover on the watershed was fair and primarily consisted of fescue grass on pasture land for cattle. The resulting curve number selected was 85.

Dissolved oxygen, temperature, pH, and salinity were measured in the main water supply channel and at the tail end of each raceway at a depth of 25-cm at dawn and dusk daily with a steady-state polarographic DO/conductivity meter (Yellow Springs Instrument Company model 85, Yellow Springs, OH) and a digital pH meter (Yellow Springs Instrument Company model pH 100, Yellow Springs, OH) as depicted in Figure 1. The majority of the water quality variables were analyzed according to the protocols described by Eaton et al., (2005).

Water samples were collected with a 90-cm water column sampler (Boyd and Tucker, 1992). Total alkalinity and chloride concentrations were measured utilizing the sulfuric acid titration method and the mercuric sulfate titration method respectively; total hardness by titration with EDTA; Secchi disk visibility was determined by measured depth, chlorophyll-*a* concentration was determined by spectroscopy of acetone-methanol extracts of phytoplankton removed from samples by membrane filtration; soluble reactive phosphorous through filterable orthophosphate (ascorbic acid procedure); total ammonia nitrogen (Nesslerization); nitrite nitrogen (diazotization); total nitrogen and total phosphorous was determined by spectroscopy following digestion in potassium persulfate solution (Gross and Boyd, 1998); chemical oxygen demand (COD – equivalent to organic matter) through sulfuric acid-potassium dichromate digestion; and total suspended solids through filtration and measured weight (Boyd and Tucker, 1992). All water quality variables, sample location(s), frequencies, and methods of analysis are given in Table 1. Water samples were also collected when well water was applied as makeup water and if and when overflow occurred.

Dark bottles prepared from 300-ml biological oxygen demand (BOD) bottles were filled with pond water and incubated weekly for 4 to 8 h between 0600 and 1400 at a 50 cm water depth (Table 1). Concentrations in DO bottles were measured with a polarographic DO meter (Yellow Springs Instrument Company model 57, Yellow Springs, OH) and BOD bottle probe before and after incubation. Water samples were re-aerated with a small diaframe air pump and aquarium size airstone if DO dropped below 5.0 mg/l. Community respiration was estimated from the decreases in DO in dark bottles as compared to initial bottles (Boyd, 2000). Community respiration was converted to a daily basis by multiplying measured values by the ratio 24 hours:hours of incubation. The ratio of the atomic weight of carbon to the molecular weight of oxygen (12/32) was utilized in converting oxygen concentrations to carbon concentrations for community respiration (Boyd, 2000). Benthic respiration was calculated utilizing the value that Boyd (1985a) reported multiplied by the average standing crop ratio of the IPRS with Boyd's (1985a) results (e.g. 9,975.9 kg/ha ÷ 3,935.8 kg/ha = 2.53 × 1.17 g O_2/m^2/day = 2.97 g/ m^2/day). Fish respiration was calculated by an equation presented by Boyd et al. (1978) and the amount of oxygen consumed was used as the reduction in COD through fish respiration.

Pond mud samples were collected with a 5-cm diameter, polycarbonate tube from the upper 15-cm stratum of bottoms at 15 locations (Table 1 and Figure 1) throughout the pond on March 13, 2008 and on November 18, 2008 and floc layer was measured to the nearest mm. Samples were air-dried, oven dried at 70^o C, pulverized to pass a 0.25-mm screen, and analyzed for total nitrogen (combustion), total phosphorus (persulfate digestion), and total carbon (loss on ignition at 300^o C). Soil analysis was performed at Brookside Laboratories, Inc., New Knoxville, Ohio.

Nine samples of feed were retained for chemical analysis. Each feed sample was oven dried at 70^o C and pulverized to pass a 0.85-mm screen. A sample of four whole fish (small and large) was taken from each cohort of fish at stocking and harvest. The fish samples were placed in a autoclave at 120^{o} C and $1.4 kg/cm^{2}$ for 1h. The fish was then homogenized using a hand mixer, and a 40-60 g sample was removed and oven-dried at 70^{o} C until a constant mass was achieved for two consecutive days (Glover et al. 2010). Total nitrogen and total phosphorus were analyzed by combustion and persulfate digestion respectively. (AOAC Method 990.03 and 985.01 respectively). Fish and feed analysis was performed by the New Jersey Feed Laboratory, Inc., Trenton, New Jersey. Paddlefish and tilapia composition values were borrowed from a previous study (Boyd and Green, 1998).

Partial budgets for nitrogen, phosphorus, and organic matter were estimated with the general, mass balance equation below:

$$FH_{in} + FD_{in} + PV_{in} + PM_{in} = FH_{out} + PV_{out} + PM_{out} \pm UN,$$

where FH = fish; FD = feed; PV = pond volume; PM = pond mud; and UN = unaccounted nutrient. Measured quantities of fish, feed, and water were multiplied by their respective concentrations of chemical substances to calculate different amounts of substances added to or removed from the IPRS. Rainfall was considered to be saturated with DO and the concentrations of other substances were taken from (NADP 2008). Seepage could not be collected and was considered to be devoid of DO but identical to pond water in concentrations of other substances. Runoff was assumed to have the same composition as rainfall because it had minimal contact time with the surrounding grass cover, soil, and levees before entering the pond.

Statistical analyses were performed using SAS (version 9.3, SAS Institute, Cary North Carolina). Data from pond mud samples were analyzed using a paired t-test to determine if significant differences existed ($P \leq 0.05$).

Results and Discussion

Rainfall during the 250-day period totaled 66.1 cm (Figure 2). August recieved the greatest rainfall, accounting for over 35% of total precipitation. Mean rainfall per event was 0.87 cm. Daily pond evaporation was 0.46 cm while the total pond evaporation over the period of this study was 116.7 cm (Table 1). Similar rates of pond evaporation have been observed in fish ponds in Alabama (Boyd, 1985b; Daniels and Boyd, 1989; Boyd et al., 2000).

Estimated storm runoff for the production season was 21.4 cm and accounted for 33.7 cm of pond depth (Table 1). Pond runoff depth exceeded watershed runoff depth because watershed area was 1.577 times greater than of the pond surface area. Pond seepage varied from 0.55 to 9.65 cm, with a mean seepage of 3.71 cm. Mean daily seepage ranged from 0.02 to 0.32 cm. The wide variation in these values is the result of the difficulty in measuring seepage by difference, but the average seepage is thought to be relatively accurate. These seepage rates were classified as very low according to Boyd (Boyd, 2009). For example, the mean daily seepage rates for two groups of ponds at Auburn, Alabama, were 0.48 cm and 0.79 cm, respectively (Boyd, 1982).

It appears that the average water budget for the pond of the IPRS is reliable because the total gains were 169.8 cm and the total losses were 176.1 cm (Table 1). Thus, there was only 6.3 cm of water loss unaccounted for. The total evaporation from the pond accounted for 66.2% of the total water loss; seepage and overflow accounted for the remaining water loss. Rain and regulated inflow water accounted for 38.9% and 41.3% of gains, respectively. The total rainfall was about half of the evaporation (Table 2). In small fish ponds at Auburn, Alabama, evaporation and seepage accounted for 31% and 61% of water losses respectively, while rain and regulated inflow accounted for 24% and 75% of respective gains (Boyd, 1982). In another study at Auburn, Alabama, overflow and seepage averaged 14.7 cm and 25.7 cm respectively. Evaporation accounted for 68%, seepage was 27%, and overflow was 15% of total water losses (Gross et al., 2000). Ponds at Auburn in the Piedmont Plateau region seep much more than pond in the Black Belt prairie (Yoo and Boyd, 1994).

The average quantity of feed and fish added to the pond of the IPRS, amount of fish harvested and the composition of fish and feed are presented in Table 3. These values closely resemble those observed by other researchers in catfish aquaculture (Boyd 1985a; Yi et al., 2003). The feed conversion ratio (FCR) averaged 1.49 which demonstrated high efficiency as compared to traditional commercial values. This FCR is close to the value reported by Boyd (1985a) who observed an FCR of 1.32 for channel catfish in small ponds at Auburn University, and Gross et al., (2000) who repoted an average FCR's of 1.40. On a dry weight basis, 42,639 kg of feed resulted in 9,467 kg of fish which yielded an actual feed conversion of 4.50. The difference between dry feed and dry fish is 33,162 kg, which as Boyd (1985a) points out, represents the chemical substances in metabolic wastes (metabolites). The catfish in the raceways consumed approximately 100 % of the feed fed because they were confined in a small area that was easily visible to the researcher. Feed barriers were also installed to reduce the chance of feed floating out of the tail end of the raceways. As a result of the previously stated factors, a negligible quantity of uneaten feed settled to the pond bottom. Even with the highly efficient FCR, considerable amounts of metabolites were released into the water column by the fish. Each kilogram of dry substance in feed produced 0.22 kg of dry fish and yielded 0.78 kg metabolic wastes.

Basic water quality variables such as DO, temperature, and pH remained within acceptable levels for catfish production throughout the study (Table 4). Other variables such as the total alkalinity, total hardness, and chloride were beneficial to fish production and equated to a more balanced and stress-free ecosystem. Even with higher than normal feeding rates, the total alkalinitydid not fall below 117 mg/l and averaged 165 mg/l. The system had a high buffering capacity against diurnal fluxes in DO and pH because of mechanical aeration and plenty on alkalinity, respectively.

Secchi disk visibility (23.66 ± 5.06 cm) had minimum and maximum values of 13.50 cm and 42.00 cm respectively (Figure 3), while chlorophyll-*a* concentration averaged 274.28 ± 178.97µg/l with a peak value of 948.65 µg/l during the early stages of the study (May). A minimal value of 49.07 µg/l was observed in March (Figure 4). Yi (2003) observed mean chlorophyll-*a* concentrations of 44, 72, and 132 µg/l in non-integrated systems, integrated pen-cum-pond systems with natural and artificial water circulation respectively. Southworth et al. (2006) found that with increased stocking density and feed rates, concentrations of chlorophyll-*a* increased nominally to about 181 ± 147 µg/l at densities of 34,600 catfish/ha. Soluble reactive phosphorous (SRP) averaged 0.086 ± 0.071 mg/l with a minimum and maximum concentration of 0.007 and

0.257 mg/l respectively (Figure 5). This is within the range (0.0 to 0.93 mg/l) that Yi (2003) observed for the culture of catfish and tilapia.

The total ammonia nitrogen (TAN) concentration averaged 1.45 ± 1.15 mg/l and reached a maximum concentration of 4.69 mg/l during the late summer season (September). The minimum level was 0.089 mg/l in May (Figure 6). Nitrite nitrogen averaged 0.17 ± 0.19 mg/l with a minimal concentration of 0.0038 mg/l in November and a maximum concentration of 0.8442 mg/l was reached in August (Figure 7). Levels of TAN, and nitrite-N remained within acceptable levels for catfish production. Yi (2003) observed levels of 3.09 to 4.13 mg/l TAN with catfish and tilapia and 0.01 to 0.02 mg/l nitrite-N, while Southworth et al. (2006) recorded values of 0.211 ± 0.165 mg/l to 0.750 ± 0.922 mg/l and 0.005 ± 0.001 to 0.144 ± 0.162 mg/l of TAN and nitrite-N, respectively, for channel catfish culture.

The concentrations of total nitrogen (TN) total phosphorus (TP), COD, and total suspended solids (TSS) within the pond are shown in Table 5. It appears that TN, COD, and TSS concentrations decreased over time possibly indicating a very high assimilative capacity. TP concentrations remained relatively unchanged from the start of the study until the final stage. Concentrations of TN, TP, COD, and TSS in the water applied from the well were much lower than those in the actual pond water. The overflow had elevated levels of TN, TP, and COD, that may have aided in the dilution and/or flushing of nutrients from the pond during tropical storm Fay. Boyd (1985a) observed an increase in concentrations of TN, TP, and COD over time in small earthen ponds in Auburn, Alabama, while Daniels and Boyd (1989) observed concentrations that remained relatively low over the production season in polyethylene-lined, brackish water ponds for the production of striped bass (*Morone saxatilis*). Green and Boyd (1995) also observed a steady increase in TN, TP, and COD over time in organically fertilized fish pond in the dry tropics. In natural and artificial, water-circulated environments, significantly lower levels of TN and TP were observed in pond effluents as compared to a non-integrated treatment (Yi et al., 2003). This supports the evidence that Nile tilapia can efficiently recover nutrients contained in the wastewater of an intensive catfish culture system, and suggests that continuous water circulation can reduce nutrient concentrations in pond effluents.

Respiration by planktonic communities and associated bacteria in the pond water was high averaging 6.8 g O_2/m^2/day. Respiration ranged from 3.7 g O_2/m^2/day in March to around 38.6 g O_2/m^2/day in June (Figure 8). Phytoplankton were responsible for most of the respiration since they comprise the majority of the microscopic biomass suspended in waters of catfish ponds (Boyd, 1982). The organic matter that was not consumed by respiration in the pond water settled to the bottom and the majority of the material was likely dead plankton (Boyd, 1985a). As stated earlier, the benthic respiration was estimated to be 2.97 g O_2/ m^2/day. Schroeder (1975) reported soil respiration rates of oxygen uptake to be between 3 to 4 g O_2/m^2/day in heavy density (11,000-13,000 fish/ha) polyculture ponds in Israel. The maximum rate of oxygen diffusion into pond soil is about 4 g O_2/m^2/day (Schroeder, 1975). This suggests that the aerobic respiration in pond bottoms of intensive aquaculture systems is limited by the supply of oxygen.

Gross photosynthesis was not measured directly; an estimate was made by subtracting the difference of the total losses from the total gains of DO. This equated to an average of 8.46 g O_2/m^2/day (3.18 g C/ m^2/day) of gross photosynthesis for the duration of the study. Boyd (1985a) observed a range of 2 g O_2/m^2/day to 14 g O_2/m^2/day, while Green and Boyd (1995) found that 4.5 to 14.0 and 7.6 to 13.5 g O_2/m^2/day was a good representation of fertilized ponds in the tropics during raining and dry seasons, respectively.

Supplemental aeration was applied an average of 4-hours per day throughout the study with an airlift pump with air supplied from a blower. Emergency aeration was applied by a paddlewheel aerator for an average of 4 h/day. The majority of the aeration (supplemental and emergency) was applied when feed rates were elevated. Both the airlift aeration device and a paddlewheel aerator were tested at Auburn University. These units transferred 1.26 kg O_2/kW·h (1.88 kg O_2/h) and 2.36 kg O_2/kW·h (12.35 kg O_2/h), respectively in pond water at 20^oC and 0 mg/l DO; the pond transfer rate computed for conditions of temperature and DO concentration in the study pond over a 24-hour period (Shelton and Boyd, 1983) averaged 0.16 and 0.31 kg O_2/kW·h, respectively.

There were significant ($P < 0.05$) changes in concentrations of total nitrogen, total phosphorous, and organic matter in bottom mud between March and November 2008 (Table 6). The primary source of nitrogen gain was from fish feed which was 83.9% of the measured input (Table 7). No attempt was made to measure nitrogen fixation because this production system had high levels of TAN and presumably of nitrate nitrogen also throughout the growing season and nitrogen fixation is thought to be low or nil in ponds with high concentrations of combined nitrogen (Boyd and Tucker, 1998). Fish harvest was the greatest measured loss of nitrogen and gains exceeded losses. Nitrogen concentrations increased in pond sediment ($p = 0.0133$) during the study by 310.2 kg. Ammonia volatilization and denitrification were estimated to account for 39.1 % of nitrogen loss (Table 7). More nitrogen would have been lost through these pathways if nitrogen fixation was greater than assumed.

Feed application and fish harvest represented the major gains and losses of phosphorous, and gains exceed losses (Table 7). Phosphorous concentrations increased in pond sediment ($p = 0.0248$) during the study by 374.2 kg. Boyd (1985a) found that phosphorous loss from pond waters resulted mainly from adsorption by pond muds, and other studies have shown that pond sediment and water-logged agricultural soils have a strong affinity for phosphorous, respectively (Rigler, 1964; Masuda and Boyd, 1994; Sanyal and De Datta, 1991).

The principal gains in COD were from feed applications and organic matter production by photosynthesis, and the main losses were from respiration by the entire pond biota (Table 7). The discrepancy between the COD and DO budgets can be explained by the difference in COD of the fish at harvest and COD in the water that flowed out of the pond (overflow and seepage).

The major source of DO was from photosynthesis by phytoplankton (Table 7), although community respiration by the pond consumed 5,958.1 kg more DO than the total amount of DO from photosynthesis, water inflow from rainfall and runoff, and aeration. The difference was assumed to be the net amount of oxygen that diffused into the pond. Net diffusion only averaged 23.9 kg/day (0.54 mg/l), but was important because the phytoplankton community only produced an amount of oxygen necessary for its complete decomposition. Of course, there was some excess phytoplankton photosynthesis over phytoplankton respiration because some of the phytoplankton was within overflow and some settled to the bottom and did not decompose during the study.

Natural diffusion aided in maintaining optimal DO levels for fish production. The survival of fish at night when DO concentration was lowest depended heavily on the DO provided by diffusion as well as that from mechanical aeration. Maintaining optimal DO levels for fish production reduces the chances of stress and/or mortality and improves production efficiency (Tucker and Robinson, 1990).

Harvest of catfish removed 33.9 % of added nitrogen, 13.1 % of added phosphorous, and 28.3 % of added COD (organic matter) applied as feed from the system (Table 7). With the additional harvest of paddlefish and tilapia, the removal increases to 39.1 % of added nitrogen, 22.2 % of added phosphorous and 31.9 % of added COD. Boyd (1985a) reported that 26.8 % of nitrogen, 30.1 % of phosphorous, and 25.5 % of COD applied to traditional channel catfish ponds were removed in fish at harvest. In striped bass ponds that received low feeding rates, fish harvest accounted for 22.2 % of nitrogen, 56.7 % of phosphorous, and 13.8 % of COD applied in feed (Daniels and Boyd 1989). Fish harvested from fish ponds in the dry tropics accounted for 19.5 % nitrogen, 17.0 % phosphorous, 27.8% of COD added in feed (Green and Boyd, 1995). Hybrid catfish incorporated 40.7 % nitrogen and 49.0 % phosphorous from the feed input in both non-integrated and natural and artificial water circulation treatments (Yi, 2003). Green and Boyd (1995) found that fish harvest accounts for a larger percentage of added nutrients in ponds when they received concentrated feeds as compared to ponds that received organic fertilizers.

Each kilogram of live catfish required 1.49 kg of feed and released into the water column 51.7 g nitrogen, 13.4 g phosphorous, and 0.41 kg COD. Metabolic wastes from fish consuming 1.49 kg of feed resulted in the production of an additional 1.77 kg of

COD in phytoplankton. Consequently, each kilogram of live catfish resulted in 2.18 kg of COD.

The concentrations of total nitrogen, total phosphorous, COD, and total suspended solids in the pond water were usually at moderate levels (Table 5). As Boyd (1985a) states, these concentrations are not as high as expected because nitrogen is rapidly lost through denitrification and ammonia volatilization, phosphorous is absorbed by the pond mud, and organic matter (COD) is constantly oxidized.

The present study demonstrates that channel catfish and hybrid catfish can be cultured in an IPRS with paddlefish and Nile tilapia stocked outside in the pond to aid in water quality management. Tilapia recycle nutrients in wastes that would normally be only partially assimilated by the pond ecosystem thereby lessening the nutrient load of effluent in receiving waters. This study also provides insight on development of the integration of intensive and semi-intensive culture systems for adoption by small and large-scale farmers. By using an IPRS, a portion of the pond can be used to produce the primary species (catfish), and the rest of the pond can produce paddlefish and tilapia. This favors more efficient utilization of costly feed through the recycling of wastes to filter-feeding species such as Nile tilapia (directly) and paddlefish (indirectly). Optimization of the catfish to paddlefish to tilapia ratio (C:P:T), pond partition ratio, and culture period(s) would maximize efficiency, enhance nutrient utilization efficiency, minimize environmental impacts of pond effluents, and increase profit potential.

References

Andrews, J.W., L.H. Knight, J.W. Page, Y. Matsuda, and E.E. Brown,1971. Interactions of stocking density and water turnover on growth and food conversion of channel catfish reared in intensively stocked tanks. Progressive Fish-Culturist 33, 197-203.

Andrews, J.W. and Y. Matsuda. 1975. The influence of various culture conditions on the oxygen consumption of channel catfish. Transactions of the American Fisheries Society. 104: 322-327.

Avault, J.W. 1980. Six tons of catfish with aeration in one acre of water. Aquaculture Magazine 7, 44.

Boyd, C.E., R.P. Romaire, and E. Johnston. 1978. Predicting Early Morning Dissolved Oxygen Concentrations in Channel Catfish Ponds. Transactions of the American Fisheries Society. 107(3): 484-492.

Boyd, C.E. 1982. Hydrology of small experimental fish ponds at Auburn, Alabama. Transactions of the American Fisheries Society. 111: 638-644.

Boyd, C.E., 1985a. Chemical Budgets for Channel Catfish Ponds. Transactions of the American Fisheries Society. 114: 291-298.

Boyd, C.E., 1985b. Pond evaporation. Transactions of the American Fisheries Society. 114: 299-303.

Boyd, C.E. and C.S. Tucker. 1992. Water Quality and Pond Soil Analysis for Aquaculture. Alabama Agriculture Experiment Station, Auburn, AL.

Boyd, C.E. and G.W. Green. 1998. Dry Matter, Ash, and Elemental Composition of Pond-Cultured Tilapia *Orechromis aureus* and *O. niloticus*. Journal of the

World Aquaculture Society. 29(1): 125-128.

Boyd, C.E. and C.S. Tucker. 1998. Pond Aquaculture Water Quality Management. Kluwer Academic Publishers, MA, 52-53 pp.

Boyd, C.E., 2000. WATER QUALITY: An Introduction. Kluwer Academic Publishers, Norwell, Massachusetts, 157-161pp.

Boyd, C.E., J. Queiroz, J. Lee, M. Rowan, G.N. Whitis, and A. Gross. 2000. Environemntal Assesment of channel catfish farming in Alabama. Journal of the World Aquaculture Society. 31(4): 511-544.

Boyd, C.E. 2009. Assessing, Reducing Pond Seepage. Global Aquaculture Adovacate. March/April, 62-63pp.

Brown, E.E., J.L. Chesness, and S.R. Chapman. 1971. Raceway and Pond Economics. Producing and marketing catfish in the Tennessee Valley. Tennessee Valley Authority, Tennessee, 90-93 pp.

Brune, D.E., 1991. Pond aquaculture. Timmons, M.B. (Editor): Engineering Aspects of Intensive Aquaculture. Natural Resources, Agriculture, and Engineering Service Publication NRAES-49, Natural Resources, Agriculture, and Engineering Service, New York, 118-130 pp.

Brune, D.E., 2003. Intensification of pond aquaculture and high rate photosynthetic Systems. Aquaculture Engineering. 28: 65-86.

Brune, D.E., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and J.A. Hargreaves. (editors): Partioned Aquaculture Systems. Elsevier, New York, 561-562 pp.

Brune, D.E., G. Schwartz, A.G. Eversole, J.A. Collier, and T.E. Schwedler. 2004. Partitioned Aquaculture Systems. SRAC Publication No. 4500.

Daniels, H.V. and C.E. Boyd. 1989. Chemical Budgets of Polyethlene-lined , Brackishwater Ponds. Journal of the World Aquaculture Society 20(2): 53-59.

Eaton, A.D., L.S. Clesceri, E.W. Rice, and A.E. Greenberg. (Editors). 2005. Standard Methods for the examination of water and wastewater, 21st edition. American Public Health Association, Washington, D.C., USA.

Fast, A.W. 1977. Floating fish rearing system. U.S. Patent No. 4,044,720.

Fast, A.W. 1991. A floating fish cage with solid plastic membrane and pumped water exchange. Journal of Applied Aquaculture 1: 99-110.

Fremont, H.J., 1972. Floating fish growing tank. U.S. Patent No. 3,653,358.

Glover, D.C., D.R. DeVries, R.A. Wright, and D.A. Davis. 2010. Sample preparation Techniques for determination of fish energy density via bomb calorimetry: an Evaluation using largemouth bass. Transactions of the American Fisheries Society. 139: 671-675.

Green, B.W., 1993. Water and Chemical Budgets for Organically Fertilized Fish Ponds in the Dry Tropics. Ph.D. Dissertation. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Green, B.W. and C.E. Boyd. 1995. Chemical Budgets for Organically Fertilized Fish Ponds in the Dry Tropics. Journal of the World Aquaculture Society. 26(3): 284-296.

Gross, A. and C.E. Boyd. 1998. A Digestion Procedure for the Simultaneous

Determination of Total Nitrogen and Total Phosphorus in Pond Water. Journal of The World Aquaculture Society. 29: 300-303.

Gross, A., C.E. Boyd, and C.W. Wood. 2000. Nitrogen transformations and balances in Channel catfish ponds. Aquaculture Engineering. 24: 1-14.

Hakanson, L., Carlsson, L., Johansson, T. 1998. A new approach to calculate the phosphorus load to lakes from fish farm emissions. Aquaculture Engineering. 17(3): 149-166.

Hawcfoft, B.A., 1994. Development and evaluation of an in-pond raceway and waste removal system.. M.S. Thesis. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Hill, T.K., J.L. Chesness, and E.E. Brown. 1974. Growing channel catfish, *Ictalurus punctatus*, in raceways. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28, 488-499.

Krom, M.D. and A. Neori. 1989. A Total Nutrient Budget fo an Experimental Intensive Fishpond with Circularly Moving Seawater. Aquaculture 83: 345-358.

Lemarie, G., J.L.M. Martin, G. Dutto, C. Garidou, 1998. Nitrogenous and phosphorusous waste production in a flow-through land-based farm of European seabass (Dicentrarchus labrax). Aquatic Living Resources. 11 (4): 247-254.

Long, C.E., 1990. Raceway culturing of fish. U.S. Patent No. 4,915,059.

Masser, M.P., and S. Duarte. 1994. The Alabama Piedmont catfish cage farming industry.World Aquaculture 25(4): 26-29.

Masser, M.P. 1995. Intensive Catfish Systems. World Aquaculture 26(3): 60-64.

Masser, M.P., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and

J.A. Hargreaves. (editors): Cages and In-pond Raceways. Elsevier, New York, 532 pp.

Masuda, K. and C.E. Boyd. 1994. Effects of aeration, alum treatment, liming and organic matter application on phosphorous exchange between pond soil and water in aquaculture ponds at Auburn, Alabama. Journal of the World Aquaculture Society 25: 405-416.

Mezainis, V.E. 1977. Metabolic rates of pond ecosystems under intensive catfish cultivation. M.S. Thesis. Auburn University. Auburn, Alabama, 107pp.

NADP data report precipitation chemistry. 2008. Blackbelt Research and Extension Center, Auburn University, Selma, AL, USA.

Naylor, R.L., R.J. Goldburg, J.H. Primavera, N. Kautsky, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney, and M. Troell. 2000. Effect of aquaculture on world fish supplies. Nature. 405(29): 1017-1024.

Nhan, D.K., A. Milstein, M.C.J. Verdegem, J.A.V. Verreth. 2006. Food inputs, water Quality and nutrient accumulation in integrated ponds systems: A multivariate approach. Aquaculture 261: 160-173.

Rigler, F.H. 1964. The phosphorous fractions and the turnover time of inorganic Phosphorous in different types of lakes. Limnology and Oceanography 9: 511-518.

Sanyal, S.K. and S.K. De Datta. 1991. Advances in soil science. Hatifield, J.L. et al., (editors): Chemistry of phosphorous transformations in soils. Springer-Verlag, Berlin. 1-120 pp.

Schmittou, H.R., 1969. Intensive culture of channel catfish, *Ictalurus punctatus* (Rafinesque), in cages suspended in ponds. Doctoral Dissertation. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Schneider, O., V. Sereti, E.H. Eding, J.A.J. Verreth. 2005. Analysis of nutrient flows in integrated intensive aquaculture systems. Aquaculture Engineering 32: 379-401.

Schroeder, G.L. 1975. Nighttime material balance of oxygen in fish ponds receiving organic wastes. Bamidgeh 27: 65-74.

Shelton, J.L., Jr., and C.E. Boyd. 1983. Correction factors for calculating oxygen-transfer rates for pond aerators. Transactions of the American Fisheries Society 112: 120-122.

Southworth, B.E., N. Stone, C.R. Engle, 2006. Production Characteristics, Water Quality, and Costs of Producing Channel Catfish *Ictalurus punctatus* at Different Stocking Densities in Single-batch Production. Journal of the World Aquaculture Society. 37(1): 21-31.

Tucker, C.S. and E.H. Robinson. 1990. Channel Catfish Farming Handbook. Van Nostrand Reinhold, New York. pp. 454.

Tucker, C.S., and S. Kingsburg. 2009. A Split-pond Aquaculture System for Growing Catfish. Presentation. Catfish Farmers of America Meeting, Natchez, MS.

United States Department of Agriculture (USDA). 2006. 2005 Census of Agriculture. Washington DC.

United States Department of Agriculture/National Agricultural Statistics Service

USDA/NASS). 2009. Production and Inventory of Channel Catfish. Washington DC.

United States Environmental Protection Agency (USEPA). 1974. Pollution aspects of catfish production-review and projection. EPA, Report 660/2-74-064. Washington DC.

U.S. Soil Conservation Service. 1972. Hydrology. In SCS National Engineering Handbook, Sec. 4, Washington, D.C.

Westers, H., 2000. A Fourteen-Year Dispute About Phosphorous Effluent Contribution and Its Impact on Platte Lake. Recirculating Aquaculture. Roanoke, Virginia.

Yi, Y., C.K. Lin, J.S. Diana. 2003. Hybrid catfish (*Clarias macrocephalus x C. gariepinus*) and Nile tilapia (*Oreochromis niloticus*) culture in an integrated pen-cum-pond system: growth performance and nutrient budgets. Aqucaulture 217: 395-408.

Yoo, K.H. and C.E. Boyd. 1994. Hydrology and Water Supply for Pond Aquaculture. Chapman & Hall, New York, NY, 31-32pp

Table 1. Water quality variables, sample location(s), frequencies, and methods of analysis for an In-pond Raceway System located in Browns, AL.

Variable	Sample location(s)	Frequency	Method of analysis
-Dissolved oxygen (DO)	A, 1-6	2X/day	Polarographic DO/conductivity meter
-Temperature	A, 1-6	2X/day	Polarographic DO/conductivity meter
-Salinity	A, 1-6	2X/day	Polarographic DO/conductivity meter
-pH	A, 1-6	2X/day	Digital pH meter
-Total Alkalinity	A	Weekly	Sulfuric acid titration
-Total Hardness	A	Start & finish	EDTA titration
-Chloride	A	Weekly	Mercuric sulfate titration
-Secchi disk visibility	A	3X/week	Measurement of Secchi disk depth
-Chlorophyll-*a*	A	Weekly	Acetone-Methanol extraction
-Soluble reactive phosphorous	A	Weekly	Filterable orthophosphate (ascorbic acid procedure)
-Total ammonia nitrogen	A, 1-6, I-V	Weekly	Nesslerizaton
-Nitrite nitrogen	A, 1-6, I-V	Weekly	Diazotization
-Total nitrogen	A, standpipe, well	4X	Persulfate digestion
-Total phosphorous	A, standpipe, well	4X	Persulfate digestion
-Chemical oxygen demand	A, standpipe, well	4X	Sulfuric acid - potassium dichromate digestion
-Total suspended solids	A, standpipe, well	4X	Filtration and measured weight
-Respiration	I-V	Weekly	Dark bottle technique (DO difference from time 1 and time 2)

Table 2. Average water budget for an In-pond Raceway System on a catfish farm in Browns, AL from March 13 to November 18, 2008. All quantities are in centimeters of depth.

Variable	March	April	May	June	July	August	September	October	November	Total
Rainfall	2.9	11.9	7.0	7.2	7.2	23.4	1.3	3.9	1.4	66.1
Runoff	0.49	3.51	1.83	1.02	0.91	25.43	0	0.48	0	33.7
Inflow	2.01	8.35	12.76	14.83	9.36	9.32	6.71	6.76	0	70.1
Evaporation	8.0	11.4	15.3	18.2	18.3	17.2	13.6	10.1	4.5	116.7
Seepage out	1.10	4.06	5.04	9.65	0.55	3.53	5.08	3.21	1.14	33.4
Overflow	0	0	0	0	0	26.1	0	0	0	26.1

Table 3. Average weights of channel and hybrid catfish stocked, feed applied, and fish harvested, and data on the composition of fish and feed from an In-pond Raceway System (IPRS). The pond of the IPRS was 2.43 ha in surface area. Values represent average and standard deviations.

Item	Feed	Small fish	Large fish
Quantity added (kg)	47,000	18,506	
Quantity harvested (kg)			49,913
Dry Matter (%)	90.7 ± 0.30	27.6 ± 1.69	29.2 ± 2.75
Nitrogen (% of dry weight)	5.77 ± 0.06	8.89 ± 0.46	8.85 ± 0.79
Phosphorous (% of dry weight)	1.14 ± 0.05	2.15 ± 0.34	1.19 ± 0.14
Carbon (% of dry weight)	42.4 ± 0.15	54.1 ± 2.50	54.1 ± 0.67

Table 4. Water quality variables measured in pond water samples collected from an In-pond Raceway System (IPRS) in Browns, AL. Values represent the average and standard deviations.

Water Quality Variable	IPRS		
Dissolved oxygen (mg/l)	6.38	±	3.62
Temperature (C^o)	25.15	±	5.12
pH	7.74	±	0.48
Total alkalinity (mg/l)	164.60	±	16.40
Total hardness (mg/l)	140.10	±	8.60
Chloride (mg/l)	705.30	±	75.60

Table 5. Mean concentrations of total nitrogen, total phosphorous, chemical oxygen demand (COD - an estimate of organic matter), and total suspended solids collected from the initial pond water, added well water, stand pipe overflow, and final pond water from an In-pond Raceway System in Browns, AL.

Water Quality Variable	Initial (pond)	Well	Overflow	Final (pond)
Total Nitrogen (mg/l)	3.19	0.53	7.38	2.18
Total Phosphorus (mg/l)	0.18	0.10	0.75	0.18
COD (mg/l)	45.12	0.00	58.08	37.75
Total suspended solids (mg/l)	70.15	0.00	64.90	43.25

Table 6. Average composition and standard deviations for sediment samples collected from the pond housing the In-pond Raceway System in Browns, AL.

	% of air-dried weight		
Date	Nitrogen	Phosphorus	Organic matter
Mar	0.20 ± 0.09	0.10 ± 0.04	2.73 ± 0.70
Nov	0.26 ± 0.10	0.12 ± 0.02	3.22 ± 0.93

Table 7. Average gains and losses (kg) for nitrogen, phosphorus, chemical oxygen demand (COD-an estimate of organic matter) and dissolved oxygen (DO) from an In-pond Raceway System located in Browns, AL.

Item	Nitrogen	Phosphorous	COD	D.O.
Gains				
Fish stocked (catfish)	454.1	109.8	2,763.2	
Fish stocked (paddlefish)	4.0	1.4	18.7	
Fish stocked (tilapia)	0.3	0.1	1.6	
Feed	2,459.7	486.0	18,074.7	
Nitrogen fixation	?			
Photosynthesis			55,631.1	55,631.1
Inflow from well	9.5	1.9	0.0	0.0
Rainfall	3.7	0.0	0.0	143.7
Runoff	1.9	0.0	0.0	73.2
Aeration			0.0	3,162.2
Net diffusion			0.0	5,958.1
Total	2,933.2	599.1	76,489.3	64,968.4
Losses				
Fish harvested (catfish)	1,289.9	173.4	7,884.9	
Fish harvested (paddlefish)	42.2	14.4	195.9	
Fish harvested (tilapia)	89.2	31.6	464.8	
Overflow	50.8	5.2	399.9	35.6
Seepage	2.9	0.3	31.0	0.0
Respiration in water column			40,057.1	40,057.1
Benthic respiration			19,483.7	19,483.7
Fish respiration			5,392.0	5,392.0
Diffusion of ammonia and denitrification	1,148.0			
Uptake by Mud	310.2	374.2	2,580.1	
Total	2,933.2	599.1	76,489.3	64,968.4

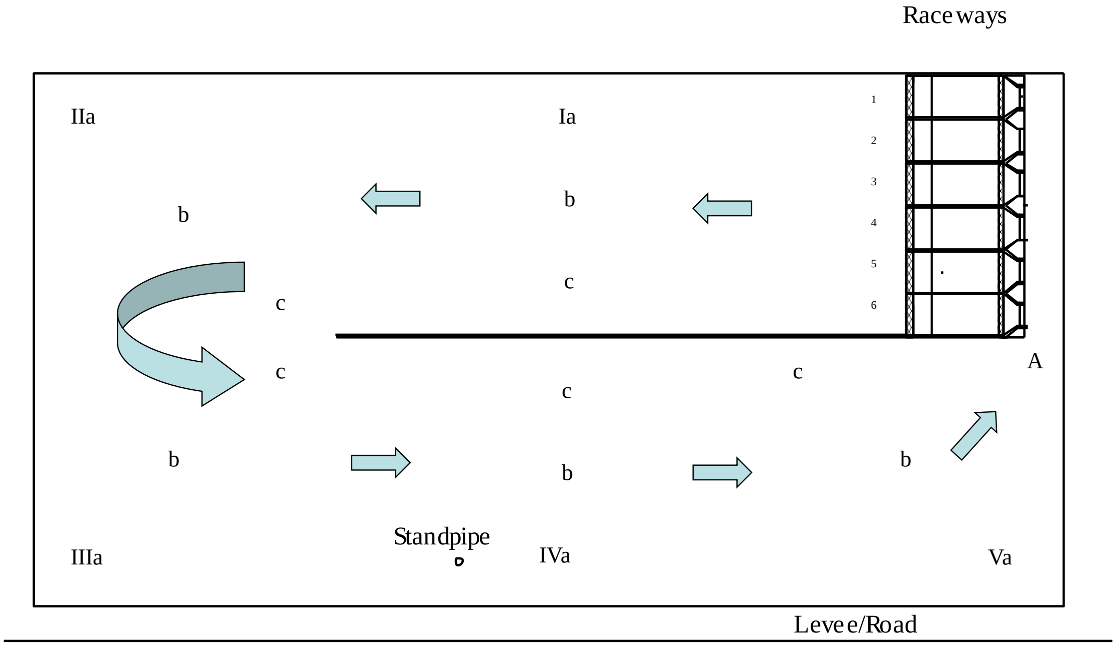

Figure 1. Aerial view of the In-pond Raceway System displaying various water quality and pond mud samples sites with arrows indicating direction of water flow (not to scale).

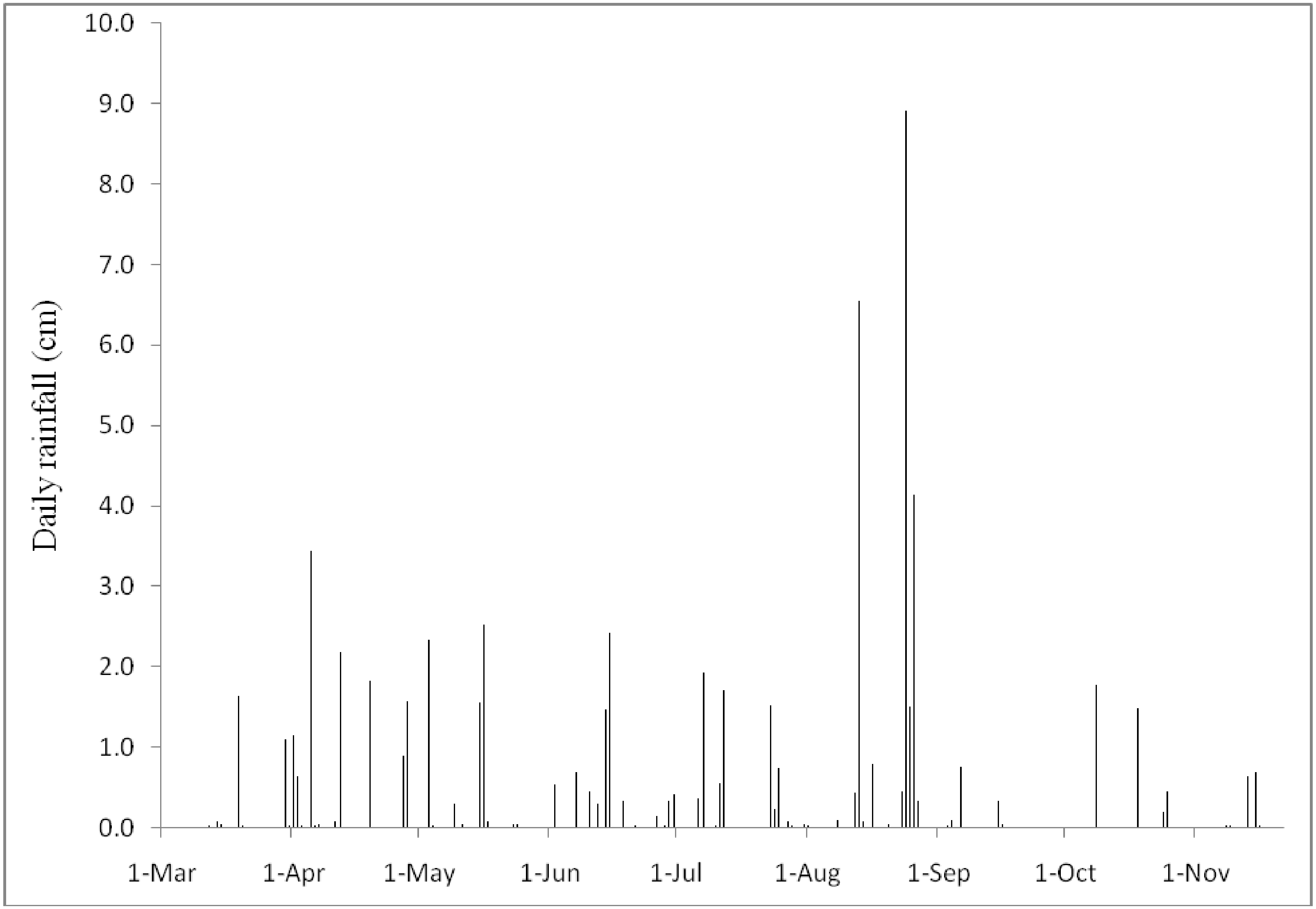

Figure 2. Distribution of rainfall during the production season of an In-pond Raceway System in Browns, AL.

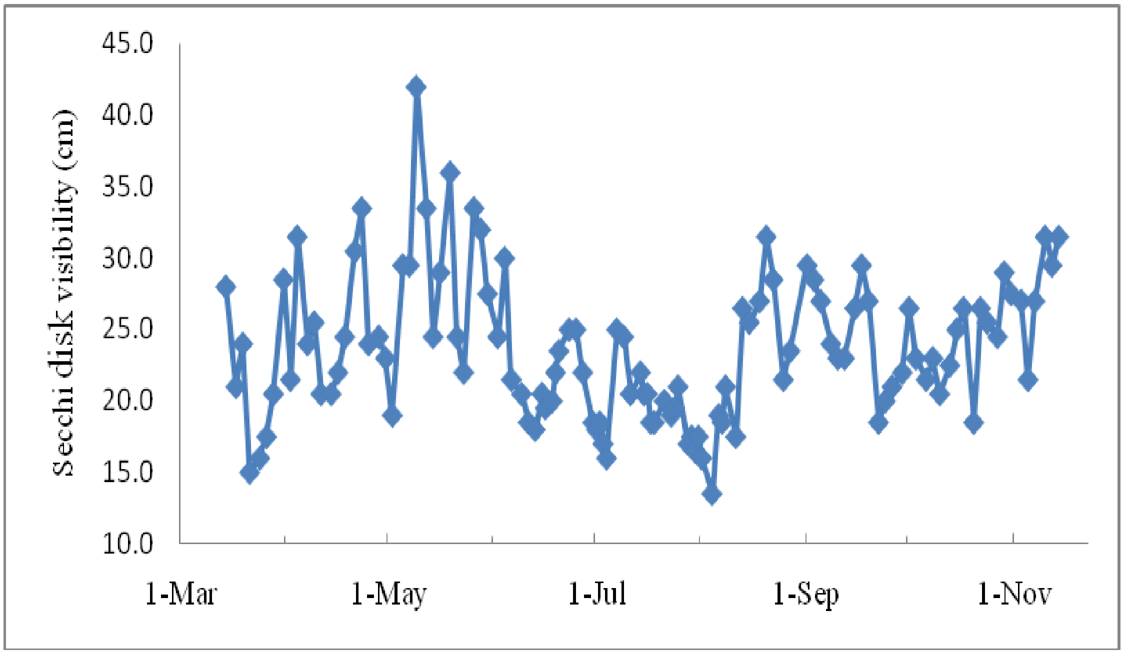

Figure 3. Observed Secchi disk visibility within the pond of an In-pond Raceway System located in Browns, AL.

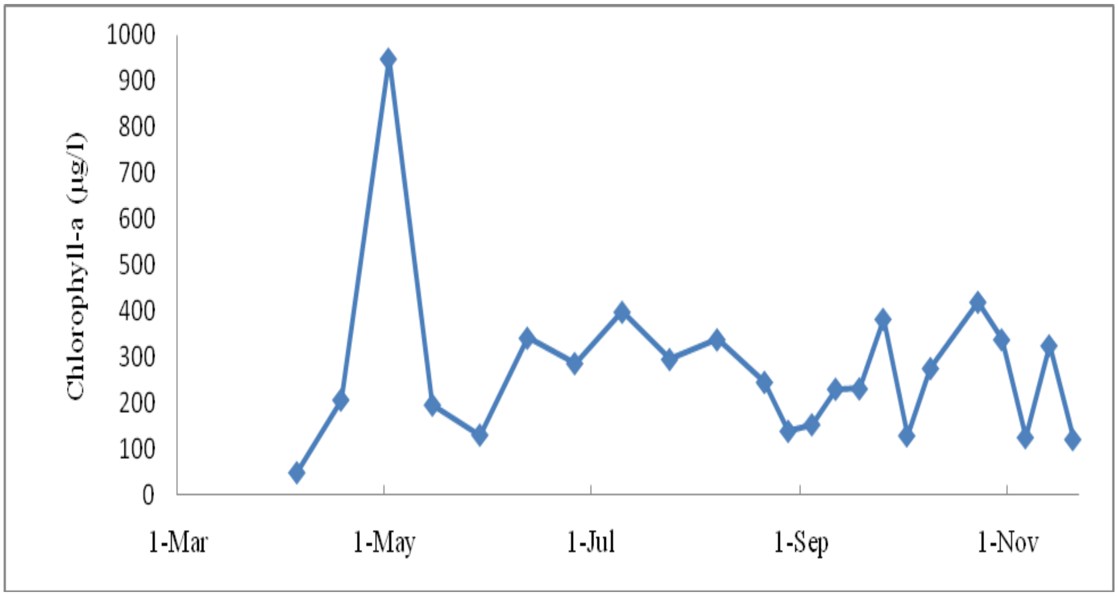

Figure 4. Observed chlorophyll-*a* concentrations within the pond of an In-pond Raceway System loacted in Browns, AL.

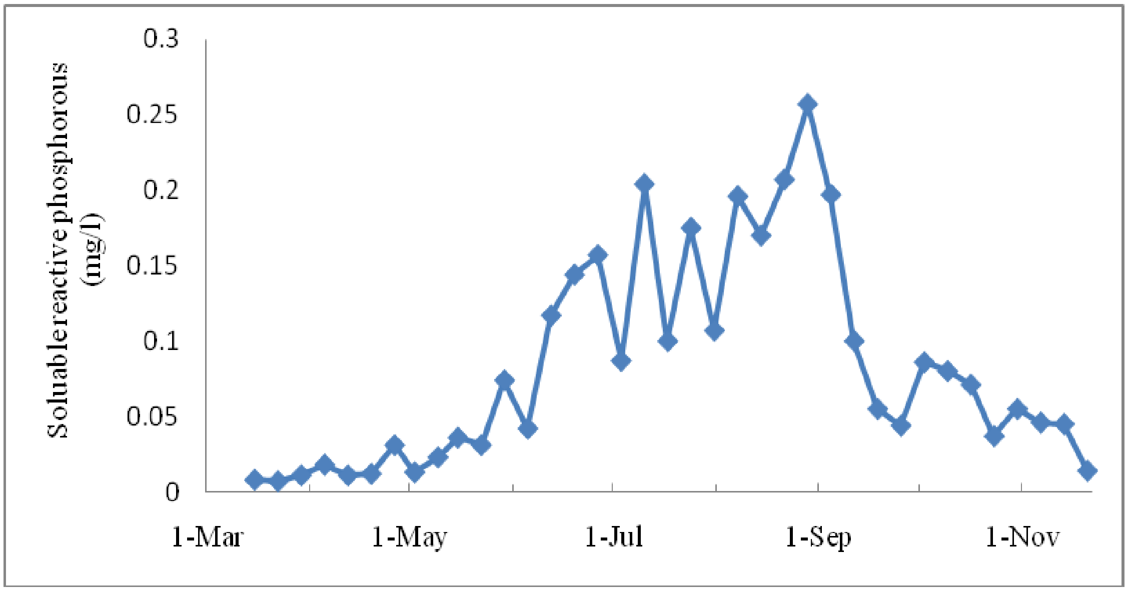

Figure 5. Soluable reactive phosphorous concentation over time within the pond of an In-pond Raceway System in Browns, AL.

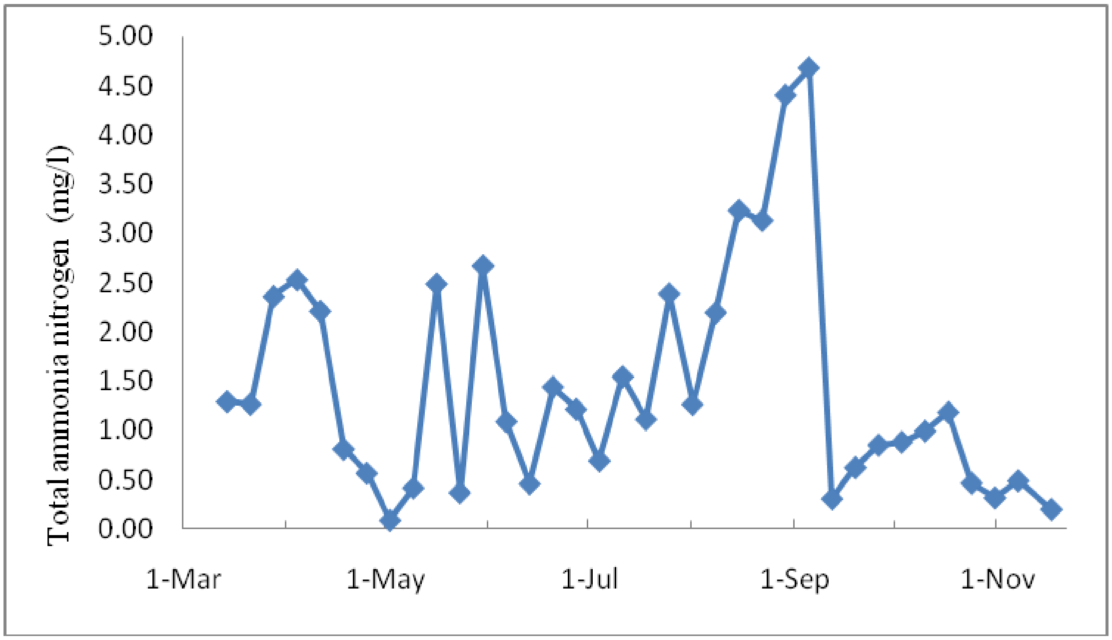

Figure 6. Total ammonia nitrogen concentations observed over time within the pond of an In-pond Raceway System in Browns, AL.

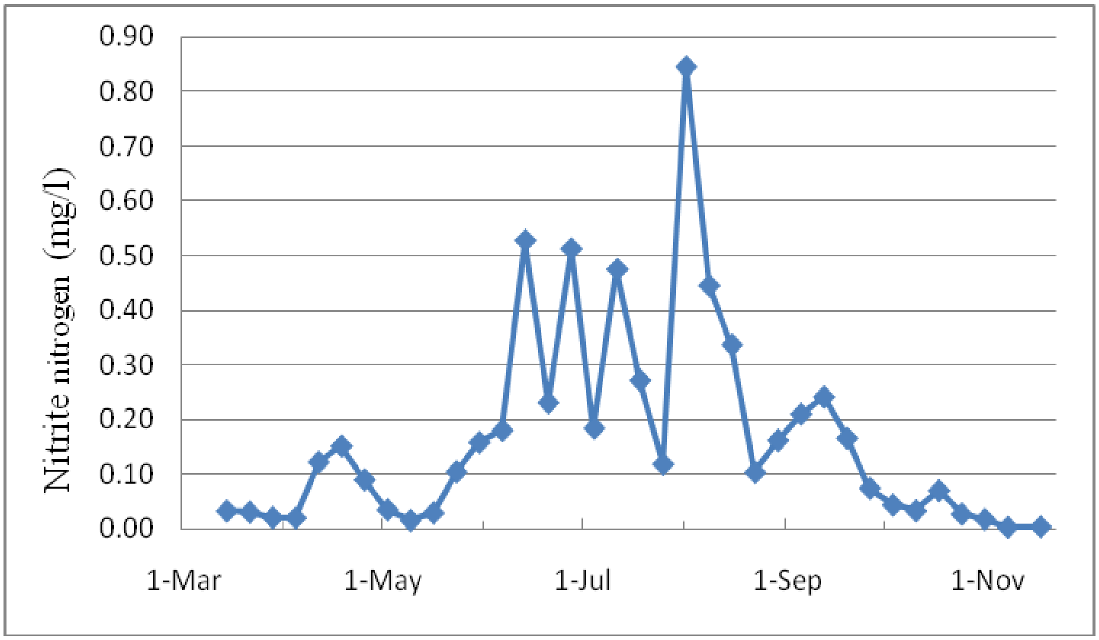

Figure 7. Nitrite nitrogen concentrations observed over time within the pond of an In-pond Raceway System in Browns, AL.

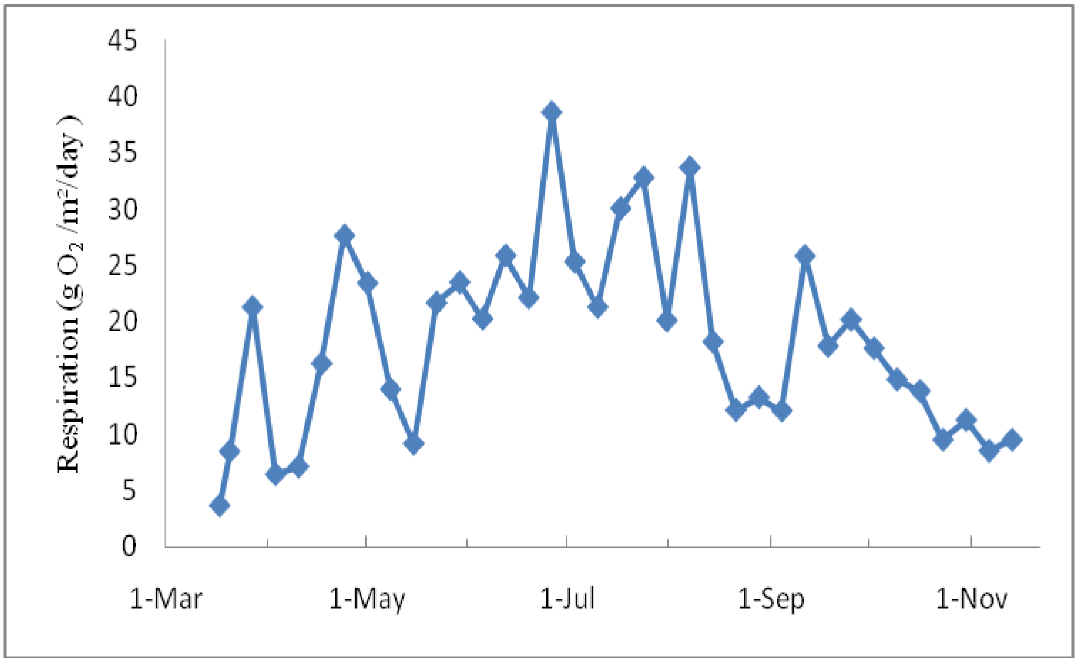

Figure 8. Respiration values observed over time within the pond of an In-pond Raceway System in Browns, AL.

Chapter IV

Development, Evaluation, and Economic Feasibility of an In-pond Raceway System for Fish Production

Abstract

The endeavor of this project was to improve productivity and profitability by demonstrating methods to achieve high levels of survival, feed performance, and efficiency in a commercial farm setting. A commercial-scale, In-Pond Raceway System (IPRS) was constructed in 2007 in a 2.43-ha earthen pond (average depth 1.67 m) on a fish farm in west Alabama. The six raceways were originally stocked with 12,000 to 30,000 advanced stockers weighing between 59.1 and 418.2g to simulate a staggered stocking and harvest production method. Results from the 2008 production season had 83.7% mean survival across all raceways. The average feed conversion ratio (FCR) for channel catfish and hybrid catfish was 1.74 and 1.36, respectively (range from 1.16 - 2.11) and total catfish harvested was 49,913 kg (20,556 kg/ha). An additional 6,365 kg of paddlefish and tilapia were harvested as co-cultured species outside of the IPRS structure. The IPRS appears to be more efficient at producing catfish as compared to the average of the whole farm performance from 2008, and approximately just as efficient as the whole farm average over a 4-year period. The economic analysis indicated food fish production cost was \$1.565 /kg (variable cost) and \$0.339/kg (fixed cost) for a total production cost of \$1.904/kg (variable plus fixed costs). When co-cultured species are included, the

overall variable costs is $1.388 /kg and fixed cost is $0.301/kg; the overall cost of production was $1.689/kg. The electrical efficiency of the IPRS was 0.535 kg of catfish produced per kW·h of electricity consumed.

Introduction

Catfish farming is the largest segment of the U.S. aquaculture industry. During 2009, approximately 216 thousand metric tons (mt) of food size channel catfish *Ictalurus punctatus* were produced with an overall value of approximately $352 million (USDA, 2010). Additionally in 2009, 1,306 operations existed in the U.S. with a total of 59,473-ha of water (USDA, 2010). As of January 2010, only 994 of the original farms still exist with a total of 46,478 ha. This decreased the number of operations and total hectares by 24.9 % and 21.9 %, respectively. About 93% of U.S. total sales are produced in Mississippi, Alabama, Arkansas, and Texas.

The channel catfish industry is the dominant form of aquaculture in Alabama. In July, 2008, there were 240 farms in Alabama which totaled 8,907 hectares of water. The total live weight of food fish harvested in 2009 was approximately 59 thousand mt of gross product (USDA 2010). The impact on Alabama’s economy is very impressive with approximately 3,000 Alabamians having jobs directly engaged in the catfish industry (Stevens et al., 2007).

Most catfish are cultured in one of two pond types: levee ponds or hillside watershed ponds. These ponds are harvested by seine which is a time consuming process. The overall land and labor required with these traditional techniques are considered large when associated with the overall yield. A traditional pond system has a net annual yield of about 4,500 to 5,500 kg/ha with a maximum annual production rate of around 7,000 kg/ha/yr (Brune, 1991; USDA, 2006). Under experimental conditions, Avault (1980) was able to produce over 13,000 kg/ha.

More efficient production practices for raising channel catfish in the U.S. have been of interest since the 1960's and continues to increase (Schmittou, 1969). Early attempts at intensifying culture methods have been applied to cages, raceways and tanks (Schmittou, 1969; Andrews et al., 1971; Hill et al., 1974). Floating in-pond raceways were originally studied in the 1920's (Masser, 2004). A vast amount of research studying the development of raceways to culture fish occurred in the 1970's (Brown et al., 1971; Fremont, 1972; USEPA, 1974; Hill et al., 1974 Fast, 1977) and 1990's with the floating in-pond raceways (Fast, 1991 Hawcroft, 1994; Long, 1990).

High rate photosynthetic systems that have new production techniques to aid in the intensification of aquaculture have recently been studied. The Partitioned Aquaculture System (PAS) at Clemson University (Brune, 2004) and the split-pond system at Mississippi State (Tucker et al., 2009) are two of these systems. They combine a number of biological, chemical, and physical intensification methods into a single integrated system (Brune, 2004). This technology is possibly more efficient and controllable at producing catfish than traditional methods.

The Department of Fisheries and Allied Aquacultures at Auburn University has utilized fixed and floating in-pond raceways for both research and intensive production of fish for many years, although it has been of a relatively small scale (non-commercial). This study reports on the methodologies deployed for the economic analysis for the production of channel catfish (*Ictalurus punctatus*), and hybrid catfish (*Ictalurus* *punctatus* x *Ictalurus furcatus*) as the primary species, and tilapia (*Oreochromis niloticus*) and paddlefish (*Polyodon spathula*) as co-cultured species in a fixed In-pond Raceway System (IPRS) and pond, respectively, over an 8-month period.

The IPRS is projected to be capable of achieving a production rate of 20,000 kg/ha/yr or greater, which is a conservative estimate as compared to the PAS, but because of several issues, the projected production has not been accomplished. For example, “down time” because there was insufficient supply of stockers when needed. However, it is important to include the current potential production rate (12-months) to allow for an understanding of the potential of the IPRS once these issues are resolved. This will then allow for the greater potential production rates to become the actual observed production rates that will reduce per unit cost of production. Therefore, the analysis will include a comparison of the results from the 8-month observed production period of food size catfish in the IPRS to a traditional catfish farm. A second analysis will include a comparison of the results from the 8-month production period to 12-months of projected production in the IPRS and the observed production in the PAS as economic indicators of profitability. A third analysis will include two partial budgets; one will include switching from traditional catfish food fish production in ponds to food fish production in an IPRS. The second will consist of switching from traditional catfish food fish production in ponds to food fish production in an IPRS with the additional harvest of co-cultured species. Last but not least, a brief electrical efficiency comparison of the IPRS, PAS, traditional farm in west AL, and traditional farm in east MS will be included.

Materials and Methods

This study was conducted on a 174-ha commercial catfish farm in Browns, Alabama. A 2.43-ha traditional earthen pond was utilized for the deployment of the IPRS (Figure 2, Chapter II). The IPRS consists of six, individual raceways that share common walls attached to a permanent concrete foundation (overall length, width and height of 30.48 × 13.72 × 1.42 m, Figure 1, Chapter II). Each raceway (13.72 × 4.88 × 1.22 m) consists of three separate components: slow rotating paddle wheel area (3.11 ×4.88 × 1.22 m); fish culture area (7.71 × 4.88 × 1.22 m); and waste settling zone (2.89 × 4.88 × 1.22m). The walls are constructed of standard cinder blocks (0.46 × 0.20 × 0.20 m) which are filled with concrete and supported with 1.3-cm, reinforcing bar. The fish are confined in the culture unit by an end partition barrier of wire mesh (12.7 x 25.4 mm, 25.4 x 25.4 mm, and 25.4 x 50.8 mm) which spans the width of each raceway unit.

Channel catfish (*Ictalurus punctatus*) and hybrid catfish (*Ictalurus punctatus* × *Ictalurus furcatus*) fingerlings were obtained throughout the experiment from commercial suppliers (hybrid catfish from Eagle Aquaculture, Indianola, MS and channel catfish from Aquacenter, Leland, MS) with a history of providing healthy fish. The results for the production of food size fish and associated economics in a continual stocking and harvest based IPRS are reported.

An initial complete inventory was assessed because a portion of the system contained fish before the start of this study. The existing fish were crowded, harvested, weighed, sampled, and restocked into selected raceways. Upon arrival, fingerlings were sampled for disease screening and estimation of initial weights. Fingerlings were then acclimated to the culture conditions using partial water exchanges (a rate no faster than 5^o

C per hour) to equalize environmental parameters. Once the initial inventory and fingerling acclimation were complete, the fish were then stocked into the raceways at densities ranging from 17.7 - 118.3 kg/m^3 (Table 1). The catfish were stocked at uniform sizes in each individual raceway, but at different cohort sizes throughout the IPRS to simulate a staggered stocking and harvest based production method that commercial farmers would likely employ to evenly distribute biomass throughout the year and provide saleable fish throughout the year as well. This also was believed to prevent fish from reaching a maximum carrying capacity of the pond. Individual stocking weights ranged from 59.1 – 418.2 g. The grow out phase ran for 89 - 250 days depending on the size of fish initially stocked. The catfish were offered a commercial (32% crude protein, 5.0 mm diameter) floating feed (Alabama Feed Mill, Uniontown, AL) 2 - 4 times per day based on fish biomass, water temperature and fish size. The experiment was conducted in six 43,660 l fixed raceways with a continual water flow of 8,853 l/min. Dissolved oxygen, pH, and temperature were measured at dawn and dusk daily, whereas total ammonia nitrogen, nitrite nitrogen (Clesceri et al., 1998), total alkalinity, and chloride (Boyd and Tucker, 1992) were measured weekly.

Assortments of fish were stocked outside of the raceways to assist with water quality issues and to aid with the co-culture of other marketable fish. Paddlefish (*Polyodon spathula*) with an average individual weight of 328 g were originally stocked at a rate of 288/ha. Tilapia (*Oreochromis niloticus*) brood stock with an average weight of 232 g were sexed and stocked at a rate of 12 breeding pairs/ha. Both species were originally acquired from Clary Seining, Greensboro, AL.

System maintenance occurred on a regular basis: recording of data (daily); cleaning probe membranes of the monitoring system (daily); checking for fish mortalities (daily); feed delivery system cleaning and calibration (weekly); calibration of DO probes (bi-weekly); chemical treatment of fish (weekly - monthly depending on water temperature); lubrication of sprockets and chains (monthly). All associated labor was recorded for future economic analysis.

All raceways were sampled monthly to determine average size and total fish biomass in each raceway to determine the proper feed allocation rate. The estimated biomass in each raceway also was adjusted daily by subtracting mortalities from the designated cohort of fish. A sample of 100 fish from each raceway was weighed and counted to determine individual average weight. Average weight (to the nearest 1.0 g) was calculated for each sub-group by dividing the sample weight by the total number of fish in the sample.

Total production (harvest weight - stocking weight) was calculated for each cohort of fish as the amount of total weight gained. Feed conversion ratios (FCR) for each cohort of fish were calculated by dividing the amount of feed fed (consumed) per amount of weight gained. Catfish were continually harvested throughout the study as they reached market size (> 454 g). The fish were crowded in the raceway and a boom truck with scoop net was used to weigh and load the fish onto a haul unit. After harvest, the fish were then transported to the processing plant.

Economic data were collected from traditional catfish ponds for 4-years (2005-2008) at the same farm where the IPRS was constructed. The farm has a total of 170-water ha in catfish production yearly, and farm records were well kept. The production data of the IPRS obtained from 2008 were used in a comparative analysis to illustrate the possible benefits of using this type of production system rather than the traditional open pond method. A comparison of the IPRS (2008) to the whole farm (2008) and the whole farm average (2005-2008) was then prepared.

Economic analysis of the observed experimental data for food fish production compared the production costs of the original 8-month trial to a 12-month projected trial. Enterprise budgets were developed to compare the observed results from the 8-month trial and the projected results from the 12-month trial to a PAS (16.2-water ha farm). The 8-month observed trial was then utilized to form a partial budget and compare the net change in profit of producing all food fish catfish in a traditional pond to the production of them in and IPRS. Another partial budget was used to compare the net change in profit of producing all food fish catfish in a traditional pond to the production of them in an IPRS with the additional production of co-culture species.

All data utilized for the 8-month trial were based on real costs, receipts, and production quantities obtained over the season. Data pertaining to the projected 12-month trial were projrcted from the previous data and additional variable costs were estimated based on additional inputs used in commercial operations. Data was collected from the farm manager and the local economic extension agent pertaining to the whole farm production for 2008 and the 4-yr average whole farm production.

A brief, electrical usage comparison was utilized in determining the overall efficiency of the IPRS using production data and electricity usage from the IPRS, PAS, a traditional farm in west Alabama, and a traditional farm in east Mississippi. The overall efficiency was calculated by dividing the total production weight by the total electrical usage during the production season. All efficiency data presented from traditional farms (west AL and east MS) are based on close estimates.

Results and Discussion

Mean survival for channel catfish (*Ictalurus punctatus*) was 78.0 %, while hybrid catfish (*Ictalurus punctatus* × *Ictalurus furcatus*) displayed an 89.1% mean survival (Table 2). Paddlefish had an 85.9% survival whereas tilapia continued to naturally spawn throughout the production season (>100% survival). The reduced survival of the channel catfish as compared to the hybrid catfish is directly related to the fact that ESC (enteric septicemia of catfish) caused significant losses on several occasions. Six individual raceways housing channel catfish were diagnosed with ESC over the 8-month production trial while only one raceway of hybrid catfish was diagnosed with ESC over the same time span.

The average FCR for channel catfish and hybrid catfish was 1.74 and 1.36, respectively and ranged from 1.16 to 2.11 across all trials. ESC may have contributed to the higher FCR and slower rate of growth with the channel catfish as compared to the hybrid catfish. The total weight of catfish harvested from the six raceway cells was 49,913 kg or 20,540 kg/ha. This is comparable to the results observed with the PAS and the split-pond systems that demonstrated FCRs ranging from 1.34 to 1.53 (Brune, 2004) and 1.8, respectively (Tucker and Kingsbury, 2010). The overall production (yield) for catfish was 31,407 kg or 12,925 kg/ha during the 8-month experiment. An additional 2,406 kg of paddlefish and 3,959 kg of tilapia were harvested as co-cultured species and no additional feed was provided to them (Table 2). Water quality variables were maintained within acceptable limits for catfish production throughout the experiment (Table 3). Growth rates ranged from 1.1 - 2.2 g/fish/day for the catfish and is comparable to growth rates observed in floating in-pond raceways and cages, respectively (Hawcroft, 1994; Masser and Duarte, 1994).

Although a greater weight of hybrid fish was harvested which contributed to an increased yield over the channel catfish, approximately the same numbers of fingerlings were stocked throughout the production season. The lower stocking density with the channel catfish was due to the fact that there was a limited supply when needed. The main reason that this experiment did not include replicates is because it is directly related to the commercial scale of the system. There were only six raceways and the research protocol initially developed was for a staggered stocking and harvest base system. This aided in maintaining a balanced production system by keeping the overall fish biomass below the total carrying capacity of the pond. If all fish of the same size were stocked at the same time and fed adequate amounts of feed throughout the production season the carrying capacity would have been reached and water quality issues would have arisen and the resulting stress would have depressed growth. A staggered management strategy would be to stock and harvest fish throughout the annual cycle spread over a period of time and this research attempted to follow what a commercial operation would do.

The financial requirements for the initial investment to construct the IPRS are shown in Table 4, and a complete enterprise budget is presented in Table 5. The comparative analysis of the IPRS to the whole farm average from the production year of 2008 indicates that the breakeven price to cover the variable expense was \$1.565/kg and \$1.819/kg, respectively (Table 6). The average breakeven price to cover variable expenses of the whole farm from 2005-2008 was $1.529/kg. If you include the co-cultured species with the IPRS, we see a reduction in the overall breakeven price to cover the variable expenses ($1.388/kg). The IPRS definitely performed better in the production year of 2008 as compared to the whole farm. When compared to the average of the whole farm over 4-yrs, the IPRS was a little less efficient, but it may not be significant economically because you have the opportunity to co-culture other species with the IPRS. When the co-cultured species are included into the economical model, there is a definite reduction in the overall breakeven price to cover the variable expenses. The better performance of the 4-yr whole farm average was also influenced by the average feed cost ($312/mt) as compared to the average feed cost in 2008 for the IPRS ($423/mt).

The gross receipts for the observed 8-month production trial and for the projected 12-month trial of the IPRS are given in Table 7. Results from the PAS (Goode et al., 2002) were compared to net returns and production costs of the IPRS. A common price of $1.694/kg was used as the processor price to the farm for all market sized catfish (0.45 – 0.9 kg) for the IPRS. All fish that were harvested by the end of the original study that were sub-marketable in size (< 0.45 kg) were valued at $1.430/kg - the standard value for these fish in west Alabama and east Mississippi fish farms at that time. Paddlefish and tilapia were estimated to be worth $5.500/kg and $6.600/kg, respectively. Total gross receipts for catfish sales were $81,479 while the co-cultured species were estimated to be worth an additional $39,363 in the 8-month observed trial, although these fish were not actually sold (Table 5). The total capital cost was $48,301 and the total equipment and machinery costs an additional $64,978 (Table 4). A total of $113,279 ($46,633/water ha) for capital costs, equipment, and machinery was required for the construction and operation of this system The gross receipts for the projected 12-month trial were estimated to total \$161,581 (\$66,494/ha) for the sales of both catfish and the co-cultured species. Total gross receipts for the PAS came to \$528,405 (\$32,618/ha).

The total variable cost of producing a kilogram of catfish was higher for the 12-month trial than for the projected 8-month trial. The main reason for this is that the projected 12-month trail was assumed to have proper stocking methods with no associated “down time” after fish harvest(s) from raceways. This would allow a higher volume of production in a given amount of time with proper sizes of fish and an improved production efficiency and lower the breakeven price. In both cases, total production costs (fixed and variable) were reduced when including the estimated value for the co-cultured species. Income above variable costs for the 8-month projected trial were \$42,717 (\$17,585/ha) as compared to the 12-month production trial (\$51,505 or \$21,202/ha). Fixed costs were the same for the two IPRS scenarios (8-and12-month). Production costs were subtracted from the receipts to derive the net returns for each trial. The net return to land for the 8-month production trial (\$25,814 or \$10,627/ha) was lower than that of the 12-month projected trial (\$34,602 or \$14,244/ha). The variable costs of producing catfish for the original 8-month trial with and without co-cultured fish was \$1.388/kg and \$1.565/kg, respectively. This amounted to \$0.033 and \$0.095 more per kilogram, respectively, than for the 12-month projected, production trial. Goode et al., (2002) calculated their variable cost to be\$1.482/kg. Total costs (variable + fixed) for the 8-month observed trial, 12-month projected trial, and for a 12-month PAS trial were \$1.904/kg, \$1.696/kg and \$1.962/kg, respectively. If you include the co-culture of fish with the production of catfish in the 8-month observed trial and the 12-month projected trial, the overall break-even price decreases to $1.689/kg and $1.563/kg, respectively.

The estimated operating costs calculated for the IPRS presented in this study fall within costs reported in the literature for multi-batch, channel catfish production systems, although the fixed costs are much higher. The elevated fixed costs are directly related to the initial investments costs for the constructing the IPRS. For example, machinery depreciation, IPRS depreciation, and interest on construction costs and equipment/machinery costs. Goode et al., (2002) points out that operating cost may be the greatest concern to producers as they relate to management decisions made throughout the production process as compared to fixed costs which occur regardless. The increased fixed costs is directly related to the initial construction of the IPRS and may be the main restraint or hurdle for most farmers when considering this type of system. However, a higher volume of fish is produced in a smaller area than traditional methods. When fixed costs are added, the total cost of production for catfish was $1.904/kg for the 8-month trial and $1.696/kg for the 12-month projected trial. When you factor in the co-cultured fish, the total cost of production was $1.689/kg for the 8-month trial and $1.563/kg for the 12-month projected trial. Goode et al., (2002) reported a $1.962/kg total cost of production for a 18.2-ha fish farm utilizing PAS technology. D’Abramo et al (2006) reported variable costs for food size catfish production ranging from $1.22 to $1.28/kg in a three-phase system which proved to be more efficient than the traditional multi-batch system which have a wide range of variable costs ($1.39 to $2.03/kg). The economic analysis for the IPRS based on different production periods and on the possible use of additional co-cultured species indicates that 12-months of production while utilizing co-cultured species would yield the highest net return and lowest production costs. Fixed costs could be reduced by examining new types of designs where initial construction costs would be much less.

The variable operating expenses for the 8-month production trial compared to the 12-month projected production trial ranged from $32,162 to $45,315/ha. The PAS calculated operating cost of $28,541/ha when scaled up to a 18.2-ha (16.2 water-ha) commercial size fish farm with a series of approximately 0.81-ha PAS units (Goode et al. 2002). Reported variable costs for multi-batch and three-phase systems range from $7,008 to $8,268/ha to $7,910 to $7,983/ha (Heikes et al., 1996; Hanson et al., 2004; D'Abramo et al., 2008). The current results of this study indicate that fixed costs for the IPRS are $2,273/ha lower than for the PAS ($9,231/ha). Reported fixed costs for traditional multi-batch systems ranged from $581 to $993/ha while the three-phase production method averaged $1,022/ha (Hiekes et al., 1996; Hanson et al., 2004; D'Abramo et al., 2008), and $6,956/ha for this IPRS.

The costs and returns associated with switching from traditional catfish food fish production in ponds to food fish production in an IPRS are shown in Table 8. The total annual additional cost and increased revenue for this change is $27,377 and $23,652, respectively. The net return is -$3,725 per hectare which indicates that the replacement of traditional food fish production in ponds to food fish in an IPRS would be an unwise decision since the switch would reduce the net farm income. The costs and returns associated with switching from traditional catfish food fish production in ponds to food fish production in an IPRS with the additional harvest of co-cultured species are shown in Table 9. The total annual additional cost and increased revenue for this change is $27,377 and $39,866, respectively. The net return is $12,509 per hectare which indicates that the replacement of traditional food fish production in ponds to food fish in an IPRS with the additional harvest of co-cultured species would be a wise decision since the switch would increase the net farm income.

The IPRS had an overall electrical efficiency of 0.535 kg of catfish produced per kW·h of electricity consumed by the system (Table 10). The PAS was the most efficient and displayed an efficiency value of 0.829 kg of catfish produced per kW·h of electricity used in the system. The traditional farm in west Alabama was estimated by using a weighted average of actual electrical value ($551.00/ha - meter charge @ 6,233 kg of food size fish/ha) and had an efficiency of 0.459 kg of catfish produced per kW·h. The traditional farm in east Mississippi was the least efficient at the utilization of electricity when compared to the total catfish produced (0.427 kg/kW·h). When the weight of the co-cultured fish was included with the harvested catfish weight, the electrical efficiency rating increased to 0.639 kg of total fish produced per kW·h of electricity consumed. Boyd et al., (2008) found that the direct energy use for production of 1 kg of channel catfish in ponds in Alabama were 0.840 kW·h for dedicated aeration and 0.613 kW·h for emergency aeration, feeding, and other vehicle use, respectively. This is equivalent to 1.453 kW·h/kg of catfish produced or about 0.688 kg of catfish produced per kW·h used. All efficiency values are closely related except for the PAS which has proven to have a very high importance when you compare all systems. The PAS system may actually be more efficient at fish production since no co-cultured fish were included in the original economic analysis (Goode et al., 2002). If co-cultured fish was included the efficiency rating would increase even more.

Ideally, the manager of an IPRS would keep a balanced system utilizing the staggered stocking and harvest based method. A balanced system would include but not be limited to an even distribution when stocking fingerlings which would allow for an ecosystem that can efficiently assimilate all nutrient (feed) input on a regular basis without contributing negatively to water quality. Even food fish harvests would follow and assist with this balanced management approach. The manager would also want to reduce the amount of down time associated with vacant raceways after a harvest. In this study an estimated overall 6 weeks of down time contributed to production values that were lower than originally predicted. This resulted from an insufficient supply of fingerlings when needed, and because when fingerlings were acquired they were of smaller size than desired. Producers should look into advanced ordering if larger fingerlings or on farm production themselves.

The IPRS outperformed the pond production system used on the farm in 2008 from a breakeven ($1.565/kg and $1.819/kg, respectively) stand point, but under-performed the farm average ($1.529/kg) from 2005-2008. It is evident of the benefits from utilizing the co-culture of the other fish species within the IPRS. Not only is there a reduction in the breakeven price to cover variable expenses but the system is more balanced as a whole due to water quality management (grazing) from outside fish.

On farm production of advanced fingerlings may be a practical approach to aid in the continual need of high quality and appropriate sizes of fingerlings and/or stockers over time. Future research is needed to develop proper partial budgets which would include but is not limited to: fingerling to food size production using a multiple batch system in ponds compared to an IPRS producing fingerlings to food size catfish; stockers to food size production using a multiple batch system in ponds compared to an IPRS producing stockers to food size catfish; and fingerlings to stockers in a single batch system in ponds compared to an IPRS producing fingerlings to stockers.

Additional research should be devoted to verifying our initial research findings over a 3 to 5-year production period. Additional investigations are also needed to identify new and existing technologies to reduce the initial construction costs, assist with water flow throughout the raceways, and improve the overall power efficiency of the system as a whole. Reduction in electrical consumption would yield a positive outcome when dealing with economic and environmental issues in aquaculture.

References

Andrews, J.W., L.H. Knight, J.W. Page, Y. Matsuda, E.E. Brown., 1971. Interactions of stocking density and water turnover on growth and food conversion of channel catfish reared in intensively stocked tanks. Progressive Fish-Culturist 33, 197-203.

Avault, J.W. 1980. Six tons of catfish with aeration in one acre of water. Aquaculture Magazine 7, 44.

Boyd, C.E. and C.S. Tucker, 1992. Water Quality and Pond Soil Analysis for Aquaculture. Alabama Agriculture Experiment Station, Auburn, AL.

Boyd, C.E. and C.S. Tucker, 1998. Pond Aquaculture Water Quality Management. Kluwer Academic Publishers, MA, 701 pp.\

Boyd, C.E., M. Polioudakis, and G.N. Whitis 2008. Direct Energy Use In Channel Catfish Production. Global Aquaculture Advocate. July/August, 48-50pp.

Brune, D.E., 1991. Pond aquaculture. Timmons, M.B. (Editor): Engineering Aspects of Intensive Aquaculture. Natural Resources, Agriculture, and Engineering Service Publication NRAES-49, Natural Resources, Agriculture, and Engineering Service, New York, 118-130 pp.

Brune, D.E., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and Hargreaves, J.A., (editors): Partioned Aquaculture Systems. Elsevier, New York, 561-562 pp.

Chappell, J.A. and J.R. Crews, 2006. 2005 Alabama Aquaculture Factsheet. Agriculture Economics and Rural Sociology, Auburn University, Auburn, Alabama.

Clesceri, L.S., A.E. Greenberg, A.D. Eaton, 1998. Standard Methods for the

Examination of Water and Waste Water, 20th edn. American Public Health Association, Washington, DC, USA.

D'Abramo, L.S., J.A. Steeby, T.R. Hanson, and P.D.Gerard. 2006. Evaluation of a Fingerling-to-Stocker Phase as Part os a New Production Strategy for the Commercial Farming of Channel Catfish. North American Journal of Aquaculture 69:22-35.

D.Abramo, L.S., T.R. Hanson., and J.A. Steeby. 2008. Production and Associated Economics of Channel Catfish Fed Diets in the Fingerling-Stocker Phase of Culture. North American Journal of Aqucaulture. 70:154-161.

Fast, A.W. 1977. Floating fish rearing system. U.S. Patent No. 4,4044,720.

Fast, A.W. 1991. A floating fish cage with solid plastic membrane and pumped water Exchange. Journal of Applied Aquaculture. 1: 99-110.

Fremont, H.J., 1972. Floating fish growing tank. U.S. Patent No. 3,653,358.

Goode, T., M. Hammig, and D. Brune. 2002. Profitability comparison of the partitioned Aquaculture system with traditional catfish farms. Aquaculture Economics and Management 6:19-38.

Hawcfoft, B.A., 1994. Development and evaluation of an in-pond raceway and waste removal system.. M.S. Thesis. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Hill, T.K., J.L. Chesness, and E.E. Brown, 1974. Growing channel catfish, Ictalurus punctatus, in raceways. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28, 488-499.

Long, C.E., 1990. Raceway culturing of fish. U.S. Patent No. 4,915,059.

Masser, M.P., and S. Duarte. 1994. The Alabama Piedmont catfish cage farming industry.World Aquaculture 25(4): 26-29.

Masser, M.P., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and Hargreaves, J.A., (editors): Cages and In-pond Raceways. Elsevier, New York, 532 pp.

Schmittou, H.R., 1969. Intensive culture of channel catfish, <u>Ictalurus punctatus (Rafinesque</u>), in cages suspended in ponds. Doctoral Dissertation. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Stevens, T., A. Hodges, D. Mulkey. 2007. Economic Impacts of the Aquaculture Industry in Alabama in 2005. University of Florida, Institute of Food and Agricultural Sciences, Institute of Food and Resource Economics Department. Gainesville, FL.

Tucker, C.S. and S. Kingsbury. 2009. A Split-Pond Aquaculture System for Growing Catfish. Proceedings of the annual conference of Catfish Farmers of America.

Tucker, C.S. and S. Kingsbury. 2010. High-Density Split-Pond Systems Offer High Output, Low Maintenance. Global Aquaculture Advocate. 13(2): 64-65.

United States Department of Agriculture (USDA). 2006. 2005 Census of Agriculture. Washington DC.

United States Department of Agriculture/National Agricultural Statistics Service (USDA/NASS). 2010. Production and Inventory of Channel Catfish.

Washington DC. http://usda.mannlib.cornell.edu/usda/nass/CatfProd//2010s/2010/CatfProd-01-29-2010.pdf. May 11,2010.

Table 1. Various In-pond Raceway System stocking and harvest densities for channel catfish and hybrid catfish in Browns, AL.

	Stocking density		Harvest Density	
Fish species and rearing location	(kg/m²)	(kg/m³)	(kg/m²)	(kg/m³)
Hybrid catfish				
Raceway 1	128.8	105.7	193.3	158.6
Raceway 3 (split into 3 & 4)				
Raceway 3a	142.6	117.0	172.5	141.5
Raceway 4	144.2	118.3	214.7	176.1
Raceway 6	42.4	34.8	261.8	214.7
Channel catfish				
Raceway 1	21.6	17.7	66.9	54.9
Raceway 2	55.4	45.4	175.5	143.9
Raceway 5	112.5	92.3	242.6	199.0

[a] Raceway 3 reached maximum density and the decision was made to partially harvest 50% of the biomass and stock into the neighboring raceway #4. Total weight of raceway 4 was known at the time of harvest, but calculations from fish samples could only be made for the remaining fish in raceway 3.

Table 2. In-pond Raceway System production characterizes for hybrid catfish, channel catfish, paddlefish, and tilapia in Browns, AL.

Fish species and rearing location	Average stocking size (kg)	Total weight stocked (kg)	Average harvest weight (kg)	Total weight harvested (kg)	Growing period (days)	Percent survival[a] (%)	FCR[b]
Hybrid catfish							
Raceway 1a	0.42	4,845	0.64	7,270	96	97.9	1.78
Raceway 3 (split into 3 & 4)	0.24	4,943	0.77	14,559	239	92.4	1.43
Raceway 6	0.06	1,594	0.47	9,844	250	82.5	1.16
	Total	11,382		31,673			
Channel catfish							
Raceway 1b	0.06	812	0.28	2,515	147	66.0	1.21
Raceway 2	0.18	2,082	0.59	6,600	220	95.1	1.54
Raceway 5	0.14	4,230	0.40	9,125	193	76.9	2.11
	Total	7,124		18,240			
Total weight (kg)	Stocked	18,506	Harvested	49,913			
			Yield	31,407			
Tilapia							
Pond	0.232	13.55	0.22	3,959	203	-	-
Paddlefish							
Pond	0.328	229.3	4.0	2,406	675	85.9	-

[a] Percent survival cannot be calculated for tilapia as natural spawning occurred throughout the production season.

[b] FCR could not be calculated for paddlefish and tilapia as no direct feed was added for them.

Table 3. Water quality variables for the observed production trial with channel and hybrid catfish reared in an In-pond Raceway System (IPRS) in Browns, AL. Values represent mean ± standard deviation.

Variable	IPRS
Dissolved oxygen (mg/l)	6.38 ± 3.62
Temperature (C^{o})	25.15 ± 5.12
pH	7.74 ± 0.48
TAN (mg/l)	1.45 ± 1.15
Nitrite-N (mg/l)	0.17 ± 0.19
Total alkalinity (mg/l)	164.6 ± 16.4
Chloride (mg/l)	705.3 ± 75.6

Table 4. Initial investment costs for the In-pond Raceway System (IPRS) in Browns, AL.

Item	Unit	Cost/unit ($)	Quantity	Percent Use	Cost ($)	Useful Life	Average Investment ($)	Annual Avg. Depreciation[a] ($)	Interest on Investment [b] ($)	Annual Repairs and Maintenance ($)
A. Capital cost										
Land purchase (not included)	hectare	1,976.00	2.91	0.00	0.00		0.00		0.00	
Pond construction (not included)	hectare	3,828.50	2.43	0.00	0.00	15	0.00	0.00	0.00	0.00
Pond modification										
- Leveling of 30.5 x 15.24m area		500.00	1.00	1.00	500.00	20	250.00	25.00	32.50	0.00
- 6" concrete raceway foundation	m³	130.80	70.80	1.00	9,260.00	20	4,630.00	463.00	601.90	0.00
- Cinder block walls										
-Cinder Blocks	each	1.52	2,100.00	1.00	3,192.00	20	1,596.00	159.60	207.48	0.00
-Concrete fill	m³	130.80	12.46	1.00	1,630.00	20	815.00	81.50		
- Center pond divider										
- Telephone polls	each	8.00	41.00	1.00	328.00	15	164.00	21.87	21.32	0.00
- Permeable membrane	m²	4.84	304.72	1.00	1,476.00	20	738.00	73.80	95.94	0.00
- Gang planks, metal	linear m	27.89	60.96	1.00	1,700.00	30	850.00	56.67	110.50	0.00
- End partition grates	each	1,115.00	14.00	1.00	15,610.00	6	7,805.00	2,601.67	1,014.65	50.00
- Rip rap levee rock	metric ton	22.68	44.10	1.00	1,000.00	20	500.00	50.00	65.00	0.00
- Settling trough (waste removal)	unit	0.00	1.00	1.00	0.00	20	0.00	0.00	0.00	0.00
Electrical panels and wiring	unit	12,500.00	1.00	1.00	12,500.00	15	6,250.00	833.33	812.50	0.00
Well	each	8,100.00	1.00	0.07	558.90	20	279.45	27.95	36.33	20.96
Storage building	m²	69.97	31.22	0.25	546.00	20	273.00	27.30	35.49	2.73
Subtotal Capital Costs					48,300.90		24,150.45	4,421.68	3,033.61	73.69
B. Equipment and machinery										
Slow rotating paddles (inclusive)	unit	4,426.00	6.00	1.00	26,556.00	10	13,278.00	2,655.60	962.66	1,327.80
Airlifts (raceways)										
-Blowers (1.1 kW-h)	each	912.00	6.00	1.00	5,472.00	5	2,736.00	1,094.40	198.36	177.84
-PVC, fittings and supplies	unit	1,700.00	1.00	1.00	1,700.00	10	850.00	170.00	61.63	78.20
-Diffuser tubing	m	4.72	274.32	1.00	1,296.00	10	648.00	129.60	46.98	298.08
Destratifyer/airlifts										
- 2.4 m "White Water"	each	1,500.00	1.00	1.00	1,500.00	10	750.00	150.00	54.38	52.50
- 4.8 m "White Water"	each	3,000.00	1.00	1.00	3,000.00	10	1,500.00	300.00	108.75	45.00
Waste holding tank (2500 gal)	each	800.00	0.00	1.00	0.00	12	0.00	0.00	0.00	0.00
Pump, 5.6 kW-h (waste pumping)	each	1,850.00	0.00	1.00	0.00	5	0.00	0.00	0.00	0.00
"Trash" pump, 5 hp (acclimating fingerlings)	each	600.00	1.00	0.25	150.00	5	75.00	30.00	5.44	9.75
Feed delivery system										
- Feed bin, steel, 9 metric ton capacity	each	4,950.00	1.00	1.00	4,950.00	20	2,475.00	247.50	179.44	49.50
- Feed hoppers per raceway	each	470.00	6.00	1.00	2,820.00	10	1,410.00	282.00	102.23	253.80
- Motor driven delivery channel	unit	460.00	6.00	1.00	2,760.00	10	1,380.00	276.00	100.05	27.60
Aerator, paddlewheel, 7.46 kW-h	each	3,397.00	1.00	1.00	3,397.00	10	1,698.50	339.70	123.14	84.93
Automated DO monitoring system (new version)	each	2,347.00	2.00	1.00	4,694.00	8	2,347.00	586.75	170.16	23.47
Mobile PTO aerator	each	2,800.00	1.00	0.05	140.00	10	70.00	14.00	5.08	2.80
Oxygen meters	each	747.00	2.00	0.01	20.92	5	10.46	4.18	0.76	2.09
Water quality monitoring kit	each	100.41	1.00	0.01	1.40	1	0.70	1.40	0.05	1.40
Tractor	each	17,474.00	1.00	0.05	873.70	15	436.85	58.25	31.67	12.23
Truck, 1/2 ton	each	17,475.00	1.00	0.05	873.75	15	436.88	58.25	31.67	12.23
Truck with boom	each	27,713.00	1.00	0.05	1,385.65	15	692.83	92.38	50.23	19.40
Generator, 56kW	each	12,735.00	1.00	0.25	3,183.75	15	1,591.88	212.25	115.41	23.88
Diesel tank on trailer, 670 liters	each	508.00	1.00	0.25	127.00	15	63.50	8.47	4.60	0.00
Office equipment[c]		200.00	1.00	0.01	2.00	10	1.00	0.20	0.07	0.02
Shop tools[c]		7,500.00	1.00	0.01	75.00	10	37.50	7.50	2.72	0.75

Item	Cost ($)	Average Investment ($)	Annual Avg. Depreciation[a] ($)	Interest on Investment [b] ($)	Annual Repairs and Maintenance ($)
TOTAL EQUIPMENT AND MACHINERY	64,978.17	32,489.08	6,718.42	2,355.46	2,503.27
TOTAL CAP., EQUIP & MACH COSTS	113,279.07	56,639.53	11,140.10	5,389.07	2,576.96
Per water hectare	46,633.22	23,316.61	4,586.01	2,218.50	1,060.85
Per land hectare	38,861.01	19,430.51	3,821.67	1,848.75	884.04

[a] Computed by the straight line depreciation method with zero salvage value for depreciable items.

[b] Land and IPRS construction is charged at a long-term interest rate and equipment items are charged at an intermediate-term interest rate. Interest for land purchase loans are based on the entire purchase amount whereas all other depreciable items are charged interest on one-half the purchase cost.

[c] Office equipment and shop tools were not itemized, instead respondents were asked to give a dollar value of all equipment.

Table 5. Enterprise budget for the 8-month operation of the In-pond Raceway System (IPRS) including staggered stocking sizes and harvests, in Browns, AL.

	Weight Each	Unit	Quantity	Price or Cost / unit	Value or Cost	Per Hectare Value	Cost Per kg of All Fish	Cost Per kg of Catfish	Percent of ALL Costs
1. Gross Receipts									
Catfish sales									
- Market size, >0.455 kg	0.64	kg	38,273	1.694	64,835	26,690			
- Submarket size, <0.455 kg	0.37	kg	11,640	1.430	16,645	6,852			
Subtotal (catfish)			49,913		81,479	33,542		1.632	
Tilapia	0.22	kg	3,959	6.600	26,130	10,757			
Paddlefish	4.00	kg	2,406	5.500	13,233	5,447			
Subtotal (tilapia & paddlefish)			6,365		39,363	16,204			
Grand Total (all fish)			56,278		120,842	49,747	2.147		
2. Variable Costs									
Feed, food fish		metric ton	47	423	19,853	8,173	0.353	0.398	21%
Fingerlings									29%
- 59.08 g	0.059	each	13,708	0.159	2,180	897	0.039	0.044	2%
- 61.58 g (hybrid)	0.063	each	25,500	0.162	4,131	1,701	0.073	0.083	4%
- 140.91 g	0.143	kg	4,230	1.100	4,653	1,915	0.083	0.093	5%
- 177.27 g	0.176	kg	2,082	1.100	2,290	943	0.041	0.046	2%
- 240.91 g (hybrid)	0.242	kg	4,943	1.430	7,068	2,910	0.126	0.142	7%
- 418.18 g (hybrid)	0.418	kg	4,845	1.430	6,929	2,852	0.123	0.139	7%
Paddlefish									
- Fingerlings	0.327	each	700	1.000	700	288	0.012	0.014	1%
- Labor (stocking/harvest)		hours	3	120.000	360	148	0.006	0.007	0%
Tilapia									
- Broodstock	0.232	kg	14	6.600	89	37	0.002	0.002	0%
- Labor (stocking/harvest)		hours	3	120.000	360	148	0.006	0.007	0%
Fathead minnows	0.012	kg	23	8.800	200	82	0.004	0.004	
Transport of harvested fish		kg	49,913	0.043	2,145	883	0.038	0.043	2%
Harvest of fish		kg	49,913	0.076	3,793	1,561	0.067	0.076	4%
Labor									0%
Management		year	1	8,750	5,833	2,401	0.104	0.117	6%
Hired labor, at various wages		hours	131	10	1,307	538	0.023	0.026	1%
Fuel									0%

	Weight Each	Unit	Quantity	Price or Cost / unit	Value or Cost	Per Hectare Value	Cost Per kg of All Fish	Cost Per kg of Catfish	Percent of ALL Costs
Gasoline		liter	886	0.85	751	309	0.013	0.015	1%
Electricity									0%
- IPRS		KwHr	55,472	0.076	4,204	1,731	0.075	0.084	4%
- Emergency paddlewheel aerator		KwHr	5,534	0.076	419	173	0.007	0.008	0%
- Well water pumping		KwHr	5,469	0.076	415	171	0.007	0.008	0%
- Meter charges		meter-month	12	35	420	173	0.007	0.008	0%
Repairs and Maintenance		month	12	100	1,200	494	0.021	0.024	1%
Bird chasing		year	1	100	100	41	0.002	0.002	0%
Chemicals									0%
- Copper Sulfate		kg	100	3.1	309	127	0.005	0.006	0%
- Diquat		liter	8	32.8	264	109	0.005	0.005	0%
- Diuron		kg	2	16.4	37	15	0.001	0.001	0%
- Formalin		liter	416	1.8	750	309	0.013	0.015	1%
- Potassium Permanganate		kg	31	5.1	158	65	0.003	0.003	0%
- Salt		metric ton	35	87.1	3,081	1,268	0.055	0.062	3%
Interest on Operating Capital		dol	74,228	0.07	3,897	1,604	0.069	0.078	4%
TOTAL VARIABLE COSTS					78,125	32,162	1.388	1.565	82.2%
3. Income Above Variable Cost					42,717	17,585	0.759	0.067	
4. Fixed Cost									
Land charge (not included)[a]		dol		0.07	0	0			0%
Machinery depreciation		dol			6,718	2,766	0.119	0.135	7%
IPRS & pond modification depreciation		dol			4,422	1,820	0.079	0.089	5%
Taxes (land)		hectare	3	2	6	2	0.000	0.000	0%
Interest on IPRS & pond modification		dol.&%	24,150	6.25%	3,034	1,249	0.054	0.061	3%
Interest on equipment/mach. Purchases		dol &%	32,489	6.25%	2,355	970	0.042	0.047	2%
Overhead[b]									
Telephone		month	12	10	120	49	0.002	0.002	0%
Accounting/legal		year	1	25	25	10	0.000	0.001	0%
Supplies and Administrative		year	1	28	28	12	0.000	0.001	0%
Office supplies		year	1	14	14	6	0.000	0.000	0%
Insurance, general liability		hectare	2	21.00	51	21	0.001	0.001	0%
Insurance on equipment, machinery		dol/$	32,489	0.004	130	53	0.002	0.003	0%
TOTAL FIXED COSTS					16,903	6,958	0.300	0.339	17.8%
6. Total of All Specified Expenses					95,028	39,120	1.689	1.904	100%

	Weight Each	Unit	Quantity	Price or Cost / unit	Value or Cost	Per Hectare Value	Per kg of All Fish	Per kg of Catfish	Percent of ALL Costs
7. Net Returns Above All Specified Expenses									
- Variable costs					42,716	17,585	0.759	0.067	
- ALL costs					25,814	10,627	0.459	-0.271	

[a] Labor and management expenses have been included, but no expenses have been included for land. Therefore net returns to land is represented by this budget.

[b] Overhead expenses include telephone, accounting, legal, supplies, administration, and insurance (general liability and equipment).

Table 6. Enterprise budget for producing food size catfish in the In-pond Raceway System (IPRS) compared to the whole farm pond production in 2008 and to the whole farm average from 2005-2008 in Browns, AL. All figures are on a per hectare basis.

Variable	IPRS (2008)	170-hectare farm (2008)	170-hectare farm (4-yr average)
Receipts			
Catfish	$33,542	$9,890	$9,590
Paddlefish	$5,447	$0	$0
Tilapia	$10,757	$0	$0
Other	$0	$503	$405
Subtotal of receipts	$49,747	$10,393	$9,996
Variable costs			
Feed costs	$8,173	$5,947	$4,198
Fingerlings	$11,218	$1,810	$1,493
Electricity	$2,247	$551	$448
Other variable costs	$8,920	$2,654	$2,732
Interest on variable costs	$1,604	$376	$628
Subtotal of variable costs	$32,162	$11,338	$9,499
Income above variable costs	$17,585	-$945	$497
Fixed costs	$6,958	$405	$433
Total costs	$39,120	$11,743	$9,932
Net return to land	$10,627	-$1,350	$64
Catfish			
Breakeven price to cover:			
Variable costs ($/kg)	$1.565	$1.819	$1.529
Variable + fixed costs ($/kg)	$1.904	$1.884	$1.599
Catfish with co-cultured species			
Breakeven price to cover:			
Variable costs ($/kg)	$1.388	-	-
Variable + fixed costs ($/kg)	$1.689	-	-
Specifications			
Kg of catfish harvested	20,556	6,233	6,213
Price of feed ($/ metric ton)	423	416	312
FCR	1.49	2.35	2.38

Table 7. Comparison of enterprise budgets for the actual 8-month production trial and 12-month projected production with channel and hybrid catfish utilizing the In-pond Raceways System (IPRS) in Browns, AL (2008). Brune's Partitioned Aquaculture System (PAS) results are included for comparison.

	IPRS				PAS[a]	
	Observed (8-month)		Projected (12-month)		Observed	
Variable	2.43-ha	Per ha	2.43-ha	Per ha	16.2-ha	Per ha
Receipts						
Catfish	81,479	33,542	122,219	50,313	528,405	32,618
Paddlefish	13,233	5,447	13,233	5,447	-	-
Tilapia	26,130	10,757	26,130	10,757	-	-
Subtotal of receipts	$120,842	$49,747	$161,582	$66,517	$528,405	32,618
Variable costs						
Feed costs	19,853	8,173	29,779	12,259	192,394	11,876
Fingerlings	27,251	11,218	40,876	16,827	76,581	4,727
Electricity	5,458	2,247	5,725	2,357	32,136	1,984
Other variable costs	21,666	8,920	28,206	11,612	115,445	7,126
Interest on variable costs	3,897	1,604	5,491	2,260	45,821	2,828
Subtotal of variable costs	78,125	32,162	110,077	45,315	462,377	28,541
Income above variable costs	$42,717	$17,585	$51,505	$21,202	$66,028	$4,077
Fixed costs	$16,903	$6,958	$16,903	$6,958	$149,539	$9,231
Total costs	$95,028	$39,120	$126,980	$52,273	$611,916	$37,772
Net return to land	$25,814	$10,627	$34,602	$14,244	-$83,511	-$5,154
Catfish						
Breakeven price to cover:						
Variable costs ($/kg)	$1.565		$1.470		$1.482	
Variable + fixed costs ($/kg)	$1.904		$1.696		$1.962	
Catfish with co-cultured species						
Breakeven price to cover:						
Variable costs ($/kg)	$1.388		$1.355		-	
Variable + fixed costs ($/kg)	$1.689		$1.563		-	

[a] This is based on an 18.2 ha (16.2 water-ha) farm utilizing a PAS system with observed production values (Goode et al., 2002).

Table 8. Partial budget of switching from traditional catfish food fish production in ponds to food fish production in an In-pond Raceway System (IPRS) in Browns, AL. All figures are on a per hectare basis.

1	**Increase in cost**		**($)**
	Variable costs		
	-Feed	(5.03 mt @ $443/mt)	2,226
	-Fingerlings & large stockers	(25,378 @ $0.37 each)	9,408
	-Electricity	(23,679 kW-h @ 0.071624/kw-h)	1,696
	-Other variable costs	(Co-cultured fingerlings, management, labor, fuel, repairs and main., bird cont., and chemicals)	6,266
	-Interest on variable costs		1,228
	Fixed costs	(Mach. depreciation., IPRS & pond mod. depreciation, land taxes, Interest on equip/mach.)	6,553
	Total costs of producing food size catfish in the IPRS		**27,377**
2	**Reduction in return**		0
3	**Increase in return**		
	-Sale of food fish		
	-Catfish	(14,323 kg @ 1.65/kg)	**23,652**
4	**Reduction in cost**		0
5	**Net return**		**-3,725**

Table 9. Partial budget of switching from traditional catfish food fish production in ponds to food fish production in an In-pond Raceway System (IPRS) with the additional production of co-culture species in Browns, AL. All figures are on a per hectare basis.

1	**Increase in cost**		**($)**
	Variable costs		
	-Feed	(5.03 mt @ $443/mt)	2,226
	-Fingerlings & large stockers	(25,378 @ $0.37 each)	9,408
	-Electricity	(23,679 kW-h @ 0.071624/kw-h)	1,696
	-Other variable costs	(Co-cultured fingerlings, management, labor, fuel, repairs and main., bird cont., and chemicals)	6,266
	-Interest on variable costs		1,228
	Fixed costs	(Mach. depreciation., IPRS & pond mod. depreciation, land taxes, Interest on equip/mach.)	6,553
	Total costs of producing food size catfish in the IPRS		**27,377**
2	**Reduction in return**		0
3	**Increase in return**		
	-Sale of food fish		
	-Catfish	(14,323 kg @ 1.65/kg)	23,652
	-Paddlefish	(990 kg @ 5.50/kg)	5,477
	-Tilapia	(1,630 kg @ 6.60/kg)	10,757
	Total sales		**39,886**
4	**Reduction in cost**		0
5	**Net return**		**12,509**

Table 10. Electrical efficiency comparison of the In-pond Raceway System (IPRS) in Browns, AL compared to the Partitioned Aquaculture System (PAS) and two traditional farms located in west AL and east MS, respectively.

	IPRS	PAS[a]	Traditional farm in west AL[b]	Traditional farm in east MS
Catfish produced (kg/ha)	12,925	18,277	6,233	10,105
Paddlefish produced (kg/ha)	896	-	0	0
Tilapia produced (kg/ha)	1,623	-	0	0
Total fish production (kg/ha)	15,444	18,277	6,233	10,105
Electrical usage (kW·h)	24,167	22,041	13,594	23,675
Efficiency (kg of catfish fish produced/ kW·h)	0.535	0.829	0.459	0.427
Efficiency (kg of total fish produced/ kW·h)	0.639	0.829	0.459	0.427

[a] The PAS system economic study did not include data for the harvest of additional co-cultured fish as no values were assumed in this comparison.

[b] A weighted average of \$0.037824/ kW·h (off-peak, intermediate, & on-peak) was used from on farm production data on a per ha basis for the traditional farm in west AL. A total electrical cost (\$) per hectare was known, but not the total kW·h/ha. The total kW·h/ha was calculated based on the percentage of farm use throughout a 24-hr period due to the difference in electrical usage prices throughout the day with Alabama power (APC SmartPOWER Rate).

Chapter V

Summary & Conclusions

Improved production efficiency and profitability are critical for the survival of the catfish industry in the United States. While the Black Belt region of west Alabama is traditionally known as being one of the most economically depressed regions of the Southeastern U.S., one bright spot in the history of the Black Belt has been the past success of the catfish industry. However this industry's success peaked in the late nineteen eighties and early nineties, but has recently been on a downward trend.

The In-pond Raceway System (IPRS) was evaluated on a commercial scale and it demonstrated efficient and reliable production characteristics for a variety of fish species including: channel catfish (*Ictalurus punctatus*), hybrid catfish (*Ictalurus punctatus* x *Ictalurus furcatus*), paddlefish (*Polyodon spathula*), and Nile tilapia (*Oreochromis niloticus*). There is no reason that other species could not be cultured in the IPRS if desired. For example, hybrid striped bass and tilapia are commonly cultured in floating raceways at another farm in west Alabama. Refined feed delivery technology and subsequent improved feed conversion ratios (FCR) were possible using this system which resulted in a reduced cost of production when comparing the percentage of feed costs associated with the overall production cost to traditional methods.

Dissolved oxygen levels can be controlled and monitored much easier in a controlled raceway environment as compared to a pond setting. While utilizing the IPRS technology, large amounts of atmospheric, and if desired, pure oxygen can be rapidly delivered to the fish in culture units. This contrasts with traditional pond culture in where inadequate paddlewheel aeration may have been installed to deliver sufficient dissolved oxygen to the pond in a short time to avoid fish stress or mortality. In the raceway environment, it is usually easier and significantly less expensive to treat fish for diseases with appropriate chemicals when compared to a whole pond. This is a more aggressive disease management approach which uses preventative measures ahead of time. Culturing fish in the IPRS also makes it easier to manage fish inventory and track mortalities. In ponds, it is very difficult to quantify fish mortalities because of the large volume and surface area of water.

Another advantage of the IPRS is improved survival through a reduction in predation by fish and by birds in particular. Uniform-sized fish are cultured in individual raceways. This culture method virtually eliminates the chance of cannibalism within the fish cohort. Ponds have fish of different sizes, and cannibalism commonly occurs. Predator netting can be inexpensively retrofitted over the IPRS to prevent any unnecessary bird predation and it also aids in partial shading of the structure which inevitably creates a more comfortable environment for the fish.

The co-cultured species assisted with the recycling of nutrients and improved the recovery of nutrients which would normally be lost to the water column. This not only improved the production efficiency of the system but also reduced and possibly eliminated the likelihood of negative environmental impacts of water exchange. Co-cultured fish (e.g. tilapia) also reduce the chances of blue-green algae blooms which are know to cause off-flavor problems in the catfish industry. The advantage(s) of the co-cultured species is not only a strategy to manage production efficiency and water quality, but a strategy to improve economic feasibility. With the additional sales of paddlefish and tilapia, the IPRS appears to be more efficient than the traditional catfish farming method in ponds. However, initial construction costs associated with this initial commercial-size model may be an unattractive avenue when describing the IPRS to a farmer. Further research is needed in order evolve and make a logical decision on a commercial scale.

Future Research

A preliminary study of waste removal technology for the IPRS was assessed during the 2008 production season. A 9,500-l conical tank was installed and retrofitted into a swirl separator (primary mechanical filter) and plumped into a drying bed (secondary mechanical filter) to allow for the quantification of solid material collected in the waste trough. Several attempts were made to quantify the solid waste removal capacity over the term on the study. Due to technical issues, an executive decision was made halfway through the study to cancel future time allotment to the waste removal system. The lack of proper resources such as man power, capital, proper tools, scuba gear, and specialty adhesives helped led us to this alternative.

Mechanical problems associated with the waste channel existed that would not allow for the proper removal of solid material. Seepage around the seals of the main waste trough door caused the pumped water to divert from the system and bypass over the settling area. Clogging and associated pump failure followed shortly after. Repeated trough cleaning and pipe flow design was not sufficient to fix the problem. Difficulty correcting the seals was related to the inability to work efficiently under water. Entire pond draining followed after the initial experiment and repairs were made.

Unfortunately, the problem still exists to date and the ability of the farm and technical engineer to resolve this issue has been ineffective. Preliminary data is presented below that shows the possible solids removal ability of the original system from 2008.

The waste collection trough was thoroughly cleaned the day prior to the preliminary study. A total of 455.5 kg of feed was feed to the catfish in the cells of the IPRS over a 24-hr period (Table 1). Solid matter was collected in the waste trough, pumped to the swirl separator, and gravity fed to the drying bed. The sludge was allowed to air dry over a 24-h period and a dry matter percentage (62.6%) was determined. Samples of feed and solid waste material were analyzed for moisture, total nitrogen, total phosphorous, and carbon concentrations. Budgets were calculated using the concentrations and quantities of inputs and outputs (i.e. collected and removed for the waste trough) respectively (Table 2).

It is obvious that solid matter settled, and was collected in the waste trough since about 70.8% of total dry matter as comparative weight to feed fed was removed after the 24-h period (Table 2). About 17 %, 137 %, and 25 % of total nitrogen, total phosphorous, and carbon were also collected and removed from the settling area, respectively. From this preliminary data, there is no absolute way to determine the origin of the solid material collected in the waste trough. A percentage of the settled material is more than likely from catfish waste. However, the 137 % of total phosphorous that was removed as solid material is an indicator of how the waste system is also capturing other material. For example, dead decaying plankton and possibly soil bound to phosphorous.

Future research is needed in order to quantify these estimates on a commercial scale and research the nature of the outcome of continued removal of settable solids as compared to fish production and biomass loading. Further economic analysis will need to determine the value of the material captured from the waste trough and possible on farm usage. Due to increased power and fertilizer costs, it may be desirable to use fish waste to produce methane that could then be used as a fuel source. Fish waste may also be a good fertilizer source for pasture land or sold as household compost. Of course, these concepts would need to be feasible and practicable.

Table 1.Total feed fed, solid capture, percentage of moisture, total nitrogen, total phosphorous, and carbon in an In-pond Raceway System located in Browns, AL.

Waste Removal Technology[a]			
Total feed fed (kg)	455.5	Total solids captured (kg)	466.2
-Dry matter (%)	90.45	-Dry matter after 24-h (%)	62.60
-Total nitrogen (% of dry weight)	5.80	-Total nitrogen (% of dry weight)	1.38
-Total Phosphorous (% of dry weight)	1.16	-Total Phosphorous (% of dry weight)	2.24
-Carbon (% of dry weight)	42.26	-Carbon (% of dry weight)	14.76

[a] Feed was fed over a 24-h period before solid waste was removed from the settling basin.

Table 2. Total inputs as feed, removal as solid material, and percentage of capture of total nitrogen, total phosphorous, and carbon in an In-pond Raceway System in Browns, AL.

Parameter	Input as Feed[a] (kg)	Removed as solid material (kg)	Amount captured
Dry weight	412.0	291.8	70.8%
Total nitrogen	23.9	4.0	16.8%
Total phosphorous	4.8	6.5	136.8%
Carbon	174.1	43.1	24.7%

[a] Feed was fed over a 24-h period before solid waste was removed from the settling basin.

Literature Cited

Andrews, J.W., L.H. Knight., K.W. Page, Y. Matsuda, and E.E. Brown. 1971. Interactions of stocking density and water turnover on growth and food conversion of channel catfish reared in intensively stocked tanks. Progressive Fish-Culturist 33, 197-203

Andrews, J.W. and Y. Matsuda. 1975. The influence of various culture conditions on the oxygen consumption of channel catfish. Transactions of the American Fisheries Society. 104: 322-327.

Avault, J.W. 1980. Six tons of catfish with aeration in one acre of water. Aquaculture Magazine 7, 44.

Bankston, J.D. and F.E. Baker. 1995. Open Channel Flow in Aquaculture. SRAC Publication No. 374.

Bardach, J.E. 1997. Sustainable Aquaculture. J.E. Bardach (editor): Aquaculture, pollution and biodiversity. John Wiley and Sons, Inc. New York. Pp. 87-99.

Bernardez, R.G. 1995. Evaluation of an In-pond Raceway System and its Economic Feasibility for Fish Production. M.S. Thesis. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL. Boyd, C.E., R.P. Romaire, and E. Johnston. 1978. Predicting Early Morning Dissolved

Oxygen Concentrations in Channel Catfish Ponds. Transactions of the American Fisheries Society. 107(3): 484-492.

Boyd, C.E. 1982. Hydrology of small experimental fish ponds at Auburn, Alabama. Transactions of the American Fisheries Society. 111: 638-644.

Boyd, C.E., 1985b Pond evaporation. Transactions of the American Fisheries Society. 114: 299-303.

Boyd, C.E., 1985. Chemical Budgets for Channel Catfish Ponds. Transactions of the American Fisheries Society. 114: 291-298.

Boyd, C.E. and C.S. Tucker. 1992. Water Quality and Pond Soil Analysis for Aquaculture. Alabama Agriculture Experiment Station, Auburn, AL.

Boyd, C.E. and G.W. Green. 1998. Dry Matter, Ash, and Elemental Composition of Pond-Cultured Tilapia *Orechromis aureus* and *O. niloticus*. Journal of the World Aquaculture Society. 29(1): 125-128.

Boyd, C.E. and C.S. Tucker. 1998. Pond Aquaculture Water Quality Management. Kluwer Academic Publishers, MA, 52-53 pp.

Boyd, C.E. and C.S. Tucker. 1998. Pond Aquaculture Water Quality Management. Kluwer Academic Publishers, MA, 701 pp.

Boyd, C.E., 2000. WATER QUALITY: An Introduction. Kluwer Academic Publishers, Norwell, Massachusetts, 157-161pp.

Boyd, C.E., J. Queiroz, J. Lee, M. Rowan, G.N. Whitis, and A. Gross. 2000. Environemntal Assesment of channel catfish farming in Alabama. Journal of the World Aquaculture Society. 31(4): 511-544.

Boyd, C.E., M. Polioudakis, and G.N. Whitis 2008. Direct Energy Use In Channel Catfish Production. Global Aquaculture Advocate. July/August, 48-50pp.

Boyd, C.E. 2009. Assessing, Reducing Pond Seepage. Global Aquaculture Adovacate. March/April, 62-63pp.

Brown, E.E., J.L. Chesness, and S.R. Chapman. 1971. Raceway and Pond Economics. Producing and marketing catfish in the Tennessee Valley. Tennessee Valley Authority, Tennessee, 90-93 pp.

Brown, T.W., J.A. Chappell, and T.R. Hanson. 2010.Commercial production of channel catfish *Ictalurus punctatus* and hybrid cafish *Ictalurus punctatus* x *Ictalurus furcatus* utilizing an In-pond Raceway System in west Alabama. Annual Meeting of Aquaculture America. Book of Abstracts. San Diego, CA. March 1-5.

Brune, D.E., 1991. Pond aquaculture. Timmons, M.B. (Editor): Engineering Aspects of Intensive Aquaculture. Natural Resources, Agriculture, and Engineering Service Publication NRAES-49, Natural Resources, Agriculture, and Engineering Service, New York, 118-130 pp.

Brune, D.E., 2003. Intensification of pond aquaculture and high rate photosynthetic Systems. Aquaculture Engineering. 28: 65-86.

Brune, D.E., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and Hargreaves, J.A., (editors): Partioned Aquaculture Systems. Elsevier, New York, 561-562 pp.

Brune, D.E., G. Schwartz, A.G. Eversole, J.A. Collier. and T.E. Schwedler. 2004. Partitioned Aquaculture Systems. SRAC Publication No. 4500.

Chappell, J.A. and J.R. Crews. 2006. 2005 Alabama Aquaculture Factsheet. Agriculture Economics and Rural Sociology, Auburn University, Auburn, Alabama.

Chappell, J.A. 2008. Personal communication. Fisheries and Allied Aquacultures, Auburn University, AL.

Chappell, J.A. 2010. Personal communication. Fisheries and Allied Aquacultures, Auburn University, AL.

Clesceri, L.S., A.E. Greenberg, and A.D. Eaton. 1998. Standard Methods for the Examination of Water and Waste Water, 20th edn. American Public Health Association, Washington, DC, USA.

D'Abramo, L.S., J.A. Steeby, T.R. Hanson, and P.D.Gerard. 2006. Evaluation of a Fingerling-to-Stocker Phase as Part os a New Production Strategy for the Commercial Farming of Channel Catfish. North American Journal of Aquaculture 69:22-35.

D.Abramo, L.S., T.R. Hanson., and J.A. Steeby. 2008. Production and Associated Economics of Channel Catfish Fed Diets in the Fingerling-Stocker Phase of Culture. North American Journal of Aqucaulture. 70:154-161.

Daniels, H.V. and C.E. Boyd. 1989. Chemical Budgets of Polyethlene-lined , Brackishwater Ponds. Journal of the World Aquaculture Society 20(2): 53-59.

Eaton, A.D., L.S. Clesceri, E.W. Rice, and A.E. Greenberg. (Editors). 2005. Standard Methods for the examination of water and wastewater, 21st edition. American Public Health Association, Washington, D.C., USA.

FAO yearbook, Food and Aquaculture Statistics. 2007.

FAO website. http://www.fao.org/fishery/topic/13530/en. May 19, 2010.

Fast, A.W. 1977. Floating fish rearing system. U.S. Patent No. 4,044,720.

Fast, A.W. 1991. A floating fish cage with solid plastic membrane and pumped water exchange. Journal of Applied Aquaculture 1, 99-110.

Fremont, H.J., 1972. Floating fish growing tank. U.S. Patent No. 3,653,358.

Glover, D.C., D.R. DeVries, R.A. Wright, and D.A. Davis. 2010. Sample preparation Techniques for determination of fish energy density via bomb calorimetry: an Evaluation using largemouth bass. Transactions of the American Fisheries Society. 139: 671-675.

Goode, T., M. Hammig, and D. Brune. 2002. Profitability comparison of the partitioned Aquaculture system with traditional catfish farms. Aquaculture Economics and Management 6:19-38.

Green, B.W., 1993. Water and Chemical Budgets for Organically Fertilized Fish Ponds in the Dry Tropics. Ph.D. Dissertation. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Green, B.W. and C.E. Boyd. 1995. Chemical Budgets for Organically Fertilized Fish Ponds in the Dry Tropics. Journal of the World Aquaculture Society. 26(3): 284-296.

Gross, A. and C.E. Boyd. 1998. A Digestion Procedure for the Simultaneous Determination of Total Nitrogen and Total Phosphorus in Pond Water. Journal of The World Aquaculture Society. 29: 300-303.

Gross, A., C.E. Boyd, and C.W. Wood. 2000. Nitrogen transformations and balances in Channel catfish ponds. Aquaculture Engineering. 24: 1-14.

Hakanson, L., Carlsson, L., Johansson, T. 1998. A new approach to calculate the phosphorus load to lakes from fish farm emissions. Aquaculture Engineering. 17(3): 149-166.

Hargreaves, J.A. and C.S. Tucker. 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and J.A. Hargreaves. (editors): Industry Development. Elsevier, New York, 1- pp.

Hawcfoft, B.A., 1994. Development and evaluation of an in-pond raceway and waste removal system.. M.S. Thesis. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Hill, T.K., J.L. Chesness. and E.E. Brown. 1974. Growing channel catfish, *Ictalurus punctatus*, in raceways. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28, 488-499.

Holland, D. G. 1999. Personal communication.

Krom, M.D. and A. Neori. 1989. A Total Nutrient Budget fo an Experimental Intensive Fishpond with Circularly Moving Seawater. Aquaculture 83: 345-358.

Lemarie, G., J.L.M. Martin, G. Dutto, C. Garidou, 1998. Nitrogenous and phosphorusous waste production in a flow-through land-based farm of European seabass (Dicentrarchus labrax). Aquatic Living Resources. 11 (4): 247-254.

Lewis, W.M., and L.W. Wehr. 1976. A fish rearing system incorporating cages, water Circulation, and sewage removal. Progressive Fish-Culturists. 38: 78-81.

Long, C.E., 1990. Raceway culturing of fish. U.S. Patent No. 4,915,059.

Masser, M.P., and S. Duarte. 1994. The Alabama Piedmont catfish cage farming industry.World Aquaculture 25(4): 26-29.

Masser, M.P. 1995. Intensive Catfish Systems. World Aquaculture 26(3): 60-64.

Masser, M.P., 2004. Biology and Culture of Channel Catfish. Tucker, C.S. and Hargreaves, J.A., (editors): Cages and In-pond Raceways. Elsevier, New York, 532 pp.

Masuda, K. and C.E. Boyd. 1994. Effects of aeration, alum treatment, liming and organic matter application on phosphorous exchange between pond soil and water in aquaculture ponds at Auburn, Alabama. Journal of the World Aquaculture Society 25: 405-416.

Mezainis, V.E. 1977. Metabolic rates of pond ecosystems under intensive catfish cultivation. M.S. Thesis. Auburn University. Auburn, Alabama, 107pp

Naylor, R.L., R.J. Goldburg, J.H. Primavera, N. Kautsky, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney, and M. Troell. 2000. Effect of aquaculture on world fish supplies. Nature. 405(29): 1017-1024.

NADP data report precipitation chemistry. 2008. Blackbelt Research and Extension Center, Auburn University, Selma, AL, USA.

Nhan, D.K., A. Milstein, M.C.J. Verdegem, J.A.V. Verreth. 2006. Food inputs, water Quality and nutrient accumulation in integrated ponds systems: A multivariate approach. Aquaculture 261: 160-173.

Parker, R. 2002. Aquaculture Science: Second Edition. Delmar, Albany, New York, 6-7 pp.

Pillay, T.V.R. and M.N. Kutty. 2005. Aquaculture Principles and Practices. Blackwell Publishing, Oxford, UK, 7-8 pp.

Rigler, F.H. 1964. The phosphorous fractions and the turnover time of inorganic

Phosphorous in different types of lakes. Limnology and Oceanography 9: 511-518.

Ruane, R.J., T.Y.J Chu, and V.E. Vandergriff. 1977. Characterization and treatment Of waste discharge from high-density catfish cultures. Water Research 2: 789-800.

Sanyal, S.K. and S.K. De Datta. 1991. Advances in soil science. Hatifield, J.L. et al., (editors): Chemistry of phosphorous transformations in soils. Springer-Verlag, Berlin. 1-120 pp.

Schmittou, H.R., 1969. Intensive culture of channel catfish, *Ictalurus punctatus* (Rafinesque), in cages suspended in ponds. Doctoral Dissertation. Department of Fisheries and Allied Aquacultures, Auburn University, Auburn, AL.

Schmittou, H.R. 2008. Personal communication.

Schneider, O., V. Sereti, E.H. Eding, J.A.J. Verreth. 2005. Analysis of nutrient flows in integrated intensive aquaculture systems. Aquaculture Engineering 32: 379-401.

Schroeder, G.L. 1975. Nighttime material balance of oxygen in fish ponds receiving organic wastes. Bamidgeh 27: 65-74.

Shang, Y.C. and C.A. Tisdell. 1997. Sustainable Aquaculture. J.E. Bardach (editor): Economic decision making in sustainable aquacultural development. John Wiley and Sons, Inc. New York. Pp. 127-148.

Shelton, J.L., Jr., and C.E. Boyd. 1983. Correction factors for calculating oxygen-transfer rates for pond aerators. Transactions of the American Fisheries Society 112: 120-122.

Southworth, B.E., N. Stone, C.R. Engle, 2006. Production Characteristics, Water Quality, and Costs of Producing Channel Catfish *Ictalurus punctatus* at Different Stocking Densities in Single-batch Production. Journal of the World Aquaculture Society. 37(1): 21-31.

Steeby, J.A., 1995. A Commercial-Based Length-Weight Relationship for Channel Catfish Fingerlings Grown under Commercial Conditions in Mississippi. The Progressive Fish-Culturist 57: 161-163.

Tucker, C.S. and E.H. Robinson. 1990. Channel Catfish Farming Handbook. Van Nostrand Reinhold, New York. pp. 454.

Tucker, C.S., and S. Kingsburg. 2009. A Split-pond Aquaculture System for Growing Catfish. Presentation. Catfish Farmers of America Meeting, Natchez, MS.

United States Department of Agriculture/National Agricultural Statistics Service (USDA/NASS). 2004. Production and Inventory of Channel Catfish. Washington DC. http://usda.mannlib.cornell.edu/usda/nass/CatfProd// 2000s/2004/CatfProd-02-05-2004.pdf. May 12,2010.

United States Department of Agriculture (USDA). 2006. 2005 Census of Agriculture. Washington DC. April, 2008.

United States Department of Agriculture/National Agricultural Statistics Service USDA/NASS). 2009. Production and Inventory of Channel Catfish. Washington DC.

United States Department of Agriculture/National Agricultural Statistics Service (USDA/NASS). 2010. Production and Inventory of Channel Catfish. Washington DC. http://usda.mannlib.cornell.edu/usda/nass/CatfProd//2010s/2010/CatfProd-01-29-2010.pdf. May 11,2010.

United States Environmental Protection Agency (USEPA). 1974. Pollution aspects of catfish production-review and projection. EPA, Report 660/2-74-064.Washington DC.

U.S. Soil Conservation Service. 1972. Hydrology. In SCS National Engineering Handbook, Sec. 4, Washington, D.C.

Westers, H., 2000. A Fourteen-Year Dispute About Phosphorous Effluent Contribution and Its Impact on Platte Lake. Recirculating Aquaculture. Roanoke, Virginia.

Whitis, G.N. 2010. Partioned aquaculture system: First year results of a commercial split-Pond in west Alabama. Annual Meeting of Aquaculture America. Book of Abstracts. San Diego, CA. March 1-5.

Williams, M.J. Sustainable Aquaculture. J.E. Bardach (editor): Aquaculture and sustainable food security in the developing world. John Wiley and Sons, Inc. New York. Pp. 15-51.

Yi, Y., C.K. Lin, J.S. Diana. 2003. Hybrid catfish (*Clarias macrocephalus x C. gariepinus*) and Nile tilapia (*Oreochromis niloticus*) culture in an integrated pen-cum-pond system: growth performance and nutrient budgets. Aqucaulture 217: 395-408.

Yoo, K.H. and C.E. Boyd. 1994. Hydrology and Water Supply for Pond Aquaculture. Chapman & Hall, New York, NY, 31-32 pp