Bioeconomic Analysis of Catfish Produced in In-Pond Raceway Systems

by

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Abstract

This dissertation describes catfish production over four-years using In-Pond Raceways Systems (IPRS). This technology consists of a floating raceway (RW) cage placed into an existing pond, which allows for more control of the production cycle by confining cultured fish into a smaller volume of water compared to a traditional pond. Also, it facilitates feeding, chemical treatments, and inventory control. Our overall objective is to support the development and establishment of a more profitable catfish production system, possibly through adoption of the IPRS as an additional, alternative method. Raceway configurations used in this project were "growout units" of 63 m^3 (located in ponds 1 and 2) and 45 m^3 (located in ponds 3 and 4) with a total of 2.5 HP WWU (White Water Unit) of aeration per pond used in study 1, and 4.0 HP WWU in study 2 (Chapter 2). Growout units refer to the final catfish product being of harvestable size and ready to go to the processing plant. For study 3, a 14 m^3 "stocker unit" was placed next to each growout unit and was used to grow fingerlings to stocker size. The idea being that once growout units were harvested, the produced stockers would be harvested and placed into the vacated, adjacent growout unit for growth to foodsize fish and future use (Chapter 3). For study 4 (Chapter 4), a 36 m^3 tilapia cage was placed into 2 of the 4 ponds (ponds 2 and 4). For studies 3 and 4, an extra blower was added totaling 5.0 HP for WWUs that maintained adequate DO levels at these high biomass levels. The following chapter briefs present study approaches and results from the four research years with details in the actual chapters.

Chapter 2 evaluated catfish growth performance and economic efficiency for two sizes of floating IPRS units using two stocking density approaches. Two year-long independent IPRS experiments were conducted using Channel Catfish and hybrid Catfish. Results from studies 1 and 2 showed that initial raceway cost had a great impact on the long-term feasibility of the system. Raceways made with less expensive materials had a higher profit potential but were characterized by

shorter economic lifespans. Lower initial farm level investment reduced the payback period, increased net present values and internal rates of return. White-water units kept homogeneous temperature and oxygen levels in pond water columns. IPRS catfish feed conversion ratios were more efficient than in traditional pond systems. Hybrid Catfish had better growth performance and economic returns than Channel Catfish.

Chapter 3 evaluated the performance and economic efficiency of producing foodsize hybrid Catfish and stocker sized fingerlings in two separate IPRS units. Results from study 3 showed that yields from these IPRS raceways surpassed those from traditional catfish pond systems. Again, initial raceway cost had a great impact on the long-term feasibility of the IPRS system. Feed conversion ratios ranged between 1.62 to 1.8 for stockers and foodsize hybrid Catfish produced in the IPRS systems.

Chapter 4 evaluated fish production and growth performance for hybrid Catfish raised in IPRS in four ponds, along with tilapia grown in cages without feed in two of the four ponds. Results from study 4 showed that we achieved remarkably consistent catfish and tilapia production results across all ponds. Hybrid Catfish raised in IPRS units had had survival rates, with very high counts at harvest compared to the stocking number, demonstrating excellent fish inventory control with this technology. IPRS promoted uniform hybrid Catfish production, with 90 to 95% of the foodfish harvested in the preferred premium size range. Feed conversion ratios ranged between 1.42 to 1.80 for stockers and foodsize hybrid Catfish. Production strategies for inclusion of co-cultured tilapia along with the catfish IPRS systems were achieved with little investment and low operating costs, resulting in overall positive net returns. Polyculture production of catfish and tilapia could provide an opportunity to reach diverse niche marketing segments. Ponds housing IPRS catfish units plus a tilapia cage had reduced investment payback periods, increased net present values, and higher internal rates of return. In-pond raceways offers yet another technology that could advance intensive fish culture in the U.S. and world.

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Nada é obtido sem esforço, portanto, tudo que fizermos, façamos com firmeza de propósito e fixando nossos olhos no topo da montanha; com paciência e perseverança inabalável, alcançaremos o sucesso.

Paciência, Fé e Recompensa!

Livro de Jó 42:15

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Chapter 1.

Introduction

Production of Channel Catfish *Ictalurus punctatus* and hybrid Catfish (Channel Catfish, *I. punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) represents more than half of all U.S. aquaculture sales, and 61% of all U.S. freshwater aquaculture production in the U.S. (NMFS, 2021). In 2020, the U.S. farm-raised catfish industry produced 147 thousand metric tons of catfish from 24,000 ha of water. The three major producing states are Alabama, Arkansas, and Mississippi, with production of 137 thousand metric tons, which is 93% of all catfish produced in the U.S. in 2020 (USDA, 2021). Alabama produced 33 % of all catfish produced in the United States, worth $99 million, from 6,534 ha (Hanson et al., 2021).

There is a continued need for the U.S. catfish industry to develop and adopt more efficient and profitable production technologies. Aquacultural economists are engaged with farmers to understand their on-farm realities and issues, and base their economic analyses on data collected from farms, research verification trials, and pond production trials, rather than models based on hypothetical situations and assumptions. Providing adequate information to producers is essential for them in making good decisions on technology adoption and management strategies that will work best on their farms (Kaliba and Engle, 2005; Bott et al., 2015; Hanson et al., 2020; Engle et al., 2021b). Catfish farmers are always trying to become more efficient to remain profitable and sustainable. Therefore, more efficient production technologies and associated research for raising catfish are continually needed to improve the farmer's bottom line profitability (Kaliba et al., 2007; Brown et al., 2010).

The In-Pond Raceway System (IPRS) was meant to overcome issues of inventory control, low dissolved oxygen, bird depredation, disease management, expensive disease treatment costs, inefficient feed conversion, and expensive harvest costs (Masser and Lazur, 1997). Initially, these systems were an alternative aquaculture production approach initiated at Auburn University in the early 1990's to grow another protein source for rural farmers (Yoo et al., 1995; Masser and Lazur, 1997). Its concept of increasing fish production with reduced environmental impact using constant water circulation to maintain optimal water quality has continued to evolve and improve through controlled pond and field research (Masser and Lazur, 1997; Masser, 2004, 2012; Brown et al., 2014; Fern, 2014; Bott et al., 2015; Stuckey, 2015). These research studies aimed at developing and establishing a profitable catfish production system for possible farmer adoption.

Present day IPRS systems consist of floating or fixed floor rectangular raceways (RW) placed into existing earthen ponds. Raceways are equipped with a water exchange and aeration device, called a WhiteWater Unit (WWU) which supplies raceway units with a constant flow of aerated water through the fish growth area, allowing high density culture of fish within each raceway cell. IPRS RWs generally occupy less than 2% of pond surface area but do need the entire pond for waste assimilation. Use of continually operated WWUs improve pond water mixing and circulation and enhances assimilation of fish waste loads. Rapid assimilation of the waste load placed into the pond through intensive fish feeding allows for a considerable improvement in pond water quality. Such improvement can lead to substantial increases in production yield compared to traditionally managed catfish ponds. Understanding the effect of this constant water flow can lead to improvements in the production environment and more predictable management of fish stocks.

This four-year research effort describes, through case studies, catfish production performance and economic results. The individual studies show how changes in species, RW size, and stock management can affect production, and whether the resulting produced biomass covers all production costs. The progression of changes over these four IPRS studies culminates in system choices that are the most economically efficient.

Chapter 2 of this dissertation describes two independent year-long case studies evaluating hybrid or Channel Catfish growth performance and economic efficiency in two sizes of floating IPRS units using two stocking density approaches. Several questions were targeted in these studies. We were interested in knowing which catfish species would perform best in the IPRS system and whether RW size influenced the final harvest quantity. Results would let us know what species to use for the following year's IPRS study. Secondly, in the hybrid and Channel Catfish studies, we were trying to determine the effect of different stocking densities (fish/m^3) on yields, and if they would be similar or not. For hybrid and Channel Catfish, we were looking at which combination of species, RW size and stocking approach resulted in the greatest yields and individual harvest weights. As buyers of bulk catfish, processors prefer a specific weight range and pay higher prices for fish in that 'premium' weight range. Thus, it was important to know which combination of variables produced the highest proportion of fish in this preferred range. Third, we were interested in what it cost to produce a unit of catfish in each of these studies, and whether the selling price would be enough to cover production costs. Answers to these initial questions guided us in the design of the third study.

Chapter 3 presents a study evaluating the performance and economic efficiency of producing two sizes of fish in two separate IPRS raceways in the same pond. The products were foodsize hybrid catfish from growout IPRS units and stocker sized hybrid fish from fingerlings in a stocker IPRS unit. Again, we wanted answers to the questions of whether different growout stocking densities (fish/m^3) would result in similar yields. We wanted to know the effect of an additional stocker raceway unit on growout yields and final mean fish weight. We wanted to know if our assumption that larger fingerlings or stockers would shorten the growout production cycle in IPRS units. Secondly, we wondered if the pond could support both growout and stocker IPRS production crops without major mortalities. With the cost and transport of stockers being too high or fraught with high mortalities, we wondered if we could purchase less expensive and easy to transport smaller fingerlings for stocking into the stocker unit to get enough stockers to stock the next growout production cycle. If this were possible, then costs would be lowered, and stockers would be available when it was time for the next production cycle. With the expected production biomass and the additional biomass from the stocker unit, we wondered if there would be any major changes in water quality that might adversely affect production. And, again, of paramount importance to producers, what would the net returns be from this combination of growout and stocker IPRS units. Answers to these questions helped in the design of the fourth study which continued to seek increases in biomass production and profitable enterprises.

Chapter 4 evaluated fish production and growth performance for hybrid Catfish raised in IPRS as in the prior year's study, with the difference being the inclusion of tilapia grown in cages without feed in two of the four ponds. This approach was carried out to answer the question of whether adding tilapia would increase total fish biomass harvested without impairing water quality and at the same time improve profitability. We also sought an answer to the question of whether the addition of a filter feeding species, such as tilapia, could improve water quality in the pond, and what the tilapia addition would do to the economics of the combined catfish growout, catfish stocker, and tilapia cage units in terms of the whole enterprise budget.

The exciting IPRS technology may be a solution to many of the woes facing the U.S. farm-raised catfish industry, or it may be an expensive new system not living up to its potential. This series of studies aims to shed light on some of these issues. It is essential to provide adequate IPRS production and economic information to farmers so they can make educated decisions on new technology adoption and understand the required management approaches that would work best on their farms.

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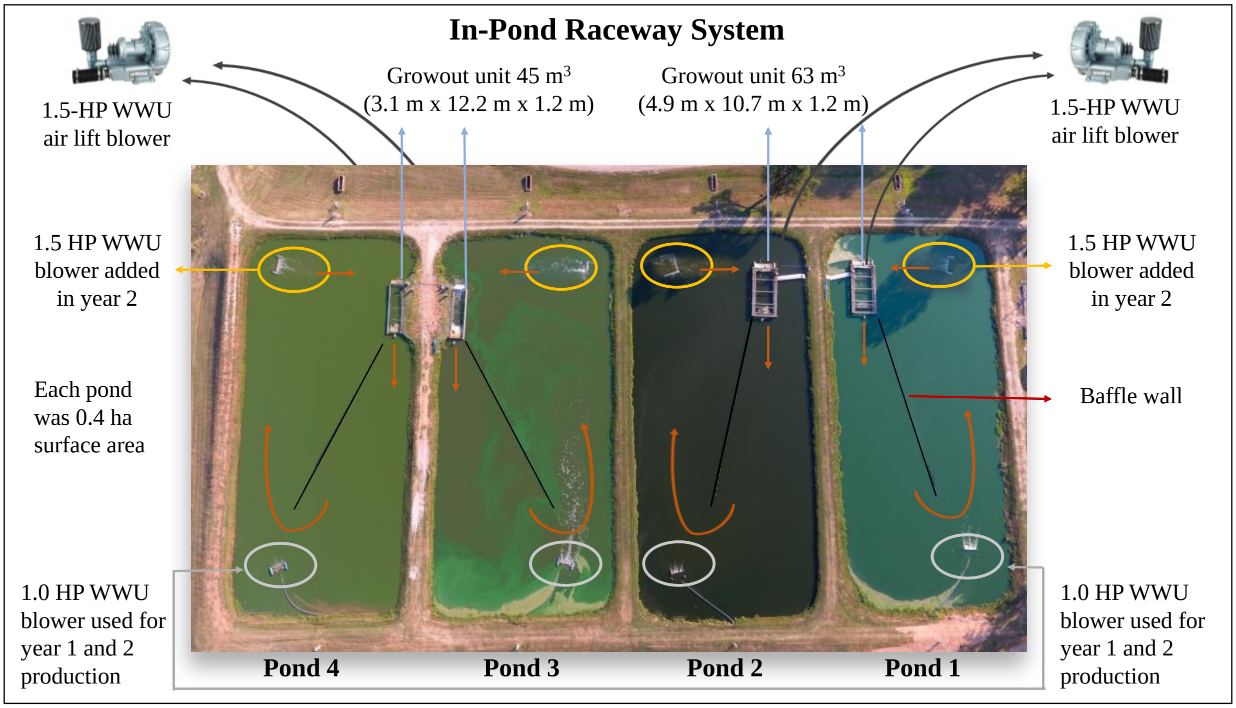

Chapter 2.

Growth performance and economic analysis of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and Channel Catfish (*I. punctatus*) produced in floating In-Pond Raceway System

Fantini-Hoag, L., Hanson, T., Kubitza, F., Povh, J.A., Corrêa Filho, R.A.C., Chappell, J. Growth performance and economic analysis of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and Channel Catfish (*I. punctatus*) produced in floating In-Pond Raceway System. Under Review at Aquaculture Reports (Accepted on November 3, 2021).

Abstract

The In-Pond Raceway System (IPRS) is a promising technology that addresses issues that have troubled the U.S. catfish industry for decades. This case study evaluated catfish growth performance and economic efficiency in two sizes of floating IPRS units using two stocking density approaches. Two year-long independent IPRS experiments were conducted using hybrid and Channel Catfish. Each IPRS unit was placed into a 0.4 ha pond. In year 1, hybrid Catfish were raised in the IPRS and net yields ranged from 12,848 kg/ha to 15,330 kg/ha, with survival from 75 to 97%. Individual hybrid Catfish harvest weights ranged from 671 to 825 g (268 days of production) with 90 to 97% of the fish in the premium size class (0.454 to 1.82 kg) and had a FCR of 1.50 to 1.64. In year 2, Channel Catfish were raised in the IPRS, with net yields from 7,416 to 9,819 kg/ha, and survival from 67 to 94%. The average Channel Catfish weight at harvest ranged from 525 to 861 g (217 days of production) with 79 to 94% in the premium size class and a FCR range from 1.78 - 2.40. Total investment for each 63 m^3 raceway was $34,570 in year 1, plus an additional $2,280 for year 2. Total investment for each 45 m^3 raceway was $14,949 in year 1, plus an additional $2,280 for year 2. Income above variable costs was positive for all four raceways in year 1, though negative for large raceways when fixed costs were included. In year 2, all four raceways had negative incomes above variable costs and net returns. This IPRS study showed better performance and economic results for hybrid over Channel Catfish and further research is needed to assess more efficient management strategies for Channel Catfish and, also, to lower initial investment and production costs.

Keywords: foodsize fish, net return, profitability, stocking density, white water unit

2.1 Introduction

Channel Catfish *Ictalurus punctatus* and hybrid Catfish (Channel Catfish, *I. punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) production represents more than half of total U.S. aquaculture foodfish sales (USDA, 2019) and 61% of total U.S. freshwater aquaculture production (NMFS, 2021). However, after a steady 20-year industry growth from the 1980s to the 2000s, catfish production in 2012 had decreased by 54% (163 million kg) from its 2003 peak of 300 million kg (Hanson and Sites, 2015; Engle et al., 2021). More recently, U.S. farm-raised catfish processed from 2011 to 2019 has remained relatively stable within the 149 to 154 million kg range (Hanson, 2020). It may take more efficient production practices to lower operating costs and make U.S. farmers profitable enough to reverse this downward trend.

Catfish ponds are land and labor intensive, and could be more efficient and profitable if production levels were increased through techniques that maintain adequate water quality (Boyd and Tucker, 1998). Production in traditional earthen catfish ponds ranges from 6,566-6,859 kg/ha (USDA, 2016, 2017). Today, many farms in west Alabama produce more than 10,000 kg/ha, though the amount of pond aeration provided is often not adequate to consistently maintain minimum dissolved oxygen (DO) concentrations above 3 mg/L (Boyd and Hanson, 2010).

Auburn University began research on floating, in-pond raceway systems (IPRS) in the late 1990s in an attempt to develop a new method of raising catfish that could be installed into existing ponds (Masser, 2004). Furthermore, this system was meant to overcome issues of inventory control, low dissolved oxygen, bird depredation, disease management, expensive disease treatment costs, inefficient feed conversion, and expensive harvest costs (Masser and Lazur, 1997). There are a number of different designs and iterations that have been evaluated, but one basic IPRS design is comprised of a floating raceway, with airlift pumps within a White Water Unit, which circulates pond water through fish-filled raceway units located in larger pond areas and volumes.

Despite all the implied benefits, U.S. catfish producers have not adopted IPRS due to the lack of performance, and high reported startup costs on commercial systems built on catfish farms (Brown et al., 2014). However, these IPRS are quickly being adopted in China, Vietnam, India, Egypt, Colombia, and Mexico (Janjua, 2019), and could potentially be of benefit to the U.S. catfish industry.

The IPRS is an approach to fish culture that endeavors to reduce production costs by intensifying production while maintaining high water quality levels. Economic analysis of production data is needed to understand the relative tradeoffs among alternative intensive pond-based catfish farming practices. This study describes research results from four small-scale IPRS catfish production systems housed in four 0.4 ha ponds over two years. The main goal of this study was to evaluate catfish growth performance and economic efficiency of IPRS units using two stocking density approaches for hybrid and Channel Catfish. Due to high variability in environmental parameters, and only two ponds per treatment per year, the results presented here are more a detailed descriptive case study than a statistical comparison, which identifies unique IPRS characteristics and interesting differences among treatments, species and profitability (Sammut-Bonnici and McGee, 2015).

2.2 Material and Methods

Catfish growth performance and associated economic analyses are described for two year-long independent IPRS experiments. In the first year, hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and second year, Channel Catfish (*I. punctatus*) were grown from fingerling size to foodfish size. Four floating IPRS raceways (RW), two RWs having volumes of 63 m^3 and two RWs of 45 m^3 were used. The 63 m^3 IPRS raceways (4.9 m wide, 10.7 m long and 1.2 m water depth), designated RW1 and RW2, were constructed with an aluminum frame, sheet polyvinyl chloride (PVC) for the walls and sheet roll metal for the floor. The 45 m^3 IPRS raceways (3.1 m wide; 12.2 m long and 1.2 m water depth), designated RW3 and RW4, were constructed with a wood frame, wire mesh walls, and high-density polyethylene (HDPE) sheet liner for walls and floor. Each floating IPRS raceway unit was placed into one of four 0.4 ha ponds, totaling 1.6 ha of pond surface area. The ponds were located at the E.W. Shell Fisheries Center, Auburn, Alabama.

During the first year, each pond had a total of 2.5 HP White Water Unit (WWU) of aeration: one 1.5 HP WWU blower propelled the airlift apparatus at the entrance of the IPRS raceway, and one 1.0 HP WWU blower propelled water in the pond. The latter was located in the pond corner diagonally opposite from the IPRS unit to sustain water movement, destratify the water column, and increase the water oxygen level. A 55 m long and 1.5 m high baffle fence or “curtain” made of woven plastic fiber was installed diagonally inside each pond to direct the water circulation around the entire pond (both years) (Figure 2.1). For the second year of production, a total of 4.0 HP WWU of aeration per pond was used, using Year 1 WWU plus one additional 1.5 HP WWU blower unit placed in each pond, at the corner perpendicular from the IPRS unit (Figure 2.1).

For the first year of production, we hypothesized that the same stocking density of fish per cubic meter in the two raceways would result in equal production. For this, RW1 and RW2 (63 m^3) were each stocked with an average of 11,058 fish, a stocking density of 176 fish/m^3 and 7.30 kg/m^3. Considering the pond area of 0.4 ha, this stocking rate is equivalent to 27,645 fish/ha. RW3 and RW4 (45 m^3) were each stocked with an average of 7,952 fish, a stocking density of 177 fish/m^3 or 7.42 kg/m^3 which is equivalent to 19,880 fish/ha.

For the second year of production, we hypothesized that stocking similar numbers of fish either in larger or smaller raceway units would result in a similar production, on a per hectare basis.

Thus, RW1 and RW2 (63 m^3) were each stocked with 10,754 fish, a stocking density of 171 fish/m^3 or 7.57 kg/m^3. This is equivalent to 26,885 fish/ha. RW3 and RW4 (45 m^3) were each stocked with 10,457 fish, a stocking density of 232 fish/m^3 or 10.58 kg/m^3. This is equivalent to 26,143 fish/ha. Fingerlings for both trials were purchased from commercial suppliers (hybrid Catfish from Jubilee Farms, Inc., Indianola, MS and Channel Catfish from Harvest Select Farm, Inverness, MS). In year 1, hybrid Catfish were stocked into the four raceways in March 2016 with an average weight of 41.8 ± 0.3 g and were raised for 268 days. In year 2, the same IPRS units were used and each were stocked with Channel Catfish in April 2017 with an average weight of 44.9 ± 1.6 g and were raised for 217 days.

2.2.1 Pond Preparation and Disease Control

Pond preparation protocols included application of salt and agricultural lime to optimize pond water chloride concentrations (~100 ppm) and alkalinity (>40 mg/L) to recommended levels in all ponds (Boyd, 1990; Boyd, 2012; Wurts and Masser, 2013). When fish had signs of disease, they were treated with formalin baths at 125 ppm for 40 minutes to prevent and control skin and gill parasites. Prophylactic treatments were initiated two days after the fish were stocked in the raceways and were repeated at biweekly intervals until water temperature stabilized in early summer at around 26 degrees ºC in June (Bott et al., 2014; Roy et al., 2009). Potassium permanganate was used to treat for parasites following Brown et al. (2011) recommendations (6 ppm lasting 45 - 60 min) to control for fin lesions. Suspension of feeding was also a strategy to reduce mortalities due to bacterial outbreaks spread by close contact among fish during feeding periods, and specifically for Enteric Septicemia of catfish, caused by *Edwardsiella ictaluri*. Application of bath treatments required the stopping of water flow through the individual raceway cell by turning off the IPRS WWU aeration, and hanging a tarp at each raceway end to keep the water with chemical within the raceway cell (Bott et al., 2015; Roy et al., 2019). When treatment was completed, tarps at both ends of the cell were removed, the water flow recommenced, and cells were flushed of any remaining treatment within minutes.

2.2.2 Water Quality and Water Dynamics

Dissolved oxygen, temperature (YSI Pro 20i) and pH (YSI EcoSenseR pH 10A) values were measured twice daily in each pond, at 8 am and 4 pm throughout the trials. Other pond water parameters were monitored twice a month: water transparency with a Secchi disk and total ammonia nitrogen, chloride, CO2, nitrite, alkalinity and hardness, using a Lamotte water quality Test kit. IPRS ponds were managed under a zero water exchange protocol, adding water only to replace losses due to evaporation, but never for flow-through to improve water quality.

The longitudinal water flow velocity was measured using a surface float (Turnipseed and Sauer, 2010) and was timed starting point at 3m from the front of the raceway and stopping at 9m for all four raceways in triplicates. The average result was divided by each length of the raceway to determine the water speed (m/s). A complete water exchange was calculated using raceway length (m) divided by water speed (m/s) and transformed into hours (raceway water exchange/h). The volume of water exchange per raceway (m^3/h) was calculated multiplying raceway water exchange/h by raceway volume (m^3). Water exchange per raceway (m^3/h) was divided by pond volume (m^3) and transformed into hours to calculate pond volume exchange (times/day).

2.2.3 Fish Feeding

During Year 1, hybrid Catfish were fed a 32% crude protein floating commercial catfish pellet (4 to 6 mm) for the entire 268-day crop cycle. In the second year, Channel Catfish were fed a 40% crude protein floating commercial catfish pellet (4 to 6 mm) for the initial 47 days, a 36% crude protein floating commercial catfish pellet (4 to 6 mm) for 64 days and a 32% crude protein floating commercial catfish pellet (4 to 6 mm) for 106 days, totaling 217 days. In both years, fish were fed twice a day depending upon water temperature. Each feeding event lasted for 5 to 10 minutes until near feeding satiation was met and quantity fed was recorded after each feeding event.

2.2.4 Production Parameters

Total raceway production (final biomass, FB) was the total weight harvested at the end of the production cycle in the first and second years of production in each raceway. Final average weight (FW) was determined by weighing 400 individual fish per raceway at harvest and dividing by the count. Biomass gain (BG) was calculated by subtracting the total weight stocked (WS) from the total harvested weight (FB) in each raceway. Net feed conversion ratio (Net FCR) for each raceway was calculated by dividing the amount of feed fed by biomass gained (Net FCR = Feed intake/BG). Standing crop within a raceway (kg/m^3) was calculated by the total harvest weight (kg) in each raceway divided by the raceway's volume (m^3). Average feeding rate (kg/ha/day) was calculated by the total feed fed in each raceway divided by the pond area (ha) and total production days. Weight gain per day (WGD, g gained/fish/day) was calculated by dividing the individual weight gain in grams by the total number of production days. Yield, as kg/ha, was determined by the total biomass of catfish harvested per raceway divided by the pond area. Net yield, as kg/ha, was determined by dividing the total biomass gain (BG) of catfish in each raceway by the pond area. Survival (%) was determined by the number of fish harvested divided by the number of fish stocked x100.

2.2.5 Cost of Production

Economic analysis focused on estimating the cost of producing food-sized hybrid Catfish in Year 1 and food-sized Channel Catfish in Year 2 with the IPRS. Standard farm management techniques were used to develop enterprise budgets for each pond to calculate the economic profit or net return above variable and fixed costs (Engle, 2010; Kay et al., 2016). Net returns were calculated by subtracting total costs (operating plus fixed costs) from sale receipts and breakeven prices to cover total costs (BEP/TC) were calculated by dividing total costs by total production. Enterprise budget variable costs were developed from production input data multiplied by industry input prices (Table 2.1).

Production input quantities came from keeping track of all inputs over the course of the study years. Specific parameters measured for calculating net revenue and production costs included quantity of fish sold and quantity of purchased inputs, specifically feed, fingerlings, chemicals, electricity, fuel, harvest/transport, management/labor, and interest on operating costs (Engle, 2010; Kay et al., 2016). Fish prices and input unit costs used in this analysis are presented in Table 2.1 Feed costs were based on bulk feed purchase prices and catfish sale prices were calculated using an average of 2016-2021 prices for each catfish size (small, premium and large) given by processors (Hanson, 2021, 2020). Direct electrical meter readings were taken on a regular basis to obtain electrical energy usage during the study period.

Fixed costs for years one and two were different, as Year 2 had equipment added and subtracted from what was used in year 1 (Table 2.2). Additionally, the materials used to construct the two sizes of raceways varied and therefore their costs varied as well (Table 2.2). We used the costs associated with operating the IPRS over a completed cycle period (268 days in year 1 and 217 days in year 2) and fixed costs were calculated for the same cycle periods. Fixed costs included depreciation on capital items, machinery and equipment (backup generator and associated components), land taxes, and interest on capital and equipment/machinery loans (Brown et al., 2014; Engle, 2010). Depreciation was calculated by subtracting an items salvage value from its initial cost and dividing by the item's economic life. System repair and maintenance costs were calculated by multiplying investment costs of each item by 3% per cycle for raceways 1 and 2, and by 5% per cycle for raceways 3 and 4 due to their less durable construction materials that required more annual maintenance at higher cost.

2.2.6 Profitability

In this study, profit was calculated as an economic profit (enterprise budget) and as an accounting profit (cash flow). The economic profit was calculated using the monetary value of all inputs, including opportunity costs for non-cash items, and the accounting profit was calculated without including the value of non-purchased or non-cash inputs (Engle, 2010; Hyman, 2010). An economic profit of zero is considered good, as all costs are covered, including salaries for the owner-manager, wages for the owner-labor and other unpaid family labor, and non-cash costs for opportunity and depreciation costs. Comparatively, an accounting profit does not include non-cash costs and its value should be positive and high, as the remainder is the actual amount the owner-manager earns from the enterprise. The accounting profit is akin to the cash flow that tracks only cash inputs and outputs and is also referred to as earnings before interest, taxes, depreciation, amortization (EBITDA) and is a measure of system performance (Beaver, 1966; Iotti and Bonazzi, 2015). It is often used to assess the performance of a company, and as an alternative to net income, and shows earnings before the influence of accounting and financial deductions. In our case, it is being used as an additional method to assess the IPRS performance, one pond and one RW at a time.

It is calculated as:

EBITDA = Net Income + Interest + Taxes + Depreciation + Amortization.

2.2.7 Cash Flow

Ten-year cash flow budgets were created using cash receipts and cash expenses from one crop per year (Engle et al. 2010). They provide an indication of when cash will be available or when operating loans are needed or when they can be paid back. Interest rates used varied by term, with long-term capital items (4.70% annual) being lower than intermediate term machinery/equipment items (4.82% annual) and operating loans (4.21% annual). Long term profitability was calculated using standard payback period (PBP), net present value (NPV), and internal rate of return (IRR) methods (Shaner, 1979; Engle, 2010; Kay et al., 2016). These investment analyses used a discount rate of 5%, and included capital, machinery and equipment reinvestment after these item's useful life was reached, in years 4, 7 and 10.

2.2.8 Sensitivity Analyses

Sensitivity analyses were conducted varying fish and feed prices in the enterprise budget to see their effect on net returns. These analyses were individually done for large (RW1, RW2) and small (RW3, RW4) raceways in years one and two. The different quantity of fish produced in each raceway, year, and fish size category meant a different selling price per kg, and thus the sensitivity analysis used a base weighted average fish selling price according to the quantity of small- and premium-sized fish sold. For the first year, both large and small raceways had a weighted average price of $2.46/kg (base), with the sensitivity analysis performed using -10, -20, +10, and +20%, price changes, that is: $1.97, $2.21, $2.70, and $2.95/kg, respectively. For year 2, large and small raceways had a weighted average price of $2.45/kg. Sensitivity selling prices used were -10, -20, +10 and +20% for large and small raceways ($1.96, $ 2.20, $2.70, and $ 2.94/kg). The feed price used in these sensitivity analyses were based on feed prices paid throughout years 1 and 2. For the first year, $430/MT was used as a base price (only one type of feed crude protein level was used for the hybrid production year). For the second year, a weighted average base price from the three different feeds equaled $664/MT for the large raceways and $696/MT for the small raceways. For the sensitivity analyses in year 1, the range of feed prices used were: $300 to $600/MT in $50/MT increments, and in year 2, the range of feed prices used were $500 to $800/MT in $50/MT increments.

A second sensitivity analysis was conducted looking at raceway unit construction costs. It was conducted by substituting in the less expensive RW materials used in RW3 and RW4 (wood and wire) for the more expensive materials used in RW 1 and 2 (aluminum). Initially, the raceway units placed into ponds 1 and 2 had a construction cost of $25,000 per RW unit (or $396 per m^3) and the raceway units placed into ponds 3 and 4 had an initial construction cost of $6,000 per unit (or $133 per m^3). When the less expensive materials were substituted in, the $133 per m3 construction cost was substituted in for the larger 63 m^3 raceways. The re-calculated construction cost would now be $8,400 per RW unit ($133 per m^3), a 66% reduction in RW construction costs due to use of the less expensive materials.

A third sensitivity analysis investigated changing the original production quantity (kg per raceway) by -5%, -10%, +5.0%, and +10.0% for hybrid and Channel Catfish to see their effect on economic indicators (PBP, NPV, IRR).

2.3 Results

2.3.1 Water Quality and Water Dynamics

Water quality measurements remained in acceptable ranges with some exceptions throughout the production cycle for all IPRS units and ponds during the first (May to November) and second (April to November) years of production (Table 2.3). Some afternoon pH (9.5 to 10) and toxic ammonia (0.5 to 1.6 mg/L) spikes and some early morning low oxygen levels (below 2 mg/L) occurred inside the raceways during the summer period. This occurred mostly in ponds with heavy phytoplankton blooms. Dissolved oxygen concentrations in ponds were often low in the early morning hours during summer months, which is normal for a high-density production system. However, inside the raceways, oxygen levels rarely fell below 3 mg/L. Dissolved oxygen levels below 2 mg/L inside the raceways were registered only once in the first year and only four times during the second year of production, when dissolved oxygen in the open pond water declined to values near 1 mg/L. No fish mortalities occurred due to these low oxygen concentrations.

Maximum levels of total ammonia nitrogen (TAN) were 1.8 mg/L in RW 4 and as high as 8.0 mg/L in RW2 (year 1) and 1.5 mg/L in RW4 and as high as 6.0 mg/L in RW1 (year 2). During Year 1 production of hybrid Catfish, fish were exposed to the highest concentration of unionized ammonia (N-NH = 1.66 mg/L) in RW1, when afternoon water pH levels in that pond reached values of 9.0 and 9.5 due to the presence of dense phytoplankton blooms. Feed consumption was reduced during these peaks of pH and unionized ammonia, but no fish mortality was observed due to these conditions. Such high unionized ammonia concentrations were not observed in the IPRS with the Channel Catfish in the second year of production. Pond chloride concentrations ranged from 100 to 300 ppm in year 1, and from 160 to 480 ppm in year 2.

The water velocity inside the raceways averaged 0.247 m/sec for 63 m^3 raceways (RW1 and RW2) and 0.262 m/sec for the 45 m^3 raceways (RW3 and RW4). With this known velocity, water flows of 5,287 m3/h and 3,496 m^3/h were estimated to have passed through the raceways, promoting water exchange rates of 83 and 77 times per hour for the 63 m^3 and the 45 m^3 raceways, respectively (Table 2.4). Such water flows passing through the raceways are equivalent to nearly 16 or 10 times the entire pond volume circulated per day. The high rate of water exchange through the IPRS WWU and pond WWU units forced the pond water column to destratify. Pond water column checks on a hot summer day in July showed temperature and dissolved oxygen as follows: 33 ± 0.26 ºC and 13 ± 2.4 mg/L at pond surface; 33 ± 0.29 ºC; 12 ± 3.3 mg/L at 0.5 m depth; 33 ± 0.31 ºC and 11 ± 2.7 mg/L at 1.0 m; 33 ± 0.34 ºC and 10 ± 2.3 mg/L at 1.5 m; and 33 ± 0.38 ºC; 11 ± 2.6 mg/L at pond bottom, at nearly 1.8 m depth.

Relying on WWUs require generators and other backup systems be in place and ready for use in case of energy failure. If water quality is maintained, production levels can be increased. In the IPRS system, dynamic flowing water created a mixed water column that, combined with efficient, plentiful aeration, better manages dissolved oxygen at the pond bottom and surface for better biological oxidation of fish and feed wastes.

2.3.2 Growth Performance

Hybrid Catfish gross and net yields ranged from 13,654 to 16,487 kg/ha and 12,848 kg/ha to 15,330 kg/ha respectively, in the first year of production with average feeding rates ranging from 72.1 to 91.6 kg/ha/day (Table 2.5). The gross and net yields for Channel Catfish in the second year of production ranged from 8,508 to 11,110 kg/ha and 7,416 to 9,819 kg/ha respectively, with average feeding rates from 65.0 to 88.7 kg/ha/day (Table 2.6). Maximum feeding rates of 296 to 351 kg/ha/day were reached in year 1 and 262 to 314 kg/ha/day in year 2, occurring in late September each year when fish weighed more than 550 g. In the first year, the average weight of hybrid Catfish at harvest ranged from 671 to 825 g (268 days of production), with 90 to 97% of harvested fish in the premium size range (0.454 to 1.82 kg). In year 2, the average weight of Channel Catfish at harvest ranged from 525 to 861 g (217 days of production), with 79 to 94% of harvested fish in the premium size range. IPRS produced fish were within the small and premium sizes ranges only, and no large sized fish were harvested in either production cycle.

A sequence of bacterial infections occurred in the two study years (first year with *Flavobacterium columnare*, and in the second year with *Edwardsiella ictaluri*) causing some fish losses in all raceways. By applying potassium permanganate baths (at 6 ppm for 30 minutes) to control *F. columnare*, and by suspending feeding after the onset of *E. ictaluri* infection, major losses of fish were prevented. Nonetheless, in year 1, 25% of the hybrid Catfish were lost in RW2, due to these diseases (Table 2.5), and in year 2, 33% of the Channel Catfish were lost in RW4 (Table 2.6). Channel Catfish showed lower resistance to these disease outbreaks than did hybrid Catfish in year one, when survival ranged from 67 to 94% and 75 to 97%, respectively. Fortunately, fish were still small at the onset of those infections, causing minor losses of biomass (in both years). Also, noteworthy is the much-reduced cost of these disease treatments in small volume raceways compared to treating entire pond volumes, as is the standard practice in pond culture of catfish. The disease outbreaks may explain part of the higher feed conversion ratio in the second year of Channel Catfish production (net FCR range: 1.78 - 2.40), which apparently had a more negative impact (Table 2.6) than in the first year of hybrid Catfish production (net FCR range: 1.50 to 1.64, Table 2.5).

2.3.3 Economic Analysis

Total investment for each 63 m^3 raceway was $34,570 in year 1, plus an additional $2,280 for year 2, increasing the total investment to $36,850 (Table 2.2). The larger raceway cost $25,000 to manufacture by a private welding company and used aluminum for the frame and walkways, and high-density polyethylene (HDPE) materials for the liner. Total investment for each 45 m^3 raceway was $14,949 in year 1, plus an additional $2,280 for year 2, increasing the total investment to $17,229 (Table 2.2). The smaller raceway unit cost $6,000 and was constructed in-house with wood, wire and HDPE materials. Machinery and equipment investment costs in year 1 were $7,034 for large and $6,413 for small raceways with the two larger raceways requiring additional boardwalk construction ($621) to access the raceways, while the smaller raceways could be accessed from the pond bank. In year 2, the extra diffuser grids located inside the raceway units were deemed unnecessary and removed (-$120), while a water mover ($1,200) and associated blower machinery ($1,200) were added to augment pond aeration and water stratification capability totaling $9,314 for large and $8,693 for small raceways.

The price paid by the processing plant for each live fish size category: small, premium and large sizes was $2.40, $2.46 and $2.01/kg, respectively. Gross receipts for fish production in the IPRS averaged a total of $15,944 for large and $13,472 for small raceway in the first year of production (Table 2.7), and for the second year, gross receipts averaged $9,608 for large and $8,991 for small raceways, respectively (Table 2.8).

In year 1, the average total variable costs were $10,977 to $12,697 (Table 2.7), and in year 2 were $12,005 to $12,429 (Table 2.8) for small and large raceways, respectively. Feed (30-33%), labor (17-19%), fingerlings (13-16%) and electricity (9-10%) comprised 73 to 76% of all variable costs in the first year, and 77 to 79% for second year (35-41%, 14-16%, 16-19%, and 8-9%, respectively). The short-term indicators of profitability (income above variable costs) were positive for all four raceways in year 1 (hybrid Catfish) but negative for all raceways in year 2 (Channel Catfish).

Depreciation on capital, machinery and equipment items was $1,679 (RW1 and RW2) and $1,181 (RW3 and RW4) in year 1 (Table 2.7), and $1,600 (RW1 and RW2) and $1,196 (RW3 and RW4) in year 2, for the large and small raceways, respectively (Table 2.8). Average fixed cost in the first year of production was $4,394 for RW1 and RW2, and $2,874 for RW3 and RW4. In the second year, average fixed costs ($3,916 for RW1 and RW2, and $2,825 for RW3 and RW4) were slightly higher than in the first year, because of the extra WWU added to each pond. In years one and two, the long-term indicator (net return) was negative when fixed costs were included for all raceways.

In year 1, net returns above all cost ranged from $-290 to $-1,380 (Table 2.7). In year 2, net returns above all costs varied between $-4,849 to $-7,519 (Table 2.8). The economic break-even price range to cover the variable and fixed costs in the first year ranged from $2.51 to $2.67/kg and in the second year ranged from $3.78 to $4.66/kg (Table 2.7 and 2.8). As the price paid to producers by the processing plant ranged from $2.45 to 2.46/kg, economic losses occurred in all pond units for years 1 and 2. The lowest total costs to produce hybrid Catfish was $2.51/kg of fish in RW3 (Table 2.7), while for Channel Catfish the lowest total cost was $3.78/kg of fish also in RW3 (Table 2.8).

Production costs varied among raceways and were influenced by survival and FCR. The lowest survival rate (67%) and highest FCR (net FCR 2.4) occurred in RW4 in the second year of production, which impacted the production cost of Channel Catfish in that raceway, at $4.32/kg of fish, the second highest cost result in this study. The highest production cost per kg of fish was found for Channel Catfish in RW2 ($4.66/kg), which had a higher fish survival (87%), but net FCR was very inefficient (2.25) leading to a high production cost. For the first year, the lowest production cost ($2.51/kg) for hybrid Catfish production occurred in RW3, which had the highest survival (97%) and most efficient FCR (net 1.59).

2.3.4 Cash flow

Cash flow and accounting results demonstrated that IPRS units performed well and could meet variable cost and debt payments with hybrid Catfish in all four ponds in year 1, with production cost ranging from $1.63 to $1.69/kg (Table 2.9). However, IPRS with Channel Catfish in year 2 had production cost ranging from $2.55 to $3.06/kg and had negative cash flow and accounting results (Table 2.10).

Financial feasibility indicators for hybrid Catfish in year 1 (Table 2.11) indicated a longer payback period (PBP) for RW1 and RW2 (3.8 and 3.0 years) compared with RW3 and RW4 (0.9 and 1.0 years). Net present value (NPV) was positive for all raceways in year 1; and internal rates of return (IRR) were greater than zero for all raceways (Table 2.11). Negative net returns resulted in negative cash flows in the second year of production for all ponds and raceway units.

2.3.5 Sensitivity Analyses

2.3.5.1 Effect of varying fish and feed prices on net returns

Results showed the fish and feed price effects on net returns above all cost for Year 1 (hybrid Catfish) and indicated that fish prices would need to increase by 10% or feed price would need to be decrease by $130 per MT (-30.2%) for net returns to be positive for the 63 m^3 raceways (Table 2.12). Likewise, for Year 1, the fish selling price would need to be increase by 10%, indicating that the current feed price of $430/MT would need to decline by $80 (-18.6%) for net returns to be positive for the 45 m^3 raceways (Table 2.12). In Year 2 with Channel Catfish, all combinations of plausible fish and feed price changes still resulted in negative net returns above all cost.

2.3.5.2 Effect of reducing raceway construction cost on net returns

The second sensitivity analysis investigated the effects of reducing the IPRS raceway construction cost on net returns above all specified costs. A 66% cost reduction was made based on the per unit construction cost of RW3 and RW4 (cost per m^3) substituted for RW1 and RW2 (63 m^3) construction. A positive net present value of $66,053 was found for RW1 and RW2, when this raceway construction reduced cost was used with the data from year 1 (hybrid Catfish) (Table 2.13). Sensitivity results show payback periods were reduced and NPV and IRR values increased accordingly (Table 2.13). These results show that the cost of the raceways has a high impact on the long-term feasibility of the operation.

2.3.5.3 Effect of increasing production quantity on net returns

From operating the IPRS units over two years, it seemed plausible that IPRS production could have been increased above the quantities produced in this study by increasing the number of fingerlings stocked in each cell or by simply increasing the biomass produced by increasing the number of crop days in a cycle, that is by starting earlier in the year. When Year 1 production (kg per raceway) was hypothetically changed by -20%, -10%, 10% and 20% (changes considered to be realistic by the researchers), the payback period (PBP) for each raceway decreased substantially for large raceways but only slightly for small raceways (Figure 2.2a), and NPV and IRR increased for large and small raceways (Figure 2.2b and 2.2c), respectively. In Year 2, these same production variations did not change the initial negative net returns to positive results.

2.4 Discussion

2.4.1. Water Quality

Pond water characteristics were within recommended ranges for catfish production most of the time (Boyd, 1998). Dissolved oxygen is the first limiting factor of fish yields in ponds. Low dissolved oxygen (DO) concentrations are the most common water quality problem in catfish farming, and it is critical because fish may die, grow slowly, or be susceptible to infectious diseases (Tucker, 1991). The white-water units in the IPRS oxygenate and lift water from the lower pond region upward to the surface where the WWU’s deflector hood guides the oxygenated water on its circular course toward the IPRS for reuse. This water dynamic is key to maintaining a homogeneous temperature and dissolved oxygen concentrations throughout the pond water column and providing enough oxygen to promote aerobic biological organic matter decomposition at pond bottom.

Brune et al. (2003) observed water exchange rates ranging from 0.226 to 0.988 times per hour within individual culture units of the partitioned aquaculture system. Brown et al. (2011) reported a water exchange every 4.9 min (12.2 times per hour) in fixed concrete IPRS raceways using paddlewheels to circulate water, and Wilcox reported a water exchange rate of once every 6.2 min (9.7 times per hour) in an in-pond, floating raceway (Wilcox, 1998). In our IPRS, the water exchange rate was estimated at 80 to 86 times per hour in the larger raceways, and 76 to 79 times per hour in the smaller raceways. Such volumes of water moved through the raceways are equivalent to 10 to 16 times the entire pond volume per day. An important piece of equipment to maintain this water circulation is the standby generator which requires personnel who fully understand how to correctly respond to an interruption in electrical power. The person responsible for being sure the generator starts and runs to produce electricity in an emergency needs to be thoroughly trained to troubleshoot operation and maintenance of this generator.

Toxic ammonia (unionized ammonia) is the second limiting factor of fish yield in intensively managed ponds and often requires water exchange, restriction of feeding and control of phytoplankton blooms to prevent high afternoon pH. In year 1, the concentration of unionized ammonia in RW1 reached sublethal levels (above 1 mg/L, up to a maximum of 1.66 mg/L). This was due to the combined high concentrations of total ammonia nitrogen (up to 4.8 mg/L) and high afternoon pH, often at 9.0 or above, due to the intense phytoplankton photosynthesis.

The IPRS ponds in this study were managed with zero external water exchange, with only water replacement occurring to replace evaporative water losses. Water level in the ponds were maintained at 100 mm below the standpipe, so ponds could accumulate rainfall water without overflowing. The relatively high levels of total ammonia nitrogen and nitrite observed in this study are typical of conditions in intensively managed systems (Kumar et al., 2019). Nitrite concentrations in all ponds (0.6 to 1.6 mg/L) remained well below the 7 mg/L (LC50 -96h) determined for Channel Catfish (Eddy and Williams, 1987). Nonetheless, salt was added to all ponds to increase chloride levels in the water, reducing the risk of nitrite toxicity.

2.4.2. Growth Performance and Economic Analysis

When IPRS systems in Alabama were first being developed in the 1980s and 1990s, the intention was for them to be placed into farm ponds not suitable for traditional catfish pond production. Particularly, these systems were thought to be a good match with watershed ponds that could not be seined easily, nor used for commercial catfish production for other economic or efficiency reasons (Masser, 2004, 2017). The idea was that no new pond construction would be required and there would only be raceway construction costs and thus, the initial investment would be kept low. As IPRS systems developed during the 2010's, this IPRS concept changed from one of supplemental catfish production for rural farm households to one of being a new technology that could perhaps rival and outperform traditional earthen commercial pond production of catfish.

Catfish producers have not adopted the use of in-pond raceways in the U.S. (Brown et al. 2014) but this system is becoming known and adopted in China, Vietnam, India, Egypt, Colombia and Mexico (Janjua, 2019). In recent years, the interest in and use of IPRSs by the fish farming industry in China has increased. To date, there are more than 6,000 IPRS cells in production in China (USSEC, 2020). The fish species that have been reared in IPRSs include Grass carp *Ctenopharyngodon idella*, Bluntnose black bream *Megalobrama amblycephala*, Largemouth Bass *Micropterus salmoides*, Yellow Catfish *Tachysurus (Pelteobagrus) fulvidraco*, Channel Catfish *Ictalurus punctatus*, and tilapia *Oreochromis* spp (Wang et al., 2019).

This study used a high stocking density averaging 27,324 ± 98 fish/ha in RW1 and RW2, and 19,649 ± 458 fish/ha in RW3 and RW4 for the first year and an average of 26,206 ± 553 fish per raceway for the second year of production. The total hybrid Catfish harvested (kg) in the first year for RW1 and RW2 were higher compared with RW3 and RW4. In the second year, the total Channel Catfish harvested (kg) was lower compared to the first year of hybrid production, but similar between all raceway cells (1, 2, 3, 4) in Year 2. Hybrid Catfish produced in 45.9 m^3 IPRS cells resulted in 7,800 kg of fish/ha harvested in their first cycle (10-12 months) and 6,194 kg of fish/ha harvested in their second cycle (12-19 months) (Roy et al., 2019). The grow-out phase in the research evaluated by Roy et al. (2019) was conducted for 10-19 months depending on initial fish size and stocking density. Different fish size were used to stagger production so harvests could be marketed throughout the year. An important observation is that when they stocked larger fingerlings (175 g) for the first production cycle, the net yield was higher in four of the five cells, suggesting that larger fingerlings result in higher production, and thus points to the need for further research in stocking larger fish in IPRS units.

Hybrid Catfish appear to be less affected by high density pond culture conditions than Channel Catfish and the latter do not do as well in high densities (Torrans and Ott, 2019). In general, hybrids demonstrated a 15 to 25 percent improvement in production over improved strains of Channel Catfish (Masser and Dunham, 1998). This increased growth is due to a combination of increased food consumption, improved feed conversion efficiency, and improved disease resistance.

In the present study, the average weight of live catfish at harvest was in the "premium" class size range (454 g to 1,820 g). Harvested fish ranged between 671 g - 825 g for hybrid Catfish in year 1 (90 to 97% of the fish harvested) and 525 - 861 g for Channel Catfish in year 2 (79 to

94% of the fish harvested); all within the premium size range. In the U.S. catfish industry (Channel and hybrids), fish are processed predominantly from the premium size range which becomes the largest quantity of fresh and frozen catfish fillet products sold by U.S. processors. In 2019 there were 2.8 million kg of fillets processed and sold from this size range, at an average wholesale price of $10.17/kg (Hanson, 2020).

Our total investment for the four ponds (1.9 ha) research system was $99,040 ($50,985/ha) for the first year and $108,160 ($56,926/ha) for the second year. Traditional pond systems have lower initial investment costs, reported at $14,695/ha and $15,463/ha (D'Abramo et al., 2013). Brown et al. (2010) reported fixed floor raceway investment costs at $1,032/m^3 for a fixed 5-cell concrete raceway, which included capital costs (land and pond construction), and machinery and equipment, while our floating IPRS systems had an investment cost of $549/m^3 for the large raceway (46% lower) and $332/m^3 for the small raceway (68% lower).

In this research, better results were found in year 1 using hybrid Catfish, however, the hybrid cycles were 51 days longer and could be the reason for negative outcomes. We know for the system to be profitable in the long run, further research to reduce variable and fixed costs is needed. One sensitivity analysis conducted here lowered raceway construction material costs for larger IPRS units, which lowered fixed costs and overall cost of production, while increasing net returns. Another alternative to improve the system's net return is working on reducing variable costs. We could do this by adding a stocker raceway, where purchased smaller sized fingerlings are grown out to larger fingerling/stocker sizes for stocking into final growout raceways. It is imagined that the stocker raceway would be alongside the growout raceway in the same pond for co-production of harvestable sized fish and stockers to restock the harvested growout raceway. This could lower production costs and warrants future research.

Traditional catfish production in ponds is between 6,843 - 7,527 kg/ha (Courtwright, 2013) and 6,566 - 6,859 kg/ha of catfish (USDA, 2016, 2017) while IPRS technology often surpasses this production quantity. Strategies producing less than 5,700 kg/ha make catfish production a riskier business and less likely to be profitable (Hanson, 2019). Alternative intensification culture practices have resulted in greater yields than those achieved in traditional open catfish ponds (Kumar et al., 2018). Our research showed a cost/kg ranging from $2.51 to $2.67/kg for catfish hybrids, and $3.78 to $4.66/kg for Channel Catfish. Kumar et al. (2019) showed costs ranging from $1.87/kg raising hybrid Catfish, and $2.36/kg and $2.27/kg raising Channel Catfish at low (6,731 fish/ha) and high stocking densities (13,462 fish/ha), respectively for intensively aerated ponds operated under a single-batch cropping system. Hanson et al. (2020) reported lower breakeven prices for various catfish pond production strategies: owner-defined multiple-batch ($2.01/kg), extension-defined multiple-batch system ($1.86/kg) and extension-defined single-batch system ($1.97/kg). In this study, the reason that the accounting and economic profits are still negative in the second year of production with Channel Catfish, was due to the lower survival and, thus, lower fish biomass and less efficient FCR, compared to the hybrid Catfish production in the first year.

Feed conversion ratios for hybrid and Channel Catfish in IPRS was improved (1.50 to 2.4) compared to FCRs reported in commercial Channel Catfish farms using ponds and single- and multiple-batch production systems (1.91 to 2.63) (Hanson et al., 2020). Brown et al. (2011) raising catfish in a commercial-scale IPRS reported average FCR for the Channel and hybrid Catfish of 1.74 and 1.36, respectively.

An advantage of the IPRS system is that small quantities can be partial harvested from a specific raceway cell. Such harvest should try to crowd and handle only the amount of fish required for sale. In large, traditional, commercial ponds, more labor effort is required to harvest small quantities of fish for local markets, and partial harvests of small quantities would be inconvenient, expensive and near impossible to do frequently. Aquaculture producers, particularly smaller-scale operations, often target specialty markets, such as live haulers/brokers (69%), direct to consumers (2%), recreational stocking (4%), wholesale to other producers (8%), and government agencies, as these markets frequently result in higher received prices (NASS, 2019). Specialty marketing is a choice to capture a high price in markets willing to pay for higher quality (Engle, 2010).

In our study, if we hypothetically calculate that a local fish market would purchase thirty percent of the premium-sized fish harvested at a price of $2.82/kg, which is $0.36/kg higher than for the premium size catfish being sold to processors in this study, we would increase our receipts to $-510 and $157 for large and small raceways, respectively. This would increase the net return by 56% and 141% in large and small raceways, respectively. In the second year, this niche market would increase the net return by only $-124 (1.8%) and $-227 (3.9%) for large and small raceways, respectively. The discerning factor is that local and specialty markets do not purchase great quantities of fish at once, as do large processors, making it hard for large commercial catfish operations to rely on niche markets. Likewise, frequent harvests with handling stress, could result in lower survival and disease issues in IPRS systems (Roy et al., 2019).

The economic viability of a production system can be determined using methods based on cash flows over several years, allowing the calculation of Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Periods (Frezatti, 2008). Successful businesses must be profitable, that is, have a cost of production lower than the selling price. In addition, businesses must have positive and increasing net worth over time; and businesses must have adequate cash flow to pay debts on time. Inadequate cash flow can result in business failure. Because cash flow measures the timing of cash receipts and expenses, it is a prime determinant of liquidity. Cash flow statements include only cash items and leave out non-cash items, such as depreciation (Engle, 2010; Engle, 2012a), as we have calculated and reported in our cash flow results section.

To survive the short run, i.e., the next year, farm businesses must be able to sell fish at a price that is greater than its break-even price above variable costs (Engle, 2012b). Our research shows positive incomes above variable costs for year 1 producing hybrids, and a negative income above variable cost for year 2 producing Channel Catfish. Engle (2012b) suggests calculating whether the farm can survive the short run by using the break-even price over variable costs and comparing it to the price that the farmer expects to receive. Our first-year production using hybrid Catfish had positive break-even prices over variable cost margin, at +$0.50/kg for catfish grown in large raceways and +$0.45/kg for catfish grown in small raceways. These margins show that the farmers would expect to receive more for their fish than it costs to produce them, and this allows the farmer to stay in business for another year.

Kumar et al. (2018), evaluating the three catfish production systems mentioned earlier, had positive incomes above variable costs, showing their viability or their ability to pay off all variable costs from production receipts. Similar results were found by Roy et al. (2019), with all raceway cells in cycle 1 and in four of the five raceway cells in cycle 2 having positive incomes above variable cost. Interestingly, the one negative return came from raceway cell 5 where fish were graded and hand selected by the farmer routinely, causing fish stress and mortality.

According to Engle (2012b), to stay in business over the long run, selling prices must be greater than the break-even cost over total cost. In the Roy study, a positive long-term net return was found for all raceway cells excepted one in cycle 1, and negative net returns above total costs were found for all cells in cycle 2. Note in cycle 1 all fish were harvested and sold at one time to a processing plant; and in cycle 2 all fish were sold to individual buyers wanting smaller quantities throughout the year.

To attain economic feasibility in the farming of catfish in IPRS, structural and functional adjustments in the raceways and improvement on fish stock management are required. IPRS can be equipped with fecal waste collection and removal devices, allowing higher fish stocking and feeding rates, while still keeping ponds water quality at adequate levels. As well, an additional aeration device inside the raceways could improve dissolved oxygen levels in the culture cell, benefiting fish condition, growth, survival and feed efficiency. Therefore, a waste collection and removal device plus additional aeration in the raceways might be effective structural adjustments for increasing fish yields and improving FCR, as raceway and pond water quality should be better preserved. Better water quality, continuous adoption of preventative management practices (earlier control of parasites and improved nutrition) and prompt action at the onset of bacterial outbreaks, should reduce fish losses and improve overall fish yields. IPRS and other high-density systems impose additional physiological and physical stresses on fish. For this, the use of high-quality feeds is imperative. Feed must be designed not only to match nutritional requirements of fish, but also to improve their condition, healing and overall health, mainly concerning mycotoxin prevention, gut integrity, balanced microbiota, and better immune response. Improved nutrition, then, should contribute to improved survival, growth, FCR and fish yields, reducing production costs and maximizing profits.

IPRS is a promising technology that addresses issues that have been troubling the U.S. catfish industry for decades. For our research ponds, the initial investments were high, which would need to be offset by increased production and reduced variable costs. Therefore, further investigations into increasing production, reducing production time, improving efficiency, and lowering the initial investment are warranted. Future research might include placement of a smaller “stocker generator” raceway in each pond, that would specifically use smaller fingerlings and grow them to a stocker size (100 to 200 g) in year 1 and for use in restocking the growout raceway for the next production cycle. This could reduce production time and fingerling costs. Intensive fish farm systems are in constant states of evolution, and the same is true for the IPRS technology. We found hybrids are better suited for IPRS than Channel Catfish, that IPRS can reduce disease treatment costs (Bott et al., 2018), shorten crop lengths (7-9 months), and achieve inventory control close to 100%. We demonstrated better performance and economic results producing hybrid Catfish and therefore they should be selected for further research using IPRS.

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Table 2.1 Per-unit price or cost used in the development of In Pond Raceway System (IPRS) enterprise budgets for hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and Channel Catfish (*I. punctatus*).

Description	Unit	Cost ($) per unit
Fish price		
Catfish fingerlings	each	0.19
Harvest-size fish price	kg	
Small: <0.454 kg	kg	2.40
Premium: 0.454 - 1.82 kg	kg	2.46
Large: >1.82 kg	kg	2.01
Feed		
40% crude protein	metric ton	1,050
36% crude protein	metric ton	948
32% crude protein	metric ton	420
Management and labor		
Management	ha/year	600
Hired labor	hour	10.00
Chemicals		
Lime, agricultural	metric ton	50.00
Lime, hydrated	kg	0.62
Salt	metric ton	135.00
Copper sulfate	22.68-kg bag	65.00
	kg	2.87
Rotenone	L	13.00
	208 L drum	440
Formalin	L	2.11
Diquat	L	3.00
Potassium permanganate	kg	11.63
Fuel		
Gasoline off-road price for agriculture	L	0.72
Diesel price off-road	L	0.79
Electricity, per KWhr at off-peak rate	KW-hour	0.07
Other		
Insurance	ha	2.53
Miscellaneous expenses	cycle	200.00
Bird netting for 2 raceways	roll	163.00

Fish price was determined by calculating an average of the price processors paid for live fish from the producer over the 2016-2019 period for small and premium catfish sizes (Hanson, 2020).

Table 2.2 Average investment and depreciation costs (US$) for two sizes of In-Pond Raceway Systems used in the 2016 and 2017 trials.

Items	U.S.$ /unit	Investment			
		Qty	63 m^3 IPRS	Qty	45m^3 IPRS
Capital Items					
Land, $/ha	2,031	0.49	986	0.49	986
Pond construction[a], $/ha	3,830	0.40	1,550	0.40	1,550
RW 1 and 2 (4.9 m x 10.7 m x 1.2 m = 63 m^3)	25,000	1	25,000	-	
RW 3 and 4 (3.0 m x 12.2 m x 1.2 m = 44 m^3)	6,000	-	-	1	6,000
Subtotal			27,536		8,536
Machinery and Equipment					
Equipment[b], $/ha	3,739	0.40	1,513	0.40	1,513
1.0 HP blowers for water movers	880	1	880	1	880
1.5 HP blower's raceway units	1,200	1	1,200	1	1,200
Water mover units	2,500	1	2,500	1	2,500
Baffle fencing and floats	200	1	200	1	200
Extra diffuser grids	120	1	120	1	120
Boardwalks - Raceways 1 and 2	104	6	621	-	0
Subtotal			7,034		6,413
TOTAL 2016			34,570		14,949
Extra diffuser grids[c] (removed)	-120	-1	-120	-1	-120
1.5 HP blowers for water movers (added)	1,200	1	1,200	1	1,200
Water mover units (added)	1,200	1	1,200	1	1,200
Subtotal			2,280		2,280
TOTAL 2017			36,850		17,229

[a]Includes construction of pond with water supply, drainage, and electrical service.

[b]Equipment costs include backup generator (20 kW plus transfer switch), propane tank for generator, electrical line for water movers, tractors, trucks, mower, electrical aerators, power take-off aerator, feeder, feed bin, pump, office, shop, tools, utility trailer, storage container, dissolved oxygen meter, and computer.

[c]Extra diffusers grids within the fish growth area were only used in the first year of production (2016) and were removed from use for the 2017 production

Table 2.3 Water quality results from hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and Channel Catfish (*I. punctatus*) production in four 0.4 ha In-Pond Raceway Systems IPRS, in the first and second year of production, respectively.

	Year 1 Hybrid Catfish				Year 2 Channel Catfish			
	Raceway 1 63 m^3	Raceway 2 63 m^3	Raceway 3 45 m^3	Raceway 4 45 m^3	Raceway 1 63 m^3	Raceway 2 63 m^3	Raceway 3 45 m^3	Raceway 4 45 m^3
DO range, mg/L	2.2 - 9.2	2.4 - 9.8	1.9 - 9.2	1.8 - 9.9	1.4 - 16.7	2.5 - 13.9	2.3 - 13.3	1.5 - 13.4
Temperature °C	12.5 - 33.0	12.3 - 32.8	12.6 - 32.5	12.4 - 32.0	13.2 - 33.1	12.7 - 32.1	12.7 - 32.4	12.8 - 32.0
Total alkalinity	100 - 117	68 - 78	52 - 72	80 - 84	60 - 108	60 - 100	40 - 70	64 - 100
Total hardness	15 - 100	24 - 68	18 - 72	18 - 82	70 - 90	70 - 100	50 - 70	70 - 100
pH	7.0 - 9.5	7.0 - 8.0	7.0 - 9.0	7.0 - 9.5	7.0 – 10.0	7.0 - 8.0	7.0 – 10.0	7.0 - 9.0
TAN mg/L	4.8	8.0	4.8	1.8	6.0	4.0	4.0	1.5
NH_3 mg/L	1.66	0.50	0.34	0.01	0.03	0.20	0.03	0.02
NO_2- mg/L	1.50	1.50	1.60	0.80	0.60	0.80	0.60	0.60
Secchi disk (m)	0.12 - 0.28	0.35 - 0.66	0.16 - 0.32	0.15 - 0.38	0.20 - 0.30	0.15 – 0.28	0.22 – 0.33	0.20 – 0.24

* DO = Dissolved oxygen inside the raceway - minimum and maximum; Temperature = minimum and maximum; Total alkalinity (range as ppm $CaCO_3$); Total hardness (range as ppm $CaCO_3$); TAN = maximum afternoon; NH_3 = Maximum afternoon; NO_2- = Maximum afternoon; pH = Inside the raceway (afternoon range); Secchi disk at summer and early fall

Table 2.4 Water dynamic results from In-Pond Raceway Systems IPRS, Summer of 2017.

	Raceway 1 63 m^3	Raceway 2 63 m^3	Raceway 3 45 m^3	Raceway 4 45 m^3
Pond volume (m^3)	8,094	8,094	8,094	8,094
IPRS unit (m^3)	63	63	45	45
Water speed (m/s)	0.256	0.238	0.247	0.256
Length of raceway (m)	10.7	10.7	12.2	12.2
Time for one complete exchange (minutes)	0.69	0.75	0.79	0.76
Exchanges (number/hr)	86	80	76	79
Volume exchanged (m^3/hr)	5,095	5,287	3,572	3,496
Pond volume exchange (number/day)	16	15	11	10

Table 2.5 Growth performance of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in four 0.4 ha In-Pond Raceway Systems IPRS, in the first year of production in the 2016 and 2017 trials.

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average (standard error) Raceway 1 and 2	Raceway 3 45 m^3	Raceway 4 45 m^3	Average (standard error) Raceway 3 and 4
Production cycle (days)	268	268	268	268	268	268
Number of fish stocked	11,030	11,086	11,058 (28.0)	8,083	7,821	7,952 (131)
Stocking density (fish/m^3)	175	176	176 (0.4)	180	174	177 (2.9)
Mean weight at stocking (g)	41.4	41.8	41.6 (0.2)	42.7	41.2	42.0 (0.7)
Stocking biomass (kg)	456	463	460 (3.4)	345	322	334 (11.4)
Mean weight at harvest (g)	671	794	732 (61.7)	700	825	763 (62.5)
Total harvested (kg)	6,383	6,595	6,489 (106.2)	5,505	5,462	5,483 (21.5)
Yield[a] (kg/ha)	15,956	16,487	16,222 (265)	13,762	13,654	13,708 (54)
Net yield[b] (kg/ha)	14,816	15,330	15,073 (257)	12,899	12,848	12,874 (25.5)
Standing crop (kg/m^3)	101.3	104.7	103 (1.7)	122.3	121.4	122 (0.5)
Feed fed (kg)	9,699	9,817	9,758 (58.7)	8,200	7,733	7,966 (233.4)
Net FCR[c]	1.64	1.60	1.62 (0.02)	1.59	1.50	1.55 (0.04)
Avg. feeding rate (kg/ha/day)	90.5	91.6	91.0 (0.5)	76.5	72.1	74.0 (2.2)
WGD[d] (g/fish/day)	2.35	2.81	2.58 (0.2)	2.45	2.93	2.69 (0.2)
Survival (%)	86	75	81 (0.1)	97	85	91 (0.1)

[a] Yield = Total harvested, kg / Pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / Pond size, 0.4 ha

[c] Net FCR (Feed conversion ratio) = Feed fed, kg / (Total harvested, kg – Stocking biomass, kg)

[d] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 2.6 Growth performance of Channel Catfish (*I. punctatus*) raised in four 0.4 ha In-Pond Raceway Systems IPRS, in the second year of production.

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average (standard error) Raceway 1 and 2	Raceway 3 45 m^3	Raceway 4 45 m^3	Average (standard error) Raceway 3 and 4
Production cycle (days)	217	217	217	217	217	217
Number of fish stocked	10,927	10,581	10,754 ± 173	10,489	10,425	10,457 (32)
Stocking density (fish/m^3)	173	168	171 (2.7)	233	232	232 (0.71)
Mean weight at stocking (g)	47.3	41.3	44.3 (3.0)	47.7	43.4	45.5 (2.1)
Stocking biomass (kg)	517	437	477 (40)	500	452	476 (23.9)
Mean weight at harvest (g)	593	556	574 (18)	861	525	693 (168.2)
Total harvested (kg)	4,444	3,403	3,924 (520.5)	3,672	3,657	3,665 (7.3)
Yield[a] (kg/ha)	11,110	8,508	9,809 (1,301)	9,180	9,143	9,161 (18.3)
Net yield[b] (kg/ha)	9,819	7,416	8,617 (1,201)	7,929	8,012	7,971 (41.5)
Standing crop (kg/m^3)	71	54	62 (8.26)	82	81	81 (0.16)
Feed fed (kg)	7,641	6,693	7,167 (474)	5,641	7,697	6,669 (1,028)
Net FCR[c]	1.94	2.25	2.10 (0.6)	1.78	2.40	2.09 (0.31)
Avg. feeding rate (kg/ha/day)	88.0	77.1	83 (5.5)	65.0	88.7	77 (11.8)
WGD[d] (g/fish/day)	2.51	2.37	2.44 (0.07)	3.75	2.22	2.99 (0.77)
Survival (%)	88	87	88 (0.01)	94	67	81 (0.13)

[a] Yield = Total harvested, kg / Pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / Pond size, 0.4 ha

[c] Net FCR (Feed conversion ratio) = Feed fed, kg / (Total harvested, kg – Stocking biomass, kg)

[d] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 2.7 Summarized enterprise budgets showing receipts and costs for hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in four 0.4 ha In-Pond Raceway Systems IPRS, in the first year of production, U.S.$.

	Raceway 1 63 m³		Raceway 2 63 m³		Average Raceway 1 and 2		Raceway 3 45 m³		Raceway 4 45 m³		Average Raceway 3 and 4	
	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg
Gross Receipts												
Catfish Sales												
Small, <0.454 kg	1,575	2.40	405	2.40	990	2.40	1,354	2.40	397	2.46	876	2.40
Primium:0.454-1.82 kg	14,093	2.46	15,814	2.46	14,954	2.46	12,159	2.46	13,033	2.40	12,596	2.46
Total	15,668	2.45	16,219	2.46	15,944	2.46	13,513	2.45	13,431	2.46	13,472	2.46
Variable Cost												
Feed, 32% Protein	4,164	0.65	4,215	0.64	4,189	0.65	3,520	0.64	3,320	0.61	3,420	0.62
Labor and Management	2,120	0.33	2,120	0.32	2,120	0.33	2,120	0.39	2,120	0.39	2,120	0.39
Catfish Fingerlings	2,096	0.33	2,106	0.32	2,101	0.32	1,536	0.28	1,486	0.27	1,511	0.28
Carp Fingerlings	65	0.01	65	0.01	65	0.01	65	0.01	65	0.01	65	0.01
Harvest and Transportation	704	0.11	727	0.11	715	0.11	607	0.11	602	0.11	604	0.11
Fuel (diesel and gas)	47	0.01	47	0.01	47	0.01	47	0.01	47	0.01	47	0.01
Repairs and Maintenance	1,145	0.18	1,145	0.17	1,145	0.18	1,145	0.21	1,145	0.21	1,145	0.21
Electricity, Aeration	225	0.04	225	0.03	225	0.03	450	0.08	450	0.08	450	0.08
Chemicals	1,438	0.23	1,452	0.22	1,445	0.22	859	0.16	1,220	0.22	1,040	0.19
Miscellaneous	132	0.02	132	0.02	132	0.02	132	0.02	132	0.02	132	0.02
Interest on Operating Capital	510	0.08	514	0.08	512	0.08	441	0.08	445	0.08	443	0.08
Total Variable Cost	12,646	1.98	12,749	1.93	12,697	1.96	10,922	1.98	11,033	2.02	10,977	2.00
Income Above Variable Cost	3,022	0.47	3,471	0.54	3,246	0.50	2,591	0.47	2,398	0.44	2,495	0.45
Fixed Cost												
Land Charge	724	0.11	724	0.11	724	0.11	724	0.13	724	0.13	724	0.13
Depreciation on Capital Items	917	0.14	917	0.14	917	0.14	464	0.08	464	0.08	464	0.08
Depreciation for Machinery and Equipment	762	0.12	762	0.12	762	0.12	717	0.13	717	0.13	717	0.13
Interest on Capital Loans	950	0.15	950	0.14	950	0.15	295	0.05	295	0.05	295	0.05
Interest on Equipment Loans	250	0.04	250	0.04	250	0.04	228	0.04	228	0.04	228	0.04
Repairs and Maintenance	23	0.00	23	0.00	23	0.00	23	0.00	23	0.00	23	0.00
Taxes	769	0.12	769	0.12	769	0.12	425	0.08	425	0.08	425	0.08
Insurance	6	0.00	6	0.00	6	0.00	6	0.00	6	0.00	6	0.00
Total Fixed Costs	4,402	0.69	4,402	0.67	4,402	0.68	2,881	0.52	2,881	0.53	2,881	0.53
Total Costs	17,048	2.67	17,151	2.60	17,100	2.64	13,804	2.51	13,914	2.55	13,859	2.53
Net Return Above all Costs	-1,380	-0.22	-931	-0.14	-1,156	-0.18	-290	-0.05	-483	-0.09	-387	-0.07

Some columns of number may not add up as presented due to integer rounding

Table 2.8 Summarized enterprise budgets showing receipts and costs for Channel Catfish *Ictalurus punctatus* raised in four 0.4 ha In-Pond Raceway Systems IPRS, in the second year of production (U.S.$).

	Raceway 1 63 m^3		Raceway 2 63 m^3		Average Raceway 1 and 2		Raceway 3 45 m^3		Raceway 4 45 m^3		Average Raceway 3 and 4	
	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg	Value or cost	Cost per kg
Gross Receipts												
Catfish Sales												
Small, <0.454 kg	2,273	2.40	1,555	2.40	1,914	2.40	518	2.40	1,701	2.40	1,109	2.40
Primium:0.454-1.82 kg	8,607	2.46	6,781	2.46	7,694	2.46	8,505	2.46	7,257	2.46	7,881	2.46
Total	10,880	2.45	8,336	2.45	9,608	2.45	9,023	2.46	8,958	2.45	8,991	2.45
Variable cost												
Feed, 40% Protein	724	0.16	637	0.19	681	0.18	532	0.14	639	0.17	585	0.16
Feed, 36% Protein	2,437	0.55	2,229	0.66	2,333	0.60	2,188	0.60	3,044	0.83	2,616	0.71
Feed, 32% Protein	1,872	0.42	1,594	0.47	1,733	0.44	1,210	0.33	1,660	0.45	1,435	0.39
Total Feed	5,034	1.13	4,460	1.31	4,747	1.22	3,929	1.07	5,343	1.46	4,636	1.27
Labor and Management	1,782	0.40	1,782	0.52	1,782	0.46	1,782	0.49	1,782	0.49	1,782	0.49
Catfish Fingerlings	2,317	0.52	2,067	0.61	2,192	0.56	2,070	0.56	2,051	0.56	2,061	0.56
Carp Fingerlings	65	0.01	65	0.02	65	0.02	65	0.02	65	0.02	65	0.02
Harvest and Transportation	490	0.11	375	0.11	432	0.11	405	0.11	403	0.11	404	0.11
Fuel (diesel and gas)	43	0.01	43	0.01	43	0.01	43	0.01	43	0.01	43	0.01
Repairs and Maintenance	987	0.22	987	0.29	987	0.26	987	0.27	987	0.27	987	0.27
Electricity, Aeration	200	0.05	200	0.06	200	0.05	400	0.11	400	0.11	400	0.11
Chemicals	1,348	0.30	1,348	0.40	1,348	0.35	788	0.21	1,233	0.34	1,011	0.28
Miscellaneous	132	0.03	132	0.04	132	0.03	132	0.04	132	0.04	132	0.04
Interest on Operating Capital	521	0.12	482	0.14	502	0.13	446	0.12	523	0.14	484	0.13
Total Variable Cost	12,919	2.91	11,940	3.51	12,429	3.21	11,047	3.01	12,962	3.54	12,005	3.28
Income Above Variable Cost	-2,039	-0.46	-3,603	-1.06	-2,821	-0.76	-2,024	-0.55	-4,004	-1.09	-3,014	0.00
Fixed Cost												
Land Charge	586	0.13	586	0.17	586	0.15	586	0.16	586	0.16	586	0.16
Depreciation on Capital Items	743	0.17	743	0.22	743	0.19	376	0.10	376	0.10	376	0.10
Depreciation for Machinery and Equipment	857	0.19	857	0.25	857	0.22	820	0.22	820	0.22	820	0.22
Interest on Capital Loans	769	0.17	769	0.23	769	0.20	239	0.06	239	0.07	239	0.07
Interest on Equipment Loans	268	0.06	268	0.08	268	0.07	250	0.07	250	0.07	250	0.07
Repairs and Maintenance	19	0.00	19	0.01	19	0.00	19	0.01	19	0.01	19	0.01
Taxes	669	0.15	669	0.20	669	0.17	531	0.14	531	0.15	531	0.14
Insurance	4	0.00	4	0.00	4	0.00	4	0.00	4	0.00	4	0.00
Total Fixed Costs	3,916	0.88	3,916	1.15	3,916	1.02	2,825	0.77	2,825	0.77	2,825	0.77

Total Costs	16,835	3.79	15,855	4.66	16,345	4.22	13,872	3.78	15,787	4.32	14,829	4.05
Net Return Above all Costs	-5,955	-1.34	-7,519	-2.21	-6,737	-1.77	-4,849	-1.32	-6,829	-1.87	-5,839	-1.59

Some columns of number may not add up as presented due to integer rounding

Table 2.9 Summarized economic and accounting profit of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in four 0.4 ha In-Pond Raceway Systems IPRS, in the first year of production (values in U.S.$).

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average Raceway 1 and 2	Raceway 3 45 m^3	Raceway 4 45 m^3	Average Raceway 3 and 4
Economic Profit						
Net return above all costs, $	-1,380	-931	-1,156	-290	-483	-387
- $/kg	-0.22	-0.14	-0.18	-0.05	-0.09	-0.07
Total cost, $/kg	2.67	2.60	2.64	2.51	2.55	2.53
Accounting Profit						
EBITDA[a], $	4,878	5,331	5,104	4,721	4,533	4,627
- $/kg	0.76	0.81	0.79	0.86	0.83	0.84
Total cost, $/kg	1.69	1.65	1.67	1.60	1.63	1.61

[a]EBITDA - earnings before interest, taxes, depreciation, amortization and is a measure of system performance

Table 2.10 Summarized economic and accounting profit of Channel Catfish (*I. punctatus*) raised in four 0.4 ha In-Pond Raceway Systems IPRS, in the second year of production (values in U.S.$).

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average Raceway 1 and 2	Raceway 3 45 m^3	Raceway 4 45 m^3	Average Raceway 3 and 4
Economic Profit						
Net return above all costs, $	-5,955	-7519	-6,737	-4,849	-6,829	-5,839
- $/kg	-1.34	-2.21	-1.77	-1.32	-1.87	-1.59
Total cost, $/kg	3.79	4.66	4.22	3.78	4.32	4.05
Accounting Profit						
EBITDA[a], $	-409	-2,013	-1,211	-332	-2,235	-1,283
- $/kg	-0.09	-0.59	-0.34	-0.09	-0.61	-0.35
Total cost, $/kg	2.54	3.04	2.79	2.55	3.06	2.80

[a]EBITDA - earnings before interest, taxes, depreciation, amortization and is a measure of system performance

Table 2.11 Indicators of the economic feasibility* of investments on farming of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) in IPRS in year 1.

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average Raceway 1 and 2	Raceway 3 45 m^3	Raceway 4 45 m^3	Average Raceway 3 and 4
Payback period, year	3.8	3.0	3.4	0.9	1.0	1.0
Net present value, U.S.$	30,579	47,574	39,007	96,252	89,187	92,720
Internal rate of return, %	18.0	23.2	20.6	60.3	57.8	59.0

*Using a discount rate of 5%

Table 2.12 Effects of varying levels of average feed and fish selling prices on net return above all expenses of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in 63 m^3 and 45 m^3 In-Pond Raceway Systems IPRS, in the first year of production.

	Raceway 1 and 2 63 m^3					Raceway 3 and 4 45 m^3				
	Fish selling price, $/kg					Fish selling price, $/kg				
Feed price $/MT	-20% (1.97)	-10% (2.21)	Base (2.46)	+10% (2.70)	+20% (2.95)	-20% (1.97)	-10% (2.21)	Base (2.46)	+10% (2.70)	+20% (2.95)
300	(3,027)	(1,433)	162	1,756	3,350	(2,005)	(658)	689	2,037	3,384
350	(3,535)	(1,941)	(346)	1,269	2,842	(2,420)	(1,072)	274	1,622	2,970
400	(4,043)	(2,449)	(854)	740	2,334	(2,834)	(1,487)	(141)	1,208	2,555
430	(4,345)	(2,750)	(1,156)	438	2,033	(3,081)	(1,733)	(387)	961	2,309
450	(4,551)	(2,957)	(1,362)	232	1,826	(3,249)	(1,902)	(555)	793	2,140
500	(5,059)	(3,465)	(1,870)	(276)	1,319	(3,664)	(2,316)	(970)	378	1,726
550	(5,567)	(3,973)	(2,378)	(784)	811	(4,078)	(2,731)	(1,385)	(36)	1,311
600	(6,075)	(4,481)	(2,886)	(1,292)	303	(4,493)	(3,146)	(1,799)	(451)	896

Shaded cells represent positive net returns.

Table 2.13 Effect of reducing the IPRS construction investment by 66% on the economic indicators of feasibility of hybrid Catfish using the 63 m^3 IPRS in year 1, each assembled in a 0.4-ha pond, (values in U.S.$).

Financial Indicators	Average Raceway 1 and 2 63 m^3	
	Original investment $396/$m^3$	Reduced investment $133/$m^3$
Investment cost, U.S.$		
Raceway cost	25,000	8,400
Other cost	9,308	9,570
Total	34,570	17,970
Payback period, year	3.4	1.5
Net present value, $	39,007	66,053
Internal rate of return, %	20.6	42.7

*Using a discount rate of 5%. Reduction of raceway construction material costs by 66% was calculated based on the less expensive material used on the smaller raceway.

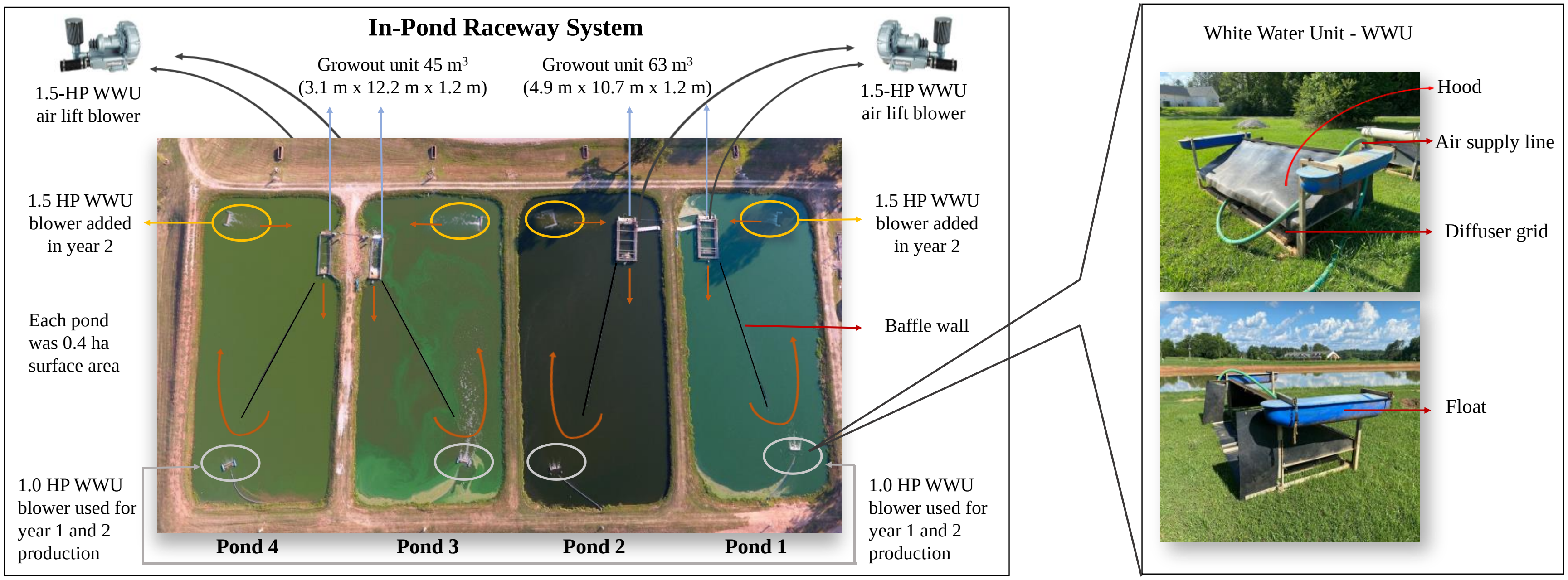


Figure 2.1 Aerial view of the four 0.4 ha ponds including the four IPRS units. Raceways RW1 and RW2 (63 m^3) were larger than raceways RW3 and RW4 (45 m^3). In each pond, a fabric curtain, called a baffle "wall", extended from the IPRS outflow to at least 2/3 of the distance of the pond diagonal, reaching from the pond bottom to just above water level and was suspended by floats. The curtain guided water circulation around the pond and toward a second and third White Water Unit devices (WWU) before re-entering the IPRS unit's fish growth area. Original aerial photo by David Cline.

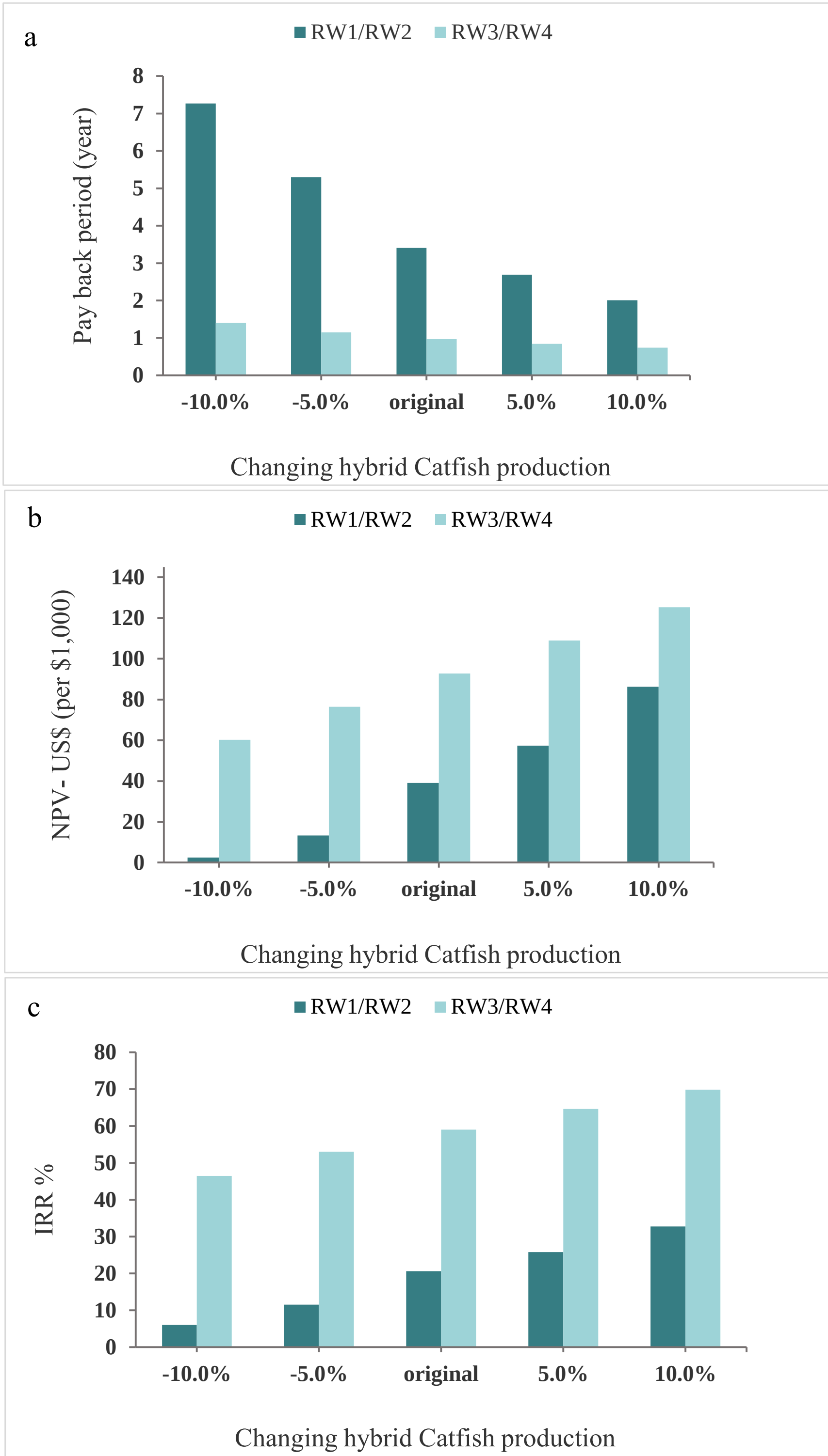
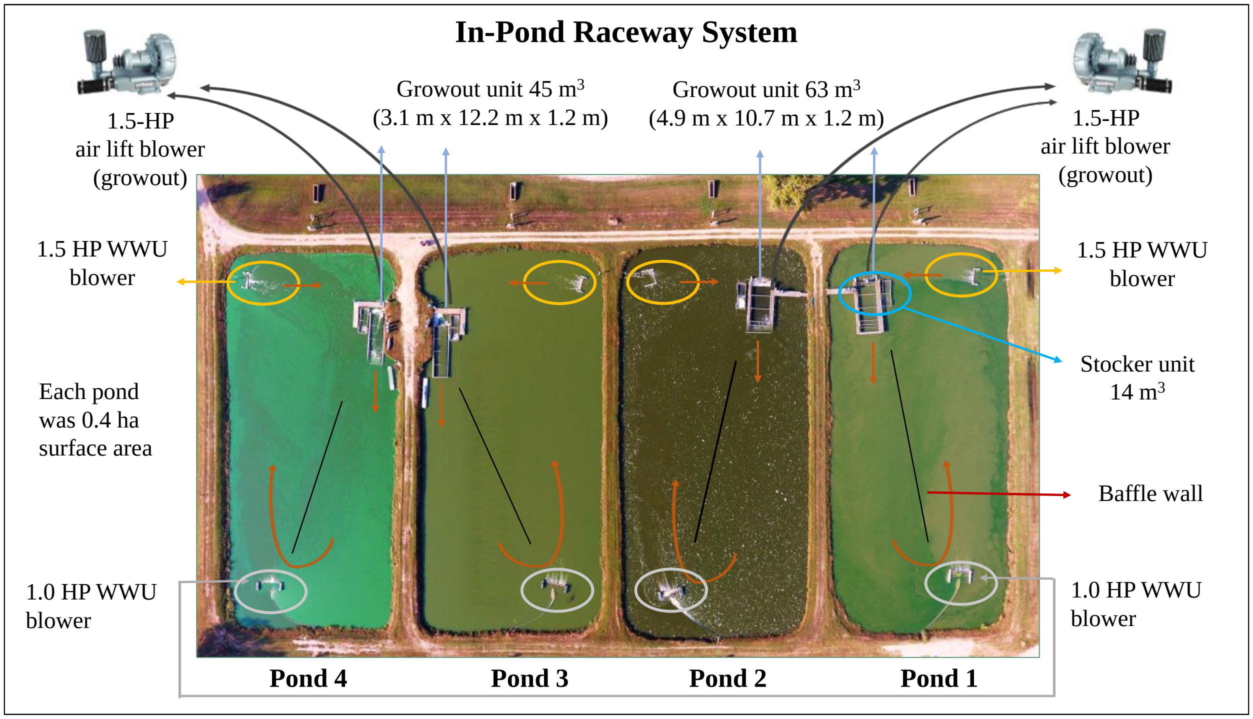


Figure 2.2 Effect of changing production (-10%, -5.0%, +5.0%, and +10.0%) from the original production obtained in year 1 of growing hybrid Catfish in the IPRS on a) Pay back period (year), b) Net present value (NPV) and c) Internal rate of return (IRR). *A discount rate of 5% was used.



Chapter 3.

Bioeconomic analysis of In-Pond Raceway System production of foodsize and stocker hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂)

Fantini-Hoag, L. Hanson, T. Chappell, J. Bioeconomic analysis of In-Pond Raceway System production of foodsize and stocker hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂). Under Review at Plos One (Submitted on October 21, 2021).

Abstract

The U.S. catfish industry is seeking production systems that are efficient, intensive and profitable. Growing foodsize and stocker-sized fish in the same pond is attractive as it is often difficult to obtain larger sized stockers early each year. This case study evaluated the performance and economics of producing foodsize hybrid Catfish and stocker sized fingerlings in In-Pond Raceway Systems (IPRS) placed into four 0.4 ha ponds. Growout raceways (RW1/RW2) in ponds 1 and 2 were 63 m^3, and 45 m^3 in ponds 3 and 4 (RW3/RW4). Each pond had one (14 m^3) stocker unit raceway. Each pond had 5.0 HP of aeration that maintained adequate DO levels. Average growout production was 12,050 kg/ha in 63 m^3 raceways and 12,078 kg/ha in 45 m^3 raceways. Average harvest weights ranged from 564 to 661 g (228 days of production) with feed conversion ratios (FCR) and survival rates of 1.72 and 90.7% (RW1/RW2); and 1.67 and 91.6% (RW3/RW4), respectively. Raceway stocker unit had production yields ranging from 3,537 to 4,388 kg/ha (143 days of production) and achieved harvest weights ranging from 123 to 234 g, with survival of 84.6% and FCR of 1.67 registered for stocker units RW1/RW2; and survival of 76.5 % and FCR of 1.70 for stocker units RW3/RW4. Stocker units in ponds 1 and 2 generated 8,540 stocker-fingerlings (21,102 fingerlings/ha) and units in ponds 3 and 4 generated 7,954 fingerlings (19,654 fingerlings/ha). An investment of $39,996 was needed for ponds 1 and 2 and $21,196 for ponds 3 and 4. When scenarios were analyzed financially, positive financial net returns occurred when farm level investment decreased, leading to reduced payback periods, increased net present values, and higher internal rates of return. IPRS used stocker units to culture fingerlings for future stocking of foodsize fish. IPRS provided good inventory control, and high production yields compared to traditional pond culture of catfish.

Keywords: enterprise budgeting, high density, profitability, sensitivity analysis, white water units

3.1 Introduction

Estimated freshwater and marine aquaculture production in the United States (U.S.) was 309 thousand metric tons valued at $1.52 billion in 2018 (NMFS, 2021; USDA, 2019). Freshwater aquaculture production is primarily composed of catfish (159 thousand metric tons, 60%), crawfish (73 thousand metric ton, 27%), and trout (22 thousand metric tons, 8%) (NMFS, 2021). Channel Catfish (*Ictalurus punctatus*) and hybrid Catfish (Channel Catfish *I. punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) production represents 53% and 47%, respectively, of the total U.S. catfish production (Hegde et al., 2021). Farm-raised catfish processed in the U.S. from 2011 to 2019 has remained relatively stable within a range of 74 to 77 thousand metric tons (Hanson, 2020). The three major producing states, Alabama, Arkansas, and Mississippi produced 137 thousand metric ton (93% of all catfish produced in the U.S. in 2020) (USDA, 2021) down 7 percent from 2019 (USDA, 2020).

The dynamics and drivers of the various periods of growth, contraction, and recovery of catfish production offer important lessons for other segments of U.S. and global aquaculture (Engle et al., 2021a). Numerous innovations in the aquaculture sector have been credited to the U.S. catfish industry, including improved aeration technologies (Boyd et al., 2018), production systems and practices, genetic improvement, and nutritionally balanced feed formulations (Kumar et al., 2018). The U.S. catfish industry is one of the few industries that has successfully navigated the treacherous and often painful causeway of a maturing industry. Regardless, fish farmers continue to face problems with high production costs relative to sales price (i.e. low profit margin). High costs occur because fish managed in traditional ponds experience predation by birds (Engle et al., 2021b), expensive disease treatments (Peterman and Posadas, 2019; Kumar and Gaunt, 2020), inefficient feed conversions (Wu et al., 2004), and difficulty in knowing and controlling fish inventories (Engle and Valderrama, 2001; Kumar et al., 2021c). There is a continued need for the U.S. catfish industry to develop and adopt more efficient and profitable production technologies.

Economists engage with farmers to understand the on-farm realities and base economic research on data collected from farms, research verification trials, and pond production trials, rather than models based on hypothetical situations and assumptions. This is essential to provide adequate information for farmers to make good decisions on technologies and management that will work best on their farms (Kaliba and Engle, 2005; Bott et al., 2015; Engle et al., 2021b; Hanson et al., 2020). Therefore, more-efficient production technologies for raising Catfish are needed to improve economic viability (Kaliba et al., 2007; Brown et al., 2010).

The use of In-Pond Raceway Systems (IPRS) allow for more control of the production cycle by confining cultured fish into a smaller volume of water compared to a traditional pond and facilitates feeding, chemical treatment, and inventory control, but can also compound risks due to high biomass densities involved (Roy and Brown, 2016). Catfish farming must become more efficient to remain profitable and sustainable. The IPRS approach presented herein intensifies catfish production by growing two products in the same pond in two raceways in an effort to reduce production costs and increase profits. The goal of this descriptive case study was to evaluate the growth performance and economic efficiency of two sizes of IPRS units using two stocking density approaches raising stocker and foodsize hybrid Catfish (Channel Catfish, *Ictalurus punctatus*, ♀ x Blue Catfish, *I. furcatus*, ♂) in IPRS units.

3.2 Material and Methods

3.2.1 Performance Analysis

For this bioeconomic evaluation of the IPRS system, an experiment was conducted in four 0.4 ha ponds totaling 1.6 ha water area at the E.W. Shell Fisheries Center, Auburn, Alabama, U.S.

Hybrid Catfish fingerlings were obtained from a commercial supplier in Mississippi (Jubilee Farms, Indianola, Mississippi). For the trials, four larger floating IPRS units were placed into each of four 0.4 ha ponds (designated RW1, RW2, RW3 and RW4), with each growing fingerling fish to foodsize. These raceways will be referred to as 'growout' raceways. The growout IPRS raceways in ponds 1 (RW1) and 2 (RW2) were 63 m^3 (4.9 m wide, 10.7 m long and 1.2 m water depth), and in ponds 3 (RW3) and 4 (RW4) were 45 m^3 (3.1 m wide; 12.2 m long and 1.2 m water depth). An additional "stocker unit", a smaller floating IPRS unit 14 m^3 (1.8 m x 5.8 m x 1.30 m) was placed into each of four 0.4 ha ponds next to the growout units, and will be referred to herein as 'stocker' units or raceways. Each pond was rectangular with dimensions of 120.7 m long × 33.5 m wide × 1.2 to 2.0 m water deep. In total, the RW1/RW2 and RW3/RW4 plus stocker units represented 1.5% and 1.2% of the 0.4 ha pond surface area, respectively.

Each pond had a total of 5.0 HP for aeration (12 HP/ha), water flow and mixing through White Water Units (WWU) (Figure 3.1). One 1.5 HP WWU blower propelled the airlift apparatus at the entrance of the larger growout RW. One additional 1.5 HP WWU blower unit was placed in each pond corner perpendicularly from the IPRS unit and diagonally from the growout IPRS unit to sustain water movement, destratify the water column and increase the water oxygen level. Additionally, one 1.0 HP WWU blower propelled water in the pond and one 1.0 HP WWU blower propelled the airlift apparatus at the entrance of the smaller stocker unit RW. A 55 m long and 1.5 m high baffle fence or "curtain" made of woven plastic fiber was installed diagonally inside each pond to direct the water circulation around the entire pond (Figure 3.1).

Dissolved oxygen, temperature (YSI Pro 20i) and pH (YSI EcoSense^R pH 10A) were measured twice a day, at 8 am and 4 pm. Other pond water parameters (total ammonia, chloride,

CO_2, nitrite, secchi disk, alkalinity and hardness were monitored twice a month using a Lamotte water quality test kit.

Hybrid Catfish, mean weight 31 g, were stocked into growout IPRS units in April 2018 and in the "stocker unit", 29 g hybrid fingerlings were stocked in July 2018. Hybrids Catfish were fed a 32% crude protein floating commercial catfish pellet (4 to 6 mm) for 228 days (growout) and 143 days (stocker). Fish were fed twice a day depending upon water temperature. Each feeding event lasted for 5 to 10 minutes, until near satiation of fish was reached.

We hypothesized that stocking similar numbers of fish in either larger or smaller growout raceway units would result in a similar production level, on a per hectare basis. Thus, RW1 and RW2 (63 m^3) were each stocked with 8,686 fish, a stocking density of 138 fish/m^3 or 4.29 kg/m^3. This is equivalent to 21,462 fish/ha. RW3 and RW4 (45 m^3) were each stocked with 8,597 fish, a stocking density of 191 fish/m^3 or 6.03 kg/m^3. This is equivalent to 21,244 fish/ha.

Total biomass produced was recorded for each raceway unit (total weight harvested at the end of the production cycle) and used to calculate biomass gain by subtracting the total weight stocked from the total harvested weight. Net feed conversion ratio (Net FCR) for each raceway was calculated by dividing the amount of feed fed by biomass gained for each unit. Weight gain per day was calculated by dividing the individual weight gain in grams by the total number of production days. Yield, as kg/ha, was determined by the total biomass of catfish harvested per raceway divided by the pond area. Net yield, as kg/ha, was determined by dividing the total biomass gain of catfish in each raceway by the pond area. Survival percentage was determined by the number of fish harvested divided by the number of fish stocked x100.

3.2.2 Economic Analysis

Enterprise budgets were developed for each growout and stocker raceway unit in a pond using standard farm management procedures (Engle, 2010; Kay et al., 2020). This included accounting for variable and fixed associated with production from 228 days of field data. Receipts, variable and fixed costs were calculated separately for each raceway unit (growout and/or stocker IPRS units) using their respective data on production for each production cycle (228 days for growout and 143 days for stocker units). Quantities sold and variable inputs were multiplied by their respective prices (Table 3.1).

Profitability metrics calculated from developed enterprise budgets included net returns above variable and fixed costs. Net return is an economic measure of profitability, as it includes cash and non-cash costs such as depreciation and any unpaid or in-kind payments. It is a measure of long-term profitability. The income above variable cost measure was calculated by subtracting total variable costs from total receipts and is an indicator of whether the business can continue to operate in the short-run. If all cash (variable) costs can be paid, then the operation can continue to operate (produce fish). The breakeven selling price ($/kg, or cost of production) is the minimum price one needs to receive to cover all variable and fixed costs. It was calculated by dividing the total cost (variable + fixed costs) by the quantity of fish harvested. The breakeven yield (kg) is the quantity of fish needed to be produced to breakeven, assuming the selling price remains constant. It was calculated by dividing the total costs by the selling price.

An accounting approach to profitability was also used to show only cash expenditures and excluded fixed costs. Cash flow analyses were conducted through development of a ten-year cash flow for each pond IPRS system. They were developed from the enterprise budgets to evaluate each system’s performance. This approach is similar to the EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) approach that only includes cash expenditures and excludes fixed costs (Hall, 2021). The EBITDA metric is a way to adjust for factors that can differ from one company to the next. For instance, when existing farm businesses already own the land, have ponds, electrical lines, and much of the required machinery and equipment, then using an accounting profitability would be the correct method for comparing alternatives. Cash flows allowed calculation of net present value (NPV), internal rate of return (IRR) and payback period (years).

Net present value takes into account the time value of money and converts a stream of cash flows over the entire life of the investment back to a single present value using a discount rate (Shaner, 1979; Gallo, 2014; Kay et al., 2020). Spreadsheet software, such as Excel, have functions to calculate NPV using a discount rate (we used 5.0%), an initial investment (Table 3.2), and the annual net return values for years 1 through 10, including replacement of equipment and machinery items as they wore out. A positive NPV means the system is a good investment opportunity, though care must be taken in only using this as the sole decision criterion, as other factors, such as the magnitude of the investment involved and potential risks need to be included in the decision process.

The IRR is similar to the NPV, but it equates NPV to zero and solves for the discount rate percentage (Shaner, 1979; Kay et al., 2020). Again, spreadsheet softwares have functions that calculate this using the initial investment and the series of annual net returns from year 1 to year 10. IRR is often used when comparing alternative investment opportunities or for comparing to other returns an investor might make in savings accounts or rate of return for another investment. The payback period is calculated by dividing the initial investment by the average annual net return from the ten-year cash flow. This provides an idea of how long it might take to pay off the initial investment given steady annual returns (Shaner, 1979; Kay et al., 2020).

3.2.3 Sensitivity Analyses

A series of sensitivity analyses were conducted based on required aquaculture investment levels for varying initial situations (scenarios) of an operation and varying fish/feed price changes on each scenario's net return. These were done to avoid overly optimistic enterprise budgets and misleading results (Engle, 2010). Four scenarios were developed. Scenario 1 represented a new aquaculture operation, requiring land purchase, pond construction, electricity, water supply, and purchase of all necessary aquaculture farm machinery and equipment. This is the base scenario to which other scenarios will be compared. Scenario 2 represented the situation in Scenario 1, except the land is already owned. Scenario 3 represented the situation in Scenario 2 but 80% of the aquaculture farm machinery and equipment was already purchased and available. Scenario 4 represented the situation in Scenario 3 with only some very specific IPRS raceway components needing to be purchased. All scenarios included separate analyses for large raceways (RW1/RW2 + stocker units) and small raceways (RW3/RW4 + stocker units).

Using the four investment scenarios, a three-way sensitivity analysis combining changes in feed and fish prices for the four scenarios with net return as the profitability metric was calculated. A base weighted average fish-selling price was calculated according to the differing prices received and quantities produced of small- and premium-sized fish. Both ponds with large raceways (RW1/RW2 + stocker unit) and with small raceways (RW3/RW4 + stocker units) had a weighted average selling price of \$2.44/kg (base). The sensitivity analysis was performed by decreasing and increasing the base price by 10 and 20 percent. Resulting fish selling prices used in this sensitivity analysis were \$1.95, \$2.19, \$2.44 (base), \$2.44, \$2.85, and \$2.92/kg. Feed prices used in this sensitivity analysis were \$370, \$400, \$430, \$460, and \$490/MT.

A second sensitivity analysis used the same four scenarios described above and their effect on net returns, initial investment cost, payback period, net present value, and internal rate of return.

RW1/RW2 was constructed using stainless steel, a very expensive material, whereas RW3/RW4 were constructed of much less expensive materials of wood, HDPE vinyl plastic, and wire grates. Thus, this sensitivity analysis investigated the economic effect when the less expensive RW materials were used in constructing the larger sized raceways. We substituted the less expensive RW materials used in RW3/RW4 (wood and wire) for the more expensive materials used in RW1/RW2 (stainless steel) for the 63 m^3 raceway construction. Initially, the raceway units placed into ponds 1 and 2 had a construction cost of $25,000 per RW unit (or $396 per m^3) and the raceway units placed into ponds 3 and 4 had a construction cost of $6,000 per unit (or $133 per m^3). When the less expensive materials were substituted in, the $133 per m^3 construction cost was substituted in for the larger 63 m^3 raceways $396 per m^3 cost. The re-calculated construction cost for RW1/RW2 would now be $8,400 per RW unit for the 63 m^3 raceway ($133 per m^3), a 66% reduction in RW construction costs due to use of the less expensive materials.

3.3 Results

3.3.1 Water Quality

Water quality measurements during production cycles raising stocker and foodsize hybrid Catfish in IPRS units were within acceptable ranges throughout the study (Table 3.3). The stocking density used in these trials required backup generators be in place and ready for use in case of electrical failure, though none occurred during this study. A total of 5.0 HP (horsepower) of aeration per pond (white water unit WWU) was enough to maintain dissolved oxygen (DO) levels in the ponds and inside of the raceways above minimum DO levels. The WWUs created dynamic water flows and mixed water columns that, combined with efficient, plentiful aeration, managed DO levels at the pond bottoms and surface waters well, and promoted efficient biological oxidation of fish and feed wastes.

Some spikes in afternoon pH (9.5) and toxic ammonia (2.1 mg/L) were observed infrequently. Likewise, some early morning low DO levels (below 3 mg/L) inside the raceways during the summer period were observed. Pond DO concentrations in the early morning hours were higher during the Spring (April and May) and Fall (October and November) months, but lower during Summer (June to September) months (Figure 3.2 and 3.3). This is normal for fish production in traditional and IPRS systems stocked at high densities. Dissolved oxygen inside the raceways rarely fell below 3 mg/L in ponds 1, 2 and 3, with the exception of pond 4, which had an average of 2.76 mg/L in the pond and 3.03 mg/L inside of the raceway at one point in the summer months. Pond 4 also had the lowest Secchi disk transparency measurement (0.18-0.28 m) resulting from heavy phytoplankton blooms. Even though DO concentrations were low during summer in pond 4, no fish mortalities occurred.

Water temperature changed markedly by season and varied from 23.8 to 27.0 ºC during spring months, 29.8 to 30.1 ºC during summer months, and 23.8 to 24.0 ºC during fall months. These temperature ranges allow hybrid Catfish to grow well during late spring, all summer and into early Fall. Total alkalinity in study ponds ranged from 60 to 110 ppm/$CaCo_3$ and hardness ranged from 45 to 90 ppm/$CaCo_3$. Pond chloride concentrations ranged from 120 to 480 ppm followed by very lower levels of nitrite (maximum level of 0.8 NO_2^- mg/L on pond 4).

3.3.2 Fish Performance

The fish stocking density for the growout foodsize system resulted in yields of 12,050 kg/ha and 12,078 kg/ha, respectively (Table 3.4). Average harvest weight for the growout raceways ranged from 564 to 661 g (228 days of production) with a weight gain per day of 2.55 g for both groups RW1/RW2 and RW3/RW4. Excellent feed conversion ratios (FCR) and high survival rates were registered for foodsize hybrid Catfish, at 1.72 and 90.7% for RW1/RW2 and 1.67 and 91.6% for RW3/RW4 respectively.

Stocker unit raceway yields ranged from 3,537 to 4,388 kg/ha (143 days of production) and achieved harvest weights ranging from 123 to 234 g (Table 3.5). In the RW1/RW2 stocker unit there was a survival rate of 84.6% and a FCR of 1.67, and in RW3/RW4 stocker unit there was a survival rate of 76.5% and a FCR of 1.70. In each case, the stocker unit harvested enough stockers to start a new production cycle. Stocker units 1 and 2 generated 8,540 stocker-fingerlings (21,102 fingerlings/ha) and units 3 and 4 generated 7,954 fingerlings (19,654 fingerlings/ha) which is similar to our stocking density for the growout units at the beginning of these trials. In total, there were 32,988 stocker fish harvested and when divided into four, there would be an average of 8,247 fingerlings available per RW in the next production cycle. Combining foodsize fish plus stocker-fingerling biomass, the total harvest weight per pond ranged from 14,500 kg/ha to 17,581 kg/ha.

3.3.3 Economic Analysis

Investment was computed for the raceway growout and stocker units in each 0.4 ha pond (Table 3.2). The investment necessary for each pond having a 63 m^3 growout raceway plus a 14 m^3 stocker unit raceway was $39,996. For ponds having a 45 m^3 growout raceway plus a 14 m^3 stocker raceway, the investment was $21,196. The investment difference was due to the raceway size difference, costlier raceway materials, and more robust, larger boardwalks. A single larger growout raceway unit (63 m^3) cost $25,000[1] to manufacture by a private welding company and used aluminum for its frame and walkways, and high-density polyethylene (HDPE) materials for

[1] Larger growout raceway unit (63 m^3): 20 years of useful life, 20% salvage value and 3% of initial cost for annual maintenance, variable repair and maintenance cost was $25/month.

its liner. A smaller growout raceway unit (45 m^3) cost $6,000[2] was constructed in-house with wood, wire and HDPE materials. All stocker raceway units (14 m^3) cost $1,867 and were constructed using wood, wire and HDPE materials.

Capital items represented 74% ($29,403) of the total investment for ponds 1 and 2, but only 49% (10,403) for ponds 3 and 4 (Table 3.2). Ponds 1 and 2 housed larger growout raceways and were 25% higher than in ponds 3 and 4. Machinery and equipment comprised 26% ($10,593) of the cost for larger growout-stocker raceway set up and 51% ($10,593) of the smaller growout-stockers raceway set up. Depreciation on capital, machinery and equipment items was $1,410 for the larger growout units and $1,030 for the smaller growout units (Table 3.6), plus $612 for the stocker units in ponds 1 and 2 and $618 for those units in ponds 3 and 4 (Table 3.7). Average fixed costs were $3,461 for large growout units (63 m^3) and $2,249 for small growout units (45 m^3). Average fixed costs were $1,477 for stocker units in ponds 1 and 2, and $1,488 for stocker units in ponds 3 and 4. Differences were due to fixed interest and depreciation cost calculations on machinery and equipment (boardwalks size and prices were slightly different) and repairs and maintenance were based on each raceway production.

Income above variable cost results were positive for all growout RW sizes, indicating the business should continue to produce foodsize fish as all cash (variable) costs were covered or paid (Table 3.6). On the other hand, income above variable costs for each stocker unit was negative for all stocker RWs, indicating that stocker production should cease, as money is being lost for every additional kg of stocker fish produced. This result is according to our stocker pricing and valuation method, which could be imperfect, as stockers are not normally sold because their size precludes shipping many fish at a time for long distances, as they can for fingerlings. Net returns above all

[2] Smaller growout raceway unit (45 m^3): 10 years of useful life, 5% salvage value and 5% of initial cost for annual maintenance, variable repair and maintenance was $50/month.

costs were negative for all growout units, except for RW3, which had a positive net return, $1,198. When enterprise budgets were combined (growout plus stocker units) all net returns above variable costs were positive ranging from $933 to $3,505 (Table 3.8), but negative when fixed costs were included ($-4,004 to $-231).

The breakeven fish selling price range to cover all costs ranged from $2.23 to $2.89/kg for foodsize fish and from $3.22 to $3.82/kg for stocker fish (Table 3.6 and 3.7 respectively, see total cost/kg cells). As the price paid to producers by processing plants ranged from $2.40 to 2.45/kg, economic losses occurred in all growout pond units, except in pond 3. The lowest total costs to produce foodsize catfish was $2.23/kg and for stocker-fingerlings was $3.22/kg in pond 3, in which the raceways had the higher survival rates and lowest FCR of any other raceways. Accounting profits for growout IPRS ranged from $2,682 to $4,920 per raceway (Table 3.9). With the exception of negative accounting profits in the pond 1 stocker unit (-$70), accounting results for the other three stocker raceway units had positive net returns, ranging from $53 to $545 (Table 3.10).

Breakeven yield for RW1/RW2 was 5,405 kg and the actual harvest was 4,820 kg which was 585 kg less yield than needed to breakeven economically; and for RW3/RW4 the breakeven yield was 4,871 kg and the actual harvest was 4,831 kg, which was 40 kg less than the yield needed to breakeven economically. The breakeven yield for the RW1/RW2 stocker unit was 2,296 kg and the actual harvest was 1,562 kg which was 734 kg less yield than needed to breakeven economically; and for the RW3/RW4 stocker unit the breakeven yield was 2,378 kg and the actual harvest was 1,679 kg, which was 699 kg less than the yield needed to breakeven economically. Foodsize and stocker production needs to be targeted to meet these breakeven yields.

3.3.4 Sensitivity Analyses

The first sensitivity analysis investigated different required IPRS investment levels according to existing farm situations, going from beginning an aquaculture farm to a fully functional aquaculture operation (Table 3.11). Raceway component purchases were required for all scenarios. Scenario 1 investment for ponds with 63 m^3 growout plus 14 m^3 stocker units was \$39,996, and \$21,196 for 45 m^3 growout plus 14 m^3 stocker units. Scenario 2 had an investment of \$39,010 for large growout plus stocker units and \$20,210 for the small growout plus stocker units. Scenario 3 had an investment of \$36,839 for large growout plus stocker units, and \$17,879 for small growout plus stocker units. The least expensive investment occurred in scenario 4 in the case where only raceway components were purchased (\$34,747 for large growout plus stocker units and \$15,747 for smaller growout raceway plus stocker units). Itemized investment requirements for the four scenarios are shown in Table 3.11.

The effect of the four investment scenarios and varying feed and fish prices produced a matrix of net returns with some positive and negative values (Table 3.12). The worse case scenario, that is the lowest net returns, always occurred in scenario 1 where the business needed a full initial investment to get the farm and IPRS system up and running regardless of fish or feed price. The best-case scenarios, that is, the highest net returns always occurred in scenario 4 where the primary investments were lowest and only for growout and stocker IPRS units and their associated components (Table 3.12). Highlighted cells in Table 3.12 indicate positive net returns under different feed and fish prices and scenarios 1 through 4. In RW1/RW2 raceways, feed prices would need to decrease by \$30/MT to \$400/MT (from the base feed price of \$430/MT) and fish selling price would need to increase by \$0.48/kg (+20%) to \$2.92/kg (from the base fish selling price of \$2.44/kg) for net returns to be positive for scenarios 1 (\$523), and even higher net returns for scenarios 2, 3 and 4. However, in scenario 1 for RW3/RW4 at average prices (feed price =

$430/MT and fish selling price = $2.44/kg), a 20% increase in fish selling price (to $2.92/kg) is required to have a positive net return ($1,351), and even higher net returns resulted for scenarios 2, 3, and 4 at these prices. Alternatively, at the same +20% fish price, a decrease in feed price by $30/MT (to $400/MT) also led to a positive net return for scenario 1 ($1,644), and higher returns for scenarios 2, 3, and 4.

Profitability measurements stemming from the cash flow analysis showed the highest NPV (Table 3.13) was realized in the smaller raceway combinations (45 m^3 growout + stocker) where lower investment was required, that is when land and most aquaculture farm equipment was already owned and appropriately configured ponds existed, that is in scenario 4. In the large raceway combinations (63 m^3 + stocker), the NPV remained negative, even in the best-case scenario, ranging from $-26,939 in scenario 1 to $-21,649 in scenario 4. In the small raceway combinations (45 m^3 + stocker), NPV values ranged from $34,797 (scenario 1) to $53,424 (scenario 4), and likewise for the IRR values that increased from 28.6% to 45.0%. Longer PBPs were found for the large raceway combinations (RW1/RW2) compared to smaller raceway combinations (RW3/RW4) with a reduction from 28.1 years to 2.7 years for scenario 1, respectively. This showed the large impact of higher initial investment for RW1/RW2 and their negative net returns to the lower initial investment and positive net returns for RW3/RW4. Lower initial investment and positive net returns are crucial for profitability. Comparison of PBP for RW1/RW2 in scenario 1 (28.1 years) to RW1/RW2 in scenario 4 (23.8 years) showed how high initial investment combined with negative net returns could do little to reduce the payback period. For small raceways, when shifting from the base investment level (scenario 1) to a scenario 4, PBP was reduced from 2.7 years to 1.9 years.

The final sensitivity analysis investigated the effects of reducing IPRS growout raceway construction cost. (Note that the stocker unit IPRS unit cost in this analysis was not changed as they were built from the lower cost materials in all four cases.) After the per unit construction material cost for the smaller growout raceways, RW3/RW4 cost per m^3 was substituted in for the per unit costs for the larger growout raceways dimensions, the reduction in investment costs ranged from -58% to -52% over scenarios 1 to 4, respectively (Figure 3.4a) (Note, in Figures 3.4a, 3.4b, 3.5a and 3.5b, the dark blue legend is for RW3/RW4 which had the lower cost construction materials, and is included in Figures 3.4 and 3.5 as a reference for comparison to the original and reduced RW1/RW2 investment costs). Sensitivity results show payback periods were reduced from 28.1 years (original raceways cost in scenario 1) to 4.0 years (reduced raceway cost for scenario 1) and to 1.9 years (reduced raceway cost reduction for scenario 4) (Figure 3.4b).

Net present value (Figure 3.5a) and IRR values (Figure 3.5b) increased accordingly at the new investment cost over the four scenarios. Net present value shifted from $-26,938 when the original raceways cost for scenario 1 was used to a NPV of $19,484 at the reduced raceway cost for scenario 1. These results show the huge influence that material costs have on initial investments. Scenario 1 is the farm level where all land, pond construction, machinery and equipment for running an IPRS needs to be purchased and is the reason for the large difference in NPV values between the original and reduced investment costs. The best-case scenario (scenario 4) had a NPV of $42,834 compared to the scenario 1 NPV of $-26,938, which is an increase of 259% (Figure 3.5a). Internal rate of return percentages also shifted from -18.0% (original raceways cost for scenario 1) to +19.3% (reduced raceway cost for scenario 1 and RW1/RW2) and to 39.7% for the reduced raceway cost for scenario 4 and RW1/RW2 (Figure 3.5b).

3.4 Discussion

3.4.1 Water Quality

Water temperatures varied noticeably with season. Seasonal temperature variations occurred in this study and were similar to values reported by Boyd for the same location (Auburn, Alabama (Boyd, 2015). Higher temperatures occurred in the summer months (July to September). The combination of elevated total alkalinity, total hardness, and chloride concentrations was thought to have been beneficial for fish production and equated to a more balanced and stress-free rearing environment, preventing nitrite toxicity or methaemoglobinaemia, commonly known as "brown blood disease" (Brown et al., 2011). Note that in IPRS systems having high biomass densities, an emergency aeration system is required and must automatically turn on when electricity to WWUs goes off.

3.4.2 Fish Performance

Our study showed superior yields from IPRS systems (14,500 kg/ha to 17,581 kg/ha) compared to traditional earthen ponds average yields of 4,500 to 5,500 kg/ha (Brown et al., 2011) and 9,000 to 14,000 kg/ha (Bott et al., 2015; Kumar et al., 2019; Hanson et al., 2020). Also, IPRS yields here were superior to the study conducted by Roy in their fixed concrete IPRS cells which resulted in 7,800 kg/ha of hybrid Catfish harvested in their first cycle (10-12 months) and 6,195 kg/ha harvested in their second cycle (12-19 months) (Roy et al., 2019). In general, good results were found producing hybrid Catfish in the IPRS, with very low observed mortalities, demonstrating that IPRS has the potential to double or triple traditional catfish farm production. Other intensively aerator and split pond systems have similar yields as found in this IPRS study (Kumar et al., 2018).

When ponds were outside of the acceptable and desired water quality ranges, we saw the negative impacts on fish survival. Pond 4 had low dissolved oxygen ranges in early morning hours (also this pond had a visible phytoplankton bloom on the water surface throughout the cycle) which possibly resulted in a lower survival rate. Small fish consume more oxygen for a given total weight than larger fish and oxygen uptake increases as water temperature increases (Tucker and Robinson, 2002). An interesting fact was observed in this particular pond, where low survival was found (stocker unit in pond 4). Even after having low oxygen levels during the summer months, the fish caught up in terms of growth by the end of the cycle and had the highest final average weight (grams) than in other raceways. It could have been that the early fish losses actually promoted rapid weight gain (Torrans and Ott, 2019).

Harvest results showed similar average production for hybrids in raceways RW1/RW2 plus stocker units (15,279 kg/ha) and RW3/RW4 plus stocker units (15,597 kg/ha) while Brown et al. (2014) harvested 26,057 kg/ha of hybrid Catfish in their IPRS research. This suggests that we could increase the number of fish produced or extend the production cycle to harvest heavier fish (grams) in the 0.4 ha ponds. In fact, we still do not know the carrying capacity of a system of this size system in this pond size. A total biomass ranging of 72 to 117 kg/m^3 was produced in the growout units and 101 to 124 kg/m^3 for the stocker units in this study. Roy et al. (2019) produced a biomass that varied between 51 to 125 kg/m^{3}for hybrid Catfish and Brown et al. (2011) produced 55 to 199 kg/m^3 for Channel Catfish and 159 to 215 kg/m^3 for hybrids. Literature shows that different species have been produced in IPRS systems in China. For example, a 220 m^3 raceway with an associated waste collector was able to produce Bluntnose Black Bream (83 kg/m^3 or 5,288 kg/ha), Channel Catfish (67 kg/m^3 or 4,322 kg/ha), Yellow Catfish (55 kg/m^3 or 3,138 kg/ha) and Largemouth Bass (48 kg/m^3 or 2,603 kg/ha) (Wang et al., 2019).

3.4.3. Economic Analysis

To survive the short run, i.e., the current operating year, farm businesses must be able to sell fish at a price that is greater than its breakeven price above variable costs (Engle, 2012b). Engle (2012b) suggests calculating whether the farm can survive the short run by using the breakeven price above variable costs and comparing it to the price that the farmer actually receives or expects to receive. The difference would be the $/kg profitability margin. In our study, the breakeven price above variable cost was less than the selling price, indicating that the short-term profitability was positive at the income minus variable cost point in the enterprise budget. Net income above variable cost determines if an operation should continue to produce. Here the higher production led to greater receipts and improved the chance of being profitable (Engle, 2010), but greater production also means greater production costs. The breakeven price covering variable and fixed costs was greater than the price received, indicating that the long-term was not profitable under the current conditions. This was the case in all but one raceway, RW3, where the highest biomass (total harvest kg) and lowest FCR occurred.

Our research found production costs ranging from \$2.23 to \$2.89/kg, having profit margins ranging from \$+0.23 to \$-0.44/kg for the four foodsize catfish (Table 3.9); and production costs for the stocker units ranged from \$3.22 to \$3.82/kg, having profit margins ranging from \$+0.17 to \$-0.48/kg (Table 3.10). When the EBITA approach was used, the breakeven price decreased and resulted in profit margins ranging from \$0.52 to \$0.93/kg for foodsize (Table 3.9) and \$0.55 to \$0.88/kg for stocker catfish (Table 3.10). As can be seen, production costs for stockers were higher than for foodsize fish in both approaches (economic and EBITDA). With a lack of information on stocker selling prices we decided to use foodfish prices for stockers grown in the stocker unit raceways. Ninety percent of produced stockers were within the small fish size category (<0.454 kg) which received a selling price of \$2.40/kg from processers for this size category. Usually, fingerlings are sold by length, up to a maximum of 23 cm (104 g), and not by weight. Our stockers from the fingerling to stocker unit had an average weight of 120 g (25 cm) and thus were valued by weight instead of length. These stockers are too large for hatcheries to transport easily and would require more technical skills and oxygen. On the other hand, it is easy to harvest them from our stocker unit and restock (transfer, split) them into the growout raceway located next to each other in the pond.

Breakeven yields for RW1/RW2 could be achieved only if we ran the trial for another 47 days (hypothetically) to achieve the breakeven yield required to be economically profitable. In this case, fish would conceivably gain more weight (2.55 g/day). Analyzing this result, it seems like we should have stocked these larger raceways (RW1/RW2) more heavily compared with the growout small raceways. Breakeven yields in RW3/RW4 could easily surpass the actual yields by increasing survival by less than 1% or by increasing production days by four (hypothetically). To be able to achieve breakeven yields in the stocker units, we would also need to stock at a higher density or by extending the production cycle by 85 days for RW1/RW2 and 75 days for RW3/RW4 (hypothetically).

A recent multi-state survey of the U.S. catfish industry (Alabama, Arkansas, and Mississippi) was conducted to identify specific reasons influencing the decisions of producers to adopt or not adopt alternative catfish production technologies (intensive-aeration, in-pond raceways, or split-pond systems) (Kumar et al., 2020a). High yield and greater control over the production process were the major reasons for the adoption of alternative catfish production technologies. Early adopters had significantly larger farms, greater numbers of ponds, and significantly greater percentages of hybrid Catfish use. The primary reason for the adoption of alternative-production technologies was “to achieve higher yields”. Our research shows IPRS can achieve higher yields in pilot scale IPRS. The most-cited reason for non-adopters having no plans to adopt alternative-production technologies in the future was “high investment cost” (Kumar et al., 2020a). Thus, it is important to investigate using less expensive IPRS building materials.

During the research period, fish prices ($/kg) were not very attractive making the IPRS system unprofitable. Our sensitivity analyses changing fish and feed prices showed interesting results and could address uncertainties that farmers have about IPRS systems being unprofitable and hinder their future adoption of this system. The sensitivity analysis (Table 3.12) demonstrated that there were price combinations that made the IPRS profitable and by how much. Additionally, the sensitivity analysis included different farmer situations, from absolute beginner to advanced aquaculture operations (Table 3.12). Such analyses were conducted to avoid overly optimistic net returns and potentially misleading results to those investigating this new technology (Engle, 2010).

The farmer can view prices they face currently and their farm investment level when considering this new technology to see if it would be profitable or not for their situation. In fact, fish selling prices have increased to $2.88/kg in August 2021, an increase of $0.44 per kg, from the prices used when this study occurred in 2018. Unfortunately, feed prices have increased as well, from $430/MT used in the study to $490/MT currently. Prices are dynamic and can change due to fish demand, supply of feed ingredients, and other supply chain issues such as covid-19 (Hanson, 2021a). The alert farmer stays abreast of price changes and reacts to these risks by changing harvest schedules, calculating when to use advanced feed booking, and timing other purchases when ‘bargain’ prices occur.

In scenario 1 for RW1/RW2, the return to the IPRS system was not profitable ($-3,209) at our study’s base prices (fish = $2.44/kg and feed = $430/MT). However, at current prices (fish = $2.85/kg and feed = $490/MT), we see that scenarios 2, 3 and 4 were positive (profitable) for

RW3/RW4, including the stocker units in all cases (Table 3.12). When feed price was $370/MT and fish prices ranged from $2.44/kg to $2.92/kg, 83% of the net returns were positive (highlighted in Table 3.12). For current price levels (August 2021) the fish price has increased by 10% over our initial sensitivity analysis fish price ($2.85/kg), and the current feed price has increased by 14% to $490/MT from the base feed price, we see three of the four RW3/RW4 scenarios had positive net returns (highlighted in Table 3.12) at these prices (none were positive for the RW1/RW2 scenarios).

Financial measures of profitability were positive at different stages of farm development, i.e., different required levels of investment for IPRS implementation (Table 3.13). Scenarios 1 and 2 had the same net return, $1,421, because the only difference between them was the land purchase. Since land is not depreciated and all other items in the cash flow were constant, net returns did not change. If a farm implemented five IPRS systems, then the financial net return would be $7,105 ($1,421 x 5) at the end of one RW1/RW2 production cycle, and for five ponds of RW3/RW4 raceway size, the financial net return would be $38,660 ($7,732 x 5). If an aquaculture farm already exists (scenario 4), the financial net return would be $9,640 ($1,928 x 5) using RW1/RW2 raceway size, and $48,500 ($9,700 x 5) for RW3/RW4 raceway size. These results confirm initial raceway investment costs strongly impact the long-term feasibility of the IPRS operation.

The average size of a catfish farm in Alabama is 99 ha (Hanson et al., 2021) and our IPRS system was placed into 0.4 ha ponds, and we had four ponds (1.6 ha total water area) which would be 1.6% of the average farm pond area. Continuing with the five IPRS pond example above, multiplying 0.4 ha pond size by five ponds we would use 2.0 ha or 2.0% of the total farm surface area only and harvest 24,130 kg of foodsize hybrid Catfish and 8,100 kg of stocker sized catfish.

When NPV is positive, then the investment is profitable because the flow of returns, after accounting for the time value of money at the specified discount rate (5% used herein) is greater than zero. When NPV is negative, then the investment earns less than its opportunity cost, i.e., potential interest earned if the IPRS investment capital was put into another investment, and is not profitable (Engle, 2010). This suggests that the key factors needing careful evaluation during the IPRS planning stage should include the initial investment, fish species selection, achievable production, and fish selling price, as well as for the largest input costs for feed and labor.

This study shows the advantage of producing stockers from the "stocker unit" to supply fish for the start of the next growout raceway production cycle, but by itself, it was not profitable. Its advantage lies in the availability of large fingerlings or even stocker sized fish to put into the next cycle's growout raceways. It is not practical to transport these larger stocker sized fish for long distances and their availability is limited. It is okay for the stocker unit to produce different size large fingerlings or small stockers as staggering the stocking of growout cells with different sized fish can allow different harvest times and have supply to sell available year-round.

Roy et al. (2019) used different fish sizes in each raceway cell to stagger production. This allowed harvests to be marketed throughout the year. When they stocked larger fingerlings (175 g) the net yield was higher in four of the five cells, suggesting that larger fingerlings result in higher production. This indicates the need for further research on stocking larger fish (stockers) in IPRS units. Recent trends in processor demand for a live catfish product indicates a 0.68 to 0.90 kg catfish would require additional grow-out time and a corresponding rise in operational expenses (D'Abramo et al., 2006). These authors suggested that a fingerling-to-stocker pond phase would be beneficial and in one treatment they stocked fingerlings approximately 10.2 to 15.2 cm (23 to 27 g) and grew them to a stocker size (92 g) during a 6-7-month period.

Our study stocked fingerlings measuring 15 cm weighing 29.1 g and achieved a final weight of 120 grams in 4.7 months (143 days). Research conducted by Bott et al. (2015) in traditional ponds showed that hybrid Catfish required at least 10 months (0.83 years) to grow from 0.031 kg fingerling to 0.86 kg premium sized foodfish, while we grew a 0.031 kg fingerling to a 0.61 kg foodfish in 7.4 months. The premium sized catfish range is currently 0.45 to 1.81 kg per fish, though this can change as processor needs change.

3.5 Conclusion

Hybrid Catfish yields from the IPRS stocker and foodsize raceway units surpassed those from traditional catfish production systems. Feed conversion ratios ranged between 1.6 to 1.8 for stockers and foodsize hybrid Catfish produced in IPRS systems and were within ranges for other intensive catfish production systems and technologies. Initial raceway cost had a large impact on the long-term feasibility of the IPRS system and raceways made with less expensive materials had a higher profit potential. However, the less expensive raceway materials may result in a shorter life span and require more repairs, maintenance, and replacement costs. Lowering initial farm level investment reduced the payback period, increased net present values and internal rates of return. IPRS shows promise at intensifying production and profitability, suggesting that further research could improve these metrics.

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Table 3.1 Per-unit value or cost used in the development of In Pond Raceway System (IPRS) enterprise budgets for stocker and foodsize hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂), 2018.

Description	Unit	Value or Cost ($) per unit
Catfish price		
Fingerlings		
- Used in growout raceways	each	0.17
- Used in stocker raceways	each	0.16
Harvest size sales price		
Small <0.454 kg	kg	2.40
Premium: 0.454 - 1.82 kg	kg	2.46
Stocker Inventory Value price	kg	
Stocker <0.454 kg	kg	2.40
Stocker > 0.454 kg	kg	2.46
Feed		
32% crude protein	metric ton	430
Management and labor		
Management	ha/year	600
Hired labor	hour	10.00
Chemicals		
Lime, agricultural	metric ton	50.00
Lime, hydrated	kg	0.62
Salt	metric ton	135.00
Copper sulfate	22.68-kg bag	65.00
	per kg	2.87
Rotenone	L	13.00
Formalin	208.19 L drum	440
	L	2.11
Diquat	L	3.00
Potassium permanganate	kg	11.63
Fuel		
Gasoline off-road price for agriculture	L	0.72
Diesel price off-road	L	0.79
Electricity, per kWhr at off-peak rate	kW-hour	0.07
Other		
Insurance	ha	2.53
Miscellaneous expenses	cycle	200.00
Bird netting for 2 raceways	roll	163.00

Fish price was determined by calculating an average using prices from January 2016 to June 2021 for small (<0.454 kg) and premium (0.454 - 1.82 kg) sizes catfish (Hanson, 2021)

Table 3.2 Land, construction of 0.4 ha ponds and In-Pond Raceway System (IPRS) capital items, machinery and equipment investment for raising stocker and foodsize hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) in the same pond, 2018.

Items	U.S. $	Investment			
		Quantity	63 m^3 IPRS	Quantity	45 m^3 IPRS
Capital Items					
Land, $/ha	2,031	0.49	986	0.49	986
Pond construction[a], $/ha	3,830	0.40	1,550	0.40	1,550
Growout RW1 and RW2, placed in Ponds 1 and 2 (4.9 m x 10.7 m x 1.2 m = 63 m^3)	25,000	1	25,000	-	-
Growout RW3 and RW4, placed in Ponds 3 and 4 (3.0 m x 12.2 m x 1.2 m = 45 m^3)	6,000	-	-	1	6,000
Stocker unit RWs, placed in Ponds 1, 2, 3 and 4 (1.8 m x 5.8 m x 1.30 m = 14 m^3)	1,867	1	1,867	1	1,867
Subtotal			29,403		10,403
Machinery and Equipment					
Equipment[b], $/ha	3,739	0.40	1,513	0.40	1,513
1.0 HP blower for white water unit	880	1	880	1	880
1.5 HP blower for raceway unit	1,200	1	1,200	1	1,200
1.5 HP blower for white water unit	1,200	1	1,200	1	1,200
1.0 HP blower for small RW unit	900	1	900	1	900
White water unit (large RWs)	2,500	1	2,500	1	2,500
White water unit (small RWs)	1,200	1	1,200	1	1,200
Baffle fencing and floats	200	1	200	1	200
Boardwalks - Raceways 1 and 2	1,000	1	1,000	-	-
Boardwalks - Raceways 3 and 4	1,200	-	-	1	1,200
Subtotal			10,593		10,793
TOTAL			39,996		21,196

[a] Includes construction of pond with water supply, drainage, and electrical service, but no wells because they are seldom used on western Alabama catfish farms. Their primary water source is from watershed runoff. [b] Equipment costs included a backup generator (20 kW plus transfer switch), propane tank for generator, electrical line for white water movers, tractors, trucks, mower, electrical aerators, power take-off aerator, feeder, feed bin, pump, office, shop, tools, utility trailer, storage container, dissolved oxygen meter, and computer.

Table 3.3 Water chemistry results from within foodsize raceways and surrounding pond water when raising hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) in four 0.4 ha In-Pond Raceway Systems, 2018.

	Pond 1	RW 1	Pond 2	RW 2	Pond 3	RW 3	Pond 4	RW 4
DO range, mg/L	2.3 – 12.9	2.6 – 11.8	1.7 – 13.8	2.4 – 13.4	1.8 – 13.4	2.4 – 12.9	1.2 – 12.5	1.7 – 12.0
Temperature °C	12.0 – 33.3	12.0 – 33.1	12.0 – 33.6	12.0 – 33.6	12.0 – 33.5	12.0 – 33.4	12.0 – 33.2	12.0 – 32.4
Total alkalinity	–	80 – 110	–	60 – 95	–	60 – 100	–	70 – 80
Total hardness	–	70 – 90	–	45 – 70	–	50 – 70	–	60 – 80
Chloride	–	240 – 380	–	120 – 400	–	120 – 400	–	140 – 400
pH	–	7.2 – 8.3	–	7.2 – 9.5	–	7.1 – 9.5	–	6.9 – 9.1
TAN mg/L	–	0.2 – 2.0	–	0.0 – 3.0	–	0.0 – 3.0	–	0.2 – 1.0
NH_3 mg/L	–	0.0 – 0.8	–	0.0 – 2.1	–	0.0 – 1.2	–	0.0 – 0.2
NO_2- mg/L	–	0.1 – 0.3	–	0.0 – 0.6	–	0.0 – 0.3	–	0.0 – 0.8
Secchi disk (m)	0.18 – 0.35	–	0.23 – 0.33	–	0.18 – 0.32	–	0.18 – 0.28	–

* DO = dissolved oxygen inside the raceway - minimum and maximum; Temperature = minimum and maximum; Total alkalinity range (as ppm $CaCO_3$); Total hardness range (as ppm $CaCO_3$); Chloride concentration as ppm = minimum and maximum; pH = inside the raceway, afternoon range; TAN (Total Ammonia Nitrogen) = maximum afternoon range; NH_3 (Ammonia) = maximum afternoon range; NO_2- (Nitrite Nitrogen) = maximum afternoon range; Secchi disk depth level during summer and early fall

Table 3.4 Growout growth performance of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in IPRS (In-Pond Raceway System) raceways placed in 0.4 ha ponds, 2018.

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average Raceways 1 and 2 (standard error)	Raceway 3 45 m^3	Raceway 4 45 m^3	Average Raceways 3 and 4 (standard error)
Production cycle (days)	228	228	228	228	228	228
Number of fish stocked	8,714	8,657	8,686 (29)	8,603	8,592	8,597 (6)
Stocking density (fish/m^3)	138	137	138 (0.5)	191	191	191 (0.1)
Stocking density (fish/ha)	21,533	21,391	21,462 (71)	21,258	21,230	21,244 (14)
Mean weight at stocking (g)	31.8	30.4	31.1 (0.7)	30.9	32.2	31.6 (0.7)
Stocking biomass (kg)	277	263	270 (6.8)	266	277	271 (5.7)
Mean weight at harvest (g)	625	602	613 (11.8)	661	564	613 (48.9)
Total harvested (kg)	4,508	5,132	4,820 (311.8)	5,277	4,385	4,831 (446.1)
Yield[a] (kg/ha)	11,271	12,830	12,050 (780)	13,193	10,963	12,078 (1,115)
Net yield[b] (kg/ha)	10,578	12,172	11,375 (797)	12,529	10,271	11,400 (1,129)
Standing crop at harvest (kg/m^3)	71.6	81.5	76.5 (4.9)	117.3	97.4	107.4 (9.9)
Total harvest (number)	7,218	8,539	7,878 (660)	7,978	7,779	7,878 (99)
Feed fed (kg)	7,321	8,298	7,809 (488.5)	7,363	7,722	7,543 (179.9)
Net FCR[c]	1.73	1.70	1.72 (0.01)	1.47	1.88	1.67 (0.21)
Average feeding rate (kg/ha/day)	80.3	91.0	85.6 (5.4)	80.7	84.7	82.7 (2.0)
WGD[d] (g/fish/day)	2.60	2.50	2.55 (0.05)	2.77	2.33	2.55 (0.2)
Survival (%)	82.8	98.6	90.7 (8.3)	92.7	90.5	91.6 (0.01)

[a] Yield = Total harvested, kg / Pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / Pond size, 0.4 ha

[c] Net FCR (Feed conversion ratio) = Feed fed, kg / (Total harvested, kg – Stocking biomass, kg)

[d] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 3.5 Stocker growth performance of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in the IPRS (In-Pond Raceway System) "stocker unit" raceways placed in 0.4 ha ponds, 2018.

	Raceway 1 14 m^3	Raceway 2 14 m^3	Average Raceway 1 and 2 (standard error)	Raceway 3 14 m^3	Raceway 4 14 m^3	Average Raceway 3 and 4 (standard error)
Production cycle (days)	143	143	143	143	143	143
Number of fish stocked	10,000	10,159	10,079 (79)	10,147	10,735	10,441 (294)
Stocking density (fish/m^3)	714	726	720 (5.7)	725	767	746 (21.0)
Stocking density (fish/ha)	24,710	25,102	24,906 (196)	25,073	26,527	25,800 (727)
Mean weight at stocking (g)	25.9	28.6	27.2 (1.4)	30.9	30.9	30.9 (0.0)
Stocking biomass (kg)	259	291	275 (15.9)	313	331	322 (9.08)
Mean weight at harvest (g)	201	123	162 (39.3)	133	234	183 (50.4)
Total harvested (kg)	1,415	1,709	1,562 (147.0)	1,755	1,603	1,679 (76.3)
Yield[a] (kg/ha)	3,537	4,272	3,904 (367.4)	4,388	4,007	4,197 (190.7)
Net yield[b] (kg/ha)	2,890	3,545	3,218 (327.7)	3,605	3,178	3,391 (213.4)
Standing crop at harvest (kg/m^3)	101.1	122.0	111.6 (10.5)	125.4	114.5	119.9 (5.4)
Total harvest (number)	7,041	10,039	8,540 (1,499)	8,919	6,989	7,954 (964)
Feed fed (kg)	2,004	2,296	2,150 (146.0)	2,335	2,255	2,295 (40.2)
Net FCR[c]	1.73	1.62	1.67 (0.06)	1.62	1.77	1.70 (0.08)
Average feeding rate (kg/ha/day)	35.0	40.1	37.59 (2.6)	40.8	39.4	40.1 (0.7)
WGD[d] (g/fish/day)	1.23	0.66	0.94 (0.3)	0.71	1.42	1.07 (0.4)
Survival (%)	70.4	98.8	84.6 (14.2)	87.9	65.1	76.5 (11.4)

[b] Yield = Total harvested, kg / Pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / Pond size, 0.4 ha

[c] Net FCR (Feed conversion ratio) = Feed fed, kg / (Total harvested, kg – Stocking biomass, kg)

[d] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 3.6 Growout enterprise budgets for four In-Pond Raceway System (IPRS) producing foodsize hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, with each raceway placed in a 0.4 ha pond, U.S.$, 2018.

	Raceway 1 63 m^3		Raceway 2 63 m^3		Average Raceway 1 and 2		Raceway 3 45 m^3		Raceway 4 45 m^3		Average Raceway 3 and 4	
	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg
Catfish Sales Receipts												
Small, <0.454 kg	2,782	2.40	2,811	2.40	2,797	2.40	1,484	2.40	3,000	2.40	2,242	2.40
Premium: 0.454-1.82 kg	8,244	2.46	9,749	2.46	8,996	2.46	11,455	2.46	7,708	2.46	9,581	2.46
Total Receipts	11,026	2.45	12,560	2.45	11,793	2.45	12,939	2.45	10,708	2.44	11,823	2.45
Variable Costs												
Feed, 32% Protein	3,143	0.70	3,562	0.69	3,353	0.70	2,760	0.52	3,315	0.76	3,038	0.64
Labor and Management	1,452	0.32	1,432	0.28	1,442	0.30	1,432	0.27	1,398	0.32	1,415	0.30
Catfish Fingerlings	1,438	0.32	1,428	0.28	1,433	0.30	1,419	0.27	1,418	0.32	1,419	0.30
Carp Fingerlings	49	0.01	49	0.01	49	0.01	49	0.01	48	0.01	48	0.01
Harvest and Transportation	497	0.11	566	0.11	531	0.11	581	0.11	483	0.11	532	0.11
Fuel (diesel and gas)	47	0.01	46	0.01	46	0.01	46	0.01	45	0.01	46	0.01
Repairs and Maintenance	200	0.04	200	0.04	200	0.04	400	0.08	400	0.09	400	0.08
Electricity, Aeration	1,191	0.26	1,180	0.23	1,185	0.25	1,180	0.22	1,162	0.27	1,171	0.24
Chemicals	1,061	0.24	1,045	0.20	1,053	0.22	1,144	0.22	1,113	0.25	1,129	0.24
Miscellaneous	100	0.02	90	0.02	95	0.02	99	0.02	96	0.02	97	0.02
Interest on Operating Capital	386	0.09	404	0.08	395	0.08	383	0.07	399	0.09	391	0.08
Total Variable Cost	9,564	2.12	10,001	1.95	9,782	2.03	9,494	1.80	9,876	2.25	9,685	2.03
Income Above Variable Costs	1,462	0.32	2,559	0.50	2,010	0.42	3,445	0.65	832	0.19	2,138	0.44
Fixed Costs												
Land Charge	493	0.11	493	0.10	493	0.10	493	0.09	493	0.11	493	0.10
Depreciation on Capital Items	761	0.17	761	0.15	761	0.16	375	0.07	375	0.09	375	0.08
Depreciation on Machinery and Equipment Items	649	0.14	649	0.13	649	0.14	655	0.12	655	0.15	655	0.14
Interest on Capital Loans	757	0.17	757	0.15	757	0.16	199	0.04	199	0.05	199	0.04
Interest on Equipment Loans	183	0.04	183	0.04	183	0.04	186	0.04	186	0.04	186	0.04
Repairs and Maintenance	10	0.00	10	0.00	10	0.00	10	0.00	10	0.00	10	0.00
Taxes	606	0.13	606	0.12	606	0.13	326	0.06	326	0.07	326	0.07
Insurance	2	0.00	2	0.00	2	0.00	2	0.00	2	0.00	4	0.00
Total Fixed Costs	3,461	0.77	3,461	0.67	3,461	0.72	2,247	0.43	2,247	0.51	2,249	0.47
Total Costs	13,025	2.89	13,461	2.62	13,243	2.76	11,741	2.23	12,124	2.77	11,934	2.50
Net Return Above All Costs	-1,999	-0.44	-902	-0.18	-1,450	-0.31	1,198	0.23	-1,416	-0.32	-110	-0.05

* Some columns of number may not add up as presented due to integer rounding

Table 3.7 Stocker enterprise budgets for four In-Pond Raceway System (IPRS) producing stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, with each raceway placed in a 0.4 ha pond, U.S.$, 2018*.

	Raceway 1 14 m^3		Raceway 2 14 m^3		Average Raceway 1 and 2		Raceway 3 14 m^3		Raceway 4 14 m^3		Average Raceway 3 and 4	
	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg
Inventory/Sale Value												
Catfish Stocker <0.454 kg	3,232	2.40	4,104	2.40	3,668	2.40	4,212	2.40	3,402	2.40	3,807	2.40
Catfish Stocker > 0.454 kg	170	2.46	0	2.46	85	2.46	0	2.46	454	2.46	227	2.46
Total	3,402	2.40	4,104	2.40	3,753	2.40	4,212	2.40	3,857	2.41	4,034	2.41
Variable Costs												
Feed, 32% Protein	861	0.61	986	0.58	923	0.59	1,002	0.57	968	0.60	985	0.59
Labor and Management	456	0.32	477	0.28	466	0.30	476	0.27	511	0.32	494	0.30
Catfish Fingerlings	1,610	1.14	1,636	0.96	1,623	1.05	1,634	0.93	1,728	1.08	1,681	1.01
Carp Fingerlings	16	0.01	16	0.01	16	0.01	16	0.01	17	0.01	17	0.01
Fuel (diesel and gas)	15	0.01	16	0.01	15	0.01	15	0.01	16	0.01	16	0.01
Repairs and Maintenance	50	0.04	50	0.03	50	0.03	50	0.03	50	0.03	50	0.03
Electricity, Aeration	419	0.30	430	0.25	424	0.27	429	0.24	442	0.28	436	0.26
Chemicals	315	0.22	329	0.19	322	0.21	329	0.19	388	0.24	358	0.21
Miscellaneous	31	0.02	33	0.02	32	0.02	33	0.02	35	0.02	34	0.02
Interest on Operating Capital	159	0.11	167	0.10	163	0.10	168	0.10	175	0.11	171	0.10
Total Variable Cost	3,930	2.78	4,138	2.42	4,034	2.60	4,152	2.37	3,315	0.76	4,242	2.54
Income Above Variable Cost	-528	-0.37	-35	-0.02	-197	-0.12	59	0.03	-474	-0.30	-207	-0.12
Fixed Costs												
Land Charge	493	0.35	493	0.29	493	0.32	493	0.28	493	0.31	493	0.29
Depreciation on Capital Items	197	0.14	197	0.12	197	0.13	197	0.11	197	0.12	197	0.12
Depreciation for Machinery and Equipment Items	415	0.29	415	0.24	415	0.27	421	0.24	421	0.26	421	0.25
Interest on Capital Loans	78	0.05	78	0.05	78	0.05	78	0.04	78	0.05	78	0.05
Interest on Equipment Loans	137	0.10	137	0.08	137	0.09	140	0.08	140	0.09	140	0.08
Repairs and Maintenance	10	0.01	10	0.01	10	0.01	10	0.01	10	0.01	10	0.01
Taxes	144	0.10	144	0.08	144	0.09	146	0.08	146	0.09	146	0.09
Insurance	2	0.00	2	0.00	2	0.00	2	0.00	2	0.00	2	0.00
Total Fixed Costs	1,477	1.04	1,477	0.86	1,477	0.95	1,488	0.85	1,488	0.93	1,488	0.89
Total Costs	5,407	3.82	5,615	3.29	5,511	3.55	5,640	3.22	5,819	3.63	5,730	3.43
Net Return Above All Costs	-2,005	-0.48	-1,511	-0.22	-1,758	-0.35	-1,428	0.17	-1,962	-0.36	-1,695	-0.09

* Some columns of number may not add up as presented due to integer rounding.

Table 3.8 Summary enterprise budgets for four In-Pond Raceway System (IPRS) producing foodsize and stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, in a 0.4 ha pond, U.S.$, 2018*.

	Pond 1		Pond 2		Average Pond 1 and 2		Pond 3		Pond 4		Average Pond 3 and 4	
	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg
Growout IPRS												
Catfish Sales Receipts												
Small, <0.454 kg	2,782	2.40	2,811	2.40	2,797	2.40	1,484	2.40	3,000	2.40	2,242	2.40
Premium: 0.454-1.82 kg	8,244	2.46	9,749	2.46	8,996	2.46	11,455	2.46	7,708	2.46	9,581	2.46
Total Receipts	11,026	2.45	12,560	2.45	11,793	2.45	12,939	2.45	10,708	2.44	11,823	2.45
Variable Costs	9,564	2.12	10,001	1.95	9,782	2.04	9,494	1.80	9,876	2.25	9,685	2.03
Income Above Variable Costs	1,462	0.32	2,559	0.50	2,010	0.42	3,445	0.65	832	0.19	2,138	0.44
Fixed Costs	3,461	0.77	3,461	0.67	3,461	0.72	2,247	0.43	2,247	0.51	2,249	0.47
Total Costs	13,025	2.89	13,461	2.62	13,243	2.76	11,741	2.23	12,124	2.77	11,934	2.50
Net Return Above All Costs	-1,999	-0.44	-902	-0.18	-1,450	-0.31	1,198	0.23	-1,416	-0.32	-110	-0.05
Stocker Inventory/Sale Value												
Catfish Stocker <0.454 kg	3,232	2.40	4,104	2.40	3,668	2.40	4,212	2.40	3,402	2.40	3,807	2.40
Catfish Stocker > 0.454 kg	170	2.46	0	2.46	85	2.46	0	2.46	454	2.46	227	2.46
Total Sales Value	3,402	2.40	4,104	2.40	3,753	2.40	4,212	2.40	3,857	2.41	4,034	2.41
Variable Costs	3,930	2.78	4,138	2.42	4,034	2.60	4,152	2.37	3,315	0.76	4,242	2.54
Income Above Variable Costs	-528	-0.37	-35	-0.02	-281	-0.18	59	0.03	-474	-0.30	-207	-0.12
Fixed Costs	1,477	1.04	1,477	0.86	1,477	0.95	1,488	0.85	1,488	0.93	1,488	0.89
Total Costs	5,407	3.82	5,615	3.29	5,511	3.55	5,640	3.22	5,819	3.63	5,730	3.43
Net Return Above All Costs	-2,005	-0.48	-1,511	-0.22	-1,758	-0.35	-1,428	0.17	-1,962	-0.36	-1,695	-0.09
Combined Growout and Stocker												
Catfish Sales Receipts												
Total Receipts	14,428	2.44	16,664	2.44	15,546	2.44	17,150	2.44	14,565	2.43	15,857	2.44
Variable Costs	13,495	4.90	14,139	4.37	13,817	4.64	13,646	4.17	14,207	4.96	13,926	4.56
Income Above Variable Costs	933	0.16	2,525	0.37	1,729	0.26	3,505	0.50	357	0.06	1,931	0.28
Fixed Costs	4,938	1.81	4,938	1.54	4,938	1.68	3,735	1.27	3,735	1.44	3,735	1.36
Total Costs	18,432	6.71	19,077	5.91	18,754	6.31	17,381	5.44	17,942	6.40	17,662	5.92
Net Return Above All Costs	-4,004	-4.28	-2,413	-3.47	-3,209	-3.87	-231	-3.00	-3,378	-3.97	-1,804	-3.48

*Some columns of number may not add up as presented due to integer rounding

Table 3.9 Summarized economic and accounting profit results for four growout In-Pond Raceway Systems (IPRS) producing foodsize hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, with each raceway placed in a 0.4 ha pond, U.S.$, 2018.

	RW 1 14 m^3	RW 2 14 m^3	Average RW 1 and 2	RW 3 14 m^3	RW 4 14 m^3	Average RW 3 and 4
Economic Profit						
Net return above all costs, $	-1,999	-902	-1,450	1,198	-1,416	-109
- NR $/kg	-0.44	-0.18	-0.31	0.23	-0.32	-0.05
Total cost, $/kg	2.89	2.62	2.76	2.23	2.77	2.50
Accounting Profit						
EBITDA[a], $	2,682	3,776	3,229	4,920	2,288	3,604
- NR $/kg	0.59	0.74	0.67	0.93	0.52	0.73
Total cost, $/kg	1.85	1.71	1.78	1.52	1.92	1.72

[a] EBITDA - Earnings Before Interest, Taxes, Depreciation, and Amortization; it is a measure of system performance.

NR = Net Return; RW = Raceway.

Table 3.10 Summarized economic and accounting profit results for four In-Pond Raceway Systems (IPRS) producing stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, with each raceway placed in a 0.4 ha pond, U.S.$, 2018.

	RW 1 14 m^3	RW 2 14 m^3	Average RW 1 and 2	RW 3 14 m^3	RW 4 14 m^3	Average RW 3 and 4
Economic Profit						
Net return above all costs, $	-2,005	-1,511	-1,758	-1,428	-1,962	-1,695
- NR $/kg	-0.48	-0.22	-0.35	0.17	-0.36	-0.09
Total cost, $/kg	3.82	3.29	3.55	3.22	3.63	3.43
Accounting Profit						
EBITDA[a], $	-70	452	191	545	53	299
- NR $/kg	0.55	0.69	0.62	0.88	0.49	0.68
Total cost, $/kg	2.45	2.14	2.30	2.09	2.38	2.23

[a] EBITDA - Earnings Before Interest, Taxes, Depreciation, and Amortization; it is a measure of system performance.

NR = Net Return; RW = Raceway.

Table 3.11 Different levels of investment required for growout (63 m^3 or 45 m^3) plus stocker unit (14 m^3) In-Pond Raceway System (IPRS) scenario sensitivity analyses for each raceway placed in a 0.4 ha pond, U.S.$, 2018.

Items	Investment Required Per Scenario[a]							
	1		2		3		4	
	63 m^3 IPRS	45 m^3 IPRS	63 m^3 IPRS	45 m^3 IPRS	63 m^3 IPRS	45 m^3 IPRS	63 m^3 IPRS	45 m^3 IPRS
Capital Items								
Land, $/ha[b]	986	986	0	0	0	0	0	0
Pond construction[c], $	1,550	1,550	1,550	1,550	1,550	1,550	0	0
RW 1 and 2 (4.9 x 10.7 x 1.2 m = 63 m^3)	25,000	-	25,000	-	25,000	-	25,000	-
RW 3 and 4 (3.0 x 12.2 x 1.2 m = 45 m^3)	-	6,000	-	6,000	-	6,000	-	6,000
RW 1, 2, 3 and 4 (1.8 x 5.8 m x 1.30 m = 14 m^3)	1,867	1,867	1,867	1,867	1,867	1,867	1,867	1,867
Subtotal	29,403	10,403	28,417	9,417	28,417	9,417	26,867	7,867
Machinery and Equipment								
Equipment[d], $/ha	1,513	1,513	1,513	1,513	303	303	0	0
1.0 HP blowers for water movers	880	880	880	880	880	880	880	880
1.5 HP blower's raceway units	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
1.5 HP blowers for water movers	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
1.0 HP blowers for small RW units	900	900	900	900	900	900	900	900
Water mover units (large RWs)	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500
Water mover units (small RWs)	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
Baffle fencing and floats	200	200	200	200	40	40	0	0
Boardwalks - Raceways 1 and 2	1,000	-	1,000	-	200	-	0	-
Boardwalks - Raceways 3 and 4	-	1,200	-	1,200	-	240	-	0
Subtotal	10,593	10,793	10,593	10,793	8,423	8,463	7,880	7,880
TOTAL	39,996	21,196	39,010	20,210	36,839	17,879	34,747	15,747

[a] Scenario 1 represents a new aquaculture operation, requiring land purchase, pond construction, and purchase of all machinery and equipment; this is the Base scenario to which other scenarios are compared. Scenario 2 represents the situation in Scenario 1 except the land is already owned. Scenario 3 represents the situation in Scenario 2 but 80% of the machinery and equipment are already on hand. Scenario 4 represents the situation in Scenario 3 with only some raceway component purchases. [b] Land charge was $2,031/ha. [c] Pond construction ($3,830/ha) includes construction of pond with water supply, drainage, and electrical service, but no wells because they are seldom used on western Alabama catfish farms. [d] Equipment costs ($3,739/ha) include backup generator (20 kW plus transfer switch), propane tank for generator, electrical line for water movers, tractors, trucks, mower, electrical aerators, power take-off aerator, feeder, feed bin, pump, office, shop, tools, utility trailer, storage container, dissolved oxygen meter and computer.

Table 3.12 Effects of different feed price, fish price and investment scenarios on net returns required for growout (63 m^3 or 45 m^3) plus stocker unit (14 m^3) In-Pond Raceway System (IPRS) from producing hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) in In-Pond Raceway Systems (IPRS), with each raceway placed in a 0.4 ha pond, U.S.$, 2018.

		RW1/RW2 (growout +stocker unit)				RW3/RW4 (growout +stocker unit)			
Feed price	Fish price	Scenario[a]				Scenario[a]			
		1	2	3	4	1	2	3	4
$370/MT	1.95	(5,385)	(4,691)	(4,431)	(4,253)	(4,390)	(3,386)	(3,108)	(2,890)
	2.19	(3,830)	(3,136)	(2,876)	(2,698)	(2,805)	(1,800)	(1,522)	(1,305)
	2.44	(2,275)	(1,582)	(1,322)	(1,144)	(1,219)	(214)	63	281
	2.85	(721)	(27)	233	411	367	1,372	1,649	1,867
	2.92	834	1,528	1,787	1,966	1,937	2,941	3,219	3,437
$400/MT	1.95	(5,696)	(4,691)	(4,742)	(4,564)	(4,683)	(3,678)	(3,401)	(3,183)
	2.19	(4,141)	(3,136)	(3,187)	(3,009)	(3,097)	(2,092)	(1,815)	(1,597)
	2.44	(2,586)	(1,582)	(1,633)	(1,455)	(1,512)	(507)	(229)	(12)
	2.85	(1,032)	(27)	(78)	100	74	1,079	1,357	1,574
	2.92	523	1,528	1,476	1,654	1,644	2,649	2,926	3,144
$430/MT	1.95	(6,318)	(5,313)	(5,053)	(4,875)	(4,976)	(3,971)	(3,693)	(3,476)
	2.19	(4,763)	(3,758)	(3,499)	(3,320)	(3,390)	(2,385)	(2,108)	(1,890)
	2.44	(3,209)	(2,204)	(1,944)	(1,766)	(1,804)	(799)	(522)	(304)
	2.85	(1,654)	(649)	(389)	(211)	(219)	786	1,064	1,282
	2.92	(99)	905	1,165	1,343	1,351	2,356	2,634	2,851
$460/MT	1.95	(6,836)	(5,624)	(5,364)	(5,186)	(5,268)	(4,264)	(3,986)	(3,768)
	2.19	(5,282)	(4,069)	(3,810)	(3,631)	(3,683)	(2,678)	(2,400)	(2,183)
	2.44	(3,727)	(2,515)	(2,255)	(2,077)	(2,097)	(1,092)	(815)	(597)
	2.85	(2,172)	(960)	(700)	(522)	(511)	494	771	989
	2.92	(618)	594	854	1,032	1,059	2,063	2,341	2,559
$490/MT	1.95	(7,355)	(5,935)	(5,675)	(5,497)	(5,561)	(4,556)	(4,279)	(4,061)
	2.19	(5,800)	(4,380)	(4,121)	(3,943)	(3,975)	(2,971)	(2,693)	(2,475)
	2.44	(4,246)	(2,826)	(2,566)	(2,388)	(2,390)	(1,385)	(1,107)	(890)
	2.85	(2,691)	(1,271)	(1,012)	(833)	(804)	201	479	696
	2.92	(1,136)	283	543	721	766	1,771	2,048	2,266

Shaded cells represent positive net returns. [a] Scenario 1 represents a new aquaculture operation, requiring land purchase, pond construction, and purchase of all machinery and equipment; this is the Base scenario to which other scenarios are compared. Scenario 2 represents the situation in Scenario 1 except the land is already owned. Scenario 3 represents the situation in Scenario 2 but 80% of the machinery and equipment are already on hand. Scenario 4 represents the situation in Scenario 3 with only some raceway component purchases.

Table 3.13 Financial measures of profitability for the four investment scenarios producing foodsize and stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, in In-Pond Raceway Systems (IPRS), per raceway placed in a 0.4 ha pond, 2018.

	Investment Scenarios[a]							
	1		2		3		4	
Item	Average Pond 1 and 2	Average Pond 3 and 4	Average Pond 1 and 2	Average Pond 3 and 4	Average Pond 1 and 2	Average Pond 3 and 4	Average Pond 1 and 2	Average Pond 3 and 4
Financial net return, U.S.$	1,421	7,732	1,421	7,732	1,737	8,794	1,928	9,700
Investment cost, U.S.$	39,996	21,196	39,010	20,210	36,839	17,879	34,747	15,747
Payback period, year	28.1	2.7	27.4	2.6	21.2	2.0	18.0	1.6
Net present value, U.S.$	-26,938	34,797	-25,998	35,737	-21,509	45,226	-18,028	53,424
Internal rate of return, %	-18.0%	28.6%	-17.7%	30.1%	-14.1%	37.5%	-11.6%	45.0%

*Using a discount rate of 5%. [a] Scenario 1: pond construction, all machinery, all land (Base scenario). Scenario 2: pond construction, all machinery, no land. Scenario 3: pond construction, some machinery, no land. Scenario 4: existing ponds, machinery, and land. Net return in scenario 1 and 2 were the same because the depreciation for both scenarios was the same; the only difference is that the land was not purchased in the scenario 2 but it is not depreciable.

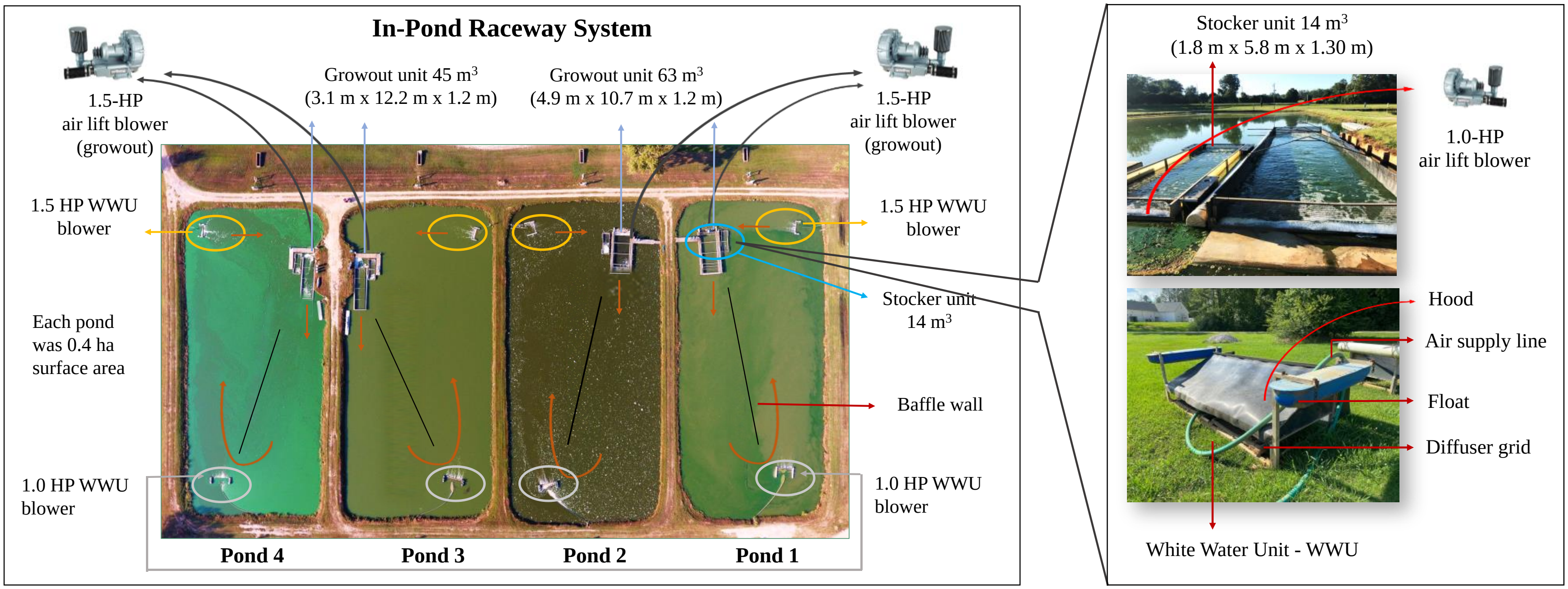


Figure 3.1 Aerial view of the four 0.4 ha ponds including the four growout and four stocker IPRS units per pond. Raceways RW1 and RW2 (63 m^3) were larger than raceways RW3 and RW4 (45 m^3). Stocker unit raceways were all 14 m^3 in volume. In each pond, a fabric curtain, called a baffle "wall", extended from the IPRS outflow to at least 2/3 of the distance of the pond diagonal, reaching from the pond bottom to just above water level and was suspended by floats. This barrier guided water circulation around the pond and toward a second and third White Water Unit devices (WWU) before re-entering the IPRS unit's fish growth area. Original aerial photo by David Cline.

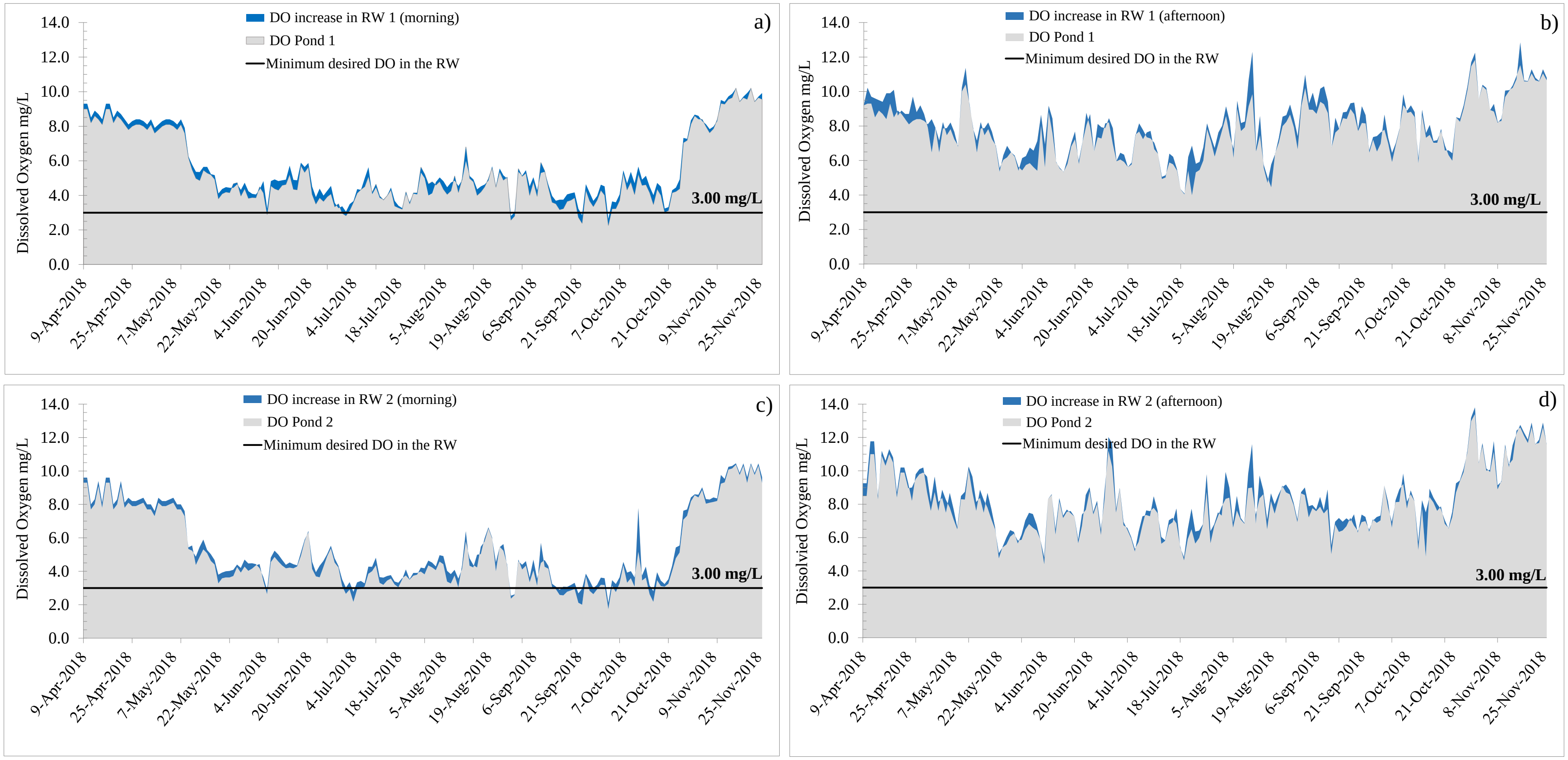


Figure 3.2 Illustration of the early morning (left) and afternoon (right) dissolved oxygen concentrations in the pond (light grey) and inside growout raceways (blue) RW1 (a and c) and RW2 (b and d). The blue area above the light grey area indicates how much more oxygen the IPRS aeration device added to the water at the entrance of the raceway, keeping dissolved oxygen levels inside the raceway at or above 3 mg/L (minimum desired level), seldom below 2 mg/L, and regularly above the outside pond water, 2018. DO = Dissolved oxygen mg/L.

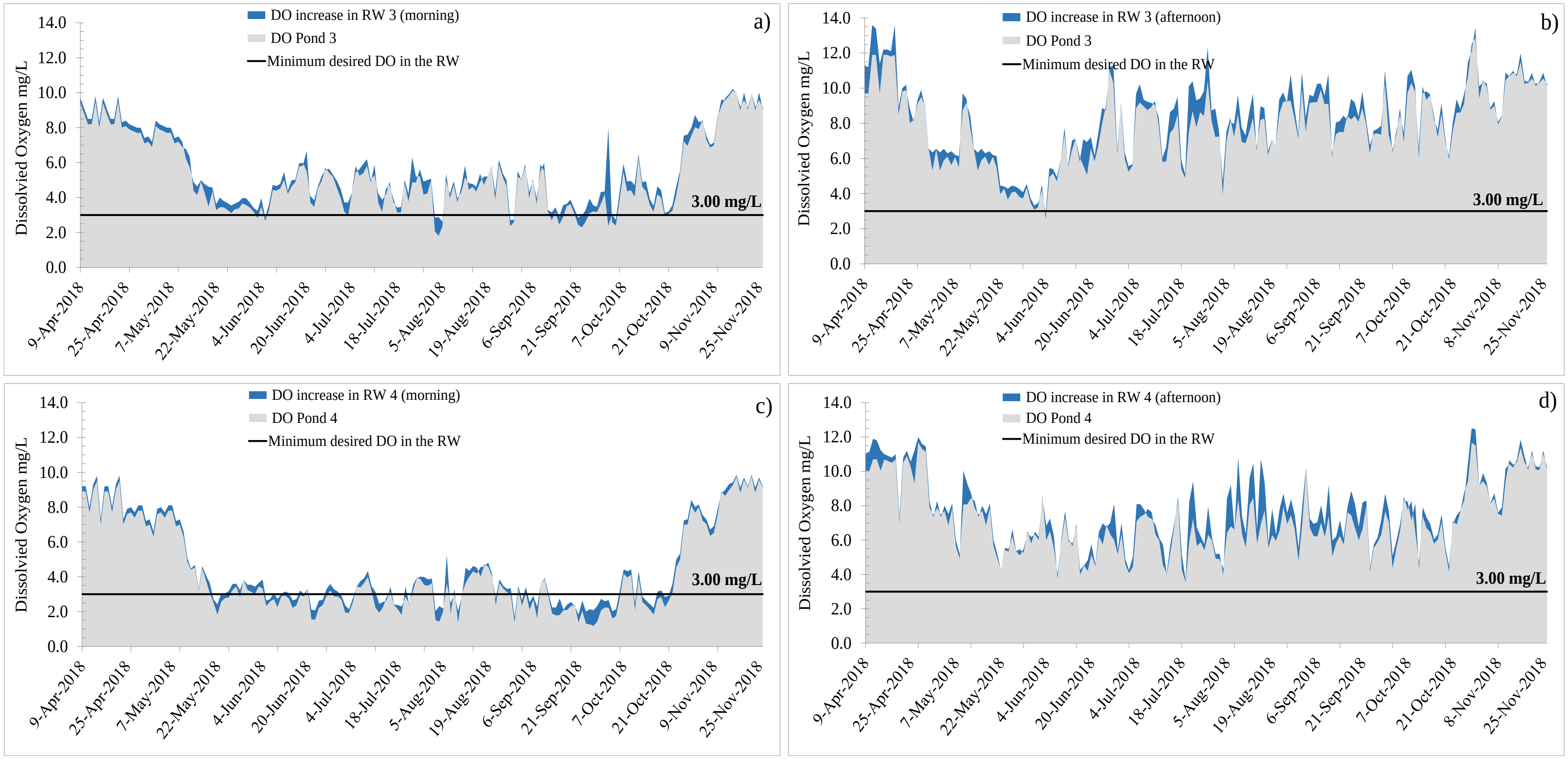


Figure 3.3 Illustration of the early morning (left) and afternoon (right) dissolved oxygen concentrations in the pond (light grey) and inside growout raceways (blue) RW3 (a and c) and RW4 (b and d). The blue area above the light grey area indicates how much oxygen the IPRS aeration device added to the water at the entrance of the raceway, keeping dissolved oxygen levels inside the raceway at or above 3 mg/L (minimum desired level), seldom below 2 mg/L, and regularly above the outside pond water, 2018. DO = Dissolved oxygen mg/L.

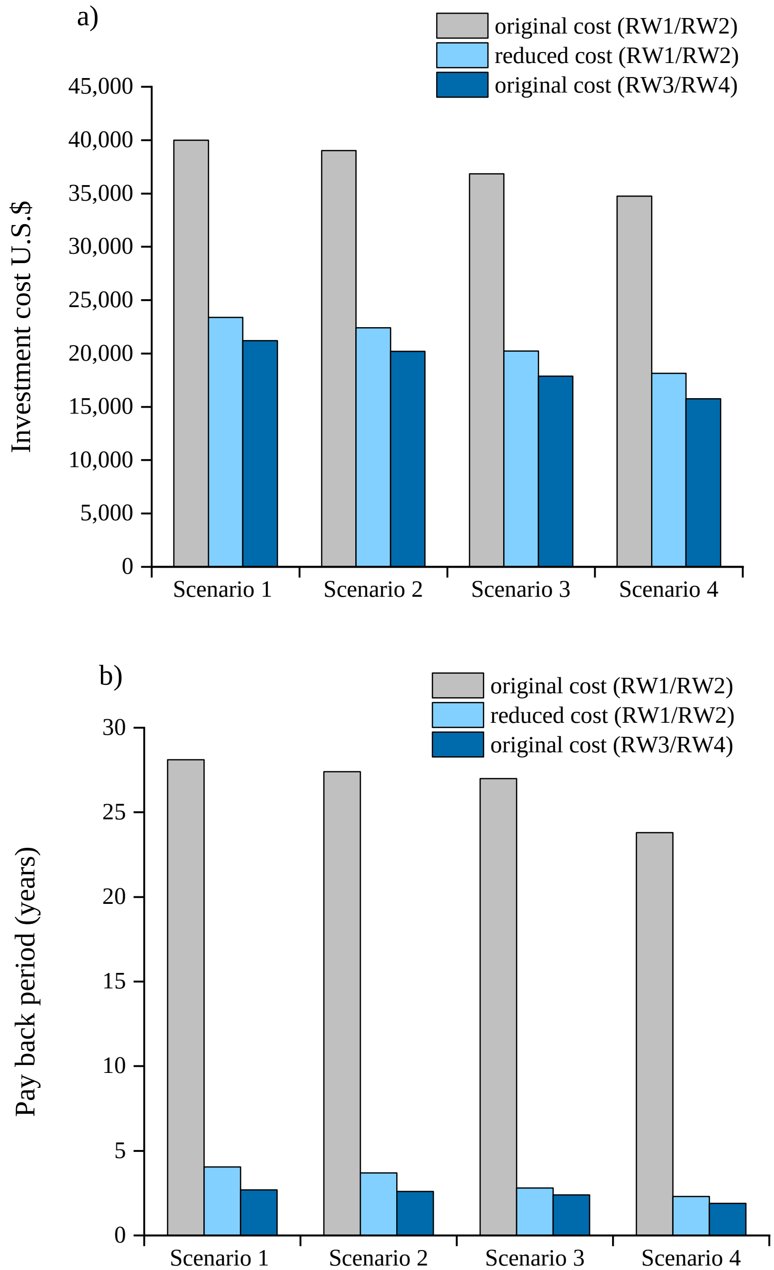


Figure 3.4 Effect of reducing the IPRS growout raceway construction investment cost by 66% on a) investment cost (U.S.$), b) payback period (years). Scenario 1 includes pond construction, all machinery/equipment cost, all land costs. Scenario 2 includes pond construction, all machinery/equipment cost, no land cost. Scenario 3 includes pond construction, 80% less machinery/equipment cost, no land cost. Scenario 4 represents an existing aquaculture operation that requires no pond construction, no machinery, and no land purchases, only some specialty IPRS items. *Stocker units were built from the less expensive materials, only growout units had their price reduced.

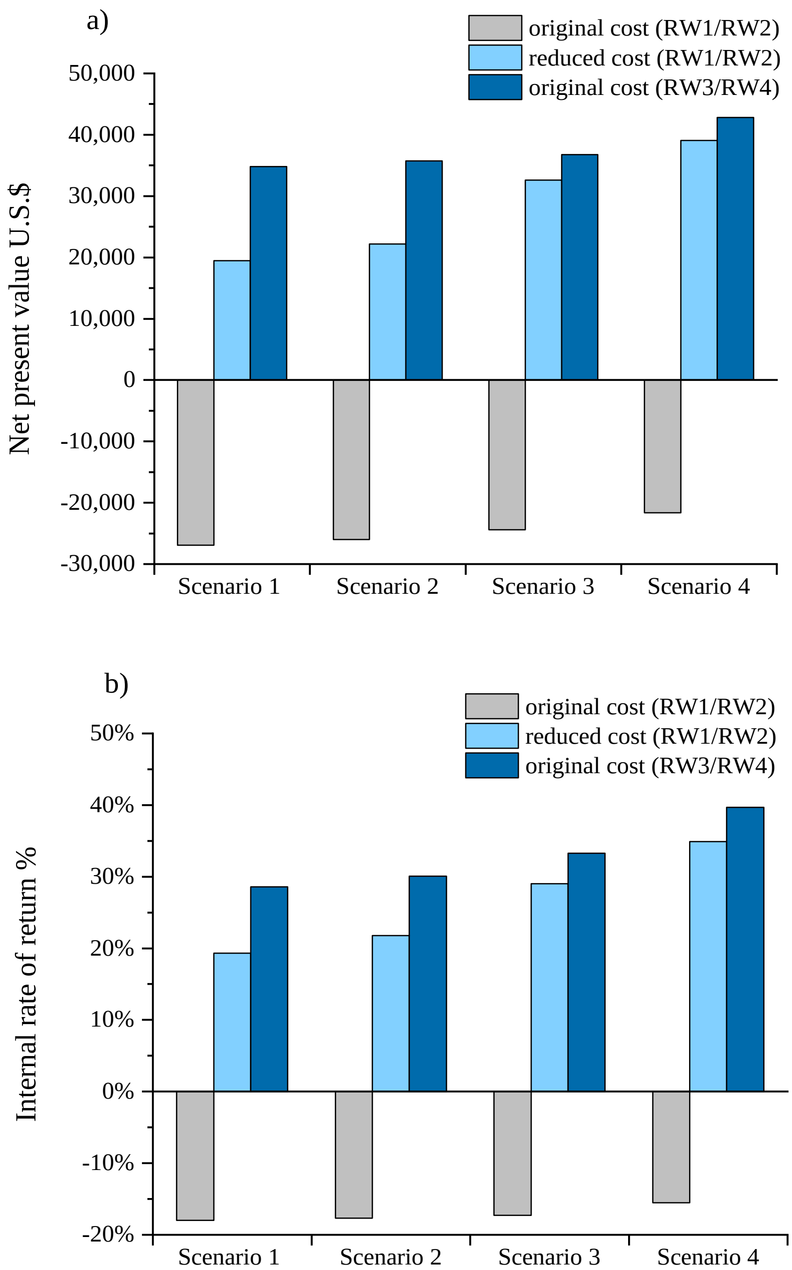
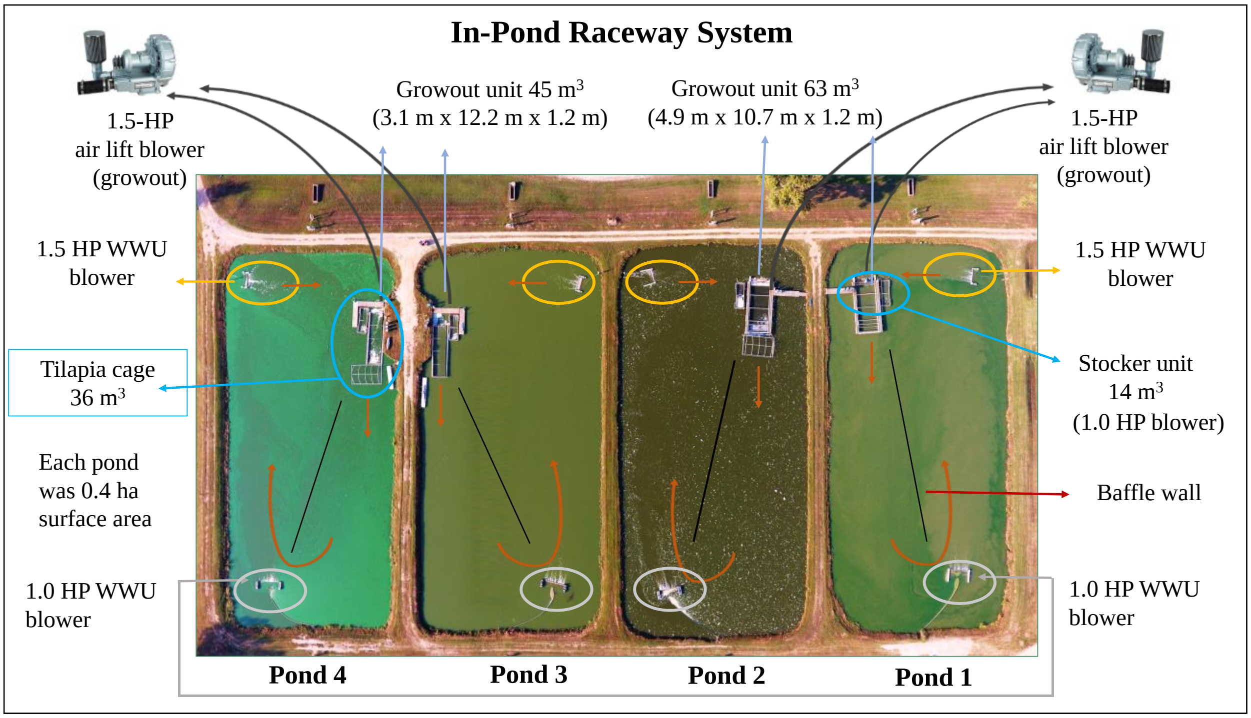


Figure 3.5 Effect of reducing the IPRS growout raceway construction investment cost by 66% on a) net present value (U.S.$), and b) internal rate of return (%). *A discount rate of 5% was used. Scenario 1 includes pond construction, all machinery/equipment cost, all land costs. Scenario 2 includes pond construction, all machinery/equipment cost, no land cost. Scenario 3 includes pond construction, 80% less machinery/equipment cost, no land cost. Scenario 4 represents an existing aquaculture operation that requires no pond construction, no machinery, and no land purchases, only some specialty IPRS items. *Stocker unit were built from the less expensive materials, only growout units had their price reduced.



Chapter 4.

In-pond raceway system production trials growing stocker and foodsize hybrid Catfish (Channel Catfish, *Ictalurus punctatus*, ♀ x Blue Catfish, *I. furcatus*, ♂) plus tilapia *Oreochromis niloticus*

Fantini-Hoag, L. Hanson, T. Chappell, J. In-pond raceway system production trials growing stocker and foodsize hybrid Catfish (Channel Catfish, *Ictalurus punctatus*, ♀ x Blue Catfish, *I. furcatus*, ♂) plus tilapia *Oreochromis niloticus*. To be submitted to PLOS ONE in December 2021.

Abstract

This case study evaluated the performance and economics of producing foodsize hybrid Catfish and stocker sized fingerlings in In-Pond Raceway Systems (IPRS) and tilapia grown in cages, placed into four 0.4 ha ponds. Growout raceways in ponds 1 and 2 were 63 m^3, and 45 m^3 in ponds 3 and 4. Each pond had one (14 m^3) stocker unit raceway plus a 36 m^3 tilapia cage placed into ponds 2 and 4. Each pond had 5.0 HP of aeration that maintained adequate DO levels. Catfish were fed a 32% CP commercial diet twice a day; tilapia were allowed only to graze the phytoplankton flow generated by the growout and stocker IPRS units. The combined production from growout (186 days) and stocker (142 days) resulted in 19,712 kg/ha in pond 1, 19,302 kg/ha in pond 2, 19,426 kg/ha in pond 3, and 16,555 kg/ha in pond 4. The same number of tilapia were stocked into the two cages and resulted in yields of 2,167 kg/ha (pond 2) and 2,160 kg/ha (pond 4); when combined with catfish production resulted in total gross production of 21,469 kg/ha in pond 2 and 18,715 kg/ha in pond 4. Foodsize average harvest weights ranged from 670 to 894 g, with survival rates ranging from 86 to 98 %, and having weight gain per day (WGD) of 1.74 to 3.22 g/day. Raceway stocker unit achieved harvest weights ranging from 173 g to 186 g, with survival rates ranging from 75 to 90% and having WGD from 1.02 to 1.37 g. In general, efficient FCRs were achieved in all growout and stocker hybrid Catfish IPRS units. Hybrid Catfish raised in IPRS demonstrated excellent fish inventory control, promoted uniform hybrid Catfish production, with 90 to 95% of the foodfish harvested in the preferred premium size range. Production strategies for inclusion of co-cultured tilapia along with the catfish IPRS systems were achieved with little investment and operating costs, resulting in overall positive net returns. Ponds housing IPRS catfish units plus a tilapia cage had reduced investment payback periods, increased net present value and higher internal rates of return.

Keywords: dissolved oxygen, filter feeder, fingerlings, net return, plankton, profitability

4.1 Introduction

In Pond Raceway systems (IPRS) are an aquaculture production approach initiated at Auburn University in the early 1990's (Yoo et al., 1995; Masser and Lazur, 1997). Its concept has continued to improve through controlled and field research ever since (Masser, 2012, 2004; Masser and Lazur, 1997; Brown et al., 2014; Fern, 2014; Stuckey, 2015; Bott et al., 2015). These research studies aimed at developing and establishing a profitable catfish production system for possible fish farm adoption. IPRS systems consist of floating or fixed floor rectangular raceways (RW) assembled or placed into existing earthen ponds. Raceways are equipped with a water exchange and aeration device (White Water Unit, WWU) which supplies raceway units with a constant supply and flow of aerated water through the fish growth area and allows for high density culture of fish within each raceway cell.

IPRS RWs generally occupy less than 2% of pond surface area but do need the entire pond for waste assimilation. Use of continually operated WWUs improved water mixing and circulation, and enhanced assimilation of fish waste loads. Rapid assimilation of the waste load placed on the pond by intensive feeding allows for a considerable improvement in pond water quality which can lead to substantial increases in production yield, compared to traditionally managed catfish ponds. This constant water flow has led to an improved production environment and more predictable management of fish stocks.

Research results using IPRS are described for many fish species, including the Bluntnose Black Bream, Channel Catfish, Yellow Catfish, and Largemouth Bass in China (Wang et al., 2019), hybrid Catfish and Channel Catfish in U.S. (Brown et al., 2011; Roy et al., 2019), and tilapia (*Oreochromis niloticus*) in Mexico (Arana et al., 2018). In the U.S., Brown et al. (2014) demonstrated economic feasibility of IPRS and advantages on a commercial farm producing catfish in RW cells, while also producing Paddlefish *Polyodon spathula* and Nile Tilapia

Oreochromis niloticus as co-cultured species in the open pond. This approach of using a co-culture species showed benefits to water quality management and profitability. Co-cultured species graze on the natural productivity of the pond, thereby potentially reducing the likelihood of off-flavor (through consumption of blue-green algae responsible for off-flavor) and the possibility for large diurnal fluxes in dissolved oxygen that have been observed in similar systems (Brown et al., 2014).

The deficiency in detailed, comprehensive production and economic data on farming fish in IPRS makes it difficult for farmers to make adoption decisions. Adoption of this new technology requires knowledge of capital investments which is greater than the alternatives of making no changes to the farm or implementing other alternatives such as split ponds or increasing aeration. For these reasons, production of catfish using IPRS systems continue to be evaluated under controlled operational protocols.

Tilapia is the third most produced fish species in the world (FAO, 2020) and production in the U.S. was 6,548 metric tons in 2018 (NMFS, 2021). Tilapia is the fifth most popular fish species among U.S. consumers, while catfish is the eighth most popular fish. The latter fish's production is very important to catfish producers and regional economies in the southern region of the U.S. (USDA, 2021). Alabama, Arkansas, and Mississippi produced 137 thousand metric tons of catfish in 2020, which is 93% of all catfish produced in U.S. (USDA, 2021).

Efficiency improvements in catfish farming must continue to keep it profitable in the competitive world of fish supply and demand. IPRS trials have and must continue to demonstrate a reliable, intensive fish production technology, if it is to be employed by finfish aquaculture industries worldwide. The goal of this work was to provide a descriptive case study evaluating fish growth performance and economic efficiency in IPRS. It details the results of using two sizes of IPRS RW units using two stocking density approaches to raise stocker and foodsize hybrid Catfish

(Channel Catfish, *Ictalurus punctatus*, ♀ x Blue Catfish, *I. furcatus*, ♂); and to demonstrate the possibility of polyculture with co-culture production of an herbivorous fish species, tilapia (*Oreochromis niloticus*).

4.2 Material and Methods

This case study was carried out in a total of 1.6 ha pond surface area at the E.W. Shell Fisheries Center, Auburn, Alabama, U.S. Hybrid Catfish fingerlings were obtained from a commercial supplier in Mississippi (Jubilee Farms, Indianola, Mississippi). For the trials, one floating IPRS growout unit was placed into each of four 0.4 ha ponds (RW1, RW2, RW3 and RW4), with each growing stocker size fish (greater than 27.2 g) to foodsize fish (greater than 0.454 kg). The IPRS growout units in ponds 1 and 2 were 63 m^3 (4.9 m wide, 10.7 m long and 1.2 m water depth), and in ponds 3 and 4 were 45 m^3 (3.1 m wide; 12.2 m long and 1.2 m water depth). A smaller 14 m^3 (1.8 m x 5.8 m x 1.30 m) IPRS stocker unit was located next to the growout unit in each of the four 0.4 ha ponds. The stocker unit's function was to grow fingerlings (equal or less than 15.2 cm or 27.2 g) to stocker size in one season for stocking the growout production unit in the next cycle. An additional 36 m^3 cage (4.2 m x 7.2 m x 1.20 m) was placed immediately downstream of the growout and stocker units and stocked with tilapia purchased from Weissinger Lakes, AL in two of the four ponds (pond 2 and pond 4). The tilapia cages did not have any aeration devices in them.

Each pond had a total of 5.0 HP (12 HP/ha) in blower motor used for aeration, water flow and water mixing (Figure 4.1). A WWU is composed of a diffuser grid, hood, and blower motor set on two floats. One 1.5 HP blower propels the airlift apparatus at the entrance of the growout unit RW by injecting air into the diffuser grid creating small air bubbles that rises and expand as they travel to the water surface. This creates an upward water flow that is directed by the hood to flow through the raceway production area and exits the RWs at the far end into the pond. In the pond corner perpendicular to the IPRS unit, one 1.5 HP WWU was placed to sustain water movement, destratify the pond water column, and increase pond oxygen levels. Additionally, one 1.0 HP WWU blower propelled water in the pond (located diagonally from the growout unit) and one 1.0 HP WWU blower propelled the airlift apparatus at the entrance of the stocker unit RW. A 55 m long and 1.5 m high baffle fence or "curtain" made of woven plastic fiber was installed diagonally inside each pond to direct the water circulation around the entire pond (Figure 4.1).

We hypothesized that stocking similar numbers of fish either in the small or large growout unit RWs would result in similar production levels, on a per hectare basis. Thus, RW1 and RW2 (63 m^3) were each stocked with 8,269 fish, a stocking density of 131 fish/m^3, equivalent to 20,433 fish/ha. RW3 and RW4 (45 m^3) were each stocked with 8,230 fish, a stocking density of 204 fish/m^3, equivalent to 20,336 fish/ha. The difference being the density within the two sizes of raceways.

4.2.1 Water Quality

Water quality parameters such as dissolved oxygen, temperature (YSI Pro 20i) and pH (YSI EcoSense^R pH 10A) were measured twice a day, at 8 am and 4 pm. Other pond water parameters (total ammonia, chloride, CO_2, nitrite, secchi disk, total alkalinity and total hardness were monitored twice a month using a Lamotte water quality test kit. Once a month water from each open pond was collected for quantification of total suspended solids (Boyd and Tucker, 2014), phytoplankton and cyanobacteria biovolume (Utermohl, 1958).

4.2.2 Fish Performance

Hybrid Catfish, mean weight 308.2 g, were stocked into growout IPRS units in May 2019. These large stockers were the product of the prior year's stocker unit. Hybrid Catfish fingerlings, mean weight 28.8 g, were stocked into the stocker IPRS units in June 2019. Tilapia fingerlings, mean weight 120.8 g, were stocked in July 2019. Hybrid Catfish were fed a 32% crude protein floating commercial catfish pellet (4 to 6 mm) for 186 days (growout) and 142 days (stocker). Fish were fed twice a day depending upon water temperature. Each feeding event lasted for 5 to 10 minutes, until near satiation of fish was met. Tilapia were not fed and allowed to graze the phytoplankton flow generated by the growout and stocker units.

For each raceway unit and tilapia cage, total production biomass was recorded (the total weight harvested at the end of the production cycle) and used to calculate biomass gain by subtracting the total weight stocked from it. Net feed conversion ratio (Net FCR) for each raceway was calculated by dividing the amount of feed fed by biomass gained for each unit. Weight gain per day was calculated by dividing the individual weight gain in grams by the total number of production days. Yield, as kg/ha, was determined by the total biomass of catfish harvested per raceway divided by the pond area. Net yield, as kg/ha, was determined by dividing the total biomass gain of catfish in each raceway (and tilapia in two of the four ponds) by the pond area. Survival (%) was determined by the number of fish harvested divided by the number of fish stocked x100.

4.2.3 Economic Analysis

For each pond, variable costs, fixed costs, and net return above all costs was calculated from the developed enterprise budgets using investment and industry input prices (Table 4.1 and 4.2). Variable costs were calculated from all production inputs used during the production cycle period multiplied by their unit costs. Depreciation, investment loan interest, repairs-maintenance, taxes, and insurance were calculated for the budget’s fixed costs. Separate enterprise budgets were calculated for the growout unit, the stocker unit, and the tilapia unit. The cost of producing a unit,

$/kg, of catfish or tilapia was calculated by dividing the total cost (variable + fixed costs) by the quantity of fish harvested. Long-term profitability of each pond RW system was calculated using standard methods (Engle, 2010), and included net return above all costs, payback period (PBP), net present value (NPV), and internal rate of return (IRR).

A two-way sensitivity analysis on net return was created varying fish and feed prices. To determine the average base fish selling price, we calculated the weighted average using the quantity of each fish class size harvested multiplied by their respective sales price and dividing overall sum by the total quantity of all fish harvested. The weighted average price used in this sensitivity analysis was $2.44/kg (base price), and to be able to reflect market risk we decreased and increased the base price ($2.04, $ 2.24, $2.64, and $ 2.84/kg) by $0.20 cents/kg. The feed price used in these sensitivity analyses were based on the average feed price from January 2016 - June 2021 ($430/MT - base price) and $50/MT increments were made to reflect market risks ($380, $480 and $530/MT).

4.3 Results

4.3.1 Water Quality

Water quality remained acceptable throughout the production cycle (Table 4.3). Some spikes in afternoon pH (9.0 to 9.5) and toxic ammonia (0.42 to 0.65 mg/L) occurred and were followed by very low nitrite levels (maximum level of 0.8 NO_2- mg/L in pond 4). Dissolved oxygen concentrations in ponds were often low in the early morning hours during summer months, which is normal for a high-density production system (Figures 4.2 and 4.3). Pond 1 had oxygen lower than 3 mg/L for 13 days, pond 2 for 3 days, pond 3 for 8 days, and pond 4 for 79 days. In pond 4, 18 of 79 days had DO levels below 2 mg/L.

However, inside the raceways, oxygen levels rarely fell below 3 mg/L. In raceway 1 there were 9 days below this level, in raceway 2 there was only 1 day, in raceway 3 there were 2 days, and in raceway 4 there were 40 days (38 days DO was between 2 and 3 mg/L and 2 days below 2 mg/L). Pond 4 also had the lowest Secchi disk transparency measurement (0.12-0.15 m) resulting from heavy phytoplankton blooms (Figure 4.4b).

Water temperature changed predictably by season and varied from 28.1 to 28.7 ºC during spring months (May to June), 29.9 to 30.3 ºC during summer months (July to August), and 23.8 to 24.0 ºC during fall months (September to November). Total alkalinity in study ponds ranged from 40 to 150 ppm/$CaCO_3$, hardness ranged from 50 to 130 mg/$CaCO_3$, and pond chloride concentrations ranged from 200 to 600 ppm.

Tilapia fingerlings were stocked into their cages in ponds 2 and 4 on July 24 and were harvested on October 22, after 90 days. During this tilapia production period, total suspended solids peaked in summer for ponds 1 and 3 with no tilapia (Figure 4.4a) and declined or maintained relatively stable levels in ponds 2 and 4 with tilapia (Figure 4.4a). The total phytoplankton biovolume also peaked in pond 3, and was stable in ponds 1 and 2, and slightly elevated in pond 4. (Figure 4.4b). Water quality samples showed that in the months that tilapia were produced almost all phytoplankton in the pond were identified as cyanobacteria (Figure 4.5a), and its abundance was very high in all ponds, with and without tilapia production (Figure 4.5b). Unfortunately, with the lack of replicates and variability no statistical conclusion can be made, but biologically there seems to be an effect of the filter feeding tilapia on the pond’s algae population in the two ponds in which they were produced.

4.3.2 Fish Performance

Production results for growout, stocker and tilapia are detailed in Tables 4.4, 4.5 and 4.6, respectively. Hybrid Catfish were stocked using similar numbers of fish into the growout and stocker raceway units and had similar results. Foodsize fish had gross and net yields ranging from 13,472 to 15,799 kg/ha and 6,238 kg/ha to 9,182 kg/ha, respectively (Table 4.4). Stocker gross and net yields ranged from 3,083 kg/ha to 4,790 kg/ha and 2,396 kg/ha to 4,081 kg/ha respectively (Table 4.5). The combined growout and stocker hybrid production was 19,712 kg/ha in pond 1, 19,302 kg/ha in pond 2, 19,426 kg/ha in pond 3, and 16,555 kg/ha in pond 4 (Table 4.7). The same number of tilapia were stocked into the two cages and resulted in similar production levels in ponds 2 and 4. Gross and net tilapia yield were 2,167 kg/ha and 917 kg/ha (pond 2) and 2,160 kg/ha and 1,023 kg/ha (pond 4), and when combined with catfish production resulted in total gross production of 21,469 kg/ha in pond 2 and 18,715 kg/ha in pond 4.

Average feeding rates for catfish growout units ranged from 129.7 to 152.8 kg/ha/day (Table 4.4) with maximum feeding rates ranging from 243 to 306 kg/ha/day. Stocker feeding rates ranged from 29.9 to 44.8 kg/ha/day with maximum rates ranging from 48 to 50 kg/ha/day (Table 4.5). Tilapia had a harvest weight and weight gain, respectively, of 314.4 g, 187.8 g (pond 2) and 329.3 g, 214.2 g (pond 4). No commercial feed was fed to tilapia, they only gained weight from grazing plankton available in the effluents flowing from the growout and stocker catfish raceways (Table 4.6). No FCR could be calculated for tilapia due to the lack of formulated feed input. Tilapia survival ranged from 67 to 70% and had WGD ranging from 2.09 to 2.38 g/fish/day.

Average growout harvest weight of hybrid Catfish ranged from 670 to 894 g after186 days of production, with survival rates ranging from 86 to 98 %, and weight gain per day (WGD) ranged from 1.74 to 3.22 g/day (Table 4.4). The pond that had the lowest yield (pond 4) also had the lowest WGD (1.74 g/day) leading to the least efficient feed conversion ratio (FCR) of 1.80 (pond

4). Even though pond 4 had the lowest production performance, 90% of harvested fish were within the desired premium size range (0.454 to 1.82 kg). Ponds 1, 2 and 3 had 90 to 95% of harvested fish in the premium size range. Only pond 1 produced fish in the large size category (3%), which are fish greater than 1.82 kg. Average harvest stocker weight ranged from 181 g to 223 g, after 142 days of production, with survival rates ranging from 75 to 90% and WGD ranged from 1.02 to 1.37 g (Table 4.5). In general, efficient FCRs were achieved in all growout and stocker hybrid Catfish IPRS units.

4.3.3 Economic Analysis

Investment costs for the IPRS system/ponds are presented as capital or machinery-equipment items. In ponds 1 and 2, capital investment costs, including land, pond construction, and IPRS RW cells (growout and stocker RWs) was $29,403 for a 63 m^3 raceway[3], plus an additional $800 for the tilapia cage ($30,203) in pond 2 (Table 4.2). In ponds 3 and 4, total investment for a 45 m^3 growout raceway unit[4] was $10,403 in ponds 3 and 4, plus an extra $800 for the tilapia cage ($11,203) in pond 4 (Table 4.2). Stocker unit (14 m^3) placed into ponds 1, 2, 3 and 4 cost $1,867 each. Machinery and equipment investment costs were $10,593 and $10,793 for the larger and smaller growout raceways, respectively. The 45 m^3 stocker units had an extra $200 cost for a longer boardwalk to access the raceways. Total capital plus machinery-equipment investment totaled $39,996, $40,796, $21,196, and $21,996 for ponds 1, 2, 3 and 4, respectively.

Gross receipts for foodsize catfish raised in the IPRS growout units were $15,458, $14,955, $14,372, and $13,230 for RWs 1, 2, 3 and 4, respectively. Gross receipts for stocker catfish were

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[3] The 63 m^3growout raceway unit cost $25,000 to manufacture by a private welding company. Aluminum was used for the frame and walkways, and high-density polyethylene (HDPE) materials for the liner.
[4] The 45 m^3 growout raceway unit cost $6,000 and was constructed in-house with wood, wire and HDPE materials.

$3,759, $3,923, $4,602, and $2,962 for stocker units 1, 2, 3 and 4, respectively. Tilapia gross receipts were $9,666 in pond 2 and $9,628 in pond 4. Growout, stocker and tilapia enterprise budgets are summarized in Table 4.8 for each pond. Detailed enterprise budgets are provided for growout (Appendix A), stocker (Appendix B) and tilapia (Appendix C).

Enterprise budgets indicated positive incomes above variable cost for ponds 2, 3 and 4, but negative for pond 1 (Table 4.8). When fixed costs were added, positive net returns above all costs occurred for ponds 2 and 4 (ponds that housed catfish growout and stocker units and tilapia cages) and negative net return for ponds 1 and 3 that only produced catfish in growout and stocker units. The economic break-even price range to cover variable plus fixed costs ranged from $2.75 to $3.24/kg for growout and ranged from $2.70 to $3.69/kg for stockers (Table 4.8). As the price paid to producers by the processing plant ranged from $2.40 to 2.46/kg, economic losses occurred in all pond units for growout and stockers analyzed separated (Appendices 1 and 2); however, ponds 2 and 4 became positive when tilapia production was added into the budget (Table 4.8). The lowest total costs to produce hybrid Catfish was $2.75/kg in RW3 (Table 4.8), while for stockers the lowest total cost was $2.70/kg of fish also in RW3 (Table 4.8).

Financial feasibility indicators were calculated from developed cash flows and led to positive results for ponds 2 and 4 (catfish plus tilapia), and negative results for ponds 1 and 3 (catfish only). This can be explained by the greater production in these ponds leading to greater receipts, notably in the ponds co-culturing tilapia in cages (Table 4.9). It is clear from Table 4.9 that ponds housing a tilapia cage had enhanced returns and positive outcomes. Ponds 2 and 4 ha positive cash flows (Figure 4.6), with payback periods (PBP) of 4.2 and 4.9 years, net present values (NPV) of $29,444 and $7,024, and internal rates of return (IRR) of 16.5 and 20.7 %, respectively. Negative net returns resulted in negative cash flows for ponds 1 and 3 (Figure 4.6) which made PBPs negative, and impossible to calculate an IRR, as the calculation equation must contain at least one positive value to calculate the IRR.

4.4 Discussion

4.4.1 Water Quality

When water quality is maintained, fish production levels can be increased. In the IPRS system, dynamic flowing water created a mixed water column that, combined with efficient, plentiful aeration, better manages dissolved oxygen at the pond bottom and surface for better biological oxidation of fish and feed wastes. Even though DO concentrations in Pond 4 were low for 38 of the 186 summer days inside the raceways, and for 61 days in the pond water (between 2 and 3 mg/L), no fish mortalities occurred, though it possibly affected growth rates. This pond (pond 4) had the lowest biomass at harvest, the lowest final harvest weight, and also the lowest weight gain per day for both production growout and stocker units. In case of energy failure, generators and other backup systems need to be in place and ready for use to maintain adequate oxygen levels. The combination of elevated total alkalinity, total hardness, and chloride concentrations was thought to have been beneficial for fish production and equated to a more balanced and stress-free fish rearing environment.

A variety of filter-feeding organisms have been proposed for controlling algal populations in aquaculture ponds (Smith, 1985; Laws and Weisburd, 1990). Silver carp, *Hypophthalmichthys molitrix*, and Nile Tilapia have been considered effective in suppressing cyanobacterial blooms in eutrophic lakes (Miura, 1990; Starling and Rocha, 1990; Starling, 1993), in sedimentation ponds (Ma et al., 2010), and also in studies using zooplankton biomanipulation to control algal blooms in farm-pond catfish aquaculture (Belfiore et al., 2021). A study conducted by Turker et al. (2003) showed that Nile Tilapia filter feeding significantly reduced several green algae and two cyanobacteria taxa in a partitioned aquaculture system. In our study, tilapia possibly reduced or helped avoided spikes in the phytoplankton community, and consequently, in the cyanobacteria algae community in ponds that had co-cultured tilapia.

Masser (2004) looked at alternative biological waste reduction systems, including tilapia, freshwater mussels, submerged bead biofilters, and/or artificial wetlands in in-pond raceways systems. He surmised that tilapia and mussels could be placed in a separate section of the in-pond raceway, downstream from the primary species, and be allowed to feed on wastes and filter plankton from the raceway effluent without any additional feed costs. In his research, tilapia densities were 400 fish/m^3 and mussel densities were 500 mussels/m^3. These organisms survived, grew, and removed settleable solids, resulting in an approximate three-fold increase in solids reduction over the tube settlers alone. However, total settleable solids reduction was only about 30% of estimated production (Masser, 2004).

Most of the algae identified in the samples for the catfish production was cyanobacteria (Figure 4.5a) and, usually they are the most common causes off-flavor problems in pond-raised catfish, and aquaculture in general (Tucker and Schrader, 2020). Relatively few species of cyanobacteria produce odorous compounds and cause flavor problems in pond-grown catfish, and odor-producing populations are not always present (Tucker and Schrader, 2020). This case study measured some phytoplankton and solids measurements to potentially see if tilapia altered their levels, but we did not identify cyanobacteria species, as our focus was on IPRS production and economic viability analyses.

4.4.2 Fish Performance

Our production results for hybrid Catfish raised in IPRS system were similar for ponds 1, 2 and 3 (Tables 4.4 and 4.5). The best results occurred when tilapia production was included (Pond

2), but no major improvement was found in Pond 4 that also had tilapia. This was probably related to water quality as there were low dissolved oxygen concentrations in the morning throughout the production cycle. Brown et al. (2011) achieved hybrid Catfish harvest weights of 49,913 kg from their six 45 m^3 raceway study, or 20,540 kg/ha for the 2.43 ha pond in which the system was located. Their total Channel Catfish and hybrid Catfish harvest weights were 18,240 kg (7,506 kg/ha) and 31,673 kg (13,034 kg/ha), respectively. In the same study, Brown harvested 2,406 kg (990 kg/ha) of paddlefish and 3,959 kg (1,629 kg/ha) of tilapia as co-cultured fish in the open pond (not in cages), while Brune et al. (2004) harvested additional co-cultured tilapia of 2,284–5,034 kg/ha/year in their partitioned aquaculture system.

One of the objectives for adding a stocker unit to each pond was to generate enough stocker fish numbers to stock into the next year's growout raceways. A study done by Roy et al. (2019) used different initial sizes of fish (catfish and hybrids) to simulate a staggered production situation, where harvests could thus be staggered and fish could be marketed throughout the year. When they stocked larger fingerlings (175 g) for the first production cycle, their net yield was higher in four of the five cells, suggesting that larger fingerlings result in higher production. For our stocker units, fingerlings grew to stocker size, having an average harvest weight of 190 g (28 cm). The objective of having enough fish (stockers) to stock the next growout cycle was mostly met, as the number of harvested fish from stocker unit 1 (8,654 fish or 21,384 fish/ha), unit 2 (8,781 fish or 21,698 fish/ha), and unit 3 (8,590 fish or 21,226 fish/ha). The harvest number of stockers were lower than desired, but would be sufficient to start a new production cycle. In this study, we originally stocked approximately 9,700 stockers per growout raceway, so the number of stockers were about 1,000 fish short from stocker units 1, 2, and 3. Additionally, stocker numbers from unit 4 were even less, at 7,119 fish (17,591 fish/ha) than our stocking density criteria to begin a new production cycle, by about 2,600 fish. While this number is low, it could work as the fish would likely grow to a larger size and provide similar harvest weights for the receipts calculation of the enterprise budget.

Producing larger fish requires different management protocols from those currently in common use in the industry. Larger catfish (0.68 to 0.90 kg) would require additional grow-out time and a corresponding rise in operational expenses (D'Abramo et al., 2006). These authors suggested that a fingerling-to-stocker pond phase would be beneficial and in one treatment they stocked fingerlings approximately 10.2 to 15.2 cm (23 to 27 g) and grew them to a stocker size (92 g) during a 6-7 month period. Southworth et al. (2006) stocked 13 to 15 cm (16 g) Channel Catfish at 17,300/ha and they reached a mean weight of 497 g in 6.7 months (single batch production). In our study, we stocked 15.6 cm fingerlings (28.8 g) that grew to 183 to 198 g in 142 days (4.7 months).

Feed conversion ratios for hybrid and Channel Catfish in IPRS was improved (1.42 to 1.80) over FCRs reported from commercial Channel Catfish farms using and single- and multiple-batch production systems (1.91 to 2.63) (Hanson et al., 2020). D'Abramo et al. (2013) reported an FCR of 1.97 for channel Catfish produced in a single batch system. Brown et al. (2011) raised catfish in a commercial-scale IPRS, reporting average FCRs for Channel and hybrid Catfish at 1.74 and 1.36, respectively.

4.4.3 Economic Analysis

In pond raceway system (IPRS) can be used where open pond aquaculture is not feasible or advantageous, emphasizing that the ideal use of IPRS is where there are already existing water bodies, and the only expenses would be for the raceways and associated components. In these situations, land acquisition and pond construction costs would not be required, thus keeping the initial investment for an IPRS operation low (Masser, 2004).

Total variable costs were 83 to 87% of total costs, and fixed cost were 13 to 17% of total costs. Fixed costs were composed of a land charge, depreciation (on capital, machinery and equipment items[5]), interest on capital and machinery-equipment loans, repairs, and maintenance, taxes, and insurance. As fixed items, they cannot be changed in the short-term, so we decided to conduct sensitivity analyses on the variable feed item, through altering feed prices. Likewise, we could alter fish selling price for the sensitivity analysis as well. Feed prices play a major role in the high percentage of the variable feed costs and fish selling prices on receipts received. Current prices for fish going to processing plants is $2.86/kg (average of June to October 2021) (Hanson, 2021b). In our study time period, we used $2.46/kg for prime sized fish, indicating how prices can fluctuate.

We used feed and fish price sets covering the January 2016 to June 2021 period for the sensitivity analysis. The average feed price was for commercial bulk feed containing 32% crude protein and the weighted average price paid by processors covered small, premium and large sized catfish (Table 4.10). Sensitivity analysis results showed the effects on net returns above all cost for the four IPRS pond setups when fish and feed prices varied. This includes the setups for IPRS including hybrid Catfish growout and stocker units, and where tilapia were present or not. Results indicated that 85% of the price combinations for pond 2 and 50% of those price combinations for pond 4 had positive net returns. None of the price combinations resulted in positive net returns for pond 1, and only 20% of the combinations were positive for pond 3. At current feed prices ($430/MT), fish prices would need to increase by $0.40 cents/kg to achieve positive net returns in Pond 3. The only two additional positive net return outcomes for Pond 3 occurred when the fish

[5] Equipment costs included a backup generator (20 kW plus transfer switch), propane tank for generator, electrical line for white water movers, tractors, trucks, mower, electrical aerators, power take-off aerator, feeder, feed bin, pump, office, shop, tools, utility trailer, storage container, dissolved oxygen meter, and computer.

price remained the same ($2.84/kg) and feed prices would decline by $50 or $100/MT (Table 4.10). Feed prices are dependent on soybean meal and corn prices as they are the primary components of fish feed, so as their prices change during the crop growing season, the price of catfish feed typically follows those trends.

Strategies producing less than 5,700 kg/ha make catfish production a riskier business and less likely to be profitable (Hanson, 2019). Alternative intensification culture practices have resulted in greater yields than those achieved in traditional open catfish ponds (Kumar et al., 2018). Our research showed breakeven fish selling price ranged from $2.75 to $3.24/kg for foodsize fish and from $2.70 to $3.69/kg for stocker fish (Table 4.8, see Total Costs $/kg cells). As the price paid to producers by processing plants ranged from $2.40 to 2.46/kg, economic losses occurred in all pond units (growout and stocker). Accounting profits, i.e., those that do not consider many of the fixed costs, for pond 2 was $9,562 and pond 4 was $2,298 (Table 4.9). Negative accounting profits were determined for ponds 1 and 3.

Breakeven selling price ($/kg, or Cost of Production, $/kg) is the minimum price one needs to receive to cover all variable and fixed costs. It was calculated by dividing the total cost (variable + fixed costs) for the growout unit by the quantity of fish harvested. Breakeven catfish price for pond 1 was $3.04/kg and compared to the growout selling price of $2.44/kg showed a $0.60/kg loss; and for pond 3 the breakeven price was $2.75/kg and a loss of $0.31/kg. For ponds 2 and 4 the breakeven prices were $2.84 and 3.24/kg, respectively, compared to actual selling prices of $2.46 and $2.43/kg, respectively, resulted in $0.38 and $0.79/kg losses.

The breakeven yield (kg) is the quantity of fish production needed to breakeven economically. It was calculated by dividing the total costs by the fish selling price. For the two ponds with tilapia, the breakeven catfish yield for pond 2 was 7,032 kg and the actual harvest was

6,087 kg which was 945 kg less yield than needed to breakeven economically; and for pond 4 the breakeven yield was 7,126 kg and the actual harvest was 5,389 kg, which was 1,737 kg less than the yield needed to breakeven economically. Breakeven yield for pond 1 was 9,829 kg and the actual harvest was 7,885 kg which was 1,944 kg less yield than needed to breakeven economically; and for pond 3 the breakeven yield was 8,710 kg and the actual harvest was 7,770 kg, which was 940 kg less than the yield needed to breakeven economically. An important point to highlight in our study is that both stocker hybrid Catfish and tilapia were stocked in the IPRS (June and July) relatively late and could have reached higher production levels if they had been stocked into RW units in late Spring or early Summer. Foodsize and stocker production needs to be targeted to meet these breakeven yields. It is clear that the addition of tilapia as a caged co-culture species outside of the raceways increased marketable biomass and helped surpass breakeven yields required for the system to be profitable.

Results by Brown et al. (2014) pointed out that using tilapia and paddlefish as co-products added enough receipts to increase marginally profitable catfish net returns to positive net returns. This co-product result could be the deciding factor for a farmer who is interested in using IPRS technology (Brown et al., 2014). Brown highlighted two main advantages of using co-cultured species: 1) it improved water quality management and 2) it improved profitability. Co-cultured species graze on the natural productivity of the pond, thereby potentially reducing the likelihood of off-flavor to the primary catfish species, and possibly mitigates large diurnal fluxes (e.g., in dissolved oxygen) that have been observed in similar systems. In addition, production of a greater biomass of marketable product with minimal associated costs could increase profitability if there is a ready market for the co-cultured fish species (Brown et al., 2014).

The economic viability of a production system can be determined using methods based on cash flows over several years, allowing the calculation of Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Periods (Frezatti, 2008; Engle, 2010; Kay et al., 2020). Successful businesses must be profitable, that is, have a cost of production lower than its selling price. In addition, businesses must have positive and increasing net worth over time; and businesses must have adequate cash flow to pay debts on time. Inadequate cash flow can result in business failure. Because cash flow measures the timing of cash receipts and expenses, it is a prime determinant of liquidity. Cash flow statements include only cash items and leave out non-cash items, such as depreciation (Engle, 2010; Engle, 2012a), as we have calculated and reported in our cash flow results section. Ponds 2 and 4 had a positive annual cash flows over the ten years of projected operation, but Ponds 1 and 3 annual cash flows were negative overall. Although Pond 4 had negative cash flow in years 4, 7 and 10 due to replacement costs, the overall cash flow was positive. The new borrowing was for replacement of items that had reached their useful life of 3 years, such as the blowers, pumps, baffle fence material, and floats.

4.5 Conclusion

We achieved remarkably consistent production results across all IPRS. Hybrid Catfish raised in IPRS had very high counts at harvest compared to the stocking number, demonstrating excellent fish inventory control with this technology. IPRS promoted uniform hybrid Catfish production, with 90 to 95% of the foodfish harvested in the preferred premium size range. Feed conversion ratios ranged between 1.42 to 1.80 for stockers and foodsize hybrid Catfish. Production strategies for inclusion of co-cultured tilapia along with the catfish IPRS systems were achieved with little investment and operating costs, resulting in overall positive net returns. Polyculture production of catfish and tilapia provide an opportunity to reach diverse niche marketing segments.

Ponds housing IPRS catfish units plus a tilapia cage had reduced investment payback periods, increased net present value, and higher internal rates of return.

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Table 4.1 Per-unit value or cost used in the development of In Pond Raceway System (IPRS) enterprise budgets for stocker and foodsize hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and tilapia (*Oreochromis niloticus)*, 2019.

Description	Unit	Value or Cost ($) per unit
Catfish prices/Value		
Stockers stocked into growout unit	kg	2.40
Fingerling stocked into stocker unit	each	0.16
Harvest size sales price		
Small < 0.454 kg	kg	2.40
Premium: 0.454 - 1.82 kg	kg	2.46
Large: > 1.82 kg	kg	2.01
Stocker Inventory Value price	kg	
Stocker < 0.454 kg	kg	2.40
Stocker > 0.454 kg	kg	2.46
Tilapia Price		6.61
Fingerlings	each	0.80
Harvest size sales price	kg	6.61
Feed		
32% crude protein	metric ton	430
Management and labor		
Management	ha/year	600
Hired labor	hour	10.00
Chemicals		
Lime, agricultural	metric ton	50.00
Lime, hydrated	kg	0.62
Salt	metric ton	135.00
Copper sulfate	22.68-kg bag	65.00
	per kg	2.87
Rotenone	L	13.00
Formalin	208.19 L drum	440
	L	2.11
Diquat	L	3.00
Potassium permanganate	kg	11.63
Fuel		
Gasoline off-road price for agriculture	L	0.72
Diesel price off-road	L	0.79
Electricity, per kWhr at off-peak rate	kW-hour	0.07
Other		
Insurance	ha	2.53
Miscellaneous expenses	cycle	200.00
Bird netting for 2 raceways	roll	163.00

Fish price was determined by calculating an average using prices from January 2016 to June 2021 for small (<0.454 kg), premium (0.454 - 1.82 kg), and large (> 1.82 kg) catfish sizes catfish (Hanson, 2021).

Table 4.2 Investment costs for land, pond construction and In-Pond Raceway System (IPRS) capital, machinery, and equipment items used for raising stocker and foodsize hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) and tilapia (*Oreochromis niloticus)*, in the 0.4 ha ponds, 2019.

Items	U.S. $	Investment			
		Quantity	63 m^3 IPRS	Quantity	45 m^3 IPRS
Capital Items					
Land, $/ha	2,031	0.49	986	0.49	986
Pond construction[a], $/ha	3,830	0.40	1,550	0.40	1,550
RW 1 and 2 (4.9 m x 10.7m x 1.2 m = 63 m^3)	25,000	1	25,000	-	-
RW 3 and 4 (3.0 m x 12.2m x 1.2 m = 45 m^3)	6,000	-	-	1	6,000
RW 1, 2, 3 and 4 "stocker unit" (1.8 m x 5.8 m x 1.30 m = 14 m^3)	1,867	1	1,867	1	1,867
Pond 2 and 4 tilapia cages (4.2 m x 7.2 m x 1.20 m)	800	1	800		800
Subtotal			30,203		11,203
Machinery and Equipment					
Equipment[b], $/ha	3,739	0.40	1,513	0.40	1,513
1.0 HP blower for white water unit (pond)	880	1	880	1	880
1.5 HP blower for white water unit (pond)	1,200	1	1,200	1	1,200
1.5 HP blower for growout RW unit	1,200	1	1,200	1	1,200
1.0 HP blower for stocker RW unit	900	1	900	1	900
White water unit (for 1.0 HP blower)	1,200	1	2,500	1	2,500
White water unit (for 1.5 HP blower)	2,500	1	1,200	1	1,200
Baffle fencing and floats	200	1	200	1	200
Boardwalks - RW 1 and 2	1,000	1	1,000	-	-
Boardwalks - RW 3 and 4	1,200	-	-	1	1,200
Subtotal			10,593		10,793
TOTAL			40,796		21,996

[a] Includes construction of pond with water supply, drainage, and electrical service, but no wells because they are seldom used on western Alabama catfish farms. Their water source is from watershed runoff.

[b] Equipment costs include backup generator (20 kW plus transfer switch), propane tank for generator, electrical line for white water movers, tractors, trucks, mower, electrical aerators, power take-off aerator, feeder, feed bin, pump, office, shop, tools, utility trailer, storage container, dissolved oxygen meter, computer, and generator.

Table 4.3 Water chemistry results from within foodsize raceways and surrounding pond water when raising hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) in four 0.4 ha In-Pond Raceway Systems, and tilapia (*Oreochromis niloticus*), in the same pond, 2019.

	Pond 1	RW 1	Pond 2	RW 2	Pond 3	RW 3	Pond 4	RW 4
DO range, mg/L	2.0 – 12.3	2.3 – 12.3	2.6 – 13.4	2.9 – 12.3	2.0 – 12.3	2.9 – 12.2	1.0 – 12.7	1.8 – 12.7
Temperature °C	12.0 – 33.3	12.0 – 33.1	12.0 – 33.6	12.0 – 33.6	12.0 – 33.5	12.0 – 33.4	12.0 – 33.2	12.0 – 32.4
Total alkalinity	–	62 – 150	–	40 – 82	–	40 – 102	–	40 – 110
Total hardness	–	80 – 130	–	50 – 90	–	80 – 100	–	80 – 120
Chloride	–	400 – 600	–	200 – 300	–	350 – 550	–	350 – 550
pH	–	7.4 – 9.0	–	7.9 – 9.5	–	7.8 – 9.4	–	7.4 – 9.2
TAN mg/L	–	0.2 – 6.0	–	0.0 – 1.2	–	0.2 – 0.6	–	0.2 – 3.6
NH_3 mg/L	–	0.01 – 0.42	–	0.00 – 0.22	–	0.00 – 0.24	–	0.00 – 0.65
NO_2- mg/L	–	0.0 – 0.4	–	0.0 – 0.3	–	0.0 – 0.1	–	0.0 – 0.8
Secchi disk (m)	0.15 – 0.30	–	0.24 – 0.38	–	0.16 – 0.40	–	0.12 – 0.15	–

* DO = dissolved oxygen inside the raceway - minimum and maximum; Temperature = minimum and maximum; Total alkalinity range (as ppm $CaCO_3$); Total hardness range (as ppm $CaCO_3$); Chloride concentration as ppm = minimum and maximum; pH = inside the raceway, afternoon range; TAN (Total Ammonia Nitrogen) = maximum afternoon range; NH_3 (Ammonia) = maximum afternoon range; NO_2- (Nitrogen Dioxide) = maximum afternoon range; Secchi disk depth level during summer and early fall. RW = Raceway.

Table 4.4 Growout growth performance of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in IPRS (In-Pond Raceway System) raceways placed in 0.4 ha ponds, 2019.

	Raceway 1 63 m^3	Raceway 2 63 m^3	Average Raceways 1 and 2 (standard error)	Raceway 3 45 m^3	Raceway 4 45 m^3	Average Raceways 3 and 4 (standard error)
Production cycle (days)	186	186	186	186	186	186
Number of fish stocked	8,222	8,317	8,269 (47)	8,126	8,334	8,230 (104)
Stocking density (fish/m^3)	131	132	131 (1)	181	185	204 (23)
Stocking density (fish/ha)	20,317	20,550	20,433 (117)	20,079	20,593	20,336 (257)
Mean weight at stocking (g)	295	291	293 (2.3)	300	348	324 (24.0)
Stocking biomass (kg)	2,961	2,414	2,688 (273.3)	2,433	2,894	2,663 (230.6)
Mean weight at harvest (g)	894	815	854 (0.04)	737	670	704 (0.03)
Total harvested (kg)	6,320	6,087	6,203 (116.3)	5,854	5,389	5,622 (232.7)
Yield[a] (kg/ha)	15,799	15,218	15,508 (291)	14,636	13,472	14,054 (582)
Net yield[b] (kg/ha)	8,397	9,182	8,790 (392)	8,554	6,238	7,396 (1,158)
Standing crop at harvest (kg/m^3)	100.3	96.6	98.8 (1.8)	130.1	119.8	124.9 (5.2)
Total harvest (number)	7,072	7,467	7,269 (280)	7,946	8,037	7,992 (45)
Feed fed (kg)	11,249	10,165	10,707 (542)	9,543	9,700	9,621 (79)
Net FCR[c]	1.78	1.67	1.73 (0.06)	1.63	1.80	1.72 (0.09)
Average feeding rate (kg/ha/day)	152.8	138.1	145.5 (7.4)	129.7	131.8	130.7 (1.1)
WGD[d] (g/fish/day)	3.22	2.82	3.02 (0.2)	2.35	1.74	2.04(0.3)
Survival (%)	86.0	89.8	87.9 (0.02)	97.8	96.4	97.1 (0.01)

[a] Yield = Total harvested, kg / Pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / Pond size, 0.4 ha

[c] Net FCR (Feed conversion ratio) = Feed fed, kg / (Total harvested, kg – Stocking biomass, kg)

[d] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 4.5 Stocker growth performance of hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in the IPRS (In-Pond Raceway System) "stocker unit" raceways placed in 0.4 ha ponds, 2019.

	Raceway 1 14 m^3	Raceway 2 14 m^3	Average Raceway 1 and 2 (standard error)	Raceway 3 14 m^3	Raceway 4 14 m^3	Average Raceway 3 and 4 (standard error)
Production cycle (days)	142	142	142	142	142	142
Number of fish stocked	9,706	9,797	9,752 (46)	9,845	9,549	9,697 (148)
Stocking density (fish/m^3)	693	700	697 (3)	703	682	693 (11)
Stocking density (fish/ha)	23,984	24,208	24,096 (112)	24,327	23,596	23,961 (366)
Mean weight at stocking (g)	28.8	28.8	28.8 (0.0)	28.8	28.8	28.8 (0.0)
Stocking biomass (kg)	280	282	281 (1.3)	284	275	279 (4.3)
Mean weight at harvest (g)	181	186	183 (2.6)	223	173	198 (24.9)
Total harvested (kg)	1,565	1,634	1,599 (34)	1,916	1,233	1,575 (341.4)
Yield[a] (kg/ha)	3,912	4,084	3,998 (85.8)	4,790	3,083	3,937 (853.5)
Net yield[b] (kg/ha)	3,213	3,378	3,295 (82.6)	4,081	2,396	3,239 (842.9)
Standing crop at harvest (kg/m^3)	111.8	116.7	114 (2.5)	136.9	88.1	112.5 (24.4)
Total harvest (number)	8,654	8,781	8,718 (63)	8,590	7,119	7,854 (735)
Feed fed (kg)	2,057	1,919	1,988 (68.8)	2,547	1,696	2121 (425.3)
Net FCR[c]	1.60	1.42	1.51 (0.09)	1.56	1.77	1.67 (0.11)
Average feeding rate (kg/ha/day)	36.2	33.8	35.0 (1.2)	44.8	29.9	37.3 (7.5)
WGD[d] (g/fish/day)	1.07	1.11	1.09 (0.02)	1.37	1.02	1.19 (0.18)
Survival (%)	89.2	89.6	89.4 (0.00)	87.2	74.6	80.9 (0.06)

[a] Yield = Total harvested, kg / Pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / Pond size, 0.4 ha

[c] Net FCR (Feed conversion ratio) = Feed fed, kg / (Total harvested, kg – Stocking biomass, kg)

[d] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 4.6 Growth performance of tilapia (*Oreochromis niloticus*), raised in cages placed immediately downstream of hybrid Catfish IPRS (In-Pond Raceway System) production cells in 0.4 ha ponds, 2019.

	Tilapia Cage 36 m^3	
	Pond 2	Pond 4
Production cycle (days)	90	90
Number of fish stocked	4,000	4,000
Stocking density (fish/m^3)	111	111
Stocking density (fish/ha)	9,884	9,884
Mean weight at stocking (g)	126.5	115.1
Stocking biomass (kg)	506	460
Mean weight at harvest (g)	314.4	329.3
Weight gain (g)	187.8	214.2
Total harvested (kg)	877	874
Total harvest (number)	2,791	2,665
WGD[a] (g/fish/day)	2.09	2.38
Survival (%)	70%	67%

[a] WGD (Weight gain per day) = (Mean weight at harvest, g – Mean weight at stocking, g) / Production cycle, days

Table 4.7 Summary of growth performance of foodsize, stocker fingerlings hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) raised in the IPRS (In-Pond Raceway System) and tilapia (*Oreochromis niloticus*), raised in cages residing in the same 0.4 ha pond, 2019.

	Pond 1	Pond 2	Pond 3	Pond 4
Growout total harvested (kg)	6,320	6,087	5,854	5,389
Growout yield[a] (kg/ha)	15,799	15,218	14,636	13,472
Growout net yield[b] (kg/ha)	8,397	9,182	8,554	6,238
Stockers total harvested (kg)	1,565	1,634	1,916	1,233
Stocker yield[a] (kg/ha)	3,912	4,084	4,790	3,083
Stocker net yield[b] (kg/ha)	3,213	3,378	4,081	2,396
Tilapia total harvested (kg)	-	877	-	874
Tilapia yield[a] (kg/ha)	-	2,167	-	2,160
Tilapia net yield[b] (kg/ha)	-	917	-	1,023
Total yield (kg/ha)	19,712	21,469	19,426	18,715

[a] Yield = Total harvested, kg / pond size, 0.4 ha

[b] Net yield = (Total harvested, kg – Stocking biomass, kg) / pond size, 0.4 ha

Table 4.8 Summary enterprise budgets for four In-Pond Raceway System (IPRS) producing foodsize plus stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, and tilapia (*Oreochromis niloticus*), in each 0.4 ha pond, U.S.$, 2019*.

	Pond 1		Pond 2		Pond 3		Pond 4	
	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg	Value or cost	Value or cost/kg
1. Receipts / Sales								
Growout catfish, kg	15,458	2.45	14,955	2.46	14,372	2.45	13,230	2.45
Stocker Inventory Value, kg	3,759	2.40	3,923	2.40	4,602	2.40	2,962	2.40
Tilapia	0	0.00	9,666	11.02	0	0	9628.2	11.02
Total Receipts	19,217	2.44	28,544	3.32	18,974	2.44	25,820	3.44
2. Variable Cost								
Growout catfish	16,406	2.60	14,483	2.38	14,244	2.43	15,601	2.89
Stocker catfish	3,462	2.21	3,456	2.12	3,854	2.01	3,235	2.62
Tilapia	0	0	3,460	3.86	0	0	3,460	3.96
Total Variable Cost, $	19,867	2.52	21,398	2.49	18,098	2.33	22,296	2.97
3. Income Above Variable Cost								
Growout catfish	-948	-0.15	472	0.04	128	0.02	-2,371	-0.44
Stocker catfish	298	0.19	468	0.29	748	0.39	-273	-0.22
Tilapia	0	0.00	6,206	7.16	0	0.00	6,169	7.06
Total Income Above Variable Cost, $	-650	-0.08	7,146	0.83	876	0.11	3,524	0.47
4. Fixed Costs								
Growout catfish	2,816	0.45	2,816	0.46	1,860	0.32	1,860	0.35
Stocker catfish	1,274	0.81	1,274	0.78	1,312	0.84	1,312	1.06
Tilapia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Fixed Costs, $	4,090	0.52	4,124	0.48	3,172	0.41	3,206	0.43
5. Total Costs								
Growout catfish	19,221	3.04	17,299	2.84	16,104	2.75	17,461	3.24
Stocker catfish	4,736	3.03	4,729	2.90	5,166	2.70	4,547	3.69
Tilapia	0	0.00	3,494	3.88	0	0.00	3,494	3.99
Total Costs	23,957	3.04	25,522	2.97	21,270	2.74	25,501	3.40
6. Net Return Above All Costs								
Growout catfish	-3,763	-0.60	-2,344	-0.39	-1,732	-0.30	-4,231	-0.79
Stocker catfish	-996	-0.62	-806	-0.49	-564	-0.29	-1,585	-1.29
Tilapia	0	0.00	6,172	7.14	0	0.00	6,135	7.03
Total Net Return, $	-4,740	-0.60	3,022	0.35	-2,296	-0.30	319	0.04

Total Net Returns, combined growout, stocker and tilapia. Note that tilapia cage was placed in ponds 2 and 4 only., therefore ponds 1 and 3 presents 0 values. Per kg values are weighted averages by values/cost and quantity of each output. *Some columns of number may not add up as presented due to integer rounding.

Table 4.9 Financial measures of profitability for producing foodsize and stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂), in In-Pond Raceway Systems (IPRS), and tilapia (*Oreochromis niloticus*) raised in cages (Ponds 2 and 4 only) placed immediately downstream of hybrid Catfish IPRS production cells in 0.4 ha ponds, U.S.$, 2019.

Item	Pond 1	Pond 2	Pond 3	Pond 4
Financial net return, U.S.$	-5,679	9,562	-4,090	2,298
Investment cost, U.S.$	39,996	40,796	21,196	21,996
Payback period, year	-7.0	4.2	-2.5	4.9
Net present value, U.S.$	-78,691	29,444	-38,823	7,024
Internal rate of return, %	-	16.5	-	20.7

*Using a discount rate of 5%.

Table 4.10 Effects of different feed and fish prices on net returns for growout (63 m^3 or 45 m^3) plus stocker unit (14 m^3) producing hybrid Catfish (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂) in In-Pond Raceway Systems (IPRS), and tilapia (*Oreochromis niloticus*) raised in cages (Ponds 2 and 4 only) placed immediately downstream of hybrid Catfish IPRS production cells in 0.4 ha ponds, U.S.$, 2019.

Feed price $/MT	Fish price $/kg	Net returns U.S.$			
		Pond 1	Pond 2	Pond 3	Pond 4
380	2.04	(7,200)	564	(4,809)	(1,736)
	2.24	(5,623)	2,108	(3,255)	(411)
	2.44	(4,046)	3,652	(1,701)	913
	2.64	(2,469)	5,196	(147)	2,238
	2.84	(892)	6,740	1,407	3,562
430	2.04	(7,893)	(66)	(5,439)	(2,329)
	2.24	(6,317)	1,478	(3,885)	(1,005)
	2.44	(4,740)	3,022	(2,331)	320
	2.64	(3,163)	4,567	(777)	1,644
	2.84	(1,586)	6,111	777	2,969
480	2.04	(8,587)	(695)	(6,069)	(2,923)
	2.24	(7,010)	849	(4,515)	(1,599)
	2.44	(5,433)	2,393	(2,961)	(274)
	2.64	(3,856)	3,937	(1,407)	1,050
	2.84	(2,279)	5,481	148	2,375
530	2.04	(9,280)	(1,325)	(6,699)	(3,517)
	2.24	(7,703)	219	(5,145)	(2,192)
	2.44	(6,126)	1,763	(3,591)	(868)
	2.64	(4,549)	3,307	(2,036)	456
	2.84	(2,972)	4,851	(482)	1,781

Net return was calculated using budgets, including cost of producing stockers from previous years. Shaded cells represent positive net returns. [a] Feed prices was determined by calculating an average of the price farmers paid for 32% crude protein (bulk feed) over the January of 2016 to June of 2021 ($430/MT). For the last year, the average of feed price is $520/MT which is covered in this sensitivity analysis. [b] Fish price was determined by calculating an average of the price processors paid for live fish from the producer over the January of 2016 to June of 2021 period for small ($2.40/kg), premium ($2.46 /kg), and large ($2.01/kg) catfish sizes (Hanson, 2021). An overall average price (small, premium, and large) of $2.86/kg was been paid by the processors in the last year (September of 2020 to August of 2021).

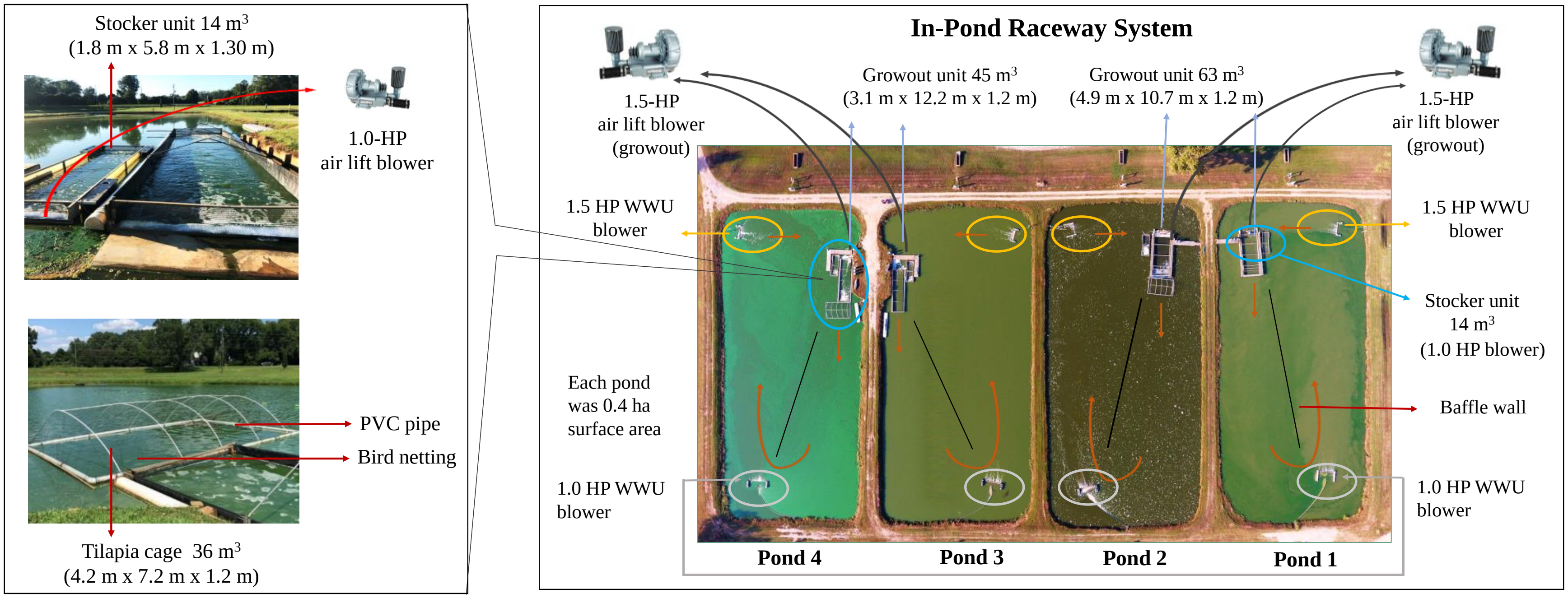

Figure 4.1 Aerial view of the four 0.4 ha ponds including the four growout and four stocker IPRS units per pond. Growout raceways RW1 and RW2 (63 m^3) in Ponds 1 and Pond 2 respectively were larger than raceways RW3 and RW4 (45 m^3) in Pond 3 and Pond 4 respectively. Stocker unit raceways were all 14 m^3 in volume. In each pond, a fabric curtain, called a baffle "wall", extended from the IPRS outflow to at least 2/3 of the distance of the pond diagonal, reaching from the pond bottom to just above water level and was suspended by floats. This curtain guided water circulation around the pond and toward the second and third White Water Unit devices (WWU) before re-entering the IPRS unit's fish growth area. Tilapia cage (36 m^3) was placed immediately downstream of the production cells stocked in Ponds 2 and 4. Original aerial photo by David Cline.

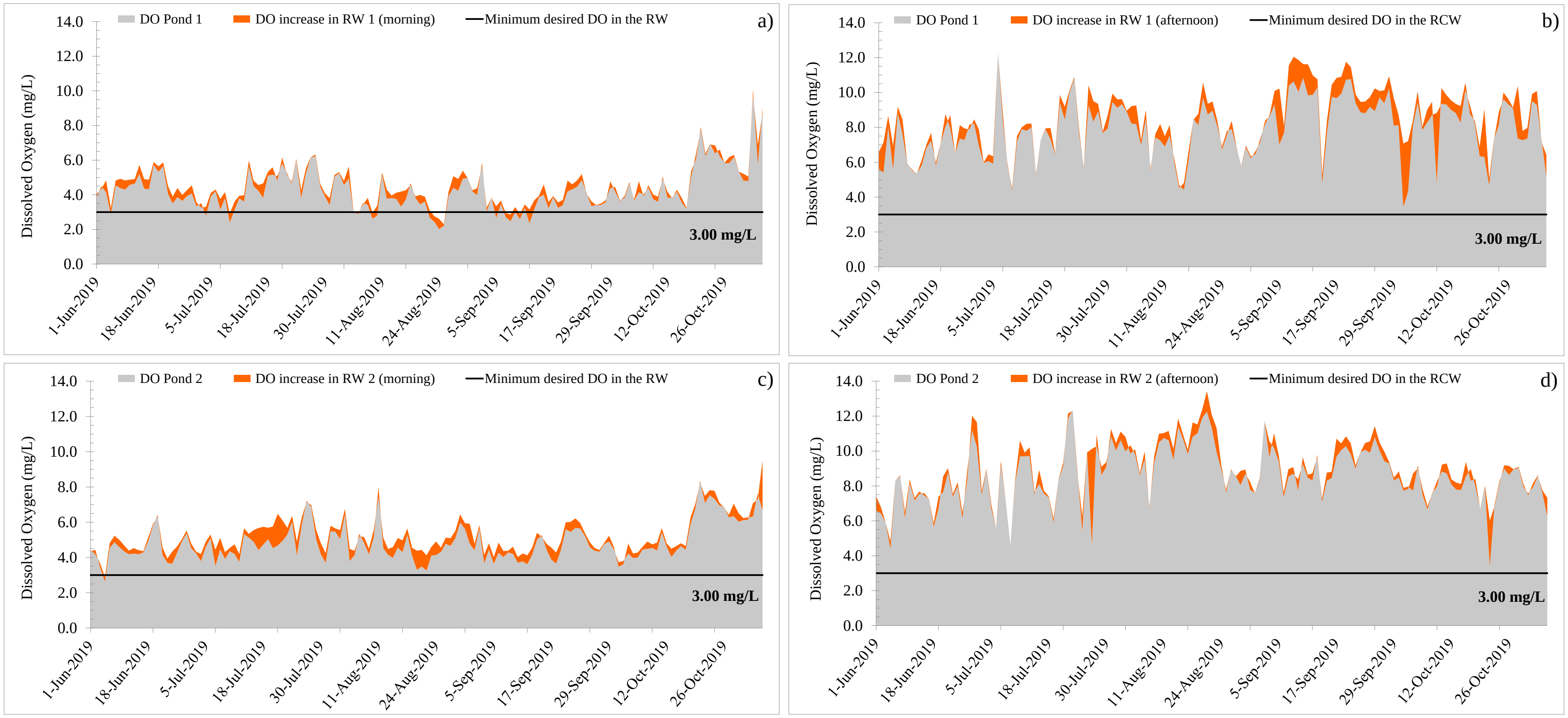

Figure 4.2 Illustration of the early morning (left) and afternoon (right) dissolved oxygen concentrations in the pond (light grey) and inside growout raceways (orange) RW1 (a and c) and RW2 (b and d). The orange area above the light grey area indicates how much more oxygen the IPRS aeration device added to the water at the entrance of the raceway, keeping dissolved oxygen levels inside the raceway at or above 3 mg/L (minimum desired level), seldom below 2 mg/L, and regularly above the outside pond water, 2019. DO = Dissolved oxygen mg/L.

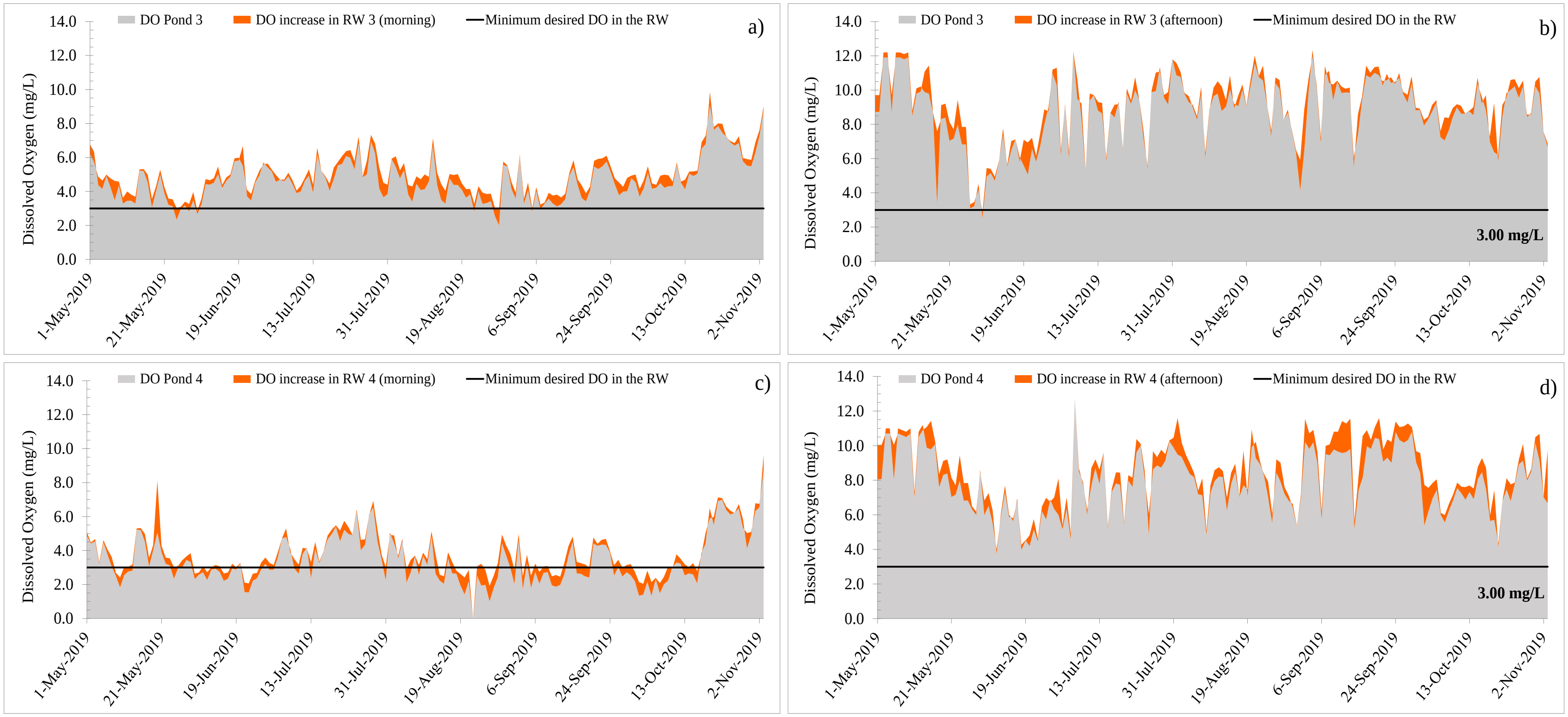

Figure 4.3 Illustration of the early morning (left) and afternoon (right) dissolved oxygen concentrations in the pond (light grey) and inside growout raceways (orange) RW3 (a and c) and RW4 (b and d). The orange area above the light grey area indicates how much oxygen the IPRS aeration device added to the water at the entrance of the raceway, keeping dissolved oxygen levels inside the raceway at or above 3 mg/L (minimum desired level), seldom below 2 mg/L, and regularly above the outside pond water, 2019. DO = Dissolved oxygen mg/L.

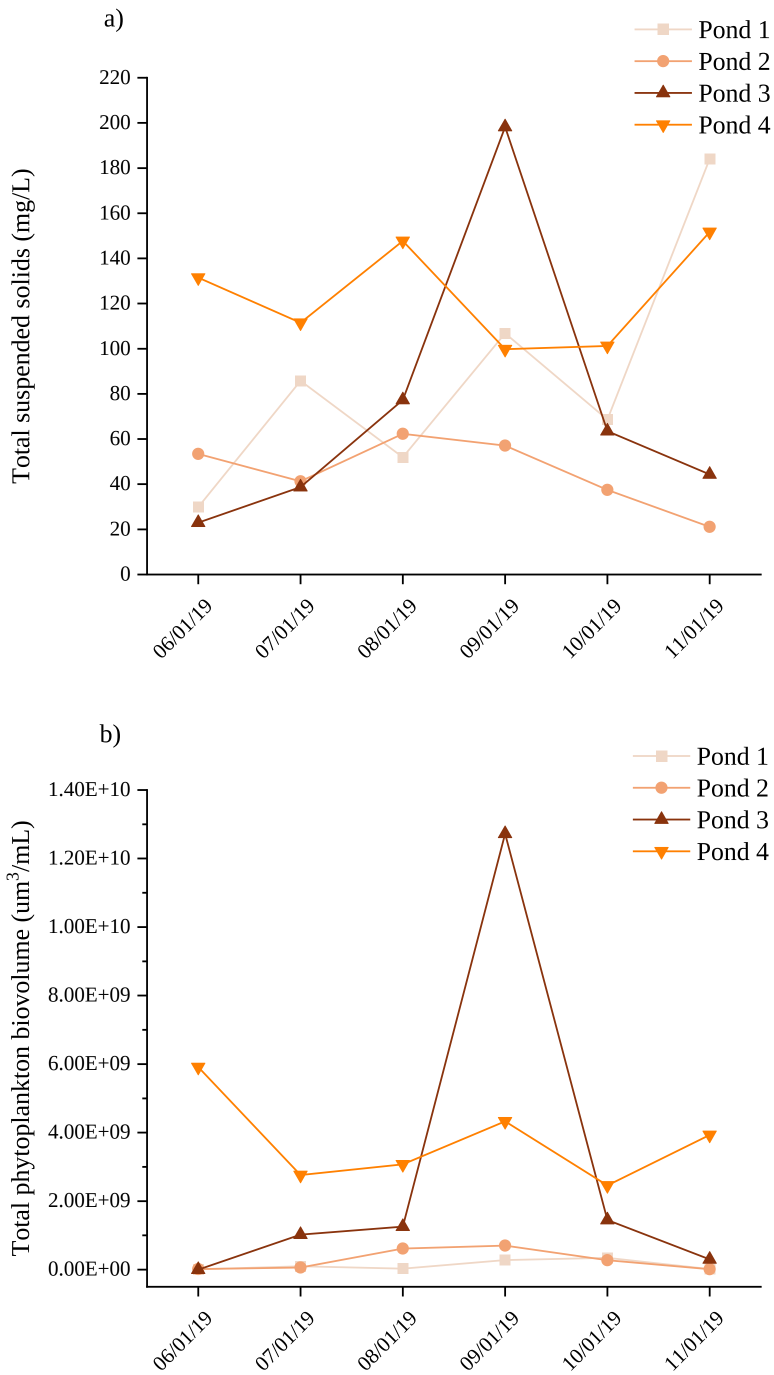

Figure 4.4 a) Total suspended solids (mg/L) and b) Total phytoplankton biovolume (um^3/mL) of ponds producing foodsize and stocker hybrid Catfish, (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂), in In-Pond Raceway Systems (IPRS) Ponds 1, 2, 3 and 4, and tilapia (*Oreochromis niloticus*) raised in cages (Ponds 2 and 4 only) located immediately downstream of the hybrid Catfish IPRS production cells in 0.4 ha ponds.

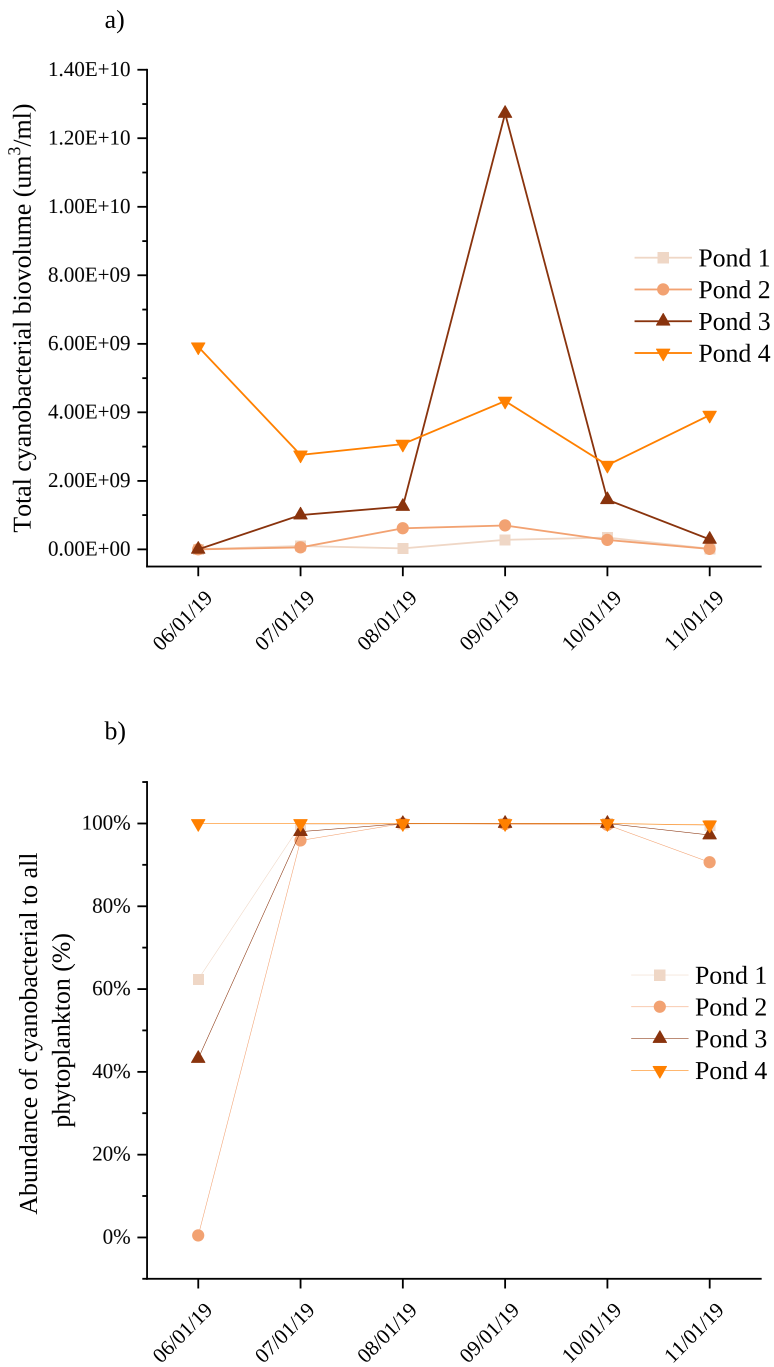

Figure 4.5 a) Total cyanobacterial biovolume (um^3/mL) and b) abundance of cyanobacteria to all phytoplankton (%) of ponds producing foodsize and stocker hybrid Catfish, (Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂), in In-Pond Raceway Systems (IPRS), and tilapia (*Oreochromis niloticus*) raised in cages (Ponds 2 and 4 only) located immediately downstream of hybrid Catfish IPRS production cells in 0.4 ha ponds.

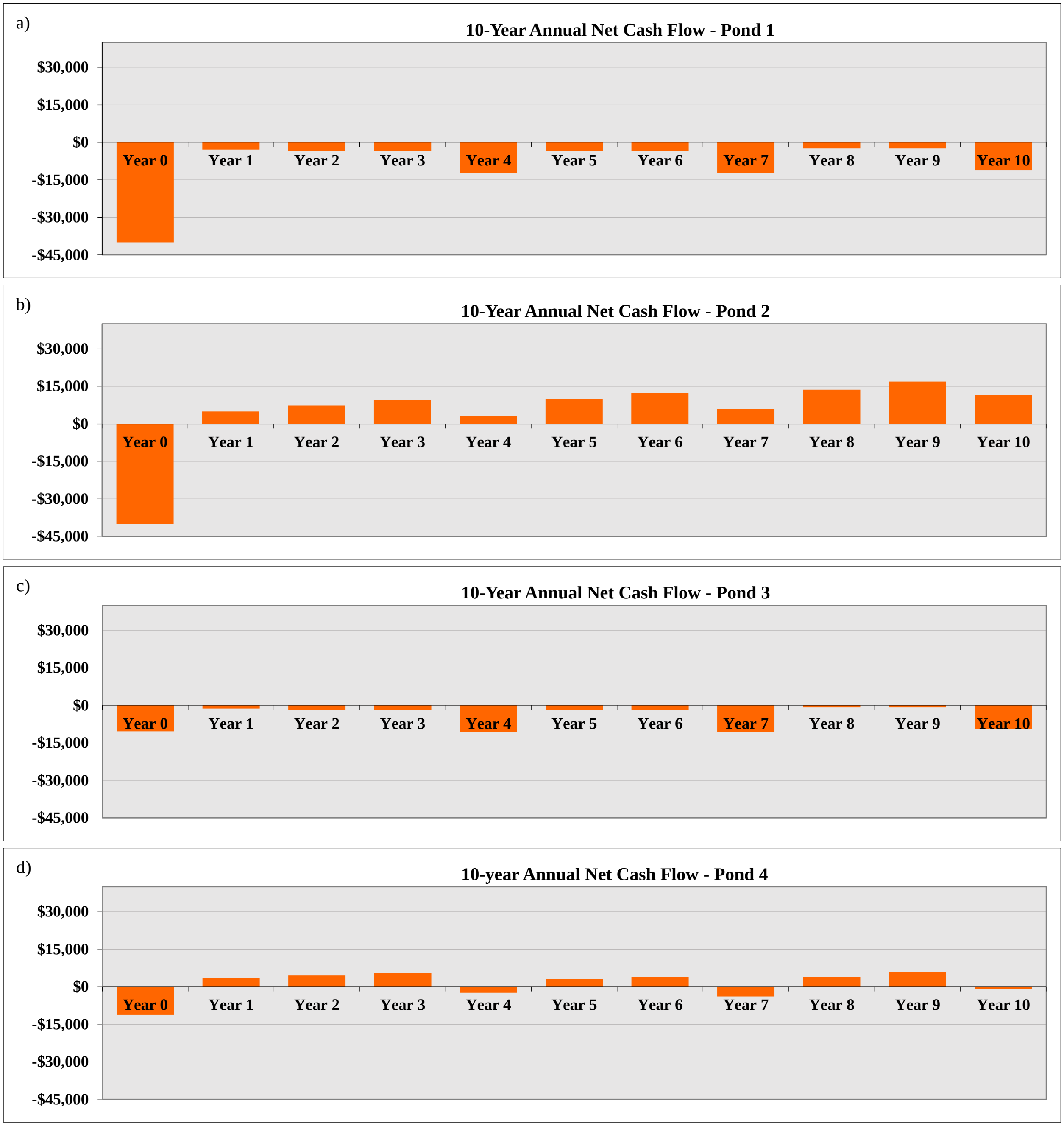

Figure 4.6 Long term annual net cash flow for producing foodsize and stocker hybrid Catfish (in In-Pond Raceway Systems, and tilapia raised in cages located immediately downstream of hybrid Catfish IPRS production cells in 0.4 ha ponds, U.S.$, 2019. Pond 1 includes a 63 m^3 RW (growout) + 14 m^3 RW (stocker) (Figure 4.6.a); Pond 2: 63 m^3 RW (growout) + 14 m^3 (stocker) + 36 m^3 tilapia cage (Figure 4.6.b); Pond 3: 45 m^3 RW (growout) + 14 m^3 RW (stocker) (Figure 4.6.c); Pond 4: 45 m^3 RW (growout) + 14 m^3 RW (stocker) + 36 m^3 tilapia cage (Figure 4.6.d).

Chapter 5.

Conclusion

This dissertation and the series of four studies demonstrate the applicability of IPRS in the catfish industry, as growth performance and economic analyses show that it can be efficient and profitable on a pilot scale, especially with higher fish selling prices seen in 2020 and 2021. Results show profitability depends on supply and demand that affect fish prices, and also on the IPRS investment level. Unfortunately, highly intensive systems are often stricken by disease outbreaks or low oxygen levels which require a specialized technician or a knowledgeable fish culturist-farmer to succeed. Relying on WWUs requires reliable generators be in place and ready for use in case of energy failure to avoid fish mortalities in a very short period of time. Thus, IPRS systems do pose a risk level greater than traditional earthen pond production systems, where low oxygen levels can be mitigated over a period of hours, rather than minutes as is often the case with IPRS systems. If water quality can be maintained, production levels can be increased. In the IPRS system, dynamic flowing water creates a mixed water column that, combined with efficient, plentiful aeration, better manages dissolved oxygen at the pond bottom and surface for better biological oxidation of fish and feed wastes.

Study 1 and 2 conclusions were that IPRS hybrid Catfish yields surpassed those from traditional catfish pond systems. Initial raceway cost had a great impact on the long-term feasibility of the system. White-water units kept homogeneous temperature and oxygen levels in pond water columns. IPRS catfish feed conversion ratios were more efficient than in traditional pond systems. Hybrid Catfish had better growth performance and economic returns than Channel Catfish.

Study 3 conclusions were that hybrid Catfish yields from the IPRS stocker generator and foodsize raceways surpassed those from traditional catfish pond systems albeit in a pilot scale system. Again, initial raceway cost had a great impact on the long-term feasibility of the IPRS system. Raceways made with less expensive materials had a higher profit potential but were characterized by a shorter economic life. Lower initial farm level investment reduced the payback period, increased net present values, and internal rates of return. Feed conversion ratios ranged between 1.62 to 1.8 for stockers and foodsize hybrid Catfish produced in the IPRS systems.

Study 4 conclusions were that we achieved remarkably consistent production results across all IPRS units. Hybrid Catfish raised in IPRS units had very high counts at harvest compared to the stocking number, demonstrating excellent fish inventory control with this technology. IPRS promoted uniform hybrid Catfish production, with 90 to 95% of the foodfish harvested in the preferred premium size range. Feed conversion ratios ranged between 1.42 to 1.80 for stockers and foodsize hybrid Catfish. Production strategies for inclusion of co-cultured tilapia along with the catfish IPRS systems were achieved with little investment and operating costs, resulting in overall positive net returns. Polyculture production of catfish and tilapia could provide an opportunity to reach diverse niche marketing segments. Ponds housing IPRS catfish units plus a tilapia cage had reduced investment payback periods, increased net present values, and higher internal rates of return.

IPRS is a promising technology that addresses issues that have been troubling the U.S. catfish industry for decades. For our research ponds, the initial investments were high, which would need to be offset by increased production and increased receipts (assisted with higher niche fish selling prices) and reduced variable costs stemming from very good feed conversion ratios. Further investigations into increasing production, reducing production time, improving efficiency, and lowering the initial investment are warranted.

The IPRS is becoming known and adopted in China, Vietnam, India, Egypt, Colombia, and Mexico. In recent years, the interest in and use of IPRSs by the fish farming industry in China have increased. To date, there are more than 6,000 IPRS cells in production. The fish species that have been reared in IPRS include Grass carp *Ctenopharyngodon idella*, Bluntnose black bream *Megalobrama amblycephala*, Largemouth Bass *Micropterus salmoides*, Yellow Catfish *Tachysurus (Pelteobagrus) fulvidraco*, Channel Catfish *Ictalurus punctatus*, and tilapia *Oreochromis spp*. In the U.S., only a few farmers attempted the IPRS method of raising catfish with dubious results. Most potential adopters were concerned with high initial investment costs, new style of production, and risks of high mortalities, and financial risk it could place on the farm. Market conditions are always changing and presently catfish are scarce causing the processors to pay more to producers for their fish. Under current fish selling and feed prices, the IPRS is potentially profitable, that is, if the high fish prices were to continue. The truth is that traditional catfish production in earthen ponds is an expensive business which requires summer of intensive labor and a more relaxed approach in winter. This is not what an IPRS system would require, as it would involve continual watchfulness over twelve months of the year, and this does not fit everyone's lifestyle in the U.S. farm-raised catfish industry.

Future IPRS research might include fecal waste collection and removal devices, allowing higher fish stocking and feeding rates, while still keeping pond water quality at adequate levels. An additional aeration device inside the raceways could improve dissolved oxygen levels in the culture cell, benefiting fish condition, growth, survival and feed efficiency. Therefore, a waste collection and removal device plus additional aeration in the raceways might be effective structural adjustments for increasing fish yields and improving FCR, as raceway and pond water quality should be better preserved. Better water quality, continuous adoption of preventative management practices (earlier control of parasites and improved nutrition), and prompt action at the onset of bacterial outbreaks should reduce fish losses and improve overall fish yields. However, these additions add costs that must be overcome with advanced planning. One approach would be to calculate the weight of fish required to breakeven economically and adjust stocking rates (plus mortality) to achieve levels of production that are profitable. Intensive fish farm systems are in constant states of evolution, and the same is true for IPRS technology.

Appendix A Growout enterprise budgets using the cost of stocker production from prior year, for four IPRS producing foodsize hybrid Catfish with each raceway placed in a 0.4 ha pond, U.S.$, 2019*.

	RW 1 – 63 m^3		RW 2 – 63 m^3		RW 3 – 45 m^3		RW 4 – 45 m^3	
	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg
Catfish Sales								
Small, <0.454 kg	296	2.40	994	2.40	1,406	2.40	1,294	2.40
Primium:0.454-1.82 kg	14,772	2.46	13,961	2.46	12,966	2.46	11,935	2.46
Large > 1.82 kg	389	2.01	0	2.01	0	2.01	0	2.01
Total	15,458	2.45	14,955	2.46	14,372	2.45	13,230	2.45
Variable Cost								
Feed, 32% Protein	4,834	0.76	4,368	0.72	4,100	0.70	4,168	0.77
Labor and Management	1,134	0.18	1,116	0.18	1,066	0.18	1,151	0.21
Catfish Fingerlings	7,111	1.13	5,799	0.95	5,843	1.00	6,950	1.29
Carp Fingerlings	52	0.01	51	0.01	49	0.01	53	0.01
Harvest and Transportation	697	0.11	671	0.11	645	0.11	594	0.11
Fuel (diesel and gas)	40	0.01	39	0.01	37	0.01	40	0.01
Repairs and Maintenance	175	0.03	175	0.03	350	0.06	350	0.06
Electricity, Aeration	1,018	0.16	1,007	0.17	978	0.17	1,028	0.19
Chemicals	578	0.09	570	0.09	502	0.09	529	0.10
Miscellaneous	105	0.02	104	0.02	99	0.02	107	0.02
Interest on Operating Capital	662	0.10	584	0.10	575	0.10	630	0.12
Total Variable Cost	16,406	2.60	14,483	2.38	14,244	2.43	15,601	2.89
Income Above Variable Cost	-948	-0.15	472	0.04	128	0.02	-2,371	-0.44
Fixed Cost								
Land Charge	493	0.08	493	0.08	493	0.08	493	0.09
Depreciation on Capital Items	621	0.10	621	0.10	306	0.05	306	0.06
Depreciation on Machinery and Equipment Items	453	0.07	453	0.07	488	0.08	488	0.09
Interest on Capital Loans	617	0.10	617	0.10	162	0.03	162	0.03
Interest on Equipment Loans	134	0.02	134	0.02	137	0.02	137	0.03
Repairs and Maintenance	16	0.00	16	0.00	16	0.00	16	0.00
Taxes	477	0.08	477	0.08	254	0.04	254	0.05
Insurance	4	0.00	4	0.00	4	0.00	4	0.00
Total Fixed Costs	2,816	0.45	2,816	0.46	1,860	0.32	1,860	0.35
Total Costs	19,221	3.04	17,299	2.84	16,104	2.75	17,461	3.24
Net Return Above All Costs	-3,763	-0.60	-2,344	-0.39	-1,732	-0.30	-4,231	-0.79

* Some columns of number may not add up as presented due to integer rounding. RW = Raceway.

Appendix B Stocker enterprise budgets for four In-Pond Raceway System (IPRS) producing stocker hybrid Catfish, Channel Catfish *Ictalurus punctatus* ♀ x Blue Catfish, *I. furcatus* ♂, with each raceway placed in a 0.4 ha pond, U.S.$, 2019*.

	RW 1 – 14 m^3		RW 2 – 14 m^3		RW 3 – 14 m^3		RW 4 – 14 m^3	
	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg
Stocker Inventory/Sale Value								
Catfish Stocker <0.454 kg	3,727	2.40	3,923	2.40	4,602	2.40	2,962	2.40
Catfish Stocker > 0.454 kg	32	2.46	0.00	2.46	0	2.46	0	2.46
Total	3,759	2.40	3,923	2.40	4,602	2.40	2,962	2.40
Variable Cost								
Feed, 32% Protein	884	0.56	825	0.50	1,094	0.57	729	0.59
Labor and Management	281	0.18	299	0.18	349	0.18	264	0.21
Catfish Fingerlings	1,563	1.00	1,577	0.97	1,585	0.83	1,537	1.25
Carp Fingerlings	13	0.01	14	0.01	16	0.01	12	0.01
Fuel (diesel and gas)	10	0.01	10	0.01	12	0.01	9	0.01
Repairs and Maintenance	50	0.03	50	0.03	50	0.03	50	0.04
Electricity, Aeration	344	0.22	355	0.22	384	0.20	334	0.27
Chemicals	152	0.10	158	0.10	176	0.09	146	0.12
Miscellaneous	26	0.02	28	0.02	32	0.02	24	0.02
Interest on Operating Capital	140	0.09	139	0.09	156	0.08	131	0.11
Total Variable Cost	3,462	2.21	3,456	2.12	3,854	2.01	3,235	2.62
Income Above Variable Cost	298	0.19	468	0.29	748	0.39	-273	-0.22
Fixed Cost								
Land Charge	493	0.32	493	0.30	493	0.32	493	0.40
Depreciation on Capital Items	85	0.05	85	0.05	85	0.05	85	0.07
Depreciation for Machinery and Equipment Items	388	0.25	388	0.24	422	0.27	422	0.34
Interest on Capital Loans	53	0.03	53	0.03	53	0.03	53	0.04
Interest on Equipment Loans	122	0.08	122	0.07	124	0.08	124	0.10
Repairs and Maintenance	16	0.01	16	0.01	16	0.01	16	0.01
Taxes	114	0.07	114	0.07	115	0.07	115	0.09
Insurance	4	0.00	4	0.00	4	0.00	4	0.00
Total Fixed Costs	1,274	0.81	1,274	0.78	1,312	0.84	1,312	1.06
Total Costs	4,736	3.03	4,729	2.90	5,166	2.70	4,547	3.69
Net Return Above All Costs	-976	-0.62	-806	-0.49	-564	-0.29	-1,585	-1.29

* Some columns of number may not add up as presented due to integer rounding. RW = Raceway.

Appendix C Tilapia (*Oreochromis niloticus*) enterprise budgets for cages placed immediately downstream of hybrid Catfish IPRS (In-Pond Raceway System) production cells in 0.4 ha ponds, 2019*.

	Pond 1		Pond 2		Pond 3		Pond 4	
	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg	Value or cost	Value/Cost per kg
Tilapia Sales Value								
Tilapia	0	0	9,666	11.02	0	0	9,628	11.02
Total	0	0	9,666	11.02	0	0	9,628	11.02
Variable Cost								
Feed, 32% Protein	0	0	0	0	0	0	0	0
Labor and Management	0	0	120	0.14	0	0	120	0.14
Tilapia Fingerlings	0	0	3,200	3.65	0	0	3,200	3.66
Fuel (diesel and gas)	0	0	0	0	0	0	0	0
Repairs and Maintenance	0	0	0	0	0	0	0	0
Electricity, Aeration	0	0	0	0	0	0	0	0
Chemicals	0	0	0	0	0	0	0	0
Miscellaneous	0	0	0	0	0	0	0	0
Interest on Operating Capital	0	0	140	0.07	0	0	140	0.160
Total Variable Cost	0	0	3,460	3.86	0	0	3,460	3.96
Income Above Variable Cost	0	0	6,206	7.16	0	0	6,169	7.06
Fixed Cost								
Land Charge	0	0	0	0.00	0	0	0	0.00
Depreciation on Capital Items	0	0	19	0.01	0	0	19	0.02
Depreciation for Machinery and Equipment Items	0	0	0	0.00	0	0	0	0.00
Interest on Capital Loans	0	0	9	0.01	0	0	9	0.01
Interest on Equipment Loans	0	0	0	0.00	0	0	0	0.00
Repairs and Maintenance	0	0	0	0.00	0	0	0	0.00
Taxes	0	0	6	0.00	0	0	6	0.00
Insurance	0	0	0	0.00	0	0	0	0
Total Fixed Costs	0	0	34	0.02	0	0	34	0.03
Total Costs	0	0	3,494	3.88	0	0	3,494	3.99
Net Return Above All Costs	0	0	6,172	7.14	0	0	6,135	7.03

* Some columns of number may not add up as presented due to integer rounding. Tilapia cages were placed into an existing IPRS growout and stocker RWs, then the fixed costs for land, depreciation and interest charges were already covered for catfish, and therefore not included for the tilapia costs. Tilapia cage budget included investment, labor, tilapia fingerlings, interest on operation capital and depreciation on capitals items.