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THE EFFECT OF MULTIPLE-BATCH CHANNEL CATFISH *Ictalurus punctatus* STOCKING DENSITY AND FEEDING RATE ON WATER QUALITY, PRODUCTION CHARACTERISTICS AND COSTS

A Thesis

Submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Aquaculture/Fisheries

by

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December 2005
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Abstract

Technological improvements have allowed aquaculture and catfish production to become more intensive over time. With this increase in production intensity, catfish producers must seriously evaluate interactions among factors related to stocking density, feeding rate and water quality on costs and net returns. Little research has been done with multiple-batch production practices to quantitatively define these relationships. Twelve 0.1-ha ponds were stocked in multiple-batch with 10-15 cm fingerlings at either 8,600, 17,300, 26,000 or 34,600 fish/ha along with 2,268 kg/ha of carryover fish ranging from 0.37-0.45 kg/fish. The study consisted of three replications per treatment to constitute four treatment groups. Fish were fed daily to apparent satiation with a 32% floating commercial catfish feed. Nitrite-N, nitrate-N, total ammonia nitrogen, chlorophyll a, total nitrogen, total phosphorus, chemical oxygen demand and Secchi disk were monitored monthly, chloride three times during the study, pH weekly, and temperature and dissolved oxygen were measured twice daily. In addition, nitrite, total ammonia nitrogen, Secchi disk visibility and total alkalinity were measured in two-week intervals. Total hardness was measured for the source water and at the midpoint of the study. Weather station data were used to determine the effects of water temperature, barometric pressure and photosynthetically active radiation (PAR) on daily feed consumption. Ponds were harvested after a 196 d culture period (5 April – 17 October 2005). The overall costs of producing channel catfish at different stocking densities and the respective effect on net returns were estimated. Fingerling (< 0.95 kg), carryover (≥ 0.95 kg), marketable (≥ 0.57 kg) and sub-marketable (< 0.57 kg) mean weights at harvest indicated no significant difference due to stocking density. Fingerling and carryover growth (g/d) was not significantly different. Gross, net and net daily yields showed no significant differences at different stocking densities. However, net yield was highly correlated with mean (r = 0.98) and maximum (r = 0.85) daily feeding rates. Carryover and marketable yield was not significantly different due to stocking density. Fingerling and sub-marketable yields increased as stocking density increased with significant differences between the two highest and the two lowest stocking densities. Mean fingerling survivals ranged from 24 to 36%, whereas mean carryover survivals ranged from 77 to 94%. However, survival rates of both size groups were not significantly different. Mean and maximum daily feeding rates ranged from 40-53 kg/ha/d and 123-188 kg/ha/d, respectively and were not significantly different. Feed conversion ratios averaged 1.75 and were not significantly different among the different stocking densities. Few significant differences in water quality were found at sampling periods. Similarly, water quality variables averaged across the production season showed no significant differences among stocking densities. Net returns varied widely across the different stocking densities, with the highest net return at 26,000 fingerlings/ha. Breakeven prices to cover both variable and total costs were lower at the higher stocking densities. Weighted average breakeven prices were \$1.50, \$1.58, \$1.32 and \$1.38/kg for densities of 8,600, 17,300, 26,000 and 34,600/ha, respectively. In spite of the higher proportion of sub-marketable fish in the higher densities, the higher yields and a similar average weight resulted in lower breakeven prices. This study found few significant differences in production and water quality parameters despite testing a variety of fingerling densities. The weight of carryover fish (stocked at a constant weight) may have had an effect on both production and water quality parameters, outweighing any effect of fingerling density. This study suggests that managing ponds based on the population structure of carryover fish may be more important to overall production efficiency than strictly focusing on fingerling stocking densities, in multiple-batch production.

Dedication

For my parents, Tuffy and Sandi, for their incredible support throughout my years as an undergraduate and as a graduate student. My parents taught me to never give up and to do my very best at whatever I may do. This dedication is also for my fiancée, Jill. Together, my parents and Jill provided me with the motivation and encouragement necessary to successfully complete this graduate degree.

Acknowledgments

This material is based upon work supported in part by the State of Arkansas 1890 Matching Funds for the UAPB Aquaculture/Fisheries Center, under Project AFC04CE. Special thanks to my major advisor, Dr. Carole Engle, for her guidance, encouragement, and extreme patience. I truly appreciate everything she has done for me over the last two years. I also thank my other graduate committee members, Dr. Nathan Stone and Dr. Andy Goodwin for all the help they have given me. I also appreciate all of the help faculty, staff and students at UAPB provided me during my research.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIX TABLES

LIST OF APPENDIX FIGURES

Introduction

The channel catfish industry plays a very important role in the U.S aquaculture industry as the largest segment of aquaculture in the United States. Most catfish are grown in the southern part of the United States, and the industry is economically important to several of these states. Since its inception in the 1960's, the channel catfish industry has undergone rapid growth, and 2004 sales were at 286 million kg (USDA 2005).

Many of the methods of raising channel catfish are considered an "art" as well as a science (Tucker and Robinson 1990). Catfish management practices on commercial farms are highly variable. Across the industry, catfish farmers stock fish at densities that vary from about 4,942 to over 19,768 fingerlings/ha of water (USDA 2003). The majority of farmers feed fish to satiation with resulting maximum daily feeding rates of 109-177 kg/ha/d (96-156 lb/ac/d) depending on farm size and intensity of production. Most farmers use a multiple batch production system where ponds contain both newly stocked fingerlings and carryover fish from the last production year. A few producers raise catfish in single batches (12%) (USDA 2003). Multiple-batch systems are used because there is less risk involved with availability of fish for processors and presence of off-flavor (Engle 2003).

Farm pond environments for freshwater fish may differ substantially from natural environments with regard to water quality, temperature, and phytoplankton. To ensure that optimal conditions exist for growth and survival, aquaculture pond water and fish must be monitored constantly for trends and physical signs that may warn of future problems. Water quality parameters that must be watched closely include dissolved oxygen, carbon dioxide, nitrite, ammonia, temperature, and pH. All of these factors have the potential to change quickly and affect the growth and feeding habits of catfish. Oxygen problems can cause death in catfish if the concentration drops too low. The oxygen levels in ponds are associated with the weather, phytoplankton abundance and stocking density, and are monitored by checking oxygen concentration twice daily and applying nightly aeration as needed. Nitrite and chloride must be monitored and a 20:1 chloride to nitrite ratio will effectively prevent fish mortalities from brown blood disease (Boyd and Tucker 1998). Ammonia is toxic at high levels and must be watched closely. Ammonia has a chronic negative effect on fish at low levels, such as, reduced growth (Hargreaves and Tucker 2004; Hargreaves and Kucuk 2001; Durborow et. al 1997b). In addition, low temperature and dissolved oxygen (Boyd and Tucker 1998) levels can limit growth. Buentello et al. (2000) found weight gain of channel catfish to increase with temperature. There exists an inverse relationship with carbon dioxide and dissolved oxygen (Boyd and Tucker 1998). High concentrations of carbon dioxide and low oxygen levels are stressful for fish.

Research has been conducted on the culture of channel catfish since the 1950’s, but interactions among stocking, feeding and water quality in relation to growth, yield and feed conversion ratio (FCR) of catfish are still not well understood (Carole Engle, personal communication, University of Arkansas at Pine Bluff). Improvements in technology have allowed aquaculture to become more intensive over time and feeding and stocking rates have increased. High stocking and feeding rates became possible in the 1990’s because of an improved understanding of water quality, improved feeds and mechanical aeration (Li and Lovell 1992a). Intensively managed ponds require the use of the entire pond area for maximum production of fish and maximum growth of individual fish in the system (Terhune et al. 1997). As catfish culture becomes more intensive, the complexity of the interactions of fish production and water quality with feed costs and feeding rates for farmers will increase. With increasing intensification, farmers now use more debt capital, which leads to higher financial risk for the business (Engle 2003). With the culture of catfish becoming more complex and intensive, farmers are in need of more research-based recommendations with regard to stocking rates, production efficiencies, and biological limits of multiple-batch fish culture.

Problem Statement and Objectives

Little replicated research has been done on the complex interactions among stocking, feeding, water quality and their effects on fish yield, growth and feed conversion ratio (FCR) in intensive catfish production. Some publications recommend a limit of 112 kg/ha/d (100 lb/ac/d) for the maximum amount of feed to be fed to a catfish production pond per day to avoid deterioration of water quality. However, this recommendation is based on a single study by Cole and Boyd (1986). Many production practices have changed since 1986 and catfish culture has become much more intensive, suggesting that this recommendation may be outdated.

In Cole and Boyd (1986), fish were initially fed at 3% of body weight daily. Feeding rates were adjusted every two weeks for growth based on an assumed 1.5 FCR until a maximum feeding rate was obtained and held constant through harvest. The entire ration of feed was applied to the pond even if the fish did not consume all the feed. Extra, wasted feed (feeding more than the fish will eat) leads to water quality deterioration, inflated feed conversion ratios and higher costs (Boyd and Tucker 1998). Tackett et al. (1988) fed fish with demand feeders and found that, if they had fed at 2-3% of body weight per day, large quantities of waste feed would have remained from over fed fish, because fish did not demand that much feed. Daily feed consumption was highly variable and they stated that it would have been hard to offer a set amount of feed. Cole and Boyd (1986) presented a graph in which FCR remained constant up to a feeding rate of 112 kg/ha/d, beyond which FCR increased dramatically. The authors mentioned that fish did not grow as well as expected and did not always consume all feed applied to the pond. Most waste products in an aquaculture system are a result of artificial feed (Cho et al. 1994). Therefore, feeding fish carefully with a quality feed source is important to minimize waste and reduce effects on water quality. An alternative approach to the study done by Cole and Boyd (1986) would be to feed fish to satiation instead of percent of body weight, which would reduce waste when fish demand less feed. Also, to be more applicable to a commercial catfish farm, the study should use the multiple-batch stocking strategy, which is now more common in the industry (USDA 2003). In Cole and Boyd (1986), actual feed consumption (feed minus waste) was not measured; however calculations were based on the assumption that all feed was consumed, thus FCR values were inflated as a result.

Dissolved oxygen in ponds in Cole and Boyd (1986) were often at or near 0 mg/L even when aerators were running. However, they do not state the location within the pond that the dissolved oxygen readings were taken. Dissolved oxygen should be taken away from aerators. Dissolved oxygen should also be taken near aerators where oxygen will be highest (Nathan Stone, personal communication, University of Arkansas at Pine

Bluff). Nevertheless, this concentration of dissolved oxygen is harmful, if not fatal to catfish; dissolved oxygen should be maintained at higher levels for optimal growth. Dissolved oxygen can affect growth and feeding rates of catfish. Low dissolved oxygen concentrations may have affected growth, yield, FCR and survival of fish in Cole and Boyd (1986). However, Boyd and Tucker (1998) state that fish will seek optimal conditions in a pond. Cole and Boyd (1986) provided 6.1-kW of aeration per hectare with a vertical turbine aerator. They initiated aeration if the dissolved oxygen concentration was predicted to fall below 2 mg/L. Aerators were turned on based on predictions of when dissolved oxygen concentrations would fall to 2 mg/L. Catfish prefer dissolved oxygen concentrations above 5 mg/L and concentrations below 3-4 mg/L will adversely affect growth (Boyd and Tucker 1998). In addition, there is some evidence that nightly aeration increases fish production, feed consumption, and assimilation of feed (Lai-Fa and Boyd 1988). Thus, it may have been less stressful to apply some form of emergency aeration when dissolved oxygen levels fell below 3 mg/L instead of 2 mg/L. However, it depends on the size of the aerator in relation to the size of the pond. The bigger the aerator and the smaller the pond, the lower can be the threshold level for initiation of aeration.

The Cole and Boyd (1986) study had no mention of the number of ponds used or the number of replicates for each treatment. Treatments should either be replicated to allow comparison of treatment means or represent a wide range of conditions to ensure that parameter values estimated approximate the population mean. Moreover, there is no indication of measurement of chloride levels in the ponds. The chloride to nitrite ratio in ponds should be maintained at 10:1 (chloride: nitrite) with 20:1 the ideal (Boyd and

Tucker 1998). Changes in the weather can indirectly cause spikes in nitrite levels in ponds as a result of bloom crashes or by the slowing of nitrifying bacteria. For this reason, a chloride concentration of 100 mg/L is recommended to reduce the effects on catfish if sudden increases in nitrite occur (Durborow et al. 1997a). Maintaining adequate chloride: nitrite ratios will significantly reduce the chances of brown blood disease in catfish.

Cole and Boyd (1986) averaged treatments for all water quality sampling dates for statistical analysis. Regression equations were run with feeding rates as a function of water quality variables. Water quality can change significantly as feed is applied from month to month. Thus, pooling water quality data over time may have obscured changes in water quality parameters due to feeding rates that may have been different at sampling points.

Little is known about the effects of multiple-batch channel catfish production on yields, FCR, survival, water quality and economics. Catfish farmers currently stock fish with the multiple-batch technique and research that uses current production practice will give farmers insight into possible new management practices for intensive fish culture.

The primary goal of this study was to determine the effects of different multiple-batch stocking densities of channel catfish on feeding rate, water quality, production characteristics, and costs. The specific objectives were:

(1) To analyze the effects of four different understocking densities of channel catfish on growth, yield and survival in multiple-batch production.

(2) To determine feed conversion ratios of channel catfish understocked at different densities in multiple-batch production when fed to satiation.

(3) To test for relationships between stocking density/feeding rate and various water quality parameters.

(4) To examine the relationship between environmental conditions (weather parameters) and feed consumption of channel catfish.

(5) To compare the costs of producing channel catfish at different densities in multiple-batch production following a protocol of satiation feeding.

The information gained from this study should provide farmers and researchers with an improved understanding of the interactions of stocking and feeding rates with water quality, production characteristics, production limits, and costs involved with raising channel catfish. These results will also provide a basis for improving management recommendations for catfish farmers.

Literature Review

Pond culture of channel catfish

Channel catfish Ictalurus punctatus are an economically and culturally important food fish raised in aquaculture in the southern United States. Channel catfish can be raised in a variety of types of facilities, but are most commonly raised in levee-type ponds. In natural settings, catfish are generally a nocturnal, bottom feeding fish. When raised in ponds, they will typically eat at any time of the day and will consume a floating or sinking type of prepared feed. Under normal circumstances in aquaculture, a catfish should be seen only in the act of feeding; any departure from this, or other abnormal behavior, can be a sign of problems with the fish or pond water quality (Robinson et al. 1998).

Catfish can be raised in either a single-batch (clean harvesting) or a multiple-batch system (topping, continuous production, understocking). A single-batch system involves stocking fingerlings at the beginning of the production season (typically March) and harvesting all fish at the same time in the fall. A multiple-batch system involves multiple sizes and year classes of fish. The multiple-batch system is the most commonly used production system today (Engle 2003, USDA 2003). Farmers that utilize multiple-batch systems selectively remove larger, faster growing fish from the ponds using a large mesh net for harvest. Large marketable fish ($\geq$ 0.57 kg) are retained in the net and smaller fish (< 0.57 kg) are able to escape. Fingerlings are then stocked once per year in the spring to replace the harvested fish. Most farmers stock fingerlings once a year in the spring, based on the number of fish they plan to harvest that year. Farmers typically remove at least 1,700 kg/ha at one time to accommodate fish hauling trucks. Over time, the multiple-batch method results in different age classes of fish, which allows the farmer to harvest fish year round without draining the whole pond. A study by Tucker et al. (1993) found the highest average total production resulted from a stocking density of 19,770 fish/ha with a single batch of fish. They also found that FCR was the best at 11,120 fish/ha in a single-batch system. Net fish production and feed conversion ratios were both superior in the single batch system, independent of stocking density. Tucker et al. (1993) noted that the higher FCR in the multiple-batch ponds was possibly due to carryover of large fish from one harvest period to another. Larger fish convert food to body weight less efficiently than do smaller fish. Single-batch production at 19,770 fish/ha resulted in the highest net revenue. The multiple-batch system, combined with a density of 19,770 fish/ha, produced both the lowest net and the lowest discounted net revenues (Tucker et al. 1993).

So with all the positives of single-batch culture, why do farmers utilize a multiple-batch strategy? The biggest reason is to be competitive with fish sales year-round. By having multiple batches of fish, it is possible to have marketable size fish at all times of the year to meet processor demands. It is possible to do this by staggering ponds so that market-sized fish are removed from the ponds at different times from different ponds. It is also important to have fish available on demand when processors need them. The multiple-batch system allows farmers to have market-sized fish available year-round and helps to avoid major off-flavor problems. Whichever pond is on-flavor, can be harvested and sold to generate the required cash flow for the business (Engle 2003). Consistent year round sales are critical to generate cash flow to meet financial needs.

The interaction of production practices and water quality

Cole and Boyd (1986) published a paper entitled “Feeding Rate, Water Quality, and Channel Catfish Production in Ponds,” that has been used for many years to suggest that feed inputs to catfish ponds should be limited to 112 kg/ha/d (100 lb/ac/d). In Cole and Boyd (1986) catfish were stocked in 0.04-ha ponds at densities of 1,200; 4,300; 8,600; 13,000; 17,300; 26,000 and 34,600 fish per hectare. Maximum, predetermined feeding rates corresponding to each density were 0, 28, 56, 84, 112, 168 and 224 kg/h/d, respectively. Feeding rates were increased with the density of fish in the pond and all fish were fed 3% of body weight per day, with adjustments every two weeks for growth assuming a 1.5 FCR. The feed administered was a 32% crude protein floating feed. Aeration was used when the dissolved oxygen dropped below 2 mg/L or was predicted to drop below this value. A 6.1 kW/ha vertical turbine type aerator provided aeration. Water samples were collected each month of the study and were analyzed for nitrite, total ammonia nitrogen, carbon dioxide, chlorophyll a and chemical oxygen demand.

Cole and Boyd (1986) found dense phytoplankton blooms and high COD concentrations at higher feeding rates. They also found that, under high density conditions, the DO values in the morning were often at or near 0 mg/L with aerators running. However, they did not mention the location of the DO measurements within the ponds.

Cole and Boyd (1986) found TAN values as high as 2.6-4.7 mg/L in ponds receiving large amounts of feed (56-224 kg/ha/d). During the study, they obtained pH values between 8.5 and 9.5 in the afternoons. According to Boyd (1979), at a water temperature of 30º C and a pH of 9.5, total ammonia nitrogen would be about 76%

unionized or toxic. Cole and Boyd (1986) had unionized ammonia concentrations in the range of 0.9-1.8 mg/L in the afternoons. These unionized ammonia levels are relatively high considering the 24h LC50 for unionized ammonia has been reported to be between 1.39-2.36 mg/L (Robinette 1976; Tomasso et al. 1980b). However, with today's culture practices, concentrations of 0.9-1.8 mg/L can be common in commercial ponds (Nathan Stone, personal communication, University of Arkansas at Pine Bluff). Moreover, Hargreaves and Kucuk (2001) have shown unionized ammonia levels of 0.91 mg/L to be a no-effect concentration (NOEC). They state that that occurrence of acutely toxic ammonia concentrations would be rare in commercial ponds.

The water quality data collected from Cole and Boyd (1986) were averaged by stocking density, and regression equations between feeding rates and water quality variables were calculated. Strong correlations were found between feeding rate and chlorophyll a, total ammonia nitrogen, dissolved oxygen, chemical oxygen demand, and carbon dioxide. Fish production increased as feeding rate increased to a rate of 112 kg/ha/d (100 lb/ac/d). Feed conversion ratio increased (feed efficiency went down) substantially after this 112 kg/ha/d (100 lb/ac/d) maximum daily feeding rate was reached. They concluded that water quality deteriorates with high stocking densities of fish and high feeding rates, and a maximum of 112 kg/ha/d (100 lb/ac/d) of feed should be applied to any single pond per day.

Cole and Boyd (1986) and Tucker et al. (1979) found that nitrite-nitrogen (NO_2-N) concentrations within their experimental ponds increased along with production days. In other words, the more feed that was applied, the higher was the nitrite-N concentration. When fish are fed a high protein diet there is more wasted or unutilized protein in the water and the potential for more nitrogenous waste exists (Li and Lovell 1992a). Li and Lovell (1992a) found the greatest increase in NO_2-N at higher protein feed levels. They also found TAN to be correlated positively with the total amount of protein fed to the fish. Total ammonia nitrogen seems to be reduced by feeding lower quantities of a lower protein feed to a pond even though this practice may not always be ideal for the farmer. A study of rainbow trout by Cheng et al. (2003) found that replacing animal protein with plant protein reduced TAN discharge levels by 28% and soluble phosphorus discharge levels by 71%. Hargreaves and Tucker (2004) consider protein reduction of feed to be a long-term solution to ammonia problems. There are a variety of proposed short-term solutions to ammonia problems in ponds, however the reality is that there is really nothing a farmer can do about it (Hargreaves and Tucker 2004). Concentrations of TAN are minimized by phytoplankton assimilation and by creating an environment with a high dissolved oxygen concentration for nitrification. Careful feeding that reduces waste feed to the pond may reduce TAN. High densities of fish can be stocked into ponds with the use of aeration, but high amounts of toxic wastes such as ammonia and nitrite will ultimately limit the density that can be stocked (Lai-Fa and Boyd 1988).

Principal Production Characteristic Parameters

Feeding strategies

Channel catfish have been raised in aquaculture for many years, but currently there is no set standard on the most efficient method for feeding; thus, a variety of methods are utilized today. The feeding rate of a particular pond is dependent on the density of the fish present, water temperature, water quality, size of the feed pellet, frequency of feeding, feeding practices, and the overall health of the fish (Wellborn 1989). Feeds should be distributed to the fish in a way that allows for the opportunity (sufficient time and space) for fish to consume all the feed and to achieve adequate growth while minimizing feed waste (Cho and Bureau 2001). The amount of feed supplied to a particular pond also depends on the size of the fish and the specific objective of the study. The amount of feed supplied to the pond is related to the density of the fish; the more fish stocked per unit area, the more feed they will likely consume. However, there is a limit to the capacity of the pond to assimilate fish waste (Hargreaves and Tucker 2003). The size of fish affects food consumption since small fish require more food in relation to body weight, whereas larger fish need a higher overall quantity of food.

An essential component of catfish feed is the protein content. Catfish require adequate protein in their diet for efficient growth. However, protein assimilation can reach a plateau in which excess protein consumed is lost through excretion (Davis et al. 1993).

Feed costs can be as much as 50% of the overall production costs of raising catfish (Garrard et al. 1990; Tucker and Robinson 1990). Feeding strategies can be based on feeding a percent of body weight or feeding to satiation (all the food the fish will eat in a certain time frame). Feeding to satiation is said to take more time and requires more management skill (Davis et al. 1993). Feeding at a percent of body weight was thought to reduce the effects of water quality deterioration by keeping the amount of food constant as well as decreasing the amount of excretion waste from the fish. According to Tucker and Robinson (1990) fish are usually fed at about 1-3% of body weight. If fish consume the entire ration, there is no direct waste of feed. However, by feeding a nominal percent of body weight, “hungry” fish may actually be restricted in the amount of feed that they could consume on a given day and their resulting growth may be less than optimal. Thus, the needs of the fish, environmental conditions and the appetite of the fish on any given day must be considered. If the fish do not eat the predetermined amount of food (% body weight), that food deteriorates and becomes waste, which can decrease water quality. Wasted feed inflates FCR values because only a portion of the actual feed fed is eaten and used for growth. Moreover, wasted feed can contribute to lower water quality that may lead to even lower food consumption levels.

The process of adjusting feeding rates can cause problems in production experiments when fish are fed at a percent of body weight (Shell 1989). The amount to be fed is estimated by physically sampling fish and determining the percent of body weight to be fed at a given time in the production process. In order to be accurate, fish must be sampled frequently and as a result may cause unnecessary handling stress over the course of the growing season. The present survival of fish must also be known, which is often hard to determine. If the pond is fed at the common rate of 3% of body weight from the first day of production, with nutrients converted into fish flesh, the fish, in those days following, are no longer being fed at 3% of body weight. After several weeks, and until the next sampling period, those fish are obtaining substantially less than 3% of body weight due to growth (Shell 1989). When feeding is eventually adjusted, some feed may be wasted while the fish adjust to the new, higher quantity of feed provided. Computer models have been developed to assist catfish farmers and researchers in predicting the percent of body weight to feed, but, as the fish grow in size, food consumption as a percent of body weight decreases while conversion of food increases (Robinson et al. 1994). Westers (1987) also found that length of the fish increases at a constant rate if held at a certain temperature, but weight gain does not remain constant. Because of this fact, it may be difficult to use weight gain as a way of determining the correct feeding levels for fish in ponds (Westers 1987). Moreover, channel catfish farmers often do not know how many pounds of fish are in their ponds.

Food intake in fishponds can vary substantially from day to day (Houlihan et al. 2001). Careful satiation feeding may aid in reducing wasted feed from daily fluctuations and allow fish to consume only the feed they want, until they are full. According to Houlihan et al. (2001), environmental variation may cause changes (uncontrollable to the farmer) that may help indicate day-to-day patterns in the entire population when the fish are fed to satiation. In a modeling analysis, Cuenco et al. (1985) found that theoretically feeding fish as a fraction of their appetite was more effective than feeding fish at a fraction of body weight. Feeding at a fixed fraction of the fish’s body weight proved to be wasteful early and late in the simulation and was also inefficient in the middle period of their study (Cuenco et al. 1985).

Robinson et al. (2000) showed that fish fed to satiation had lower feed conversion efficiency. They recommended that channel catfish be given a ration that is “close” to all that they can eat, or in other words, an amount of food that is slightly less than that of true satiation.

One disadvantage of feeding fish to satiation is the potential for increased fat content of the fish. Robinson et al. (2000) found that fish fed to satiation had a higher visceral fat content when compared to fish fed less than or equal to 90 kg/ha/d (restricted feeding). This could be due to the fact that the fish fed to satiation have the opportunity to eat more feed, even if it is not necessary for growth, thus causing excess fat to form. Munsiri and Lovell (1993) found the mean fat content in meat of catfish fed to satiation to be 8.3% while restrictively fed fish had a fat content of only 7.0%.

Protein level is also a consideration when choosing between feeding a set percent of body weight and feeding to satiation. Weight gain of the fish can differ according to the protein level fed. Li and Lovell (1992b) found that weight gain was inversely related to the dietary protein concentration of the feed (i.e. weight gain decreased as protein went up) in satiation feeding. Thus, higher protein feeds are not necessary for growth when fish are fed at a high rate to satiation. The study also suggested that amino-acid-balanced feed, containing low protein would be satisfactory when feeding to satiation, but a high protein feed would be best for restricted feeding conditions. Protein content of feed as low as 25% has resulted in yields equivalent to those obtained with a feed with a higher protein content as long as the fish were fed to satiation (Robinson et al. 1994). A study by Robinson et al. (2000) indicated differences in fish growth with regard to the protein level of feed consumed and the feeding strategy employed. Catfish fed 28% protein gained the same weight as catfish fed 32% protein as long as the fish were fed to satiation. Feeding strategy had a significant effect on total feed fed to all fish, individual feed consumption, weight gain, and FCR. The fish fed to satiation gained more weight with a lower FCR than fish restricted to a certain amount of feed (less than or equal to 90 kg/ha/d). Most food fish are stocked at what are called “advanced fingerlings” in the range of 13-15 cm and fed a 28-32% protein floating feed, 4.0-4.8 mm (Robinson et al.

2001). It is recommended that fish in the size range of advanced fingerlings up to market size fish be fed with 32% crude protein (Tucker and Robinson 1990).

A preliminary report by Garrard et al. (1990) compared water quality in ponds with scheduled or satiation feeding of farm raised catfish. Total ammonia nitrogen levels were 0.71 mg/L for scheduled feeding and 0.93 mg/L for satiation feeding. Chlorophyll a was 222 µg/L for scheduled feeding and 309 µg/L for satiation feeding. This may indicate, if satiation feeding is not done carefully, (i.e. if feed is wasted by careless application) wasted feed may cause water quality to deteriorate. Nevertheless, all water quality parameters measured were within ranges commonly found in commercial catfish ponds. Fish production, FCR, and aeration usage did not differ due to feeding strategy.

Nutritional requirements of catfish

Catfish in commercial production ponds are typically fed an artificial floating or sinking feed. There is little nutritional difference between different manufactured feeds; all commercially manufactured feeds are high quality (Robinson et al. 2002). However, floating feed has many advantages over sinking feed. Floating feed allows farmers to monitor the feeding activity of the fish. It also enables the farmer to monitor for disease by way of a substantial decrease in daily feeding rate. Feeding to satiation with floating feed can also reduce the occurrence of wasted uneaten feed.

Older studies from Auburn University indicated that 2.5% of protein and 0.80% of energy required by channel catfish is obtained from natural food items in ponds at high stocking densities. As a result, these nutrients were supplemented in older feeds. Older research indicated that catfish would have vitamin deficiencies when fed feeds lacking vitamins in the lab. However, similar studies have now been done in ponds and lab results could not be replicated in a natural pond environment. It is possible that some nutrient requirements were being met by natural food in the ponds. Studies on minerals and essential fatty acids have had the same results; catfish have positive benefits from consuming natural food items (Robinson et al. 2001).

Many studies have looked at dietary protein level and feeding rate effects on weight gain, feed efficiency, body composition and production of channel catfish. Robinson and Li (1997) looked at low protein levels for catfish at high stocking densities. Fish were fed either 32, 28, 24, 20 or 16% crude protein with digestible energy to protein (DE:P) ratios ranging from 8.9-16.2 Kcal/g protein. Weight gain was not significantly different among the fish fed diets with 32, 28 and 24% protein. Fish that were fed the lower protein (16 and 20%) gained significantly less than fish fed 28 and 24% protein. Feed conversion ratios became worse as protein level in feed decreased. However, there was no significant difference in the FCRs of fish fed 28 and 32% protein.

Another aspect of protein content that is often looked at is its effects on visceral fat content. Robinson and Li (1997) found that fat content of the fish increased as protein decreased. Their study found a protein level as low as 24% to be adequate for channel catfish production, but levels below 24% might cause excess and unacceptable amounts of fattiness due to high digestible energy to protein ratios. A study by Li et al. (2003) also found that fish fed 28% protein had significantly higher levels of visceral fat and fillet fat than fish fed 32% protein. However, Li et al. (2003) found no significant differences in net production, feed consumption, weight gain, FCR, survival, processing yield, fillet moisture, protein or ash concentration in fish at different protein levels.

Fingerling catfish should be fed to satiation with a crumbled feed or floating feed about 3.2 mm in diameter. These feeds should contain protein made of fishmeal or meat and bone meal (Robinson et al. 2001). Some of the most common protein supplements in catfish feeds are soybean meal, fishmeal, meat and bone meal, blood meal, and catfish offal meal. Recently, plant products are replacing fishmeal and animal products in channel catfish feeds (Rebecca Lochmann, personal communication, University of Arkansas at Pine Bluff). Reigh (1999) studied catfish in multiple-batch production for three consecutive years and found no significant difference in FCR, mean weight, or yields between fish fed animal or all plant protein diets. All of the feeds that contain the ingredients above have 20% or more protein, but differ in specific percentages of protein and minerals. Soybean meal is the major source of protein for commercial catfish feeds.

Grains and milling by-products are important for starch content that is easily digested by catfish (Tucker and Robinson 1990). Fats and oils are used in catfish feeds because they are digested easily and because they are a good source of energy. Grains, milling by-products and also fats and oils are energy sources and typically contain less than 20% fiber. There are 10 essential amino acids that all fish must have to remain healthy and grow properly. They are phenylalanine, valine, threonine, tryptophan, isoleucine, methionine, histidine, arginine, leucine and lysine.

Growth and feeding rates at different densities

High stocking densities of fish (standing crop) are associated with negative effects on feeding, growth, and other physiological processes (Wedemeyer 1997). High density conditions are stressful due to intraspecific competition for space and for feed. At higher stocking densities, fish may suffer from deterioration of water quality and an uneven distribution of food (Houlihan et al. 2001). Thus, physical stress from high stocking densities is not only a direct effect of crowding but also an indirect effect of water quality and feed distribution. Survey data from 1996 production data by Losinger et al. (2000) indicated that most farmers are stocking fingerlings at the recommended level of 15,000/ha. A more recent survey indicates that farmers are stocking at rates from less than 4,950/ha to over 19,768/ha, with most surveyed farmers stocking about 4,950/ha to 9,884/ha (USDA 2003).

Feeding rates differ for different densities and standing crops of fish. Generally, more feed is needed to satiate catfish stocked at higher stocking densities than at lower densities. Not only is more feed necessary at a higher stocking density, but the fish convert feed less efficiently to energy and for growth (Li et al. 2003). A lower weight gain in high density populations of fish could be due to lower per fish feed consumption as a result of density dependent factors (Li et al. 2003). Some of these density dependent factors mentioned by Li et al. (2003) include competition for food, deterioration of water quality and increased susceptibility to diseases.

Catfish grow more slowly at higher stocking densities and will likely take longer to reach market size (0.57 kg). Fish stocked at low densities reach a marketable size faster than fish stocked at higher densities. In other words, growing more fish in a given pond area will increase net yield, but will also reduce the average weight gain of individual fish (Terhune et al. 1997). Stocking at a higher density would be reasonable when catfish prices for marketable sized fish are high, but the benefits of higher stocking densities are reduced as catfish prices decrease (Losinger et al. 2000).

Feed conversion ratio (FCR)

When growing fish, one must consider how efficiently the fish are utilizing feed. Feed is expensive and catfish producers are paid by live weight; thus, fish weight and FCR are two essential parameters (Robinson and Li 1997). The FCR is the ratio of the mass of feed fed to the mass of fish produced. The higher the FCR, the less efficient and less economical is feed utilization. Small fish tend to consume more feed per kg of fish, grow faster, and convert feed to energy more efficiently than do larger fish. This means that fingerlings should have lower FCRs and conversion efficiency should decline steadily as fish approach a harvestable size. Thus, multiple batches of fish will have higher FCRs.

Busch (1984) found differences in FCR between fish raised in single-batch ponds (1.6) and those raised in multiple-batch ponds (2.1). However, it is unclear from the publication if this was a significant difference. Ponds stocked with 14,826 fish/ha in single-batch gained 300 kg/ha more than fish in ponds stocked with an equal amount of fish in multiple-batch. The average FCRs for fish in the single-batch and multiple-batch ponds in this particular study were 1.6 and 2.1, respectively. Although not indicated as significantly different within the paper, there are obvious differences in the two different methods of production. Busch (1984) speculated that the higher FCR of 2.1 in the multiple batch study might be due to competition between different size groups of fish.

Yield at different densities and feeding rates

In the catfish industry, technological advances over the years have resulted in increased yields of fish (Engle 2003). Higher yields over time are a result of advances in such things as, higher quality feeds, better management, improved knowledge of important water quality parameters and use of aeration equipment. Higher feeding levels are more efficient when applied in combination with improved equipment such as blower-feeders, tractors and aerators (Nerrie et al. 1990).

Dasgupta et al. (2002) showed that stocking density and feeding rate were the inputs with the greatest effect on average annual yield of catfish. Yield of market-sized fish is more sensitive to feeding rate at a higher stocking density (Cuenco et al. 1985). For any stocking rate, when feed is increased, the yield of market-sized fish increases at a decreasing rate until a maximum yield is reached. Increasing feeding rate beyond the yield-maximizing rate will result in decreasing marketable yield (Cuenco et al. 1985). Recent studies have found no decrease in yield with increasing stocking density or biomass. Over a three-year study period, Tucker et al. (1993) obtained yields that ranged from 3,881 to 7,253 kg/ha at a stocking density of 11,120/ha, and 5,177 to 11,214 kg/ha at a stocking density of 19,770/ha. Pomerleau and Engle (2003) stocked fingerlings (6.7 cm) in single-batch at rates of 50,000, 100,000 or 150,000/ha. Net yields in their study increased as stocking density increased, and were 4,343, 6,220 and 7,231 kg/ha in the 50,000, 100,000 and 150,000 fish/ha treatments, respectively. Green and Engle (2004) raised fish in single-batch production at a stocking rate of 11,155 fish/ha to weights of 0.60 (98 d), 0.72 (134 d), 0.91 (164 d) and 1.17 kg/fish (210 d) with net yields of 3,062 to 8,355 kg/ha. Again, yields increased linearly with time.

Survival rates in pond culture

Survival rates in pond culture depend on factors such as temperature, water quality, disease, and stress. Stress is a physiological response to adverse environmental conditions or rough handling. However, actual mortality can be difficult to measure due to bird predation and removal of dead fish by turtles and other animals. Also, some dead fish sink and decompose on the pond bottom instead of floating. For this reason it is likely that the amount of dead fish predicted for a given pond throughout the production year will be significantly less than true mortality. Observed losses in a pond will always be less than the total losses and may even be as much as seven times less (Tucker et al. 1993). Busch (1984) showed no effect of density on survival of fish. Busch (1984) stocked fish at 9,884, 14,826 and 19,768 fish/ha. Fish survival was 85, 92 and 84% at the low, medium and high densities respectively. However, significant differences were not mentioned within the paper.

Water Quality Parameters in Channel Catfish Ponds

Channel catfish have many biological and physiological requirements in order to remain healthy in culture systems. Channel catfish grow better in warm water and climates. They also require dissolved oxygen to be above 1.0 mg/L. This is the lethal level for catfish, and higher concentrations of dissolved oxygen are preferred for optimal growth. Non-lethal concentrations below 3-4 mg/L cause a reduction in overall growth of catfish (Wellborn 1988) with levels above 5 mg/L preferred (Boyd and Tucker 1998). Catfish also require a certain set of water quality parameter values for optimal growth.

Nitrite (NO_{2-}) and nitrate (NO_{3-})

Nitrite results from the biological transformation of ammonia by bacteria within the pond (Durborow et al. 1997a). Ammonia is excreted as waste to the water through the gills of fish as total ammonia nitrogen (TAN), which consists of NH_3 and NH_4^+. Total ammonia nitrogen is converted to nitrite (NO_{2-}) by nitrifying bacteria (Nitrosomonas). Nitrobacteria then convert nitrite (NO_{2-}) to nitrate (NO_{3-}).

Unequal growth rates of Nitrosomonas and Nitrobacteria can cause accumulations of nitrite (the intermediate product) to form in the water (Konikoff 1975). Nitrite enters into the fish's circulatory system through the gills (Boyd and Tucker 1998). Nitrite crosses the gills by way of the same mechanism that chloride is transported into the fish. Nitrite is far more toxic to all fish than nitrate and toxicity of nitrite depends on the individual species as well as concentrations of chloride in the water. High nitrite concentrations occur more often when temperatures are fluctuating (fall/spring) (Durborow et al. 1997a). Temperature fluctuation creates unstable phytoplankton blooms and bloom die-offs. Nitrifying bacteria are also less efficient at cooler temperatures. Konikoff (1975) ran an experiment on the toxicity of nitrite to channel catfish. He found that the 24-hour TL_m value for the fish used (40 g) at 21° C was 38.8 mg/L. The 46, 72 and 96-hour TL_m values declined as time progressed. In other words, it took less of a dose (lower mg/L) to kill with a longer exposure. However, this study was at a time when researchers did not know the effectiveness of chloride concentrations in the prevention of nitrite toxicity.

A disease called brown blood disease can result when catfish are exposed to excessive amounts of nitrite within water with low chloride levels. This disease is characterized by chocolate brown-colored blood. The brown blood that forms is unable to carry enough oxygen to keep the fish alive and they ultimately die. Hemoglobin, which transports oxygen in the blood, combines with nitrite to form methemoglobin, which is incapable of transporting oxygen. The brown blood cannot carry sufficient amounts of oxygen and the fish suffocates even though there is adequate environmental oxygen. High nitrite concentrations occur more often in the water when small amounts of plankton are present due to a plankton die-off, during herbicide treatments for aquatic weeds and at times of high feed input. Nitrite concentrations are usually below 0.1 mg/L in ponds during the year due to the assimilation of ammonia by the phytoplankton present (Boyd and Tucker 1998). Problems can arise when heavy feeding rates have created an abundant plankton bloom, which suddenly dies off and leaves nothing to assimilate ammonia. Catfish are a species that are considered “fairly” sensitive to nitrite (Durborow et al. 1997a).

Some research has indicated that channel catfish can acclimate to certain amounts of nitrite in the environment (Urrutia and Tomasso 1987). Despite these findings, there is a limit to the amount of nitrite that the fish can be acclimated to at different concentrations and exposure time frames. In order to avoid reduced growth, it is better to prevent high nitrite levels in the pond or reduce the effects of the present levels. There are several ways to treat and prevent nitrite toxicity to catfish. Nitrite can be controlled indirectly, like ammonia, by reducing feeding rates, but this is not always viable for the farmer. Second, sodium chloride (NaCl) or calcium chloride (CaCl) can be used to decrease the uptake of nitrite by the fish. Maintaining a concentration of 10:1 chloride: nitrite is sufficient with 20:1 preferred. It may be best to keep chloride levels at 100 mg/L at all times to avoid problems due to sudden increases in nitrite concentrations (Durborow et al. 1997a). The extension program at UAPB currently (2005) recommends 100 mg/L of chloride in channel catfish ponds.

Unionized ammonia (NH_3) and ammonium (NH_4+)

Ammonia is the end product of the protein breakdown of fish feed applied to ponds, feed assimilated in fish and diffusion from pond sediments. Ammonia is excreted in feces and also through the fish's gills (Durborow et al. 1997b). Feeding rate and feed protein level directly influence the rate at which fish excrete ammonia (Hargreaves and Tucker 2004). The unionized form (NH_3-N) of ammonia is toxic to catfish and the proportion of the unionized, toxic form increases as the pH and temperature of the culture system increase. At a pH of 8.0 it can be assumed that less than 10% of total ammonia is in the toxic form, but the percentage increases quickly as pH increases (Hargreaves and Tucker 2004). If the unionized ammonia in the environment becomes too high, ammonia movement out of the fish can become reversed and it can accumulate in the blood (Boyd and Tucker 1998).

Unionized ammonia can be lethal to catfish in the area of 0.6 mg/L, but kidney damage, growth reduction, malfunctioning of the brain, and reduced oxygen carrying capacity can result from exposure to as little as 0.06 mg/L. Hargreaves and Kucuk (2001) found hybrid striped bass, blue tilapia, and channel catfish (at all growth periods) showed decreased growth as ammonia concentration was increased. Thus, some decreased growth at high stocking densities may be due to sublethal (chronic) concentrations of ammonia. However, they found that brief exposures of 0.91 mg/L did not negatively affect catfish.

Some feel it is ideal to keep unionized ammonia levels below 0.02-0.05 mg/L if possible. However, TAN levels in commercial catfish ponds are usually in the range of 2-5 mg/L with spikes up to 10 mg/L (David Heikes, personal communication, University of Arkansas at Pine Bluff). Amounts in the unionized form will depend on the temperature and the pH of those commercial ponds. With temperature and pH fluctuations during the day, it is difficult to know what percent is in the unionized form at any given time. TAN concentrations tend to be higher in the winter in catfish ponds (Hargreaves and Tucker 2004). Robinette (1976) found a significant difference among growth between catfish fingerlings grown at 0.12 and 0.13 mg/L NH_3-N and a control. He also found no surviving fish at a concentration as high as 2.8 mg/L of total ammonia nitrogen in the unionized form. The toxic level of ammonia in the unionized form has been said to be 1.50-3.10 mg/L for channel catfish (Summerfelt 1998). However, this value has a wide range depending on the fish species, study conditions and fish exposure time.

Phosphorus (P)

Phosphorus is an important nutrient in ponds because it plays a large role in the regulation of primary productivity (Boyd and Tucker 1998). Phosphorus is generally the most limiting nutrient in freshwater pond systems. About 65-75% of the phosphorus added to pond water from commercial feeds is lost to the pond while the rest is retained by fish. In ponds, the major phosphorus cycle is an exchange of phosphorus between mud and water (Boyd and Tucker 1998). Phosphorus in fishponds is commonly measured as total phosphorus (TP) or soluble reactive phosphorus. Soluble reactive phosphorus concentrations in ponds are low; the available phosphorus is quickly removed by plants and pond bottom mud (Boyd and Tucker 1998). Total phosphorus is made up of both soluble and particulate phosphorus within the ponds. Total phosphorus concentrations are usually less than 1,000 µg/L in ponds containing fish and most of the phosphorus is in the form of phytoplankton. Concentrations of phosphorus are highest in the summer and lowest in the winter (Tucker and van der Ploeg 1993). In heavily fed catfish ponds, Tucker and van der Ploeg (1993) found that total phosphorus was less than

400 µg/L in the winter and over 600 µg/L in the summer. In ponds fed artificial feeds, it is probably unnecessary to add phosphorus fertilizers.

Nitrogen (N)

Nitrogen is an important part of protein and other components of cellular protoplasm; thus it plays a major role in the productivity of aquatic ecosystems. Fish obtain nitrogen by consuming either prepared or natural feeds (Boyd and Tucker 1998). When fish are fed a manufactured feed in aquaculture, nitrogen from animal excretion can cause an accumulation of nitrogen-containing compounds such as nitrite and unionized ammonia. Ammonia is the most common form of inorganic nitrogen in ponds. In ponds fed artificial feeds, it is probably unnecessary to add nitrogen fertilizers. The nitrogen fixation pathways are as follows: (1) electrical discharges (2) bacterial fixation from plants and free-living bacteria (3) industrial fixation in the creation of fertilizers (Boyd and Tucker 1998).

Chlorophyll a and phytoplankton

Phytoplankton is most abundant in the summer with warm water temperatures and high-feeding rates that create ideal environments of nutrients for plants (Hargreaves and Tucker 1996). Phytoplankton plays a major role in oxygen, pH, and ammonia concentrations in ponds. An increase in the surface water temperature under dense blooms can also occur. This, coupled with calm weather, can cause thermal stratification (variation in water temperature at different depths). Most of the phytoplankton in a fishpond results from the amount of feed applied, mainly because fish feed is a major source of nitrogen and phosphorus. The availability of nitrogen and phosphorus is the primary factor governing growth of phytoplankton in freshwater systems (Paerl and

Tucker 1995). Nitrogen and phosphorus feeds fertilize the pond and increase the primary productivity (phytoplankton concentration). It has been estimated that 2.57 kg (on a dry weight basis) of waste is produced per kilogram of catfish (Brunson et al. 1994). Some of this waste is utilized by phytoplankton for growth. Phytoplankton also shades the bottom (Brunson et al. 1994) of the pond to prevent growth of aquatic macrophytes. Phytoplankton produces large quantities of oxygen during daylight hours through photosynthesis ($6CO_2 + 6H_2O + \text{light energy} \longrightarrow C_6H_{12}O_6 + 6O_2$). The phytoplankton of a pond is also a major consumer of oxygen during nighttime hours through respiration ($C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{heat energy}$).

Dense phytoplankton blooms can cause fluctuations in the pH of a water system. Photosynthesis by phytoplankton during the day takes up CO_2, which causes the water to be less acidic, raising the pH. Thus, ponds with abundant phytoplankton have higher pH values during the afternoon. Blue-green algae are generally dominant in catfish ponds in the summer time (50-75% of all algae) (Brunson et al. 1994). Green algae generally are the dominant form found during the cooler parts of the year. The presence of certain blue-green algae can cause what is called “off-flavor” and is undesirable in marketable fish. Off-flavor is absorbed by the fish and creates an undesirable smell and flavor in the fish flesh (Paerl and Tucker 1995). The most common form of off-flavor in catfish is the earthy-musty type.

Aquaculture ponds are typically operated as static systems (little water exchange); thus algae blooms are important for the assimilation of nitrogenous waste products that may accumulate (Brunson et al. 1994). The fish waste and the feed in the pond help to fertilize the plankton and keep it alive while the plankton remove and/or change the waste products present into something less harmful to the fish. The role of ammonia removal by plankton is one of the most important factors in reducing the actual amount of ammonia present in the water (Durborow 1997b). Plankton bloom density can fluctuate depending on feeding rates, fish density and time of the year. Ammonia tends to increase in the fall and winter when less plankton is present in the ponds or because the surviving populations of plankton are not as efficient at waste assimilation (Durborow 1997b).

As of 1994, "no good practical and effective means of regulating plankton blooms had been developed" (Brunson et al. 1994). In other words, there is really no economical way to reduce phytoplankton blooms in ponds. Farmers currently use copper sulfate ($CuSO_4$-) and diuron to control phytoplankton blooms. Farmers must feed at high rates to stay competitive in the market and that, in turn, produces excess phytoplankton. The only feasible management strategy is to feed carefully and use aeration at night and during times of potential crashes of the phytoplankton blooms.

There are three basic ways that the amount of phytoplankton in a system can be estimated: in the lab by measuring chlorophyll a, secchi disk, and the use of a submersible PAR sensor. Chlorophyll a concentration in a water system is often used to measure phytoplankton biomass (Lloyd and Tucker 1988). Phytoplankton is the main source of chlorophyll a in a pond system. The most recommended lab method for analysis of chlorophyll a for phytoplankton in the delta region is the chloroform-methanol method (Lloyd and Tucker 1988). Secchi disk is a more subjective measurement, but will provide a means of measuring phytoplankton abundance in the field. The LICOR PAR sensor is the most recent technology, capable of reading at all depths of the pond.

However, the PAR sensor unit and the Secchi disk cannot sense the difference between mud and plankton turbidity.

Dissolved oxygen concentrations and aeration

Dissolved oxygen is considered one of the most important water quality parameters in a culture system (Hargreaves and Tucker 2002). Oxygen enters pond water from either diffusion from the atmosphere, mechanical aeration, or from photosynthesis by phytoplankton. The most important factor in determining dissolved oxygen saturation levels is water temperature. Typically, dissolved oxygen concentrations are highest in the afternoon and lowest just before sun up (dawn) in the morning (Jensen et al. 1989).

Low dissolved oxygen problems in ponds are most prevalent in the late summer and early fall (June through September in Arkansas) because of four factors: 1) water temperatures and oxygen saturation levels are inversely related; 2) respiration of living organisms within the pond increases with increasing temperatures; 3) hazy or cloudy days may reduce oxygen by photosynthesis inhibition, and 4) Large amounts of feed are generally applied to ponds at this stage of the growing season. Oxygen depletion can occur from a plankton die-off or if the amount of oxygen produced during the day by the plankton is less than what is used by the fish and the plankton at night.

It is recommended, in ponds where artificial feed is applied to the fish, that dissolved oxygen concentrations be checked twice daily (Jensen et al. 1989). This daily monitoring (dusk and dawn) of the oxygen concentration is not only to keep dissolved oxygen at optimal levels, but also serves to identify problems that may arise in the future. Measurements of dissolved oxygen in the pond should be made at a minimum of 61 cm from the bank and 46 cm below the surface of the water (Hargreaves and Tucker 2002).

It is important to maintain dissolved oxygen concentrations above 3 ppm at all times for optimum growth of catfish. Dissolved oxygen concentrations below 3-4 mg/L will stress fish and adversely affect growth (Boyd and Tucker 1998). Mount (1960) found that ventilation rates of five different fish tested (rockbass, whitebass, lake emerald shiners, yellow walleyes and smallmouth bass) increased at a dissolved oxygen concentration of 5 mg/L and stress signs were noticeable at concentrations below 3 mg/L. Dissolved oxygen can also affect the physiology of catfish in many ways. Andrews and Matsuda (1975) determined that dissolved oxygen levels have a substantial effect on growth and feed conversion in catfish. They also found that food consumption rates were higher for fish in water maintained at 100% oxygen saturation.

Mechanical aeration of a cultured system is essential to maintain dissolved oxygen at an appropriate level. In the past, 1.85-kW/surface ha has been recommended for catfish production (Jensen et al. 1989) but the recommended rates have increased in recent years. The extension program at the University of Arkansas at Pine Bluff currently (2005) recommends 3.7 kW/ha with a minimum of 1.85-kW/ha. Nightly aeration has been found to increase fish production, feed consumption and assimilation of feed (Lai-Fa and Boyd 1988). Lai-Fa and Boyd (1988) also found that nightly aeration would be profitable with moderate feeding rates.

Alkalinity, pH, hardness and carbon dioxide

Alkalinity, pH, hardness and carbon dioxide are all interrelated in a pond system. The combination of the four can have an impact on the productivity of a culture system (Wurts and Durborow 1992). These parameters can affect the physical stress level of fish, oxygen in the system, and ammonia toxicity.

The pH of the water system indicates the hydrogen ion concentration and is a measure of how acidic or basic the water is. The recommended pH range for aquaculture ponds is from 6-9. The upper and lower lethal limits for catfish are 11 and 4, respectively. Respiration in ponds causes CO_2 levels to rise. Free CO_2 reacts with the water to form carbonic acid (H_2CO_3) and, as a result, the pH of the system decreases. Carbon dioxide is stressful to channel catfish at 35 mg/L and can cause mortality at 70 mg/L (Andrew Goodwin, personal communication, University of Arkansas at Pine Bluff). Toxicity also increases as the dissolved oxygen of the system decreases. Due to the inverse relationship between oxygen and carbon dioxide in ponds, high CO_2 levels are found if there is a lack of oxygen in the pond and vice versa. Carbon dioxide in ponds results from fish respiration and from decomposition of organic matter. Carbon dioxide problems will occur more often if the pond has a thick algal bloom and will be more prevalent in the summer time (Hargreaves and Brunson 1996). One way to reduce carbon dioxide in a system is by aeration. According to Hargreaves and Brunson (1996) aeration and mixing of the water are the most effective methods to keep CO_2 levels at manageable levels.

Total alkalinity is the sum of the titratable bases in water and in most water systems; total alkalinity consists of bicarbonate (HCO_3-) and carbonate (CO_3^{2-}). Total alkalinity is expressed as mg/L as $CaCO_3$ (Boyd and Tucker 1998). Alkalinity is determined by the quality of the water supplying the system as well as the composition of the pond soil (Boyd and Tucker 1998). An alkalinity of 20 mg/L and greater is suitable for aquaculture, but 75-200 mg/L $CaCO_3$ is most desirable for fish culture (Wurts and Durborow 1992). The extension program at UAPB recommends the same total alkalinity for catfish culture. Large changes in alkalinity do not occur in ponds unless certain chemicals or large amounts of water are added to the pond (Boyd and Tucker 1998). The benefits of alkalinity in a water system include pH buffering, increased fertility and decreased toxicity to metals like copper (Boyd and Tucker 1998).

Total hardness is the quantity of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in water and is expressed as mg/L as $CaCO_3$. Extension recommendations at UAPB indicate total hardness in ponds should be above 20 mg/L for culture and 75-200 mg/L is preferred. Channel catfish do not need an abundance of calcium in the environment to survive, although growth may be slowed if calcium levels are too low. Calcium can be supplemented by calcium in fish feed or calcium chloride (CaCl) can added to the water to increase calcium concentration. Limestone or gypsum can also be added to ponds to increase hardness (Boyd and Tucker 1998). Hardness is important for egg and larval development, nutrition, and osmoregulation in fish (Boyd and Tucker 1998). Tomasso et al. (1980a) found that elevated calcium levels increased fish tolerance to ammonia.

Water Quality and Fish Disease

Farmers consider infectious disease as one of the biggest problems that they face during the production of catfish (Tucker and Robinson 1990). There are two general categories of fish diseases (Noga 1988): (1) infectious diseases such as a virus, bacterium, fungus or parasites and (2) noninfectious diseases due to toxic substances in the water or nutrient deficiencies. The skin, gills or the gastrointestinal tract are areas of the fish that come into contact with an infectious substance and are susceptible to infection. Fish diseases become a problem in aquaculture when three factors are present. These three factors are often depicted as the following equation: $H + P + S^2 = D$ where

(H) is the host, (P) is the pathogen, (S) is a stress caused by the environment and (D) is the disease. When all three of these factors come together, fish become sick (Wedemeyer et al. 1976).

Water temperature plays a major role in the health of the fish in a system by influencing immune function of the fish and the occurrence of some infectious diseases. There is a limited time frame for the presence of diseases in aquaculture ponds dictated by seasonal temperatures (Boyd and Tucker 1998). The most common disease that farm raised channel catfish encounter is caused by the bacterium Edwardsiella ictaluri and is called Enteric Septicemia of Catfish (ESC) (Tucker and Robinson 1990). This disease is most prevalent in catfish when the water temperature is in the range of 22-28 C. The second most encountered bacterium in a channel catfish pond is Flavobacterium columnare (Columnaris). Columnaris in catfish is a rare occurrence unless the fish encounter stress from handling or suboptimal environmental conditions (Tucker and Robinson 1990). The temperature range that columnaris most commonly occurs at is between 18-29 C (Tucker and Robinson 1990). Columnaris has the lowest probability of occurrence in the middle of the winter in Arkansas (Andrew Goodwin, personal communication, University of Arkansas at Pine Bluff).

Common parasites on the gills of channel catfish are Trichodina. These are saucer-shaped parasites and are common on healthy catfish, but can become a problem if they are too abundant on the fish (Tucker and Robinson 1990). There are several species of Trichodina present in fresh water and catfish are vulnerable to the parasite at a wide range of temperatures (5-35 C). Another parasite of channel catfish is proliferative gill disease (PGD). This disease deteriorates the gills of the fish and the fish essentially suffocate despite adequate dissolved oxygen (Mitchell et al. 1998). The disease is most common in the spring at temperatures of 15-22 C. There exists an oligochaete worm or tubifex Dero worm that lives in the pond mud and serves as an intermediate host for the pathogen. Fish must be moved to another pond away from the worms to stop the progression of the disease. The only other option is to process the fish.

Another disease is channel catfish virus disease (CCVD). This disease affects channel catfish that are less than 15 cm long and outbreaks are most common in June-September (hot summer months in Arkansas). Susceptibility to the disease varies among the different strains of catfish and they are the only fish that can get the disease (Tucker and Robinson 1990). This disease is less common when water temperatures are below 27 C.

Environmental Influences on Pond Characteristics

Channel catfish are a nocturnal species, but are willing to feed regardless of the time of day. Robinson et al. (1995) found no significant differences in weight gain of channel catfish fed at different times of the day. There were no significant differences in FCR, survival, fat, protein, ash, or moisture among fish fed at different times of the day.

Environmental conditions such as light and temperature are important for production, but cannot be controlled when working with an outdoor system like a pond. Ambient temperatures influence water temperature of the culture system and temperature, in turn, changes the physiology of the fish as well as the water chemistry. Channel catfish do not feed consistently when the water temperature falls below 21 C (Buentello et al. 2000). Catfish will feed poorly until about May in the southern United States (Robinson et al. 2002). Catfish experience optimal growth at around 30 C (Andrews and

Stickney 1972). Buentello et al. (2000) found a slightly lower optimal growing temperature of 27-28 C. They also found the best feed efficiency to be below the optimal temperature for catfish growth, at 24-26 C.

The growing season for channel catfish is longer in the southern part of the United States, with most of the U.S. production occurring in the Mississippi Delta area. According to a recent survey (USDA 2003) Mississippi has 34,800 ha of foodsize production. Arkansas, Alabama and Louisiana follow in pond hectares with 11,534, 9,267 and 3,480 respectively. It is warm enough the majority of the year for fish to grow economically during the months from March-October. In a colder climate it is less economical to raise channel catfish outdoors because it would take too long to grow to market size. There are about 185-205 growing days in Arkansas, whereas there are only 120-140 in the North Central Region of the U.S. With these lower temperatures, it would take an additional 3-6 months to grow a fish to market size in the North Central Region (Morris 1993).

In feeding catfish, it is important to spread the feed over as large an area as possible in the pond. With a blower-feeder, the farmer must feed “with the wind” in order to keep feed from washing ashore before it is eaten. Little literature is available on wind duration, direction and intensity and the amount of feed waste that results from using a blower type feeder.

Other environmental factors to consider in fish production include site location, source water quality (ground vs. surface), and the soil properties. The properties of the soil and the water source can significantly influence water quality of the culture system in channel catfish ponds at different locations even if the pond nutrient inputs are similar

(Hariyadi et al. 1994). Hariyadi et al. (1994) found that differences in pH, total alkalinity, and total hardness were the result of water supply and also an interaction with the water and the pond soil.

Economics and Costs Involved in Catfish Production

Engle and Killian (1996) created and compared budgets on the costs of producing catfish on commercial farms in levee ponds in Arkansas. The Engle and Killian (1996) budgets assumed that 12,355 fish/ha were stocked into ponds on three different size farms, 65, 130 and 259 ha. Land values of $2,471/ha and earth moving costs of $0.53/cubic meter were used for the analysis. It was found that the total annual cost was highest for the 259-ha farm but the total annual cost per ha and total cost per kg of fish were the lowest for the largest farm. The total cost per kg for the 65, 129 and 259 farms were $1.61/kg, $1.55/kg and $1.52/kg, respectively. It is apparent from budget analysis that it is more cost effective to produce catfish on larger farms.

Feed costs constitute the largest single cost to produce a marketable size catfish (Garrard et al. 1990; Engle and Killian 1996). The majority of the costs involved in intensive catfish production come from feed (45%), fingerlings (8%), and manual labor (9%) (Losinger et al. 2000). The price of the feed depends on the amount of protein it contains. Feed is also cheaper if it is purchased in bulk.

With feed cost at such a high percentage of total cost, feeding strategies that result in low FCRs are critical to the economic efficiency of the farm. At higher stocking densities of fish, producers will be less likely to maximize profit while meeting the biological needs of the fish (Dasgupta et al. 2002). Thus, they may not be able to feed economically at high feed prices.

The amount of feed fed to a particular pond also changes the overall cost of production and is directly related to the stocking density of the pond. Tucker et al. (1979) found that fish stocked at a high density (20,385/ha) required almost twice the amount of feed per kg as the fish stocked at a lower density (4,942/ha). Pomerleau and Engle (2003) found that operating costs increased with stocking density in catfish stocker production (50,000, 100,000 or 150,000 fingerlings/ha) as a result of increased costs of fingerlings, feed and harvest costs.

Feeding rates are related to stocking density and increase up to a point where water quality begins to deteriorate (Losinger et al. 2000). This means that there is a point where additional feeding increases costs more than revenue. For example, Losinger et al. (2000) found that marginal product begins to decrease at feeding rates higher than 40,000 kg/ha/year. They also noted that the optimal stocking density decreased with increasing price of feed. Nerrie et al. (1990) found that the marginal product of stocking rate increased along with feeding rates. Although profit-maximizing stocking densities (16,942-21,312 fingerlings/ha) decreased with higher feed prices, the profit-maximizing stocking density was found to increase with catfish prices (Losinger et al. 2000).

Current Related Research

A 2003 pond production study at the University of Arkansas at Pine Bluff (UAPB) Aquaculture Research Station tested four single-batch-stocking densities of fingerling channel catfish (Southworth et al. in review). Stocking densities of 8,600, 17,300, 26,000 and 34,600/ha were used to determine how densities affect feeding rate, water quality, production characteristics and economics. All fish in the study were fed daily to apparent satiation with a 32% floating commercial catfish feed. The study was conducted in 12 0.10 ha ponds with three replicates per treatment. Water quality parameters monitored monthly included nitrite-N (NO_2-N), nitrate-N (NO_3-N), total ammonia nitrogen (TAN), chlorophyll a, total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) and Secchi disk. In addition, pH was measured weekly and dissolved oxygen and temperature twice daily. Yield, growth, survival, and economics were compared across different densities. Data were used to test for relationships between stocking density/feeding rate, production parameters, and various water quality parameters, as well as to compare the costs of producing channel catfish at different single-batch densities with satiation feeding.

Net yield increased significantly ($P < 0.05$) as stocking density increased, reaching an average of 9,026 kg/ha at the highest density. Growth and marketable yield ($\geq$ 0.57 kg) decreased with increasing stocking density. Survival was not significantly different among densities. Mean and maximum daily feeding rates increased with density, but feed conversion ratios did not differ significantly among treatments (overall average of 1.42) despite the fact that at the higher stocking densities the feeding rates sometimes exceeded 112 kg/ha/d (100 lb/ac/d). Morning dissolved oxygen concentrations fell below 3 mg/L only once in a 34,600/ha pond. Concentrations of chlorophyll a, chemical oxygen demand, nitrite-N, and total ammonia nitrogen increased nominally with increasing feed quantities, but did not reach levels considered problematic even at the highest stocking densities. Breakeven prices were lowest for the highest stocking density even after accounting for the additional time and growth required for sub-marketable fish to reach market size. While total costs were higher for the higher density treatments, the relatively higher yields more than compensated for higher costs.

Materials and Methods

A pond production study was conducted to analyze the effects of channel catfish stocking density and feeding rate on water quality, production characteristics, and costs. Twelve, 0.1-ha earthen ponds at the University of Arkansas at Pine Bluff (UAPB) Aquaculture Research Station were used for the study. The ponds were an average depth of 1.2-m. All twelve ponds were filled with groundwater (Sparta aquifer) and stocked on 29 March 2004. Ground water, before reaching the ponds, had total alkalinity and total hardness values of 46 and 22 mg/L, respectively.

Treatments consisted of understocked precision-graded fingerlings (Trimpey et al. 2004) 11-15 cm (9-27 kg/1000) at either 8,600, 17,300, 26,000 or 34,600 fish/ha. Carryover fish ranging from 0.37-0.45 kg were stocked at 2,268 kg/ha. Growth of fish over the production season was assumed and a weight of 2,268 kg/ha was stocked in order to have enough fish for two partial harvests (removing the same amount of fish as would be removed by a hauling truck from a commercial farm pond), while still leaving carryover fish in the pond through harvest. Treatment densities were assigned randomly to ponds, with three replicates per treatment. Individual weights of 75 fish from each size group (fingerlings (< 0.95 kg) and carryover (≥ 0.95 kg)) were obtained at stocking to determine the initial size distribution of fish.

Fish were fed once daily to apparent satiation (feed was applied until fish appeared to be full or satiated) with a 32% protein floating commercial catfish feed. The point at which fish were considered satiated was a subjective measurement of when feeding activity began to slow and waste feed began to accumulate. A blower-type feeder and a tractor were used to feed to all ponds. The amount of feed fed daily was recorded to the nearest 0.05 kg. The blower feeder was equipped with a 6 kW motor and a Rice Lake Weighing System® and IQ Plus 590-DC digital weight indicator. Feed left in the ponds after all fish had been fed was estimated visually and recorded according to kilograms of feed left after ½-1 hour. Feed waste estimation was used to obtain a daily estimate of the efficiency of feeding and fish consumption of feed. Excess feed was left in the pond, not collected.

A single 0.37 kW/ha electric floating paddlewheel aerator per pond provided nightly aeration. Aerators were adjusted for day length and ran nightly on timers from dusk until dawn. All aerators were placed the same distance from the drainpipe in each pond to ensure equal aeration and water flow. The placement of the aerators was sufficient distance from the levee to minimize erosion and turbidity. Dissolved oxygen was monitored twice daily (dawn and afternoon) with a YSI 550A DO meter. If the morning or afternoon dissolved oxygen fell below 3 mg/L, emergency aeration was administered immediately with a PTO-driven paddlewheel emergency aerator. When afternoon dissolved oxygen concentration indicated a possible bloom crash by a decreasing trend in the oxygen level of the pond, timers were adjusted to allow for more aeration time or a second, 0.56 kW vertical pump aerator was added to the affected pond. Both aerators were run in tandem until the bloom recovered and pond oxygen levels indicated an upward trend in dissolved oxygen. After chemical treatments of potassium permanganate or copper sulfate for disease control, single paddlewheel aerators were run 24 h/d for 2-5 d, until the bloom recovered. All supplemental and emergency aeration hours were recorded and added to the nightly aeration data.

Water was only added to the ponds to compensate for evaporation and seepage. Water samples from each of the twelve ponds were collected every two weeks starting in April and ending in October for a total of 14 different sampling periods. Water samples were collected with a column sampler (160 cm) from three different locations in each pond (standpipe, middle edge, and shallow end), mixed, and the composite sample analyzed. Variables measured monthly included nitrite-N, nitrate-N, total ammonia nitrogen (TAN), chlorophyll a, total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), Secchi disk, temperature and pH. Bloom related parameters were also measured at two-week intervals. The variables measured in two-week intervals included nitrite-N, total ammonia nitrogen (TAN), Secchi disk, temperature and pH. Chloride, total alkalinity, and total hardness were measured prior to the time of stocking in March. Chloride concentrations were brought up to 100 mg/L by the addition of salt (NaCl) and checked every other month to maintain a minimum of 60 mg/L. Total alkalinity and total hardness were checked again at the midpoint of the experiment. In addition, total alkalinity was measured when the pH of any pond fell bellow 7.2, indicating possible high CO_2 levels. When the pH of a pond fell below 7.2, the most recent total alkalinity and current temperature and pH was used to estimate the concentration of $CO_{2.}$ If the estimated CO_2 concentration was greater than 25 mg/L, the current total alkalinity was measured and CO_2 calculated again. In addition to the two-week and monthly water quality parameters measured, pH and temperature (Orion model 610) were recorded for each pond in the afternoon once per week for a total of 27 sampling periods.

Nitrite-N (diazotization method), nitrate-N (cadmium reduction method), TAN (salicylate method), chlorophyll a (chloroform methanol method) (Lloyd and Tucker 1988), TN (persulfate digestion method), TP (acid persulfate digestion test'n tube procedure), and COD (reactor digestion method) were analyzed on a spectrophotometer (HACH DR 4000). Secchi disk, dissolved oxygen, pH, and temperature were all taken immediately on site at the time of sample collection. Total alkalinity (digital titration using sulfuric acid), total hardness (digital titration using EDTA), and chloride were determined by digital titration in the lab (mercuric-nitrate method). Water quality parameters were analyzed according to the HACH Company (2002) water analysis handbook. Catfish disease was monitored and controlled as needed with the use of medicated feed, potassium permanganate and copper sulfate treatments.

A weather station (Onset Technologies Inc.) was installed near the experimental ponds. Water temperature was monitored by the weather station with the use of thermisters at three depths (10 cm from the surface, 50 cm from the surface and 10 cm from the bottom) in the pond closest to the weather station. In addition, separate temperature data loggers recorded temperature, 15 cm under the water, every six hours in two randomly assigned ponds. Data were used to determine relationships between daily feed/kg of fish and water temperature. The weather station recorded atmospheric temperature, barometric pressure and photosynthetically active radiation (PAR). The information from the weather station was downloaded in two-week intervals to correspond to water quality sampling periods. The data from the weather station was then compared to the feeding response of the fish during periods of steady temperatures (Hargreaves and Steeby 1999).

Water levels in the ponds were not lowered during fish sampling periods to ensure minimal exchange of water throughout the study. Data from fish sampled during two sampling periods (10-week intervals) and harvest were used to develop growth curves. Sampled fish were counted (at least 200 understocked fish/pond and 75 carryover fish/pond) and group weighed to calculate average weights for each size group of fish in each pond. Carryover and understocked fish were hand sorted during sampling and precision graded at harvest into three groups, $\geq$ 0.60 kg, 0.34-0.60 kg and $\leq$ 0.34kg. Data were then sorted into fingerling (< 0.95 kg) and carryover ($\geq$ 0.95 kg) fish categories. Fish were group weighed and counted to obtain average weights. Carryover fish were partially harvested during each of the two sampling periods, removing 1,134 kg/ha on sampling period one and 1,587 kg/ha on sampling period two. Harvested fish (19 October 2004) were graded and group weighed according to fingerling and carryover size groups. These size groups were further divided into marketable and sub-marketable groups for data analysis. Five sub-samples (baskets of fish) from each size group were group weighed and counted to obtain an average weight. At least 75 fish/pond of each size group (fingerlings and carryover) were weighed individually.

Enterprise budgets were developed for a single 4-ha pond assumed to be part of a 130-ha farm. Engle and Killian (1996) budgets were modified to reflect the quantities of fingerlings, feed, aeration, fixed costs and costs of stocker production and were used for a base stocking scenario of 17,300/ha. A 19-year average feed price for 32% crude protein feed was obtained from Hanson and Sites (2005). Net returns and breakeven prices above both total costs and total variable costs were calculated for each stocking density including the value of sub-marketable fish at full market value. Net returns and breakeven prices were also calculated by adding in the cost of growing the sub-marketable fish to market size. Individual weight gain of sub-marketable fish held over winter was assumed to be 10% of the mean body weight of the sub-marketable fish. Growth to market size during the remainder of the growing season was assumed to be 0.07 to 0.09 kg/month and the mortality 2.10%/month as observed for carryover fish in the study. An extra month of mortality was added to account for winter mortality of sub-marketable fish. A lower percentage of mortalities in winter than during the main growing season was assumed due to the combination of lower temperatures, less frequent incidence of disease and increased dissolved oxygen concentrations.

The net yield for the study was determined by subtracting the initial stocking weight of fish from the harvest weight of fish. Net daily yield was determined by dividing the net yield by the number of days in the growing season (196 d). At harvest, fish were graded into fingerling and carryover size classes, and from those size classes, marketable and sub-marketable fish were determined. The yield of carryover and fingerlings were determined by the weight of all fish $\geq$ 0.95 kg and < 0.95 kg, respectively. Marketable and sub-marketable yield was determined by the weight of all fish $\geq$ 0.57 and < 0.57 kg, respectively. Growth (g/d) was calculated by subtracting average weight at stocking from harvested average weight in grams and dividing by the number of days of the growing season (196 d). Yield, survival and growth were calculated for each size group and for the total pond. The FCR of each pond was determined by dividing the amount of feed fed by the net yield.

A one-way analysis of variance (ANOVA) was used to test for treatment effects on percent survival of both size groups, mean individual weight at harvest of marketable and sub-marketable fish, carryover and fingerlings, and growth (g/d) of fingerlings and carryover fish throughout the production period. A one-way analysis of variance was also done on gross yield, net yield, net daily yield, sub-marketable yield, marketable yield, fingerling yield and carryover yield of each density. If significant differences were found, least significant difference (LSD) multiple comparison tests were used to identify significantly different treatment levels.

A one-way analysis of variance was done for each water quality variable at each sampling period. Water quality parameters from each of the sampling periods were then averaged and a one-way analysis of variance tested for treatment effects on seasonal water quality variables. A one-way analysis of variance was also done for water temperature at three different pond depths. If significant differences were found, least significant difference (LSD) multiple comparison tests were used to identify significantly different treatment levels.

A one-way analysis of variance was done on FCR, total quantity of feed fed, days fed above 112 kg/ha/d (100 lb/ac/d), and maximum and average daily feed of the different treatments to determine if feed parameters were different at different densities. If significant differences were found, least significant difference (LSD) multiple comparison tests were used to identify significantly different treatment levels.

Simple regressions were run on feed response as a function of same day weather parameters and feed response one day after weather parameters. Simple regressions tested for relationships between daily feeding rates and pond water temperatures. Simple regressions were also run for water quality parameters in relation to feed parameters and for net yield in relation to feed parameters.

Results

Yields and survival

Mean gross yields ranged from 6,943-9,194 kg/ha (Table 1). Gross, net, and net daily yields showed no significant differences ($P > 0.05$) among stocking densities. However, net yield was highly correlated with mean ($r = 0.98$) and maximum ($r = 0.85$) daily feeding rates (Fig. 1a, b). Carryover yields (all fish $\geq$ 0.95 kg) were not significantly different due to stocking density. Fingerling yields (all fish $<$ 0.95 kg) increased as stocking density increased with significant differences between the two highest and the two lowest stocking densities (Table 1). The two lowest stocking densities had significantly fewer sub-marketable fish ($<$ 0.57 kg) than the two highest stocking densities (Fig. 2). However the yield of marketable fish ($\geq$ 0.57 kg) did not differ significantly due to stocking density.

Fingerling survival rates were not significantly different ($P > 0.05$) and mean values ranged from 24 to 36%. Mean survival rates of carryover fish ranged from 77 to 94% and were not significantly different (Table 1). Fish in all ponds were affected by periodic disease episodes during the production season. Catfish were mainly affected by common parasites, columnaris, and enteric septicemia of catfish (ESC). Diseases were controlled by potassium permanganate, copper sulfate and medicated feed before significant losses occurred. However, one high-density treatment pond (34,600/ha) was lost early in the production season to *Ichthyophthirius multifiliis* (Ich) and was subsequently removed from analysis.

Growth

Fingerling (< 0.95 kg), carryover (≥ 0.95 kg), marketable (≥ 0.57 kg) and sub-marketable (< 0.57 kg) mean weights at harvest indicated no significant difference due to stocking density. Mean weight of fingerlings averaged 0.33 kg per fish and mean weight of carryover fish averaged 1.43 kg per fish at harvest (Table 1). Fingerling growth (g/d) was not significantly different at any time over the course of the 196 d production season (Fig. 3). Growth of carryover fish was also not significantly different over the 196 d production season (Fig. 4).

Feeding rates and FCRs

Mean and maximum daily feeding rates ranged from 40-53 kg/ha/d and 123-188 kg/ha/d, respectively. Total feed fed, and mean and maximum daily feeding rates were not significantly different among the different stocking densities (Table 2). However maximum daily feeding rate had a p-value of 0.101. Maximum daily feeding rate reached 188 kg/ha/d and the feeding rate exceeded 112 kg/ha (100 lb/ac/d) an average of 9 d at the 26,000 fingerling/ha density. However, days fed in excess of 112 kg/ha/d (100 lb/ac/d) were not significantly different among stocking densities (Table 2). Feed conversion ratios averaged 1.75 and were not significantly different among the different stocking densities (Table 2).

Water quality

Concentrations of nitrate-N showed significant differences among different stocking densities on the second sampling period (26 April 2004) and pH showed significant differences on the ninth sampling period (3 August 2004) ($P < 0.05$). Values of chlorophyll *a*, Secchi and nitrite-N approached significance at various sampling periods, with p-values ranging from 0.06-0.10. However, there was no clear pattern to these results (Appendix Table 9). Unionized ammonia was not significantly different among densities and was never found at a level known to reduce fish growth (Hargreaves and Kucuk 2001) at any of the sampling periods (Table 3). However, simple regressions indicated that TAN concentrations were somewhat correlated with mean ($r = 0.66$) and maximum ($r = 0.70$) daily feeding rates (Fig. 5a, b). No other water quality variables were strongly related to feeding rate. Mean afternoon pH values ranged from 7.91 to 8.09 with the highest value at the 26,000 fingerlings/ha density; this value was significantly different from all other densities (Table 3). All other water quality variables averaged across the production season showed no significant differences among stocking densities (Table 3). Total alkalinity averaged 126 mg/L in ponds and total hardness values averaged 160 mg/L at the midpoint of the study. Frequency of carbon dioxide levels above 25 mg/L (measured if pH dropped below 7.2) was not significantly different ($p = 0.077$) among stocking densities.

Morning dissolved oxygen concentrations fell below 3 mg/L only once in one pond stocked at 34,600 fish/ha and three times in a 26,000/ha pond. Afternoon dissolved oxygen fell below 3 mg/L once in a pond stocked at 26,000 fish/ha as a result of a crash of the phytoplankton bloom. Extra 0.56 kW vertical pump aerators were necessary periodically throughout the study in ponds of varying densities due to bloom crashes. Supplemental aeration ranged from 91 to 124 h. Averages were 96, 91, 117 and 124 extra aeration hours in the 8,600, 17,300, 26,000 and 34,600 fish/ha treatments, respectively. Total production season hours of aeration ranged from 2,247 to 2,278 h and were not significantly different.

Weather station

Simple regressions of weather station parameters indicated little or no relationship between daily feed response of fish with PAR or barometric pressure. Similarly, regressions indicated little or no relationship between weather parameters and feed response of fish the following day (Appendix Table 8). Analysis of variance of daily average water temperature at three different pond depths was not significantly different. Simple regressions of the kilograms of feed fed per kilogram of fish in response to daily water temperature over 196 d indicated little or no relationship (Appendix Fig. 2, 3, 4, 5).

Budgets

A base enterprise budget for a 4-ha catfish pond (as part of a 130-ha farm) stocked at 17,300 fingerlings/ha is presented in Table 4. Feed and stocker catfish were the greatest components of variable costs at \$2,301/ha and \$3,606/ha, respectively. Income above variable costs was positive at \$828/ha. Net returns/ha were - \$587/ha, with breakeven prices of \$1.42/kg to cover variable costs and \$1.62/kg to cover total costs. Thus, with a density of 17,300 fingerlings/ha, fish must be sold at \$1.42/kg to cover variable costs of production and \$1.62/kg to cover total costs of production.

Table 5 shows the changes in fingerling cost, feed cost, and total and variable costs as stocking density was varied. Net returns varied widely across the different stocking densities, with the highest net return at 26,000 fingerlings/ha. Breakeven prices to cover both variable and total costs were lower at the higher stocking densities. The lowest breakeven prices were found at a stocking density of 26,000 fingerlings/ha (Table 5). Net returns/ha were negative across all densities and decreased with an increased stocking density if only market-sized fish were considered as revenue. Breakeven prices to cover total costs (including the weight of all fish harvested) for the 8,600/ha, 17,300/ha, 26,000/ha and 34,600/ha stocking densities were $1.53, $1.62, $1.35 and $1.42/kg, respectively (Table 5).

At 17,300/ha, revenue of market-sized fish ($\geq$ 0.57 kg) was $9,191/ha and the revenue of sub-marketable fish (< 0.57 kg) was $1,757/ha. Thus, for this density, 84% of the total weight of fish was from market-sized fish, whereas, 16% was from sub-marketable fish (Table 6). Only 66% of the total cost of production can be attributed to the production of market-sized fish in the first year for the two highest stocking densities. In contrast, at the two lowest densities, 84% of the total cost can be attributed to market-sized fish during the first year of production.

After accounting for the costs of additional time, feed, mortality and other costs associated with growing sub-marketable fish to market size, the weighted average breakeven price ($/kg) of all fish by treatment was still lowest at the two highest stocking densities (Table 6). Weighted average breakeven prices were $1.50, $1.58, $1.32 and $1.38/kg for densities 8,600, 17,300, 26,000 and 34,600/ha, respectively. In spite of the higher proportion of sub-marketable fish in the higher densities, the higher yields and a similar average weight produced lower breakeven prices.

Discussion

Raising channel catfish under a continuous, multiple-batch production system has become a common production practice for catfish farmers. This method is used in order to maintain cash flow throughout the year and to decrease the risk caused by off-flavor (Engle 2003). About 88% of US catfish are raised in the multiple-batch production system (USDA 2003).

The current multiple-batch study has shown few significant differences in production and water quality parameters despite variable understocking densities of fingerlings (8,600-34,600 fingerlings/ha). Ponds contained the same biomass of large carryover fish throughout the entire production period and it is possible that these fish dominated, having a profound effect on fingerling survival and production across all densities. Partial harvests removed carryover fish at two different periods over the 196 d production season, but removal may not have been enough to reduce the effects of carryover fish on fingerling production.

Percent survival of fingerlings and carryover fish showed no significant differences due to density (Table 1). The current study had high survival of carryover fish and low survival of fingerlings at all densities. Although fish were handled carefully at stocking, they became sick early in the production season. The reason for the low fingerling survival is unknown. Actual mortality can be as much as seven times that of observed mortality (Tucker et al. 1993); thus disease may have resulted in low fingerling survival. However, there was no significant difference in survival; thus density was not a likely cause of mortality. A possible reason for the low survival may have been the interaction of the two widely varying sizes of fish as a result of the multiple-batch system. Unprasert et al. (1999a) showed the potential for aggressive behavior between catfish size classes when fingerlings were stocked two weeks after carryover fish. Randolph and Clemens (1976) found that large fish dominate over small fish during feeding. They found a size-based hierarchy in relation to feeding. In their study, aggressive behavior from large fish was observed. Unprasert et al. (1999b) stocked a mixed size of channel catfish into ponds and found no indication of competition for feed. However, the small fish in the study were 70 g fish, more than four times larger than fish stocked in our study. Larger fingerlings may have competed better with carryover fish.

The current study used a blower-type feeder, which distributed feed evenly in a wide area of the pond, but competition may have still been a factor in fish growth and survival. According to Unprasert et al. (1999b), an unpublished study at Mississippi State University claims that the stomachs of small fish in multiple-batch production contained more natural feed from the pond itself and less artificial feed than did small fish in single-batch culture. Bush et al. (1984) found fish grown in multiple-batch to have higher feed conversion ratios than fish grown in single-batch, presumably due to size class competition. However, a more recent study evaluating different sizes of fingerlings understocked in multiple-batch, obtained low FCRs and 76% survival of 5-inch fingerlings (Engle and Valderrama 2001). Kleinholtz et al. (2005) found 18 g fingerling survival to be unaffected by multiple-batch culture. It is clear that additional research is needed in the area of competition between size classes of fish and its effects on fingerling production in multiple-batch culture.

Overall gross yields were relatively high and ranged from 6,943 kg/ha to 9,194 kg/ha (Table 1). Gross, net, and net daily yields were not significantly different due to stocking density. Net yield was highly correlated with mean (r = 0.98) and maximum (r = 0.85) daily feeding rates, suggesting that the amount of daily feed has a positive relation with the weight of fish produced (Fig. 1a, 1b). Cole and Boyd (1986) obtained decreasing yields at their highest stocking densities when fish were fed at a percent of body weight (3%) in single batch production. The current study showed no such trend with multiple-batch culture and satiation feeding. Carryover (≥ 0.95 kg) and marketable (≥ 0.57 kg) yields were not significantly different, presumably due to equal mortality and average weights at harvest, and identical numbers of carryover fish stocked. Tucker et al. (1993) found that increases in stocking density did not significantly improve net yield of fish greater than or equal to 0.34 kg. In the current study, fingerling (< 0.95 kg) and sub-marketable (< 0.57 kg) yields increased with an increase in stocking density. The two highest stocking densities had significantly more sub-marketable fish than the two lowest stocking densities (Fig. 2). Mean weights of sub-marketable fish at harvest were not significantly different (Table 1). Similar average weights and survivals combined with a higher stocking densities most likely caused the increase in yield of sub-marketable fish at the higher densities. No significant differences in growth of carryover fish or fingerlings were found at sampling periods or harvest, suggesting that similar stocking weights of carryover fish overshadowed the effects of the different understocking densities (Fig. 3, 4).

Daily feed consumption of catfish was highly variable across all stocking densities. Other studies have found daily feed consumption for large fish (0.26 kg) to be highly variable (Tackett et al. 1988). In the current study, total feed fed was not significantly different among stocking densities (Table 2). Mean and maximum daily feeding rates were not significantly different due to stocking density. No significant differences were found among any of the feed related parameters (Table 2). Low survival of fingerlings across all densities, plus high survivals and identical stocking weights of carryover fish may have caused no significant difference in total feed fed as well as other feed related parameters. Fish were fed carefully with little waste feed and FCRs remained low for multiple-batch culture. Feed conversion ratios were not significantly different and ranged from 1.63 to 1.85. These values are similar to a multiple-batch study by Engle and Valderrama (2001). Although calculated differently, weighted average feed conversion ratios across the catfish industry are between 2.0-2.3, depending on farm size (USDA 2003). Feeding rates did not get as high as expected and feed in excess of 112 kg/ha/d (100 lb/ac/d) was reached only an average of 3, 1, 9, and 8 times in the 8,600, 17,300, 26,000 and 34,600 fish/ha stocking densities, respectively (Table 2). Tucker et al. (1993) compared two different densities of catfish in single and multiple-batch. Fish reached 112 kg/ha/d 110 times at the high density (19,770) single-batch treatment, but only 16 times in a high density (19,770) multiple-batch treatment.

Water quality variables showed few significant differences among densities at 14 different sampling periods (Appendix Table 9). Water quality variables averaged across the production season showed no significant differences due to stocking density (Table 3). A similar single-batch study took place at the University of Arkansas at Pine Bluff (UAPB) in 2003. This study found few significant water quality differences at sampling periods and no significant differences in seasonal average water quality variables despite high stocking densities and feeding rates (Southworth et al. in review). In the current study, average afternoon pH was significantly higher than all other densities at a stocking density of 26,000 fingerlings/ha. However, all average pH values were in an acceptable range for catfish production. Ghate et al. (1993) found that high multiple-batch stocking densities (12,500-37,500 fish/ha) did not cause reduced water quality conditions. Nitrite-N, nitrate-N, TAN and total phosphorus remained low in ponds.

Ponds with 1.8-3.7 kW/ha of aeration enable farmers to feed at rates around 100-125 kg/ha/d without water quality problems. This is considered by Hargreaves and Tucker (2003) to be a maximum sustainable feeding rate. They suggest that this maximum sustainable feeding rate can be exceeded by 50-75 kg/ha/d on a short-term basis. In the current study, mean daily feeding rates averaged about 47 kg/ha/d. Maximum daily feeding rates averaged 160 kg/ha/d. These feeding rates are in the range of what Hargreaves and Tucker (2003) consider sustainable. This could explain why water quality did not deteriorate with an increase in stocking density. Reported average daily feeding rates on commercial fish farms in the U.S. (45 kg/ha/d in 1997 and 56 kg/ha/d in 2003), assuming a 200 d growing season (USDA 1997; USDA 2003), are similar to those in this study.

Total ammonia nitrogen was positively correlated with mean (r = 0.66) and maximum (r = 0.70) daily feeding rates, suggesting that TAN concentration is somewhat related to feeding rate (Fig. 5a,b). However, TAN concentrations remained low throughout the study and were not at levels high enough to affect fish growth (Hargreaves and Kucuk 2001). Unionized ammonia was low at all sampling periods and assumed to be low throughout the entire culture period due to low TAN values and moderate afternoon pH. Thus, it is assumed that fish growth was not affected by unionized ammonia or any other water quality variable. Probable reasons for favorable and non-significant water quality variables include: 1) moderate phytoplankton blooms as judged by an intermediate amount of chlorophyll a; and 2) no significant differences in the total amount of feed fed among densities. Li et al. (2003) compared catfish stocked at different densities fed to satiation and found no significant difference in the concentration of unionized ammonia as stocking density increased from 14,820 to 44,460 fish/ha.

Weather station data indicated that PAR, barometric pressure and water temperature were not related to daily feed response of fish; correlations for all three variables were very low. Hargreaves and Steeby (1999) found a weak, inverse relationship with solar radiation and occurrence of low dissolved oxygen. However, they also found that dissolved oxygen concentration did not effect feed consumption if aeration was initiated at measured concentrations above 2.2 mg/L. In the current study, temperature sensors indicated that there was no significant difference in pond water temperature at three different depths, suggesting no thermal stratification.

Generally, higher stocking densities will produce more sub-marketable fish than lower stocking densities. Total cost of production also tends to increase with increases in stocking density. In this study, the two highest stocking densities had the highest net returns/ha (Table 5). The density found to be most profitable was stocked at 26,000 fingerlings/ha. Breakeven prices to cover both total and variable costs were lowest for the highest stocking densities (Table 5). The reason for the higher returns at the higher stocking densities can be attributed to three factors. First, there was no significant difference in the weight of sub-marketable and market sized fish among densities.

Second, total feed fed and feed conversion ratios were not significantly different. Third, the higher stocking densities had a greater number of sub-marketable fish that outweighed the higher production costs when an inventory of sub-marketable fish was considered at full market value. If just market-sized fish were considered as revenue, net returns decreased with stocking density due to increased production costs and a similar weight of market sized fish (Table 5). In contrast, Tucker et al. (1993) found that their highest multiple-batch stocking density (19,770/ha) had the lowest net returns. In the current study, the proportion of costs attributed to each fish size class shifts as stocking density is increased, with an increasingly higher proportion going to sub-marketable fish at a higher density. The weighted average breakeven price after accounting for growth and mortality of fish grown to market size still indicates that the two highest stocking densities are able to sell fish for less and still break even (Table 6). Mean sub-marketable fish weight at harvest for all densities was not significantly different and reached 0.34 kg per fish. With these average weights fish could be quickly raised to market size (0.57 kg) the next production season. The similar average weight, FCR, and survival of all densities combined with higher numbers of fish caused the weighted average breakeven price to remain lower for the higher stocking densities, even after additional time for growth, and mortality were considered as they grew to market size.

Conclusions

This study provides a basis for a better understanding of the relationships between fish feed response, water quality variables, production characteristics, and costs in multiple-batch channel catfish production. The most interesting part of this research is the fact that few significant differences were observed in growth, yield, survival, water quality and feed related parameters despite different numbers of understocked fish. Large, carryover fish seemed to dictate the production in ponds. For this reason, farmers may benefit from careful records of the biomass of large carryover fish within their ponds. This research also suggests that marketable yield is not significantly affected by the number of understocked fish added that production season, if ponds contain the same amount of carryover fish.

Although feeding rates did not get as high as expected, it seems that fish can be fed to satiation at relatively high rates without water quality problems. Water quality variables remained low throughout the production season. Similar water quality results were found the previous year in a single batch study at UAPB (Southworth et al. in review). In the 2003 study and in the current study, fish were fed in excess of 112 kg/ha/d at various points throughout the year with no negative effects on water quality.

The current study indicates that it is more economical to raise fish at a higher stocking density, even when additional mortality, growth, and time factors are considered when raising sub-marketable fish to market size. The same results were found in the 2003, single batch study at UAPB. However, the current study had low survival of fingerlings and lower FCRs than the catfish industry. This study was not an optimal stocking density study and we are not suggesting that farmers stock fish at higher rates at this time.

This study found that there is possibly a profound effect of large carryover fish on aspects of fingerling production, when the two sizes of fish are grown together. The current study had low survival of fingerlings and high survival of carryover fish. These survival rates may have been a result of early disease outbreaks causing high mortality of fingerlings. Survival rates could also have been a result of competition between the two different sizes of fish stocked. However, mortality was unlikely due to stocking density differences. Additional research is needed to determine the effects of multiple-batch stocking on growth, yield and survival of understocked fish to better understand the interaction of the two different size classes of fish.

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Tables

Table 1. Yield, survival and mean weight at harvest of catfish stocked at four different stocking densities. Values with the same letter in the row are not significantly different. All values are mean ± SD.

Production parameter	Unit	Stocking density (fish/ha)			
		8,600	17,300	26,000	34,600
Survival					
Fingerlings	%	31 ± 2.7 a	24 ± 8.8 a	36 ± 5.3 a	30 ± 2.1 a
Carryover	%	94 ± 9.2 a	83 ± 18.6 a	89 ± 13.2 a	77 ± 27.4 a
Yields					
Gross	kg/ha	7,684 ± 1,092 a	6,943 ± 1,113 a	9,194 ± 485 a	8,189 ± 2,208 a
Total net	kg/ha	5,247 ± 1,091 a	4,334 ± 1,113 a	6,415 ± 485 a	5,236 ± 2,208 a
Net daily	kg/ha/d	27 ± 5.6 a	22 ± 5.7 a	33 ± 2.5 a	27 ± 11.3 a
Carryover [a]	kg/ha	6,674 ± 1,163 a	5,262 ± 1,645 a	6,059 ± 818 a	4,766 ± 2,507 a
Fingerling [b]	kg/ha	1,011 ± 79 b	1,681 ± 832 b	3,135 ± 382 a	3,423 ± 299 a
Mean weight at harvest					
Carryover [a]	kg	1.54 ± 0.08 a	1.44 ± 0.30 a	1.50 ± 0.09 a	1.17 ± 0.40 a

Fingerling [b]	kg	0.34 ± 0.02 a	0.35 ± 0.0 a	0.32 ± 0.02 a	0.33 ± 0.02 a
Marketable [c]	kg	1.53 ± 0.12 a	1.43 ± 0.24 a	1.54 ± 0.07 a	1.29 ± 0.26 a
Sub-marketable [d]	kg	0.33 ± 0.01 a	0.34 ± 0.01 a	0.32 ± 0.02 a	0.34 ± 0.04 a

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[a] All fish greater than or equal to 0.95 kg at harvest.

[b] All fish less than 0.95 kg at harvest.

[c] All fish greater than or equal to 0.57 kg at harvest.

[d] All fish less than 0.57 kg at harvest.

Table 2. Satiation feed results for catfish stocked at four different stocking densities. No significant differences were observed in feed related parameters due to stocking density. All values are mean ± SD.

Production parameter	Unit	Stocking density (fish/ha)			
		8,600	17,300	26,000	34,600
Total feed fed	kg/ha	8,820 ± 1,200 a	7,835 ± 1,112 a	10,477 ± 359 a	9,371 ± 2,676 a
Mean daily feeding rate	kg/ha/d	45 ± 6.1 a	40 ± 5.6 a	53 ± 1.8 a	48 ± 13.6 a
Maximum daily feeding rate	kg/ha/d	145 ± 19.5 a	123 ± 6.6 a	188 ± 19.3 a	182 ± 44.5 a
Feed in excess of 112 kg/ha/d	days	3 ± 3 a	1 ± 1.5 a	9 ± 3.5 a	8 ± 9.2 a
Feed conversion ratio	feed/mass	1.70 ± 0.13 a	1.84 ± 0.20 a	1.63 ± 0.08 a	1.85 ± 0.26 a

Table 3. Average seasonal water quality variables at four different stocking densities. Numbers are average values across all sampling periods ± SD. Values with the same letter in the row are not significantly different.

			Stocking density (fish/ha)			
Water quality parameter	Unit	N	8,600	17,300	26,000	34,600
Temperature	C	196	25.3 ± 0.20 a	25.3 ± 0.21 a	25.3 ± 0.11 a	25.3 ± 0.21 a
Afternoon pH		27	7.91 ± 0.08 b	7.95 ± 0.09 b	8.09 ± 0.03 a	7.92 ± 0.06 b
Morning pH		14	7.39 ± 0.05 a	7.41 ± 0.06 a	7.35 ± 0.07 a	7.48 ± 0.11 a
Total ammonia nitrogen	mg/L	14	0.614 ± 0.183 a	0.522 ± 0.219 a	0.781 ± 0.302 a	0.726 ± 0.177 a
Un-ionized ammonia	mg/L	14	0.009 ± 0.003 a	0.008 ± 0.006 a	0.011 ± 0.006 a	0.009 ± 0.003 a
Nitrite-N	mg/L	14	0.062 ± 0.034 a	0.044 ± 0.021 a	0.050 ± 0.012 a	0.046 ± 0.031 a
Nitrate-N	mg/L	7	0.33 ± 0.15 a	0.30 ± 0.10 a	0.27 ± 0.06 a	0.25 ± 0.07 a
Total nitrogen	mg/L	7	4.22 ± 0.71 a	4.51 ± 1.24 a	5.05 ± 2.03 a	3.97 ± 0.18 a
Total phosphorus	mg/L	7	1.43 ± 0.26 a	1.51 ± 0.21 a	1.49 ± 0.22 a	1.55 ± 0.57 a
Chlorophyll a	ug/L	7	192 ± 42 a	158 ± 45 a	163 ± 26 a	166 ± 27 a

Chemical oxygen demand	mg/L	7	43.7 ± 6.2 a	50.3 ± 10.8 a	50.2 ± 5.1 a	54.0 ± 12.2 a
Secchi disk	cm	14	11 ± 0.6 a	10 ± 2.1 a	11 ± 1.2 a	12 ± 0.00 a
Pond alkalinity	mg/L	7	134 ± 8 a	123 ± 6 a	125 ± 6 a	122 ± 3 a
Pond hardness	mg/L	1	171 ± 14 a	160 ± 36 a	150 ± 17 a	159 ± 9 a

Table 4. Enterprise budget for a 4-ha catfish pond (130-ha farm) stocked at 17,300 fingerlings/ha in multiple-batch using treatment means.

Item	Unit	Unit cost ($)	Quantity	Price/cost ($)	Cost per ha ($)
Gross receipts					
Revenue of market sized fish	kilogram	1.54	23,874	36,766	9,191
Inventory of sub-marketable fish	kilogram	1.54	4,564	7,029	1,757
Total receipts				43,795	10,948
Variable costs					
Fingerlings	fish	0.070	69,200	4,844	1,211
Stockers	kilogram	1.59 [a]	9,072	14,424	3,606
Feed	metric ton	253	36.38	9,204	2,301
Harvesting and hauling	kilogram	0.088	23,874	2,101	525
All other variable costs	dollars	6,229	1	6,229	1,557
Interest on operating capital	dollars	36,802	0.10	3,680	920
Total variable costs				40,482	10,120

Income above variable costs				3,313	828
Fixed costs	dollars	5,661	1	5,661	1,415
Total fixed costs				5,661	1,415
Total costs				46,143	11,535
Net returns to operators labor and management				- 2,348	- 587
Net returns/ha					- 587
Breakeven price					
to cover variable costs					1.42
to cover total costs					1.62

[a] Production cost per kilogram of fish from Engle and Killian (1996).

Table 5. Breakeven prices ($/kg) for a 4-ha catfish pond (130-ha farm) at four different stocking densities using treatment means.

							Breakeven prices[c]	
Stocking density (fish/ha)	Fingerling cost ($/ha)	Feed cost ($/ha)	Total variable costs[a] ($/ha)	Total costs[b] ($/ha)	Net returns/ ha of all fish ($/ha)	Net returns/ha of fish $\geq$ 0.57 kg ($/ha)	Breakeven variable costs ($/kg)	Breakeven total costs ($/kg)
8,600	$602	$2,301	$9,452	$10,867	$81	- $1,676	$1.33	$1.53
17,300	$1,211	$2,301	$10,120	$11,535	- $587	- $2,346	$1.42	$1.62
26,000	$1,820	$2,301	$10,792	$12,207	$1,711	- $3,015	$1.19	$1.35
34,600	$2,422	$2,301	$11,454	$12,869	$1,048	- $3,678	$1.27	$1.42

[a] Includes harvesting and hauling, all other variable costs, and interest on operating capital, calculated as detailed in Table 4.

[b] Includes fixed costs of $1,415/ha, calculated as detailed in Table 4.

[c] Calculated including the weight of both marketable and sub-marketable fish.

Table 6. Percent of total cost attributed to marketable and sub-marketable sized fish and breakeven prices after accounting for the mortality, time, and growth required for sub-marketable fish to reach market size. Numbers were obtained from treatment means.

Stocking density (fish/ha)	Portion of costs at harvest attributed to fish $\geq$ 0.57 kg (%)	Portion of costs at harvest attributed to fish < 0.57 kg (%)	Production costs including growing all fish to 0.57 kg [a] ($/ha)	Total weight after additional growth of < 0.57 kg fish (kg/ha)	Weighted average breakeven price [b] after accounting for growth of fish to market size ($/kg)
8,600	84%	16%	$11,664	7,800	$1.50
17,300	84%	16%	$12,334	7,800	$1.58
26,000	66%	34%	$14,326	10,836	$1.32
34,600	66%	34%	$14,988	10,836	$1.38

[a] Calculated by adding the costs of production through harvest of the first year with the estimated cost of growing sub-marketable fish to 0.57 kg.

[b] Above total costs.

Figures

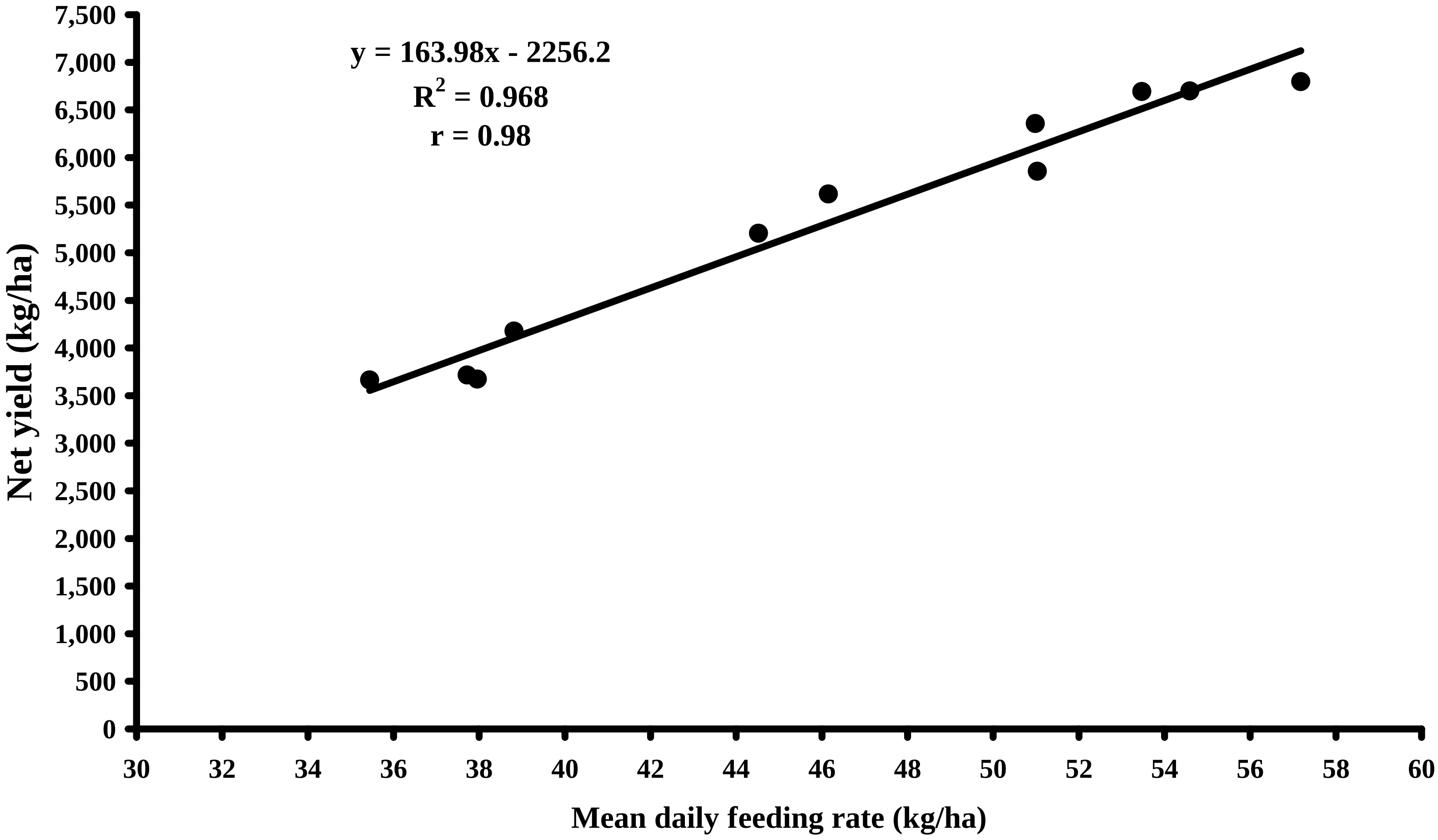

Figure 1a. Net yield in response to mean daily feeding rate for catfish (pooled data from four different stocking densities).

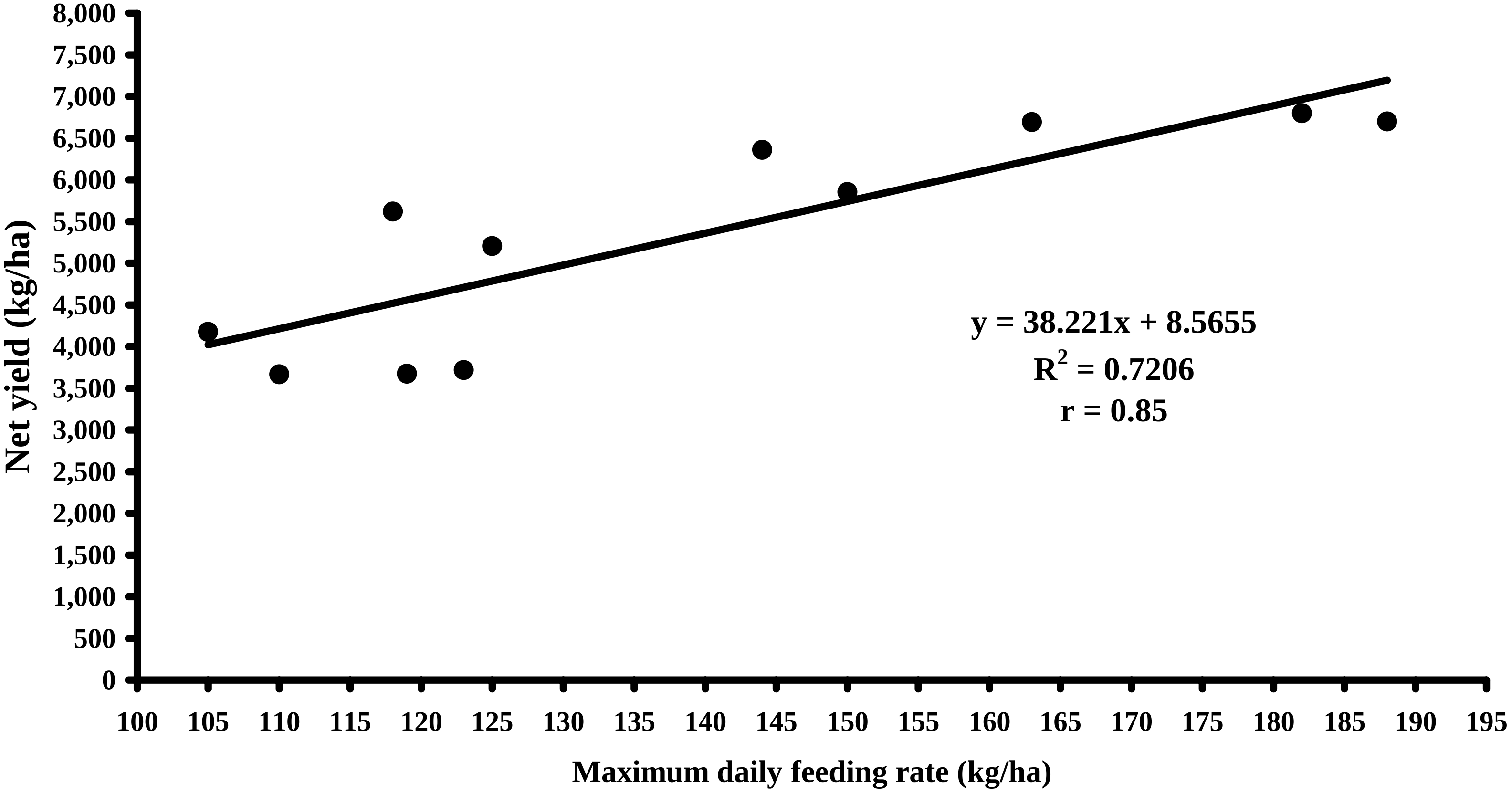

Figure 1b. Net yield in response to maximum daily feeding rate for catfish (pooled data from four different stocking densities). Maximum daily feeding rate is defined as the highest daily quantity of feed fed to each density.

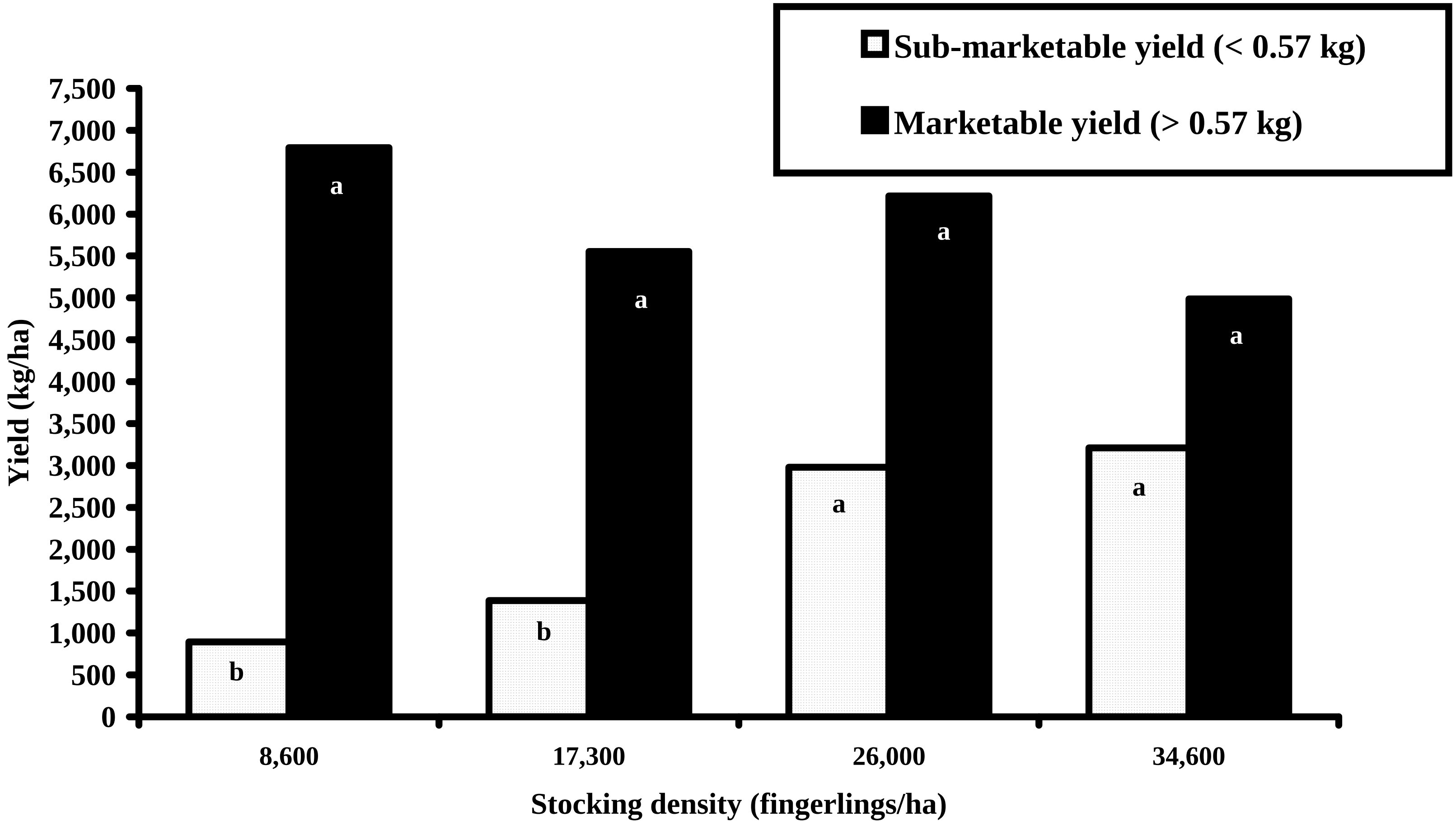

Figure 2. Marketable and sub-marketable yield of catfish at four different stocking densities. Different letters within the graph indicate significant differences within each size class among treatments.

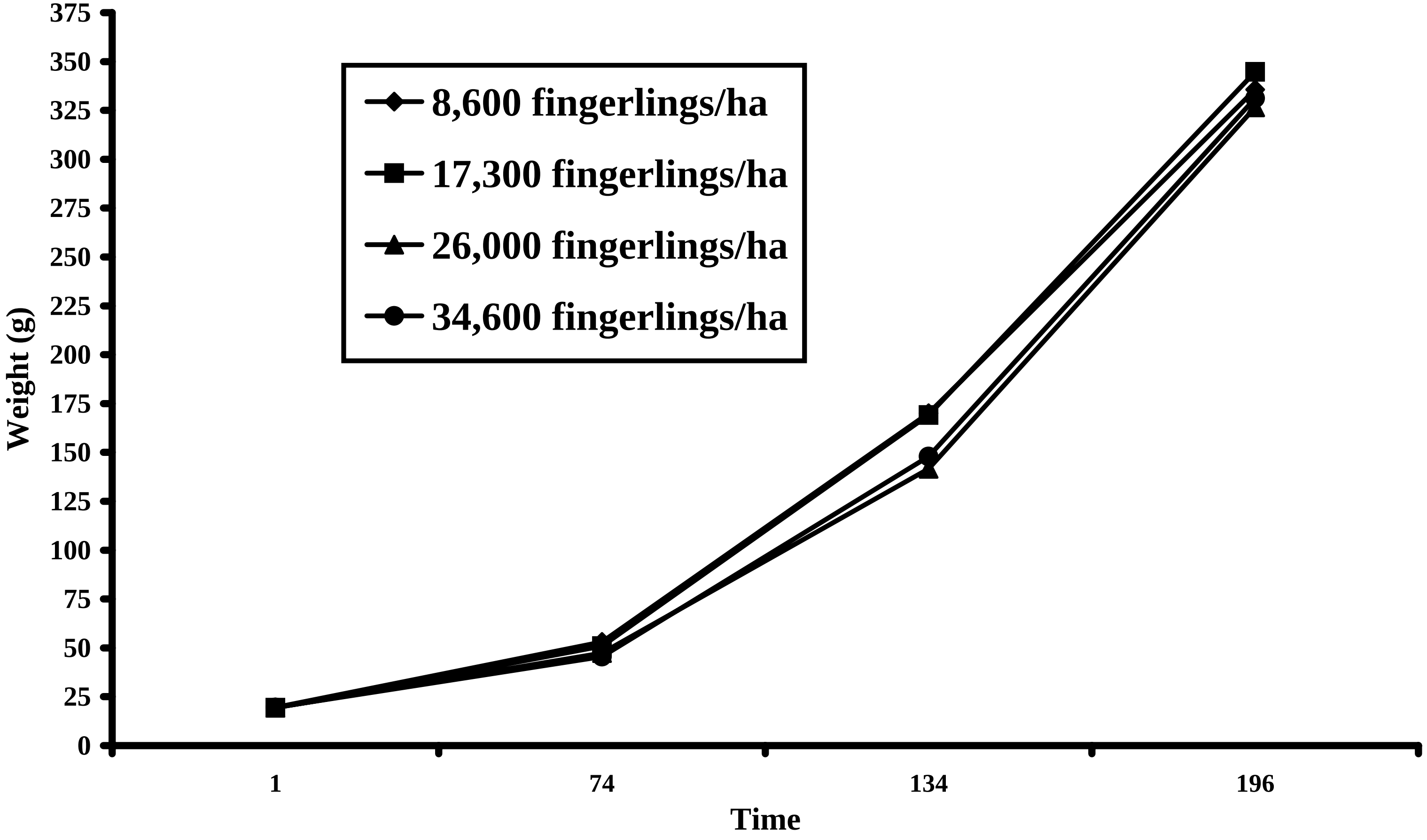

Figure 3. Mean weight of fingerlings (< 0.57 kg) over time at stocking, harvest, and two different sampling periods during the 196 d growing season.

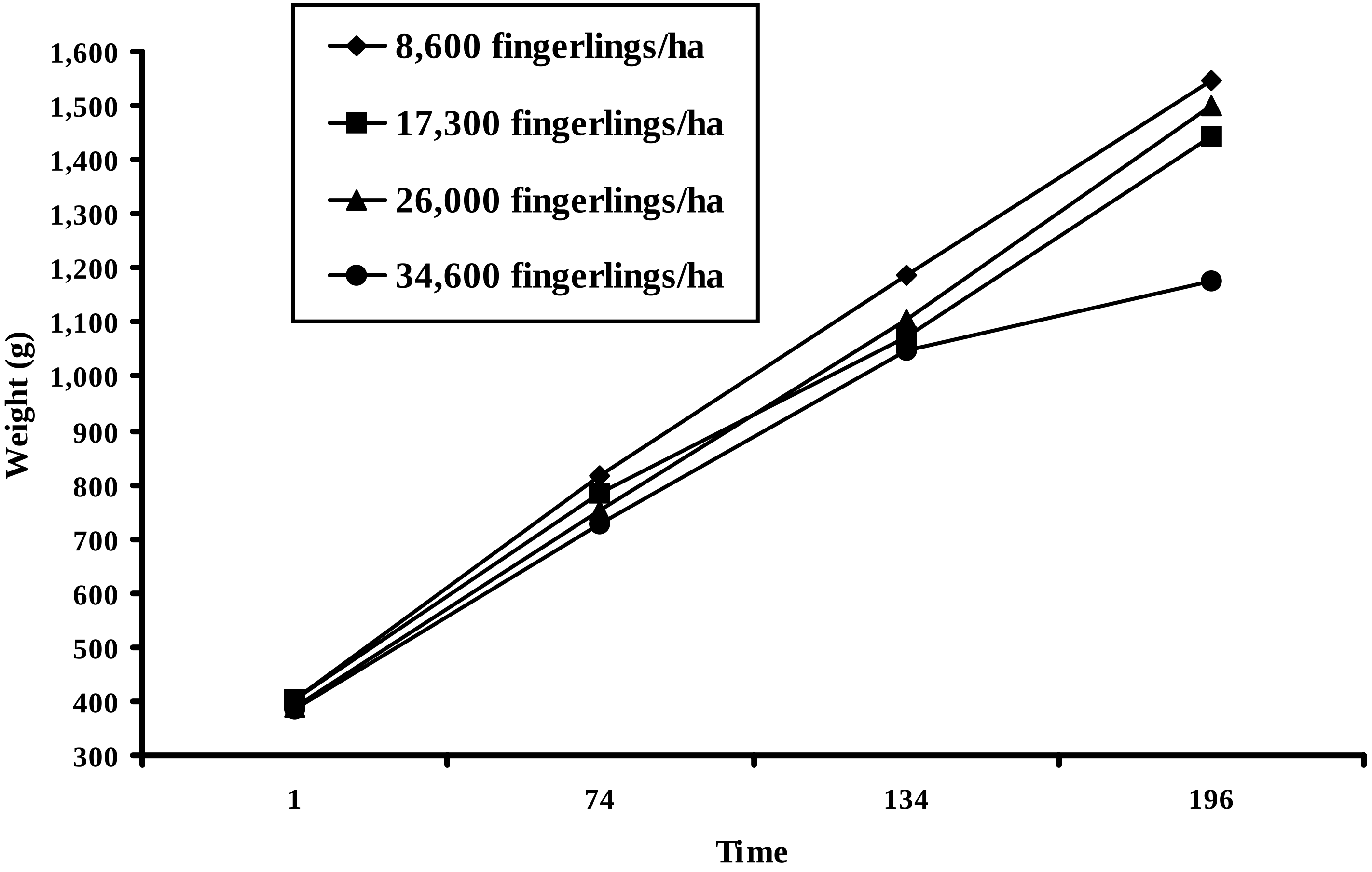

Figure 4. Mean weight of carryover fish (≥ 0.57 kg) over time at stocking, harvest, and two different sampling periods during the 196 d growing season.

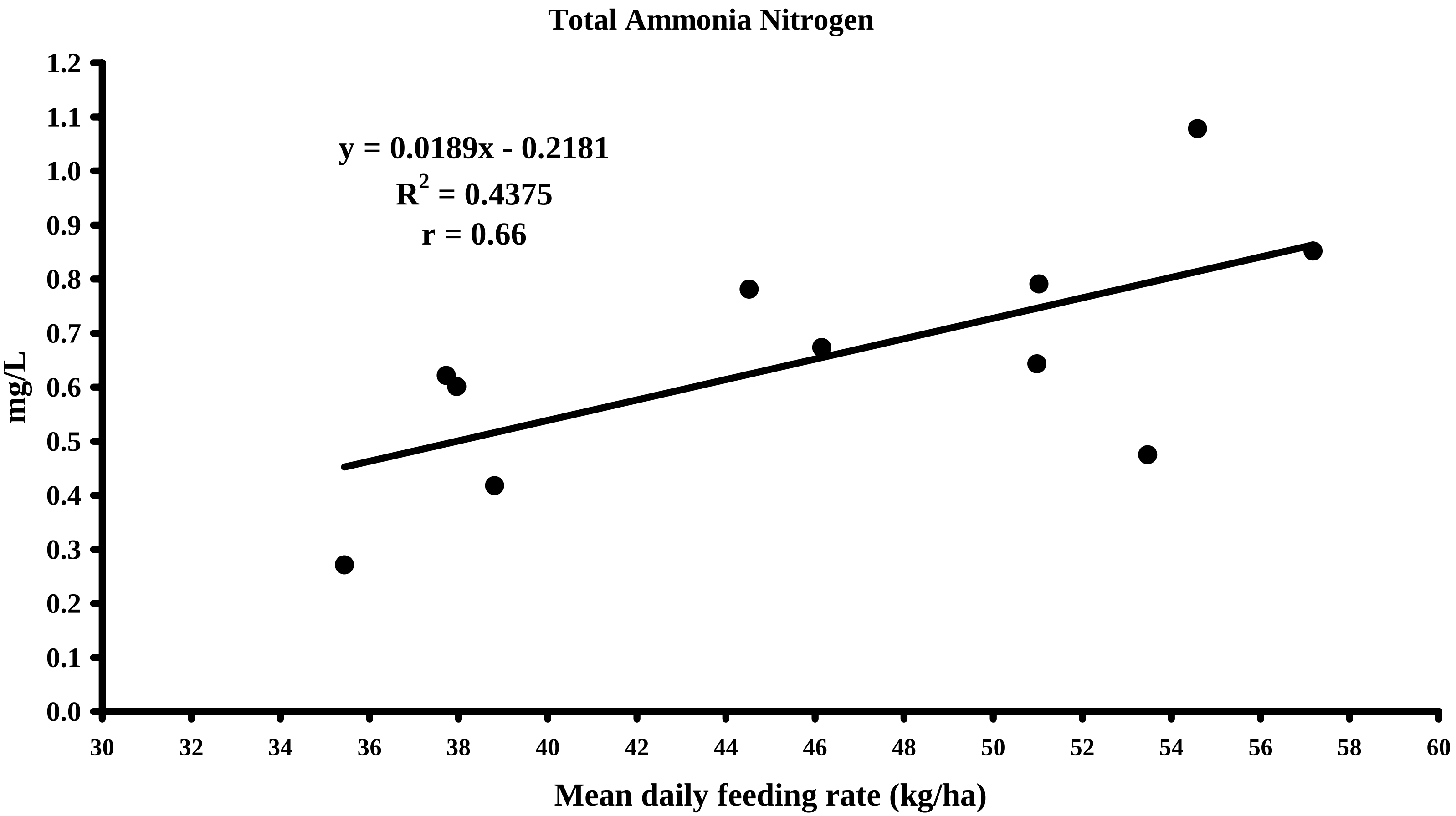

Figure 5a. Total ammonia nitrogen in relation to mean daily feeding rate for catfish (pooled data from four different stocking densities).

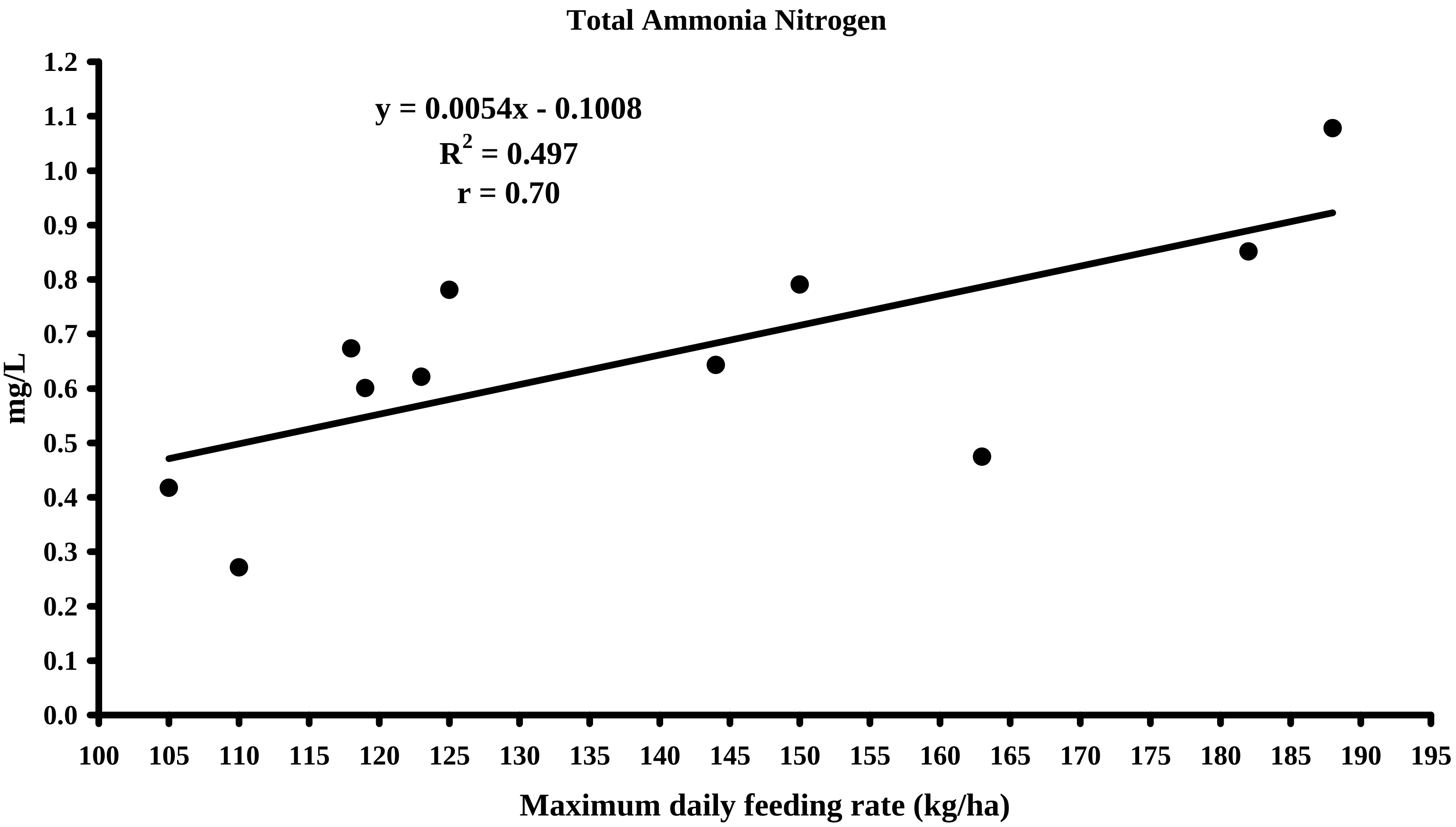

Figure 5b. Total ammonia nitrogen in relation to maximum daily feeding rate for catfish (pooled data from four different stocking densities). Maximum daily feeding rate is defined as the highest daily quantity of feed fed to each density.

Appendix

Appendix Tables

Appendix Table 1. Growth of catfish stocked at four different stocking densities. No significant differences were found at sampling periods or harvest. All values are mean ± SD.

Production parameter	Unit	Stocking density (fish/ha)			
		8,600	17,300	26,000	34,600
Fingerling growth					
Stocking – sample 1	g/d	0.45 ± 0.03 a	0.42 ± 0.09 a	0.38 ± 0.03 a	0.35 ± 0.08 a
Sampling 1 – sampling 2	g/d	1.95 ± 0.30 a	1.97 ± 0.20 a	1.57 ± 0.08 a	1.71 ± 0.21 a
Sampling 2 – harvest	g/d	2.72 ± 0.06 a	2.90 ± 0.34 a	3.01 ± 0.34 a	3.00 ± 0.01 a
Stocking – sampling 2	g/d	1.12 ± 0.14 a	1.12 ± 0.14 a	0.91 ± 0.02 a	0.96 ± 0.13 a
Stocking – harvest	g/d	1.60 ± 0.10 a	1.66 ± 0.01 a	1.56 ± 0.11 a	1.59 ± 0.11 a
Carryover growth					
Stocking – sample 1	g/d	5.56 ± 0.86 a	5.13 ± 0.23 a	4.91 ± 0.17 a	4.66 ± 0.83 a
Sampling 1 – sampling 2	g/d	6.15 ± 1.06 a	4.80 ± 1.02 a	5.90 ± 1.02 a	5.30 ± 0.30 a

Sampling 2 – harvest	g/d	5.90 ± 1.59 a	6.09 ± 3.52 a	6.47 ± 0.86 a	2.11 ± 5.54 a
Stocking – sampling 2	g/d	5.82 ± 0.29 a	4.98 ± 0.52 a	5.36 ± 0.40 a	4.95 ± 0.33 a
Stocking – harvest	g/d	5.81 ± 0.50 a	5.30 ± 1.35 a	5.68 ± 0.53 a	4.04 ± 1.95 a

Appendix Table 2. Enterprise budget for a 4-ha catfish pond (130-ha farm) stocked at 8,600 fingerlings/ha in multiple-batch. Parameters were not averaged across treatments.

Item	Unit	Unit cost ($)	Quantity	Price/cost ($)	Cost per ha ($)
Gross receipts					
Revenue of market sized fish	kilogram	1.54	27,167	41,837	10,459
Inventory of sub-marketable fish	kilogram	1.54	3,573	5,502	1,376
Total receipts				47,339	11,835
Variable costs					
Fingerlings	fish	0.070	34,400	2,408	602
Stockers	kilogram	1.59 [a]	9,072	14,424	3,606
Feed	metric ton	253	35.28	8,926	2,231
Harvesting and hauling	kilogram	0.088	27,167	2,391	598
All other variable costs	dollars	6,229	1	6,229	1,557
Interest on operating capital	dollars	34,378	0.10	3,438	859
Total variable costs				37,816	9,453

Income above variable costs				9,523	2,382
Fixed costs	dollars	5,661	1	5,661	1,415
Total fixed costs				5,661	1,415
Total costs				43,477	10,868
Net returns to operators labor and management				3,862	967
Net returns/ha					967
Breakeven price					
to cover variable costs					1.23
to cover total costs					1.41

[a] Production cost per kilogram of fish from Engle and Killian (1996).

Appendix Table 3. Enterprise budget for a 4-ha catfish pond (130-ha farm) stocked at 17,300 fingerlings/ha in multiple-batch. Parameters were not averaged across treatments.

Item	Unit	Unit cost ($)	Quantity	Price/cost ($)	Cost per ha ($)
Gross receipts					
Revenue of market sized fish	kilogram	1.54	22,217	34,214	8,554
Inventory of sub-marketable fish	kilogram	1.54	5,555	8,555	2,139
Total receipts				42,769	10,693
Variable costs					
Fingerlings	fish	0.070	69,200	4,844	1,211
Stockers	kilogram	1.59 [a]	9,072	14,424	3,606
Feed	metric ton	253	31.34	7,929	1,982
Harvesting and hauling	kilogram	0.088	22,217	1,955	489
All other variable costs	dollars	6,229	1	6,229	1,557
Interest on operating capital	dollars	35,381	0.10	3,538	885
Total variable costs				38,919	9,730

Income above variable costs				3,850	963
Fixed costs	dollars	5,661	1	5,661	1,415
Total fixed costs				5,661	1,415
Total costs				44,580	11,145
Net returns to operators labor and management				- 1,811	- 452
Net returns/ha					- 452
Breakeven price					
to cover variable costs					1.40
to cover total costs					1.61

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[a] Production cost per kilogram of fish from Engle and Killian (1996).

Appendix Table 4. Enterprise budget for a 4-ha catfish pond (130-ha farm) stocked at 26,000 fingerlings/ha in multiple-batch. Parameters were not averaged across treatments.

Item	Unit	Unit cost ($)	Quantity	Price/cost ($)	Cost per ha ($)
Gross receipts					
Revenue of market sized fish	kilogram	1.54	24,858	38,281	9,570
Inventory of sub-marketable fish	kilogram	1.54	11,919	18,355	4,589
Total receipts				56,636	14,159
Variable costs					
Fingerlings	fish	0.070	104,000	7,280	1,820
Stockers	kilogram	1.59 [a]	9,072	14,424	3,606
Feed	metric ton	253	41.91	10,603	2,651
Harvesting and hauling	kilogram	0.088	24,858	2,188	547
All other variable costs	dollars	6,229	1	6,229	1,557
Interest on operating capital	dollars	40,724	0.10	4,072	1,018
Total variable costs				44,796	11,199

Income above variable costs				11,840	2,960
Fixed costs	dollars	5,661	1	5,661	1,415
Total fixed costs				5,661	1,415
Total costs				50,457	12,614
Net returns to operators labor and management				6,179	1,545
Net returns/ha					1,545
Breakeven price					
to cover variable costs					1.22
to cover total costs					1.37

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[a] Production cost per kilogram of fish from Engle and Killian (1996).

Appendix Table 5. Enterprise budget for a 4-ha catfish pond (130-ha farm) stocked at 34,600 fingerlings/ha in multiple-batch. Parameters were not averaged across treatments.

Item	Unit	Unit cost ($)	Quantity	Price/cost ($)	Cost per ha ($)
Gross receipts					
Revenue of market sized fish	kilogram	1.54	19,945	30,715	7,679
Inventory of sub-marketable fish	kilogram	1.54	12,810	19,727	4,932
Total receipts				50,442	12,611
Variable costs					
Fingerlings	fish	0.070	138,400	9,688	2,422
Stockers	kilogram	1.59 [a]	9,072	14,424	3,606
Feed	metric ton	253	37.48	9,482	2,371
Harvesting and hauling	kilogram	0.088	19,945	1,755	439
All other variable costs	dollars	6,229	1	6,229	1,557
Interest on operating capital	dollars	41,578	0.10	4,158	1,039
Total variable costs				45,736	11,434

Income above variable costs				4,706	1,177
Fixed costs	dollars	5,661	1	5,661	1,415
Total fixed costs				5,661	1,415
Total costs				51,397	12,849
Net returns to operators labor and management				- 955	- 238
Net returns/ha					- 238
Breakeven price					
to cover variable costs					1.40
to cover total costs					1.57

[a] Production cost per kilogram of fish from Engle and Killian (1996).

Appendix Table 6. Breakeven prices ($/kg) for a 4-ha catfish pond (130-ha farm) at four different stocking densities.

							Breakeven prices [c]	
Stocking density (fish/ha)	Fingerling cost ($/ha)	Feed cost ($/ha)	Total variable costs [a] ($/ha)	Total costs [b] ($/ha)	Net returns/ ha of all fish ($/ha)	Net returns/ha of fish ≥ 0.57 kg ($/ha)	Breakeven variable costs ($/kg)	Breakeven total costs ($/kg)
8,600	$602	$2,231	$9,453	$10,868	$967	- $411	$1.23	$1.41
17,300	$1,211	$1,982	$9,730	$11,145	- $452	- $2,576	$1.40	$1.61
26,000	$1,820	$2,651	$11,199	$12,614	$1,545	- $3,045	$1.22	$1.37
34,600	$2,422	$2,371	$11,434	$12,849	- $238	- $5,172	$1.40	$1.57

[a] Includes harvesting and hauling, all other variable costs, and interest on operating capital, calculated as detailed in Table 4.

[b] Includes fixed costs of $1,415/ha, calculated as detailed in Table 4.

[c] Calculated including the weight of both marketable and sub-marketable fish.

Appendix Table 7. Percent of total cost attributed to marketable and sub-marketable sized fish and breakeven prices after accounting for the time, mortality, and growth required for sub-marketable fish to reach market size.

Stocking density (fish/ha)	Portion of costs at harvest attributed to fish ≥ 0.57 kg (%)	Portion of costs at harvest attributed to fish < 0.57 kg (%)	Production costs including growing all fish to 0.57 kg [a] ($/ha)	Total weight after additional growth of < 0.57 kg fish (kg/ha)	Weighted average breakeven price [b] after accounting for growth of fish to market size ($/kg)
8,600	88%	12%	$11,497	8,284	$1.39
17,300	80%	20%	$12,068	7,675	$1.57
26,000	68%	32%	$14,547	11,005	$1.32
34,600	61%	39%	$14,874	9,637	$1.54

[a] Calculated by adding the costs of production through harvest of the first year with the estimated cost of growing sub-marketable fish to 0.57 kg.

[b] Above total costs.

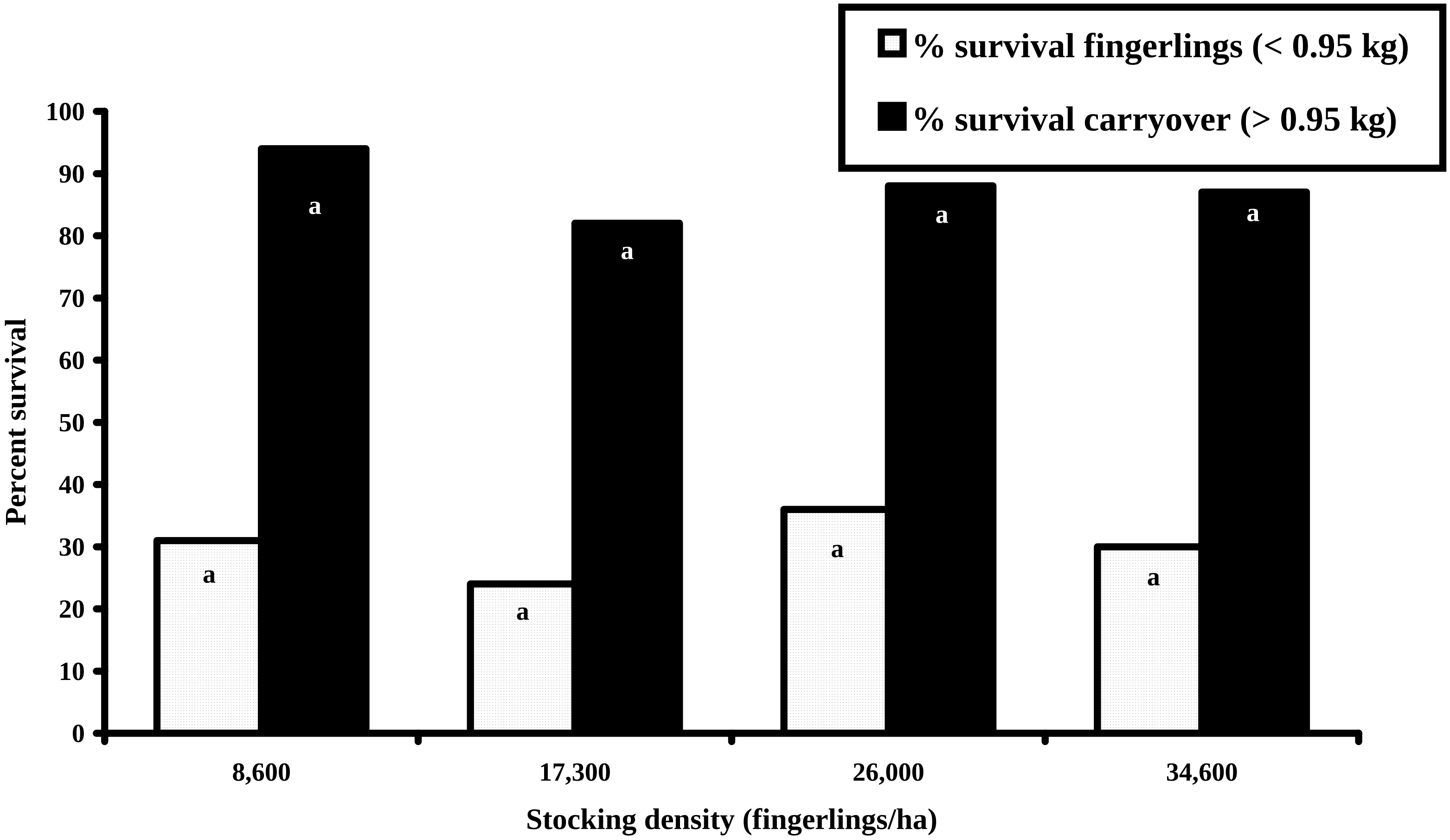
Appendix Table 8. Simple regressions of the effect of photosynthetically active radiation (PAR) and barometric pressure on feed response of catfish at four different stocking densities. The R^2 values are for the period of 1 July to 1 September at a time of steady water temperature.

	Stocking density (fish/ha)			
Weather station parameter	8,600	17,300	26,000	34,600
PAR and feed response	0.0010	0.0279	0.0006	0.0002
PAR and lagged (1 d) feed response	0.0040	0.0001	0.0009	0.0131
Barometric pressure and feed response	0.0130	0.0246	0.0463	0.0102
Barometric pressure and lagged feed response	0.0466	0.0180	0.0103	0.0244

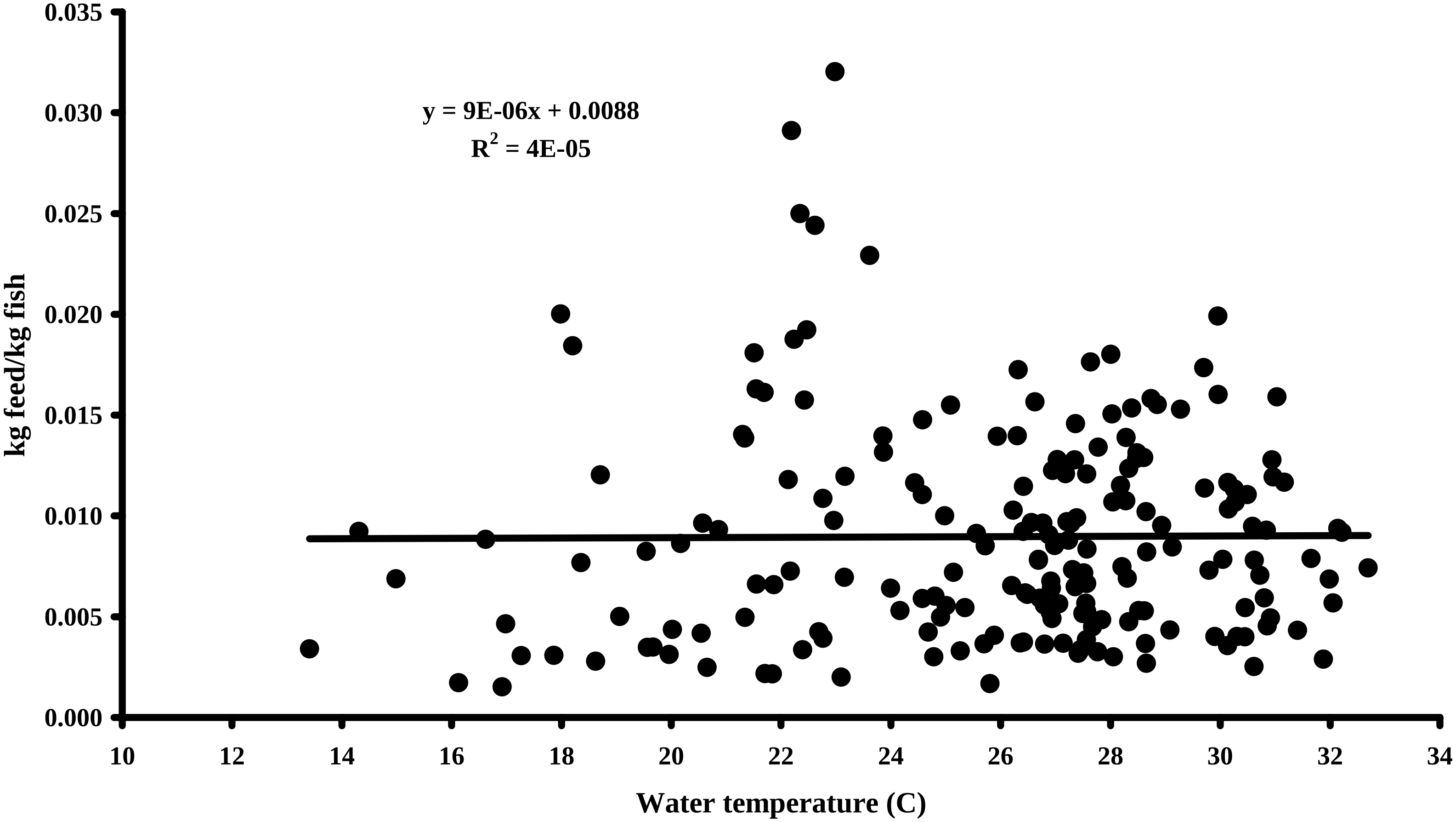
Appendix Table 9. Significant water quality variables compared for each stocking density at each sampling period. All numbers represent p-values.

	Sampling date													
Water quality parameter	4/12	4/26	5/10	5/25	6/8	6/22	7/6	7/21	8/3	8/19	8/31	9/16	9/28	10/14
Temperature	1	0.73	0.27	0.75	0.20	0.51	0.47	0.30	1	1	1	0.22	0.47	0.99
pH	0.48	0.31	0.87	0.70	0.71	0.13	0.61	0.88	0.04	0.07	0.72	0.18	0.50	0.62
Secchi disk	0.15	0.75	0.84	0.71	0.81	0.48	0.14	0.11	0.29	0.94	0.66	0.31	0.36	0.30
Total ammonia nitrogen	0.97	0.22	0.57	0.39	0.49	0.62	0.65	0.27	0.56	0.56	0.84	0.38	0.74	0.32
Nitrite-N	0.30	0.31	0.57	0.82	0.17	0.82	0.09	0.52	0.53	0.99	0.27	0.39	0.37	0.98
Nitrate-N	N/A	0.04	N/A	0.58	N/A	0.78	N/A	0.22	N/A	0.41	N/A	0.78	N/A	0.37
Chemical oxygen demand	N/A	0.81	N/A	0.44	N/A	0.40	N/A	0.59	N/A	0.51	N/A	0.97	N/A	0.19
Total nitrogen	N/A	0.27	N/A	0.72	N/A	0.93	N/A	0.51	N/A	0.63	N/A	0.37	N/A	0.16
Total phosphorus	N/A	0.44	N/A	0.94	N/A	0.23	N/A	0.97	N/A	0.79	N/A	0.73	N/A	0.21
Chlorophyll _a_	N/A	0.10	N/A	0.52	N/A	0.78	N/A	0.75	N/A	0.06	N/A	0.44	N/A	0.26

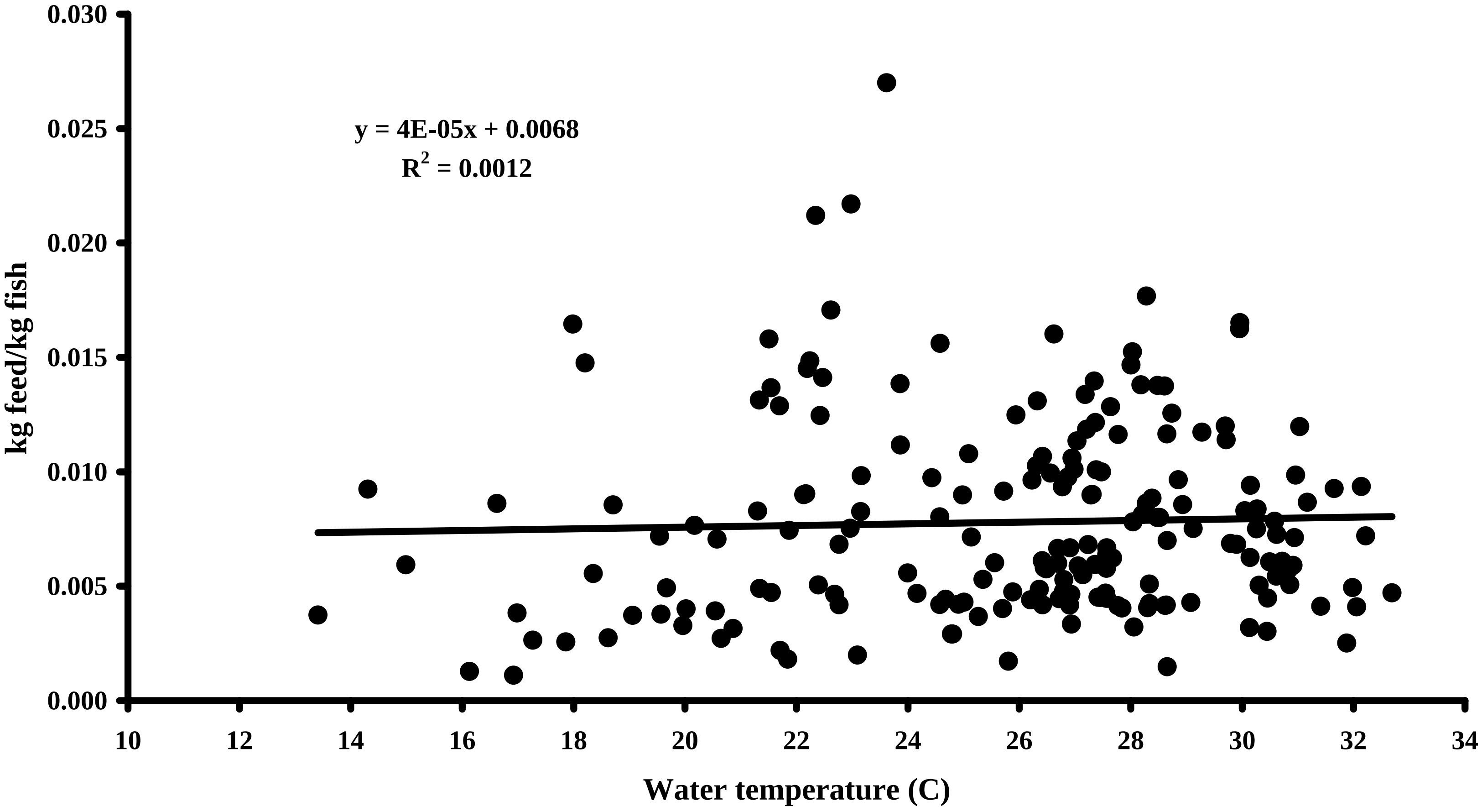
Appendix Figures



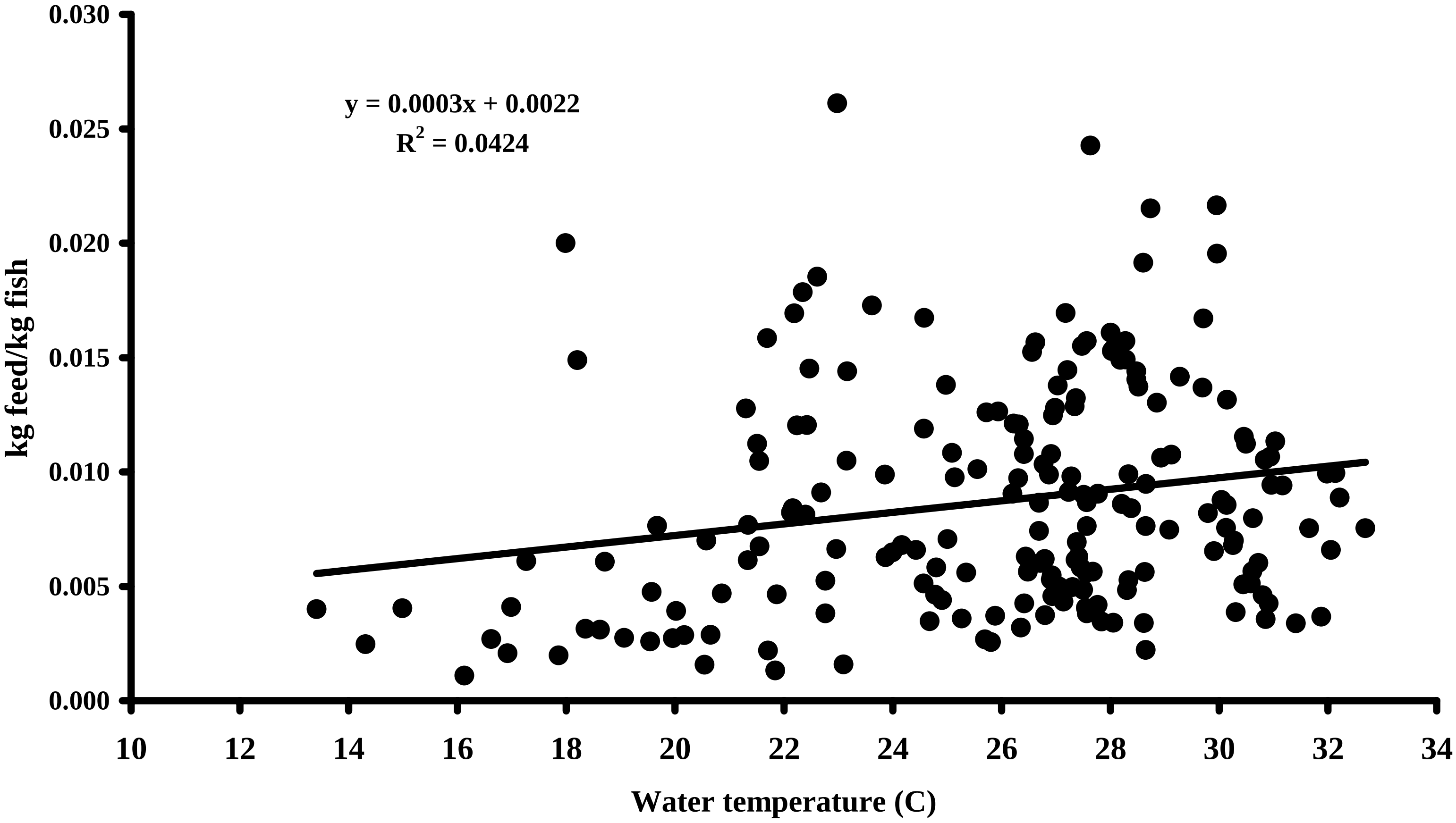
Appendix Figure 1. Percent survival of fingerlings (< 0.95 kg) and carryover fish ($\geq$ 0.95 kg) at four different stocking densities. Different letters within the graph indicate significant differences within each size class among treatments.



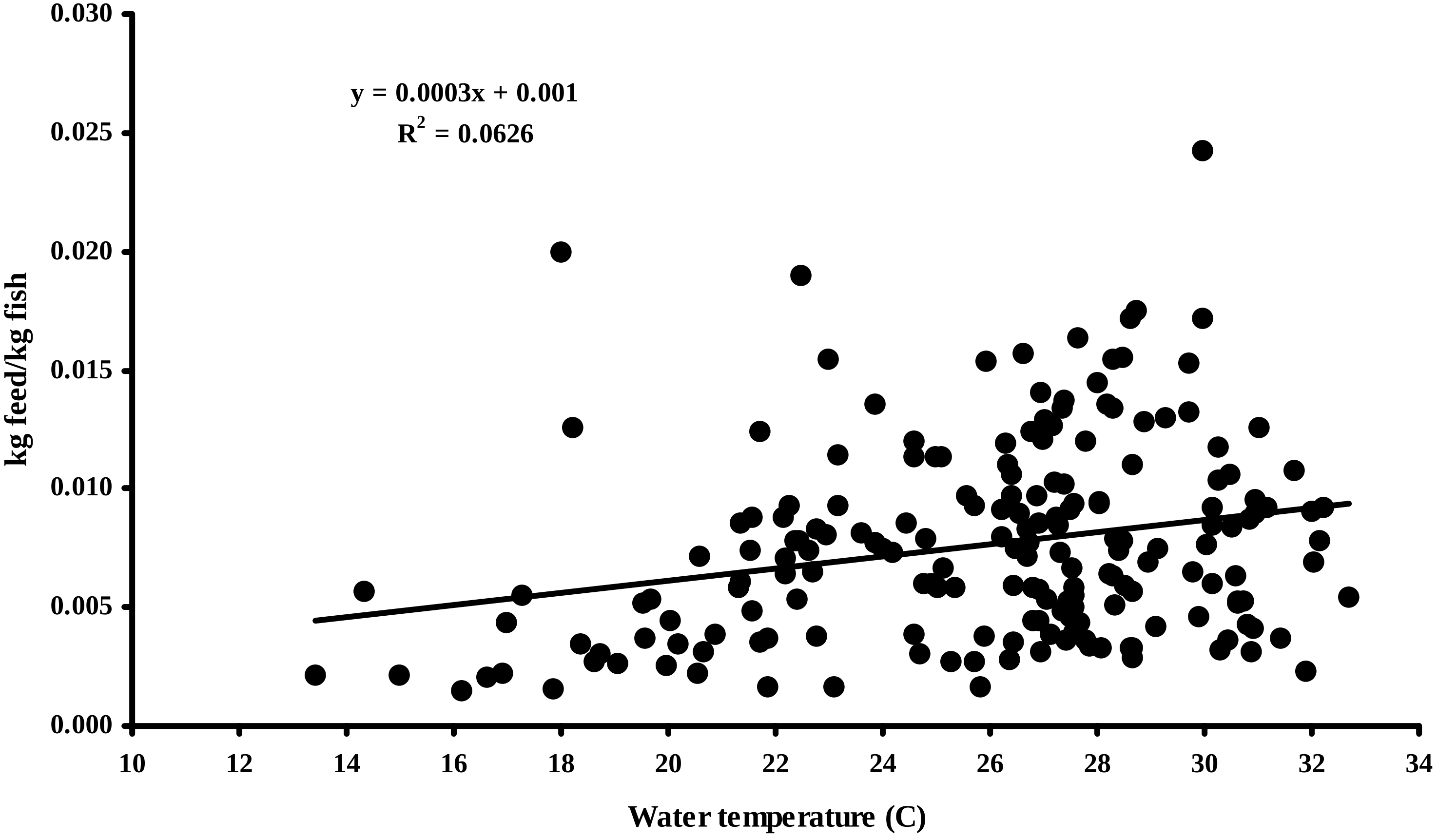
Appendix Figure 2. Daily feed response (kg feed/kg fish) to average daily water temperature for catfish stocked at 8,600 fingerlings/ha.



Appendix Figure 3. Daily feed response (kg feed/kg fish) to average daily water temperature for catfish stocked at 17,300 fingerlings/ha.



Appendix Figure 4. Daily feed response (kg feed/kg fish) to average daily water temperature for catfish stocked at 26,000 fingerlings/ha.



Appendix Figure 5. Daily feed response (kg feed/kg fish) to average daily water temperature for catfish stocked at 34,600 fingerlings/ha.