Using Fisheries Techniques to Estimate the Age and Growth of Hybrid Catfish (*Ictalurus punctatus* ♀ × *I. furcatus* ♂) in West Alabama Commercial Ponds

by

Julia Leann Palmer

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Approved by

Luke A. Roy, Chair, Associate Extension Professor, School of Fisheries, Aquaculture, and Aquatic Sciences
Anita M. Kelly, Extension Professor, School of Fisheries, Aquaculture, and Aquatic Sciences
Peter C. Sakaris, Professor of Biology, School of Science and Technology, Georgia Gwinnett College
Russel A. Wright, Associate Professor & Extension Specialist, School of Fisheries, Aquaculture, and Aquatic Sciences

Abstract

In west Alabama, catfish producers routinely face the challenge of fish that exceed market size (aka "Big Fish") in their commercial ponds. These fish are skilled at evading seine nets during harvest and can increase in size significantly before subsequent harvests occur. This is problematic for catfish producers because processing plants prefer catfish within the 0.45 – 1.81 kg range, and farmers are paid a premium price for catfish of this size. Depending on the market and processing plant, a catfish producer can receive little-to-no monetary value for an oversized catfish. Due to their larger size and growth potential, hybrid catfish (*Ictalurus punctatus* ♀ × *I. furcatus* ♂) can become a more significant issue than Channel Catfish if they evade harvest. Unfortunately, little is known about the age structure and growth rate of hybrid catfish that repeatedly evade capture and remain in commercial ponds for extended periods or multiple production seasons. The objectives of this study were to quantify the age structure and growth of hybrid catfish that evade capture, remain in commercial ponds following harvest, and grow beyond acceptable market size as defined by catfish processing plants (i.e., Big Fish). From December 2021 to August 2022, twelve recently harvested hybrid catfish ponds were sampled prior to re-stocking fingerlings using an electrofishing boat. Lapilli otoliths were removed from 1,005 hybrid catfish to estimate the total length and weight at age from seven commercial catfish farms in west Alabama, with the successful aging of 1,001 fish. Results of this study indicate that hybrid catfish exceeded the premium size threshold at age 2.72 years and should be harvested after one production cycle. Additionally, from age 2 to age 3, hybrid catfish can gain 2.9 kg, growing from an average of 0.4 kg to 3.3 kg.

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Table of Contents

List of Tables

List of Figures

Introduction

Aquaculture has grown tremendously this past century. Advancements in technology and education have contributed to this sector's growth to now provide more than half of the world's fish for human consumption (FAO 2019). This increase aligns with an ever-growing world population with a substantial demand for marine and freshwater fish products, paired with wild capture fisheries that are either fully or over-exploited (77%) (Lucas 2019).

The catfish industry remains the leading aquaculture sector in the United States (U.S.) (Engle 2003; Hargreaves and Tucker 2004; Mischke et al. 2016, Engle et al. 2021, Hegde et al. 2021), and farms are primarily located in the southeast. This industry has dominated the southern region and total U.S. aquaculture sales for numerous years, contributing about 75% of total finfish volume with a 35% value share (FAO 2020). In the U.S., catfish sales have remained the precedent over other aquaculture species since 1998. However, throughout the past two decades, several external economic factors have played a role in reducing catfish sales. Along with the rapid growth of other aquaculture sectors, inexpensive imports, and numerous other factors, catfish sales have decreased (46% to 24%) over a twenty-year period (Engle et al. 2021).

Through new advancements, the production of hybrid catfish (*Ictalurus punctatus* ♀ × *I. furcatus* ♂) has increased markedly in recent years. Adoption rates of hybrid catfish production is most prominent in Mississippi (69%), followed by Arkansas (32%), with Alabama having the lowest adoption rate of 24% (Hegde et al. 2022). Researchers have noted improvements in growth (Giudice 1966; Yant et al., 1976) due to genotype-environment interactions (Dunham et al. 1990), tolerance for low dissolved oxygen (Dunham et al. 1983, 1990), disease resistance (Dunham et al. 1990; Wolters et al. 1996), angling and seine-ability (Dunham and Argue 1998), higher carcass yield, and skin-on and skin-off fillet yield compared to the Channel Catfish

(Bosworth et al. 2004). Production of hybrid fingerlings has increased to meet farmer demand, and hybrid catfish now account for slightly more than 50% of total catfish production in aquaculture (Hegde et al. 2022).

As opposed to Channel Catfish, which are typically produced in continuous multiple-batch systems (Engle and Valderrama 2001; Engle 2003), farmers prefer to raise hybrid catfish using a single-batch production strategy (Bott et al. 2015; Mischke et al. 2016). A single-batch production system, such as used by farmers producing hybrid catfish, can decrease fish mortality from infectious diseases and bird predation during winter (Mischke et al. 2016). Tucker et al. (2004) described how single-batch production could make calculating survival, inventory, and production characteristics easier for best management decisions. Hybrid catfish can reach harvest size much faster than Channel Catfish (10 – 14 months versus 18 – 24 months), hence a farmer using single batch production can have additional crops compared to a producer using a multiple-batch production strategy with Channel Catfish over time (Bott et al. 2015; Hanson et al. 2020).

While hybrid catfish are considered easier to capture and harvest with commercial seines than Channel Catfish (Dunham et al. 1987; Dunham and Argue 1998), they often evade seine nets by burrowing into the bottom of the pond (Creel et al. 2021). The pond bottom can have many holes mainly formed by commercial aerators on the edge of the ponds to help maintain optimal dissolved oxygen concentrations. Over time, these aerators can create large holes and ruts where catfish seek refuge when the pond is seined. There are also natural depressions in the bottom of ponds around drainage pipes and near rocky banks that provide additional locations for refuge. Over time, these holes can grow larger, along with the catfish hiding in these depressions. Watershed ponds that are irregularly shaped and have not been renovated for an extended time (often decades) are notoriously difficult to seine efficiently, allowing large numbers of hybrid catfish to evade harvest each year and grow above market size. This reoccurring problem has been described as the “Big Fish” problem in the catfish industry (Creel et al. 2021).

Fish that grow too large after evading capture at harvest are problematic to farmers because processing plants prefer live fish in the weight range of 0.45 kg to 1.81 kg (Hanson 2023), and farmers are paid a premium price per pound for catfish that fall in this range (Creel et al. 2021). Typically for most catfish processors, the price paid per kilogram is comparable until the weight of a live fish reaches 3.63 kilograms, though this changes yearly based on the market (Figure 1), the processing plants’ needs, and the supply of catfish (Weise et al. 2006, Creel et al. 2021). Oversized fish (>1.82 kg), herein called “Big Fish,” are comprised of three categories as defined by most catfish processors, including “Large (1.82-2.71 kg),” “Very Large (2.72-3.64 kg),” and “Extra Large (3.64+ kg).”

Furthermore, fish that are missed and grow beyond market size become a financial burden on farmers by eating large quantities of feed intended for fingerlings and sub-market-size catfish. As stated earlier, one of the benefits of hybrid catfish is how quickly they can attain market size. However, this becomes inapt when fish are not removed from the pond promptly, as the enhanced growth rate can work against the farmer, leading to large amounts of expensive commercial feed consumed by larger hybrid catfish for which they receive less financial return.

Hybrid catfish that are missed by the seine at harvest present another potential problem in production ponds. Some catfish farmers in Alabama suspect that, in some cases, cannibalism might be occurring shortly after fingerlings are stocked. Despite this suspicion, this phenomenon has not been adequately examined in Big Fish, particularly those within the 5 to 20 kg or larger range. Anecdotal evidence from farmers, as well as researchers at the Alabama Fish Farming Center (Greensboro, Alabama), suggests that leftover hybrids which remain from previous production seasons could be preying on the smaller-sized fingerlings stocked for subsequent production seasons. In one instance, a 0.59 kg hybrid catfish was found in a larger hybrid catfish (>22 kg) that researchers collected from a commercial aquaculture pond in west Alabama (Dr. Luke Roy, Alabama Fish Farming Center, personal communication).

Creel et al (2021) conducted a study that assessed the age and growth of hybrid catfish in commercial aquaculture ponds that were delivered to a catfish processing plant in Alabama. Before that study, no research had been conducted to estimate the age and growth of this species raised in an aquaculture setting. One potential method to assess the extent of the Big Fish problem in west Alabama is to use traditional fisheries sampling techniques, such as electrofishing, to target these larger fish in aquaculture ponds, particularly right before a new crop of fingerlings is stocked. In parallel with sampling, fish age can be estimated using otoliths, a common technique used by fisheries biologists that sample natural bodies of water. These techniques could allow researchers to quantify the age structure of hybrid catfish cultured in commercial catfish ponds and determine when these catfish grow beyond a "premium" weight.

Electrofishing is a popular method used to determine the abundance of fish species in lentic and lotic habitats worldwide (Chiaramonte et al. 2020). Since we are dealing with the offspring of two species, we must consider how Blue Catfish and Channel Catfish respond to electroshocking. Low-frequency, pulsed-DC (15Hz) electrofishing is the most efficient way to sample Blue Catfish in reservoir and riverine environments (Bodine and Shoup 2010). But ictalurids, in general, are regarded as vulnerable to electricity because of their vestigial scales.

Both alternating and pulsed direct current are used to sample fish with electrofishing. First, alternating current (A.C.) flows in both directions, with the voltage increasing from zero to a maximum and back down to zero again. The second is direct current (D.C.) which only flows in one direction because the negative and positive terminals of the circuit are the same (Thompson et al. 1998). Negative charge carriers are repelled from the anode (droppers) and attracted to the cathode (boat hull). In this study, we used pulsed-D.C. In this approach, a unidirectional current is produced with periodic interruptions that result in square waves (pulses) of voltage. The benefit of using D.C. is the production of an “attraction” zone; hence, fish enter a state of galvanotaxis where they involuntarily swim toward the positive (anode) electrode. When implemented correctly, this current is usually less injurious to fish and operators (Thompson et al. 1998).

Estimating fish age and growth is an established technique in fisheries management that allows us to analyze and better understand fish population dynamics. Growth can be described as a measure of change in length or weight over the life of an organism, and age and growth can be measured across several temporal intervals. Growth is expressed as a mathematical relationship between fish size and age estimated from the fish’s hard parts (e.g., otoliths, skeletal bones). Biologists can determine age at recruitment, maturity schedules, age-specific fecundity, and vulnerability to predation and fishing, which help to inform the development of management strategies (Kerns and Lombardi-Carlson 2017). In this study, these fisheries techniques were applied to aquaculture ponds to estimate the age of leftover hybrid catfish in west Alabama commercial ponds.

When using calcified structure, periodic bands are typically visible under magnification. These bands are formed from environmental and endogenous factors, otherwise known as annuli (Whitledge 2017). In young fish, annuli may be produced daily in otoliths. Otoliths are paired, calcareous structures found in the inner ear of ray-finned fishes. The purpose of these structures is to aid in hearing and balance (Campana 1999). In catfish, the lapillus otolith has been confirmed as the largest otolith (Secor et al. 1992) and was used for age estimation in this study.

Objective

The objective of this study was to quantify the age structure and growth potential of carryover hybrid catfish that remain in single-batch production catfish ponds after a complete commercial harvest (3 or more seines) and before restocking the pond with fingerlings for a successive crop. To accomplish this goal, the age and growth of catfish removed from commercial ponds were assessed using traditional fisheries science techniques. Based on a preliminary study conducted in 2019, we expected to find hybrid catfish that far exceeded the premium weight category, with hybrid catfish growing rapidly within the first few years, particularly since ponds that are irregularly shaped are expected to have a wide range of age and growth in their populations based on the lack of seining efficiency associated.

Materials and Methods

Catfish were sampled from December 2021 to July 2022, following the final harvest of 12 commercial hybrid catfish ponds, immediately prior to re-stocking a subsequent single batch crop. The study was carried out on seven farms in west Alabama. The 12 ponds were selected to represent the catfish industry as a whole (“global population”), with each pond serving as a subpopulation (or “experimental unit”) of the global population.

During the study, a total of 1,005 catfish were collected from the 12 ponds. An electrofishing boat was used to shock and collect fish. Once collected, fish were brought back to the Alabama Fish Farming Center (AFFC) and processed. All catfish were measured to the nearest mm (total length [TL]) and weighed to the nearest 0.01 kg to analyze hybrid catfish growth in west Alabama commercial ponds, and both lapilli otoliths were extracted for age estimation. The sex of each catfish was also recorded.

An electrofishing boat (Midwest Lake Electrofishing Systems. Polo, Missouri) and electroshocking control box (Infinity HC-80. Polo, Missouri) were used for this project. The boat was constructed of aluminum and was flat-bottomed; the hull was wired to act as the cathode and equipped with two insulated booms that support the metal dropper arrays (anodes), which extend past the bow up to seven feet. The bow was enclosed by a rail and was equipped with a safety foot switch/pedal that was controlled by the dip netter.

Following several field tests on commercial catfish ponds to determine how hybrids respond to different electricity settings. We determined that using a pulse rate of 60 Hz, with a 50% pulse width, while keeping the total watts under 8,000 was effective for shocking hybrid catfish in commercial aquaculture ponds. Hybrid catfish were stunned for collection, and the shock did not fatally wound any young catfish or forage fish present in the pond. When collecting fish, we implemented a 10-fish limit on any fish that weighed less than 0.45 kg. This size fish falls into the under-market size category employed by processing plants, and we did not want to take away from the farmer’s future profits. Collected fish were euthanized with MS-222 according to the Auburn University Institutional Animal Care and Use Committee protocol.

After fish were weighed and measured, the “guillotine” method was used to extract the lapilli otoliths from the cranial cavity. The lapillus is anterior, distal, and above the sagitta and asteriscus otoliths in the cranial cavity (Secor et al. 1992). It is dorsoventrally flattened, with a hump (gibbus maculae) on the ventral face. In bilaterally symmetrical fishes, otoliths exist as mirror images of one another, and no previous studies have reported noticeable differences (Long and Grabowski 2017). Using a hacksaw, the extractor made a vertical cut through the skull, aligning the cut with the front of the pectoral fins (Figure 2). Ideally, the extractor lined up the saw with two indentations at the top of the head. Due to otolith fragility, this cut was performed carefully, as the otolith can easily break or be damaged (Long and Grabowski 2017). Once the cut was made, otoliths were removed with fine-tipped forceps, cleaned of brain tissue or fluids, and stored dry in plastic vials with appropriate labels for further processing.

The otoliths were processed following the methods described by Sakaris and Bonvechio (2020). First, each pair of otoliths were burned on a hot plate to achieve a medium yellow-brown color. Next, a clear epoxy resin (West System, Bay City, Michigan) was continuously mixed with a slow hardener (West System, Bay City, Michigan) for four minutes to ensure a homogenous mixture. This mixture was then applied to form a bottom layer in the wells of rubber embedding molds (PELCO double-end tapered embedding molds; Ted Pella, Inc., Redding, California). Once all bottom layers were applied, the resin mixture sat for at least 45 minutes to allow it to cure.

Then, otoliths were mounted flat on the first layer, aligning the round, anterior end to the right and the pointed, posterior end to the left. The otolith was placed to the right of the well to ensure plenty of room to position the resin mold in the holding section of the saw (Figure 3). After all the otoliths were mounted, the second resin layer was mixed, as described previously, and applied to the molds to form the top layer to successfully embed the otolith and saturate each well. Cutting into the otolith did not proceed for 24 hours to ensure the resin was completely hardened. Then, a high-precision, low-speed sectioning saw (IsoMet LS, Buehler, Lake Bluff, IL) was used to make two cuts into the otolith and surrounding resin. The first cut was made at the otolith core (gibbus maculae) along a transverse plane, and the second cut was made into clear resin just beyond the posterior end of the otolith to free the cut otolith from the saw.

Once freed, each otolith was fixed to a microscope slide perpendicular to the slide plane using Crystalbond (Ted Pella, Inc., Redding, California) as an adhering agent. The anterior side, revealing the core, faced upwards, while the pointed posterior end faced downwards (Figure 4). After the Crystalbond had hardened, light sanding was performed on the core with 1200 grit 'wet or dry' sandpaper. Sanding was done to smooth out any jagged edges produced by the saw and assist in revealing the core if the cut was not made correctly. This technique is called the cut method because we are not producing a thin section of the otolith, i.e., two cuts through the otolith, but cutting into the otolith to reveal the core (Figure 5).

When estimating the ages of catfish, two readers independently viewed the otoliths and estimated age based on the number of annuli observed projecting from the core. Annual rings were considered one opaque zone (tan, wider space) followed by a translucent zone (thin, white ring), which forms during reduced growth or spawning periods. Applying mineral oil to the surface of the otolith provided a clearer image and reduced any scratches from further sanding if the core was not visible. All four orientations were viewed for each otolith in the left, right, up, and down positions. Once optimal light conditions and position were decided, four images were captured. This project used a JENOPTIK GRYPHAX (Model No. S9D. Jena, Germany) microscope camera and corresponding software attached to a Leica Microscope (Hesse, Germany). Once each reader decided on an age estimation, they revealed it to each other, and a final age was assigned to the fish. If the two readers could not agree on a final age, a third independent reader was brought in to view the core and deliver their age estimation. If all three readers did not agree, the fish in question was removed from the study. Following age estimation using the cut method, there were a total of four fish the researchers could not assign an age.

Hence, these fish were removed from this part of the analysis. Additionally, five fish from the age class 1 were removed. As such, age analyses were carried out on 996 fish.

Data from this study were analyzed in R Core Team (2023), R Studio, Excel, and SigmaPlot were used to develop figures and tables. The size and age structure of west Alabama hybrid catfish found in commercial ponds was analyzed by constructing length-and-weight-frequency histograms for all hybrid catfish combined and split between three ponds with the youngest age distributions and three ponds with the oldest age distributions to facilitate comparisons. The total length and weight data were $\log_{10}$ transformed to meet assumptions of normality, and a simple linear regression was fit to the data to describe the relationship between length and weight. An ANOVA test was then conducted to test for a significant relationship between our response variable ($\log_{10}$ Weight) and the explanatory variable ($\log_{10}$ Total Length). Like the length and weight frequencies, one age structure was created for all twelve ponds sampled (Figure 10), and then separated by three of the youngest age distributions and three of the highest age distributions (Figure 11). Age structure histograms were created for premium size fish (0.45-1.81 kg) and all oversized fish (>1.81 kg) as well. These age structures established the majority age class for both categories defined by the processing plants.

Due to differences among our twelve sub-populations (ponds) a Kruskal-Wallis test was performed individually for the three independent variables of total length, weight, and estimated age, with ponds being our dependent factor. Further pairwise comparisons were then utilized by Wilcoxon rank sum tests to describe which ponds were significantly different from each other when testing our independent variables against our dependent variable.

Descriptive statistics were calculated for each age class to find the mean weight of estimated ages 2 through 11. This allowed us to estimate how quickly the average hybrid catfish was gaining weight from one age to the next. The information provided would theoretically allow farmers and researchers to understand when the average hybrid catfish will exceed the weight categories established by processing plants. Total weight and percentage of weight of hybrid catfish collected during this study for the categories of premium, Large-Very Large, and Extra-Large were established by farm, as well. Separating the leftover hybrid catfish into these categories allows farmers to track what size catfish were missed and how to more efficiently manage their ponds.

Next, mean weight and length at age were calculated for each age class in each pond. A weight-to-age linear regression was computed for each pond, as these relationships were clearly linear. A TL-to-age growth model was also computed for each pond, with the model being either linear or non-linear (von Bertalanffy model). For some ponds, the growth trajectory was linear and not asymptotic, or only younger age classes were sampled and fit best to a linear model. Once the predicted mean lengths and mean weights were gathered for all age classes and ponds, this data was then used to build three global models (Allen et al 2002; Bonvechio et al. 2005).

The first global model described the growth in terms of length at age using the common von Bertalanffy growth model (VBGM). This nonlinear regression model can estimate age based on length. With the equation $L_t = L_\infty*(1- e^{(-K (t - t0)})$, researchers can estimate the age of fish given their current length by using the length of the catfish and the starting values (L_∞, K, and t_0) to solve for t. L_t is the length of the fish at a specified time t, L_∞ is the theoretical average maximum length of this fish population, K is the growth coefficient, t is the age expressed in years, and t_0 is the hypothetical age at which the average length is 0. The equation found from this model is only appropriate to use in an aquaculture setting because of the increased growth rate which results from providing a nutritionally complete commercial catfish diet as a food source. A von Bertalanffy model was computed for both sexes combined, but also for male and female hybrid catfish separately.

For the second global model, growth in terms of weight at age was described with a linear model for both sexes combined, as well as for male and female hybrid catfish separately. This linear regression can provide a predicted weight of a hybrid catfish based on the estimated age of the hybrid catfish. Lastly, the third global model, involved a linear regression that was fit to the predicted mean lengths data to estimate the age of a catfish given the weight of the catfish. The second and third global models included the same predicted mean weight-at-age data that was found for each pond, the difference being what was established as the predictor variable and what was established as the explanatory variable. With this last model, a farmer or researcher can estimate the age of an oversized fish to calculate how long it has been in the pond and how many times it has potentially escaped the seine at harvest. To determine how many times an aged hybrid catfish was potentially missed during harvest, researchers subtracted one year from the estimated age. Commercial catfish hatcheries that were surveyed for this study stated that the average hybrid catfish fingerling was typically 10 months old when stocked into commercial grow-out ponds.

Results

The total length (TL) of hybrid catfish (n = 1,005) collected on 7 commercial farms ranged from 209 to 1,117 mm, and weight ranged from 0.085 to 24.21 kg (Figure 6). Of those hybrid catfish, 546 weighed 1.81 kg or less (54%), 207 weighed between 1.82 kg and 3.63 kg (21%), and 251 weighed over 3.64 kg (25%). Comparison of the youngest age distributions revealed length ranges from 300 mm to 800 mm, conversely the highest age distributions had length ranges from 300 to 1,200 mm. For weight, the youngest age distributions ranged from

0.37 to 6.26 kg and the highest age distributions ranged from 0.24 to 24.21 kg. A significant relationship was found between log TL and log weight ($p < 0.001$, $R^2 = 0.97$, Figure 9) and ANOVA results concluded that a model with length explains more of the variability in weight versus a model without length ($p < 0.01$).

Hybrid catfish were represented in all-year classes from ages two ($n = 457$) to eleven ($n = 2$), excluding ages 1 and 10 (Figure 10), with age 2 being the most populous. The youngest age distributions revealed age ranges from 2 to 5. In contrast, the highest age distributions had age ranges from 2 to 11. One pond in the youngest age distributions (pond E2) had only age classes 2 and 3 present, but a pond in the highest age distributions (pond 4) had at least one hybrid catfish present in age classes 2 through 9. Of the premium-size hybrid catfish collected, 400 (80%) were age 2. Of all age 2 fish collected, 88% belonged to the premium size category. In contrast, the oversized fish age structure comprised all estimated age classes, excluding age 1. For age 3 hybrid catfish, 252 were considered oversized (>1.82 kg), though 103 age 3 catfish were considered premium size. As mentioned, farmers had the opportunity to make a comparable rate for some of the oversized fish that fell in the “Large” and “Very-Large” categories in the year 2022. This category was established with a weight range of 1.82 to 3.63 kg, and age classes 2 through 5 comprised this age structure. A total of 205 hybrid catfish were found in this category, and 160 of these fish were age 3 (Figure 15).

The Kruskal-Wallis test of the independent variable of age versus the dependent variable of ponds yielded highly significant results ($\chi^2(11) = 203.86$, $p < 0.0001$). Replacement of the independent variable of age with total length yielded highly significant results, as well ($\chi^2(11) = 99.69$, $p < 0.0001$). Finally, the independent variable of weight, also yielded highly significant results ($\chi^2(11) = 132.89$, $p < 0.0001$). This indicated the twelve sampled ponds were not from the same population. Further pairwise comparisons using a Wilcoxon rank sum test found that 60% of ponds were statistically different ($p < 0.05$) from each other when testing the independent variable weight (Table 4).

Mean weight at age revealed that the average hybrid catfish from west Alabama will exceed the threshold premium weight category (1.81 kg) by age 3 (Figure 12). Since farmers made a comparable price per kilogram for the year 2022 for Large to Very Large fish (1.82 – 3.63 kg), results described that hybrid catfish exceeded the Very Large category threshold weight by age 4. Though, the majority of our aged hybrid catfish belonged to age classes 2 and 3, 108 hybrid catfish belonged to age class 4 which was approximately 10% of all catfish collected.

Furthermore, from age-1 to age-2, the average hybrid catfish has the capacity to grow from 0.51 kg to 1.03 kg. From age-2 to age-3, the average hybrid catfish can more than double in size, growing from 1.03 kg to 2.77 kg, exceeding the threshold for the premium weight category. Finally, from age-3 to age-4, the average hybrid catfish doubled in size once more, growing from 2.77 kg to 5.69 kg (Table 1). Weight variation by ponds was described to compare mean ± standard error weight (Figure 14). Pond E2 (youngest age distribution pond) had the lowest mean (1.27 kg) and lowest standard error (± 0.11 kg) of weight out of the twelve commercial ponds sampled. In contrast, Pond 4 (highest age distribution pond) had the highest mean weight (5.4 kg) and the second highest standard error of weight (± 0.58 kg). As mentioned previously, total length is typically not as important for farmers and researchers in aquaculture, but length varied widely among age similarly to weight. Overall, mean length at age-2 was 443 mm, with catfish growing to a maximum mean length of 1,063 mm by age-8 (Table 2).

The total weight and percentage of weight for the categories of premium, Large-Very Large, and Extra-Large categories varied greatly by farm (Table 3). Farm B had the second lowest mean weight (1.92 ± 0.09 kg) and the lowest percentage of weight (61%) for all oversized fish, but Farm A had the lowest total weight (174.34 kg) and percentage of weight (17%) for Extra-Large fish. Conversely, Farm C had the lowest total weight (17.75 kg) and percentage of weight (4%) for premium-size fish. Farm F had the second lowest total weight (34.44 kg) and percentage of weight (9%) for premium-size fish.

The predicted mean TL-at-age separated by male and female in each pond (Table 5) varied among sexes and throughout ponds. Pond W4 had a predicted mean TL at age 2 for males of 397 mm, in contrast the females for the same age and pond had a predicted mean TL of 465 mm. By age 3 in the same pond, males had a predicted mean TL of 608 mm and females had a predicted mean TL of 570 mm. For sexes combined (Table 6), age 2 had predicted mean TL that ranged from 366 to 466 mm. Age 3 had predicted mean TL that ranged from 491 to 669 mm. In general, mean TL-at-age varied widely among ages 2 through 5 across the ponds. Each of these age classes had a range that was equal to or greater than 100 mm.

Predicted mean weight at age separated by male and female in each pond (Table 7) had similar weights among the sexes for age 2, but overall, the ponds varied in predicted mean weight. By age 3, male weight was greater than female weight in all but one pond. Both sexes combined (Table 8) had a wide range of weights among ages 3 through 6. Age class 5 had the second highest range in weight from 4.13 to 11.27 kg and age class 6 had the highest range in weight from 7.23 to 15.07 kg.

A von Bertalanffy Growth model was created for males and females separately, as well as for the sexes combined (Figure 16). Males had a higher L_∞ than females, which indicated the ability to reach a higher average maximum length. Females had a higher growth coefficient (K), which expresses the rate at which asymptotic length is approached. A higher absolute K value indicated that females would reach their average maximum length quicker than males. Finally, males had a higher t_0, though not substantially, which indicated they were bigger at age 0, but this parameter has no biological significance and is just a parameter for model fitting. By age 5, length at age appeared to separate between the average male and female. The average male at age 5 was predicted to be 864 mm, in contrast the average female at age 5 was predicted to be 819 mm. Within two years, length at age separation was more prominent as males had an average predicted length of 1,023 mm and females had an average predicted length of 948 mm. The equations for all three and their starting parameters can be found in Table 9. Although length is not an important measurement in aquaculture because producers and processors are more concerned about the weight of live fish, this model was included to show the difference in growth between the male and female sexes. Since catfish cultured in a commercial aquaculture setting have a more rapid growth rate than those found in a natural system, the VBGM was unsuccessful in predicting weight at age.

A weight-at-age linear model was created for males and females separately ($R^2 = 0.89$ and $p < 0.001$) and for both sexes combined ($R^2 = 0.92$ and $p < 0.001$, Figure 17). Females weighed on average 5.6 kg at age 4, while males weighed 6.6 kg. Separation in growth between the two sexes appeared to start at age 4 and continued throughout age 11. Again, males had a higher growth potential than females. For the sexes combined, at age 4 the average hybrid catfish weighed on average 6.2 kg.

Finally, an age-at-weight linear model was created for males and females separately ($R^2 = 0.90$ and $p < 0.001$) and for both sexes combined ($R^2 = 0.92$ and $p < 0.001$, Figure 18). With these models, given the weight of a fish, a farmer or researcher can predict how old the fish is. This is especially helpful when determining when a crop of hybrid catfish may exceed the premium weight category in which adequate compensation could be received from a processor. Given the weight of 1.82 kg, we found that the average hybrid catfish would grow to that size by the age of 2.72 years. The average male will reach that weight at 2.6 years, and the average female would reach that weight at 2.78 years based on their individual models. Given the discrepancy in sex related growth, a farmer could potentially underestimate the age (male) or overestimate the age (female). Determination of the sex of the catfish prior to using this equation would address this issue. To assess the accuracy of our age-weight regression, the equation gained from the model was used to predict age from our given weights of hybrid catfish. Then the predicted ages were graphed against our known variable, estimated final age, and a one-to-one line was fit over the plot (Figure 19). From age 2 to age 8, the one-to-one line crossed through the data points, and this equation was suitable to use for those aged fish.

Discussion

Production of hybrid catfish in the U.S. has been gaining momentum in U.S. aquaculture over the last several years, and for good reason, as there are many advantages for commercial farmers culturing this species compared to Channel Catfish. Despite the advantages, raising this species has notable challenges, particularly harvest efficiency, which can be difficult. This pond study demonstrated that hybrid catfish could grow rapidly, evade harvest for multiple years, and ultimately result in reduced or no monetary value to the farmer in as little as two production cycles or by age three. Most of the sampled catfish in our study, in terms of what processing plants would deem a premium weight, were aged two. If a catfish was missed within its first grow-out year, within two more production years, the catfish would have the potential to grow into an oversized fish (Figure 19). Based on these results, farmers should strive to have all hybrid catfish harvested from production ponds following just one production cycle. Unfortunately, even a skilled seining crew will miss many food-sized hybrid fish, particularly in irregularly shaped watershed founds typically used in west Alabama. Torrans et al. (2016) found that even in small-scale research ponds used to raise hybrids, which are much easier to seine efficiently than large commercial ponds, up to 10% of hybrids were missed by seining.

Overall, 51% of collected hybrid catfish in our study were considered a premium size, 46% were considered oversized (>1.82 kg), and 4% were fish that belonged to the small size category. Since processors were paying farmers for larger fish (>1.82 kg but <3.63 kg) during the 2022 study period, we were able to demonstrate that 20% of the fish collected would have resulted in an acceptable price at the processing plant if those fish had been harvested. However, it is important to note that the price received by farmers for fish that exceed 1.82 kg varies by processing plant and current market trends (Creel et al. 2021).

Based on the age-at-weight model, the average hybrid catfish at age 2 would weigh 0.4 kg (note: at stocking hybrid catfish are already near or at age 1). By age 3, the average hybrid catfish would weigh 3.3 kg. Since the late 1990s, catfish rejected from processing plants have increased from around 2% per truckload to 8% if considered oversized by the plant (Gosh et al. 2021). Depending on the market and growth rate, age 3 catfish could potentially result in a favorable fish price for the farmer, but this may not always be the case depending on a number of different circumstances and production scenarios.

Automation in processing plants explains why oversized fish are rejected or discounted from incoming truckloads from commercial farms (Wiese et al. 2006). Processing plants have automated the beginning stages of processing fish with machines to increase efficiency and processing times. After catfish are euthanized upon entry into the plant, catfish are placed on conveyor belts leading to an automatic deheader, where the head and most of the viscera are removed and then dropped onto a holding table where an operator will then position them into a filleting machine (Silva et al. 2001). Larger catfish will not fit into those machines and require manual hand-filleting (Silva et al. 2001), which in turn creates additional time and labor at the plant, and ultimately results in a discounted price on said fish.

Seining efficiency at harvest likely plays a huge role in the Big Fish issue in west Alabama. The most common number of seine net pull-throughs during harvest for the ponds prior to restocking in this study was three. One farm had a much higher number than the rest (9 and 10 seines), and this farmer had no fish over age 5. Hence, this would suggest that extra seining of hybrid catfish ponds effectively removed larger fish. When considering the two oldest hybrid catfish collected in our study, which were age 11, we can surmise that those two fish may have evaded harvest close to thirty times, assuming ponds had been harvested 3 times per year.

Oversized catfish have major implications for revenue losses of catfish producers, particularly due to dockage (Gosh et al. 2021). Fish that exceed the maximum size for the automated equipment at the processing plant are weighed to assess the weight to be subtracted from the total amount the farmer will be paid for, which is known as dockage. Dockage can also include additional fish captured in seine halls and transported to the processing plant, such as threadfin shad, gizzard shad, centrarchids, or other species that might be in the pond. Ponds with large amounts of Big Fish result in more dockage for the producer, reducing overall financial returns for the farm.

Aside from revenue losses at the processing plant, catfish that evade harvest may potentially forage on newly stocked fingerlings, albeit this phenomenon has not been adequately studied. If losses to cannibalism do occur, this would lead to an additional revenue loss for the producer. Many catfish farmers suspect big fish cannibalize fingerlings, particularly in the weeks immediately following stocking in the winter months when little if any commercial feed is fed, until fingerlings reach a size where they are no longer vulnerable to predation. No published information suggests hybrid catfish raised on commercial farms turn to cannibalistic behavior; studies that have evaluated this problem have typically focused on hybrids that are less than 3 kg (Torrans and Ott 2016), which were much smaller than some of the older fish sampled in this study. However, not enough research has been done to solidify that argument, particularly since hybrids are known to be more aggressive and can reach extremely large sizes in commercial ponds (> 20 kg). Our study alone saw the capture of 320 catfish that were 3 kg or larger, and from our two weight and age models, it was established that by age 3, the average hybrid catfish was greater than 3 kg. In addition, many catfish sampled in this study were much larger than just 3 kg (5 – 20 kg or larger).

In the wild, channel and blue catfish are considered opportunistic omnivores having diets comprised of fish as they increase in size (Busbee 1968; Perry 1969; Devaraj 1976). Channel Catfish larger than 380 mm were found to have opportunistic carnivore diets (Busbee 1968), and blue catfish within the range of 200 to 330 mm shifted to fish consumption (Brown and Dendy 1961). A more recent study in the Chesapeake Bay found that blue catfish diets significantly shifted to fish-based at various lengths (500 to 900 mm TL), and overall blue catfish are an omnivore-generalist that can feed on multiple trophic levels when available (Schmitt et al 2019). Around 90% of the catfish collected for this study were >400mm, with 900 fish falling into that category, indicating once again that these fish would be within the size range that a shift to a piscivorous diet occurs in their natural environment for their parental species. Despite the shift to piscivory that occurs in larger wild catfish, aquaculture is a completely different scenario in terms of food availability. Catfish farmers, during peak feeding seasons, feed a nutritionally complete feed (28% or 32% protein), often at rates which exceed 170 kg/ha. During the winter, catfish farmers feed sparingly, and it is during the wintertime that cannibalism is suspected by commercial producers. There is often forage available in catfish ponds, such as shad or centrarchids which are an additional food source, and it is not known if larger hybrid catfish would preferentially forage on these other species over catfish fingerlings. The sheer number of extremely large catfish observed in this study, along with existing anecdotal evidence noted by farmers and researchers involved in this study, perhaps merits a closer examination of the cannibalism issue by hybrid catfish at some point in the near future.

Fish that escape harvest also continue to consume feed not intended for them. Feed cost is the single most significant contributor to the expense of raising a crop of fish on a catfish farm, accounting for anywhere between 37% to 47% of total variable costs (Engle et al. 2020). Li et al. (2014) conducted a study from 2012 to 2013, where they measured feed conversion ratio (FCR) of hybrids in single-batch systems for one growing season and two growing seasons to compare FCRs. Fish were carried out to a second growing season because of a specialty market which demanded a larger fillet size. Hybrid fingerlings quickly reached market size in this study, achieving a size between 0.68 kg to 0.91 kg in one growing season with an FCR of around 1.60. Hybrid catfish that are appropriately managed and entirely harvested can have FCRs in a desirable range to help eliminate the burden of high feed costs. Still, this study showed that as hybrids grow, the feed needed for catfish to reach satiation increased, resulting in large amounts of commercial feed devoted to growing fish that will not result in an optimal financial return.

Alabama catfish farmers are raising hybrid catfish, but not to the extent of catfish farmers in Mississippi, in which hybrid catfish production has now exceeded channel catfish production. Hegde et al. (2022) reported that only 24% of farmers had adopted hybrid catfish in Alabama compared to 69% in Mississippi. Hence, most Alabama catfish farmers are still raising Channel Catfish. One of the reasons Alabama catfish farmers have not fully embraced hybrid catfish is because of inefficiencies associated with seining watershed ponds stocked with hybrid catfish. Watershed ponds are typically irregularly shaped and are much more difficult for seine crews to harvest efficiently than levee style ponds, which are more popular in Mississippi and Arkansas. Many of these watershed ponds have never been renovated, further making it more difficult for harvest crews to seine efficiently. Since Channel Catfish do not attain the larger sizes of hybrid catfish and have a slower growth rate (Creel et al. 2021), they tend to be a little more forgiving if they are missed by the seine and carry through additional production cycles. Channel Catfish can be advantageous to have in inventory compared to hybrid catfish when catfish processing plants are not buying as many fish and farmers are forced to hold market size fish for long periods of time. Since Channel Catfish grow at a slower rate, and do not attain the super large sizes of hybrid catfish, not as many will exceed market size when harvests are delayed for whatever reason.

Application of our age-at-weight global model that have hybrid catfish combined, regardless of sex, could potentially underestimate or overestimate the age (based on weight). Sex of hybrid catfish had a significant impact on growth, and it may be beneficial to determine the sex of the catfish and use the appropriate male or female model. Additionally, growth varied widely among all ponds, and that factor could potentially underestimate (or overestimate) age, as well. These differences in growth could be due to environmental and management differences. There were significant differences between most ponds in terms of final age, weight, and total length of hybrid catfish, even between ponds located on the same farms. These differences between the ponds could be due to a number of different reasons such as different feeding strategies, aeration levels, genetics differences, disease history, stocking density, size of fingerlings stocked, pond size, average depth of pond, the amount of big fish remaining in the pond from previous production cycles, and many other factors.

Conclusions

With the rapid growth of hybrid catfish in commercial west Alabama aquaculture ponds, catfish producers can quickly see negative impacts of Big Fish. Hybrid catfish can exceed the premium weight (1.81 kg) in as little as one production cycle. Ultimately, Big Fish can have a negative impact on farm feed costs, dockage rates, and handling fees at catfish processing plants. Additional clean-up seines at the end of the production cycle prior to restocking fingerlings is one strategy commercial farmers can employ to reduce the number of Big Fish remaining in production ponds for the subsequent production cycle. In addition, pond renovation to make commercial harvest via seining more efficient, mainly by reducing ruts and holes that larger hybrid catfish can use to evade harvest would likely contribute to lesser percentages of large carryover fish in commercial hybrid catfish ponds. Future research is planned to analyze different pond characteristics that lead to higher rate of escapements at the individual pond level. Examples of some of these characteristics that will be analyzed include average pond depth, pond area, water volume index, shoreline index, the type of pond (watershed versus levee pond), average seining frequency, and seining crew (internal versus external), and other factors.

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Tables

Table 1. Average weight (kg) of hybrid catfish that were collected from twelve west Alabama commercial ponds. Hybrid catfish were found in age classes 1-11, excluding 10, with NA standing for non-applicable. Mean and Standard Error (*SE)* and the weight range for all estimated age classes were measured in kilograms. Note: Commercial catfish hatcheries surveyed by the research team stated that hybrid catfish are typically an average of 10 months old (0.83 years old) when stocked into commercial grow out ponds.

Age (year)	***n***	**Mean Weight** (kg)	**± *SE* Weight** (kg)	**Weight Range** (kg)
1	5	0.51	± 0.23	0.08 – 1.35
2	457	1.03	± 0.02	0.21 – 3.00
3	355	2.77	± 0.07	0.47 – 7.11
4	108	5.69	± 0.20	1.31 – 12.39
5	50	6.76	± 0.51	2.31 – 15.95
6	15	14.30	± 0.83	5.46 – 18.43
7	3	18.99	± 1.81	15.26 – 21.61
8	4	20.52	± 2.04	15.69 – 24.21
9	2	14.47	± 1.71	12.76 – 16.18
10	0	NA	NA	NA
11	2	19.83	± 1.05	18.78 – 20.88

Table 2. Average total length (TL, mm) of hybrid catfish that were collected from twelve west Alabama commercial ponds. Hybrid catfish were found in age classes 1-11, excluding 10, with NA standing for non-applicable. Mean and Standard Error (*SE)* and the total length range for all estimated age classes were measured in millimeters. Note: Commercial catfish hatcheries surveyed by the research team stated that hybrid catfish are typically an average of 10 months old (0.83 years old) when stocked into commercial grow out ponds.

Age **(years)**	*N*	Mean TL (mm)	± *SE* TL (mm)	TL Range (mm)
1	5	328.93	± 49.12	209 – 482
2	457	443.29	± 2.73	266 – 660
3	355	589.61	± 4.45	355 – 787
4	108	732.98	± 6.85	508 – 920
5	50	768.99	± 14.26	571 – 1003
6	15	939.80	±17.45	742 – 1028
7	3	1035.05	± 20.41	996 – 1066
8	4	1063.63	± 30.40	977 – 1117
9	2	974.73	± 41.28	933 – 1016
10	0	NA	NA	NA
11	2	1041.40	± 50.8	990 – 1092

Table 3. The total weight (kg) and percentage of the total weight of hybrid catfish collected from twelve catfish ponds on seven commercial farms in west Alabama. Weight classes were defined according to criteria in place at processing plants for premium-size fish. The mean weight and standard error (*SE)* for overall collected catfish were reported, as well.

Farm	***N***	**Mean ± *SE* Weight (kg)**	**Total Weight (kg)**				**% of Weight**			
				Oversized				Oversized		
			Premium[1]	Large-Very Large[2]	Extra-Large[3]	Combined Oversized[4]	Premium[1]	Large-Very Large[2]	Extra-Large[3]	Combined Oversized[4]
A	171	1.60 ± 0.08	99.77	129.38	44.96	174.34	36	47	17	64
B	213	1.92 ± 0.09	157.81	86.38	165.48	294.86	39	21	40	61
C	81	5.38 ± 0.58	17.75	70.11	348.33	477.71	4	16	80	96
D	91	2.61 ± 0.33	57.38	28.12	151.75	281.13	24	12	64	76
E	91	2.09 ± 0.18	50.81	31.83	108.30	237.68	27	17	56	73
F	77	4.95 ± 0.60	34.44	27.13	319.28	448.66	9	7	84	91
G	277	3.26 ± 0.19	141.28	184.91	576.71	706.09	16	20	64	84

[1]*Premium: 0.45-1.81 kg* [2]*Large-Very Large: 1.82-3.63 kg* [3]*Extra-Large: >3.64 kg* [4]*Combined Oversized: 1.82 kg+*

Table 4. Pairwise comparisons using a Wilcoxon rank sum test for our independent variable: weight (kg) and dependent variable: pond. The header and first column represent individual ponds and their corresponding labels. Cells with three asterisks had a *p*-value < 0.001. Any cell with a *p*-value < 0.05 had a significant difference between the independent and dependent variables.

	10	**13**	**14**	**2**	**3**	**4**	**6**	**B1**	**B30**	**E2**	**E5**
13	0.623										
14	0.011	0.005									
2	***	***	0.036								
3	0.648	0.479	0.001	***							
4	0.494	0.057	***	***	0.249						
6	***	***	0.184	0.512	***	***					
B1	***	***	0.494	0.167	***	***	0.373				
B30	***	***	0.098	0.921	***	***	0.774	0.494			
E2	***	***	***	0.016	***	***	0.004	***	0.016		
E5	***	***	0.041	0.361	***	****	0.345	0.249	0.345	0.2	
W4	0.001	0.009	0.494	0.921	***	0.001	0.909	0.615	0.774	0.005	0.098

Table 5. The predicted mean weight (TL) for each male (M) and female (F) age class in all twelve commercial catfish ponds sampled for this study. To develop one overall global model for the meta-population (west Alabama catfish industry), the mean TL in each sub-population (ponds) was determined. A von Bertalanffy model or linear model was run once for females and once for males for each pond for a total of 24 models. The models were then used to predict the total length at each age.

Mean TL (mm) at age

Pond	Aged Fish	Age 2		Age 3		Age 4		Age 5		Age 6		Age 7		Age 8		Age 9		Age 11	
	n	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
E2	57	431	427	629	568														
E5	59	447	448	614	577		707												
W4	53	397	465	608	570						886								
B1	114			497	486			708	691										
B30	98	451	445		566	694	687												
4	81	336	378	592	555	764	693	881	799	959		1012		1047			1034		
6	91	438	449	625	654		798	873	968	953	1016								
2	91	439	430	647	662	719	695	744	700										
10	77	467	436	677	656	826	797	931	886	1007	943	1060	980						1033
3	101	449	427	615	595	752	715	864	800		861						958		
13	86	456	481	649	599	789	717	890	835									1199	
14	88	458	462	679	646		785			977					1070				

Table 6. The predicted mean total length (TL) for each age class in all twelve commercial catfish ponds sampled for this study. To develop one overall global model for the meta-population (west Alabama catfish industry), the predicted mean total length in each sub-population (ponds) was determined. A mix of von Bertalanffy models and linear models were used to determine mean TL at age.

		Mean TL (mm) at age								
Pond	Aged Fish *n*	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 11
E2	57	428	593							
E5	59	448	591	734						
W4	53	446	578			973				
B1	114		491		701					
B30	98	448	570	692						
4	81	366	584	743	859	943	1004	1049	1082	
6	91	443	641	781	881	951				
2	91	434	655	706	717					
10	77	450	669	811	905	965	1005			1066
3	101	438	609	731	818	880			980	
13	86	466	631	759	857					1118
14	88	461	659	800		972		1060		

Table 7. The predicted mean weight (WT) for each male (M) and female (F) age class in all twelve commercial catfish ponds sampled in this study. To develop one overall global model for the meta-population (west Alabama catfish industry), the predicted mean weight in each sub-population (ponds) for each sex was determined. A linear regression was run once for females and once for males for each pond for a total of 24 regressions. Once the regression was run, the equation from the fitted model was used to predict each weight for the age classes represented in the pond.

Mean WT (kg) at age

Pond	Aged Fish	Age 2		Age 3		Age 4		Age 5		Age 6		Age 7		Age 8		Age 9		Age 11	
	n	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
E2	57	0.82	0.79	2.75	2.09														
E5	59	1.06	1.14	2.98	2.48		3.81												
W4	53	0.7	1.15	2.86	2.5						6.54								
B1	114			1.29	1.24			4.2	4.04										
B30	98	1.05	1.01		2.44	4.15	3.87												
4	81	-0.4	0.25	3.1	2.62	6.59	4.98	10.07	7.34	13.56		17.04		20.53			16.8		
6	91	0.84	0.89	3.99	4.26		7.62	10.31		13.47	14.34								
2	91	1.08	1.22	2.92	2.73	4.76	4.24	6.6	5.76										
10	77	0.88	1.49	4.88	4.35	8.9	7.2	12.91	10.05	16.92	12.91	20.93	15.76						27.17
3	101	1.02	0.88	3.36	2.91	5.7	4.94	8.03	6.97		8.99						15.08		
13	86	1.79	1.1	4.17	3.69	6.55	6.28	8.92	8.86									23.2	
14	88	1.06	0.98	4.59	4.5		8			15.17					15.01				

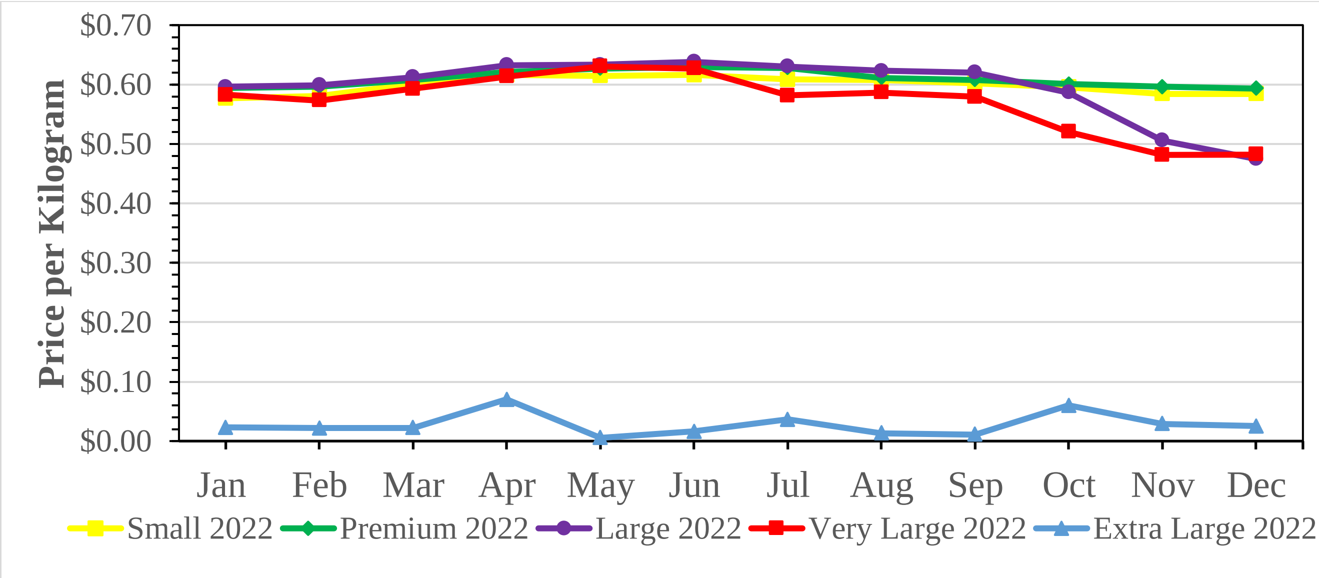
Table 8. The predicted mean weight (WT) for each age class in all twelve commercial catfish ponds sampled for this study. To develop one overall global model for the meta-population (west Alabama catfish industry), the predicted mean weight in each sub-population (ponds) was determined. A linear regression was run once for each pond for a total of twelve regressions. Once the regression was run, the equation from the fitted model was used to predict each weight for the age classes represented in the pond.

		Mean WT (kg) at age								
Pond	Aged Fish *n*	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 11
E2	57	0.8	2.4							
E5	59	1.11	2.66	4.21						
W4	53	1.04	2.58			7.23				
B1	114		1.26		4.13					
B30	98	1.03	2.54	4.05						
4	81	-0.9	3.09	6.29	9.48	12.68	15.87	19.06	22.25	
6	91	0.88	4.09	7.31	10.52	13.73				
2	91	1.15	2.8	4.45	6.1					
10	77	1.36	4.57	7.78	10.98	14.2	17.41			30.2
3	101	1.02	3.13	5.24	7.35	9.47			15.79	
13	86	1.52	3.96	6.39	11.27					23.46
14	88	1.01	4.53	8.04		15.07		22.07		

Table 9. Growth equations for total length (TL) and weight (WT) for hybrid catfish collected from twelve commercial catfish ponds in west Alabama. Hybrid catfish age classes for these models included ages 2 through 9 and age 11. The von Bertalanffy equation parameters are described in the results section.

	Growth Equation	R^2	***P*-value**
Log_{10} Weight-Length	$Log_{10}(WT) = -9.03 + 3.41*Log10(TL)$	0.97	< 0.05
Weight Predicting Age			
Combined	AGE = 2.06 + 0.31(WT)	0.92	< 0.05
Males	AGE = 2 + 0.3(WT)	0.90	< 0.05
Females	Age = 1.99 + 0.36(WT)	0.90	< 0.05
Age Predicting Weight			
Combined	WT = -5.4 + 2.9(AGE)	0.92	< 0.05
Males	WT = -5.4 + 3(AGE)	0.89	< 0.05
Females	WT = -4.4 + 2.5(AGE)	0.89	< 0.05
Von Bertalanffy Model	$L_t = L_\infty * (1-e^{-K\,(AGE - t_0)})$		
Combined	$L_t = 1168 * (1-e^{-0.27(AGE - 0.29)})$		
Males	$L_t = 1301 * (1-e^{-0.22(AGE - 0.19)})$		
Females	$L_t = 1131 * (1-e^{-0.27(AGE - 0.16)})$		

Figures



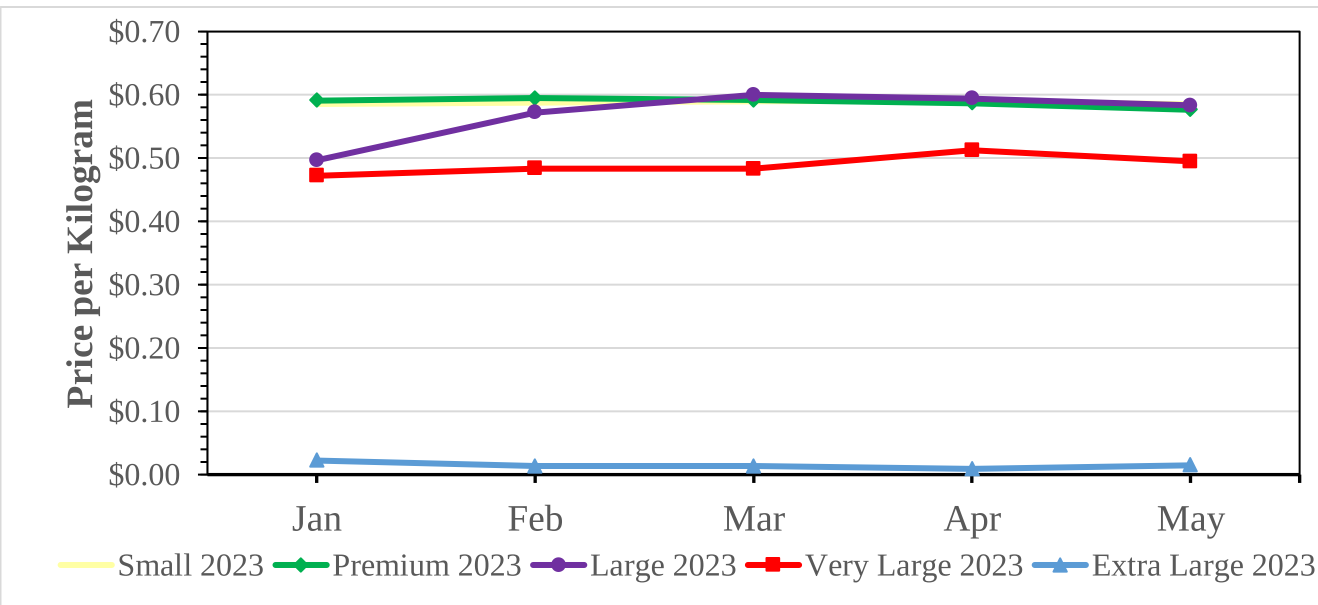


Figure 1. The average price paid to farmers from processing plants in 2022, based on the live weight of the catfish (Top). The average price paid to farmers from processing plants in 2023, based on the live weight of the catfish (Bottom). Processing plants categorize live fish into "Small (0-0.44 kg)," "Premium (0.45-1.81 kg)," "Large (1.82-2.71 kg)," "Very Large (2.72-3.63 kg)," and "Extra-Large (3.64+ kg)." As of January 2023, any fish in the "Small" and "Premium" category received of $0.59 per kilogram. "Large" and "Very Large" fish have a profit of around $0.48 per kilogram, and any fish that fall into the "Extra-Large" category returns only $0.02 per kilogram (Hanson 2022; Maples 2023).

Figure 2. Extracting lapilli otoliths from a Big Fish using the guillotine method.

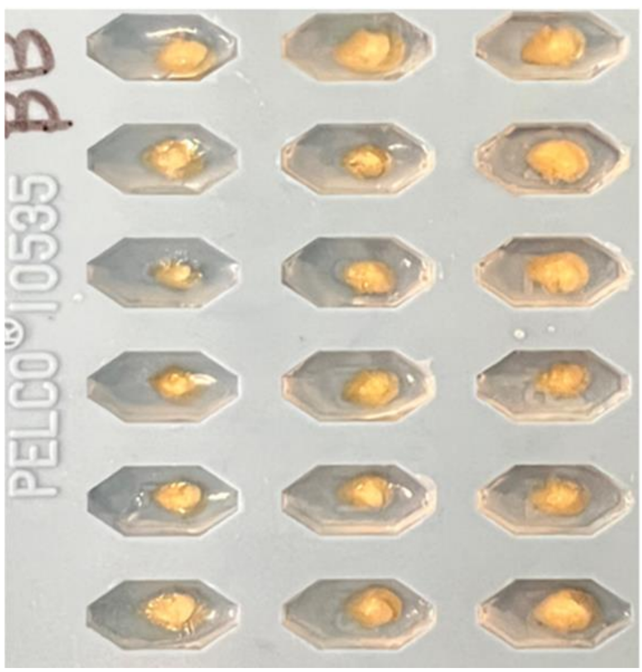


Figure 3. Lapilli otoliths were embedded in resin before being cut at the gibbus maculae to expose the core for age estimation.

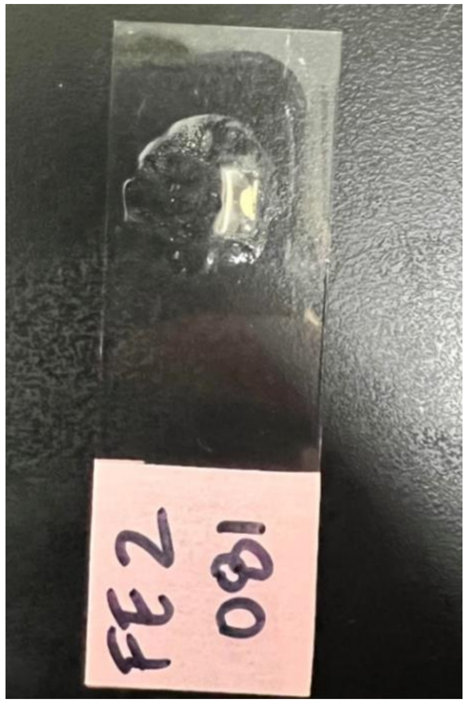


Figure 4. Otolith that was cut by a low-speed, IsoMet saw and adhered to a labeled microscope slide with Crystalbond and used to capture images and estimate age.

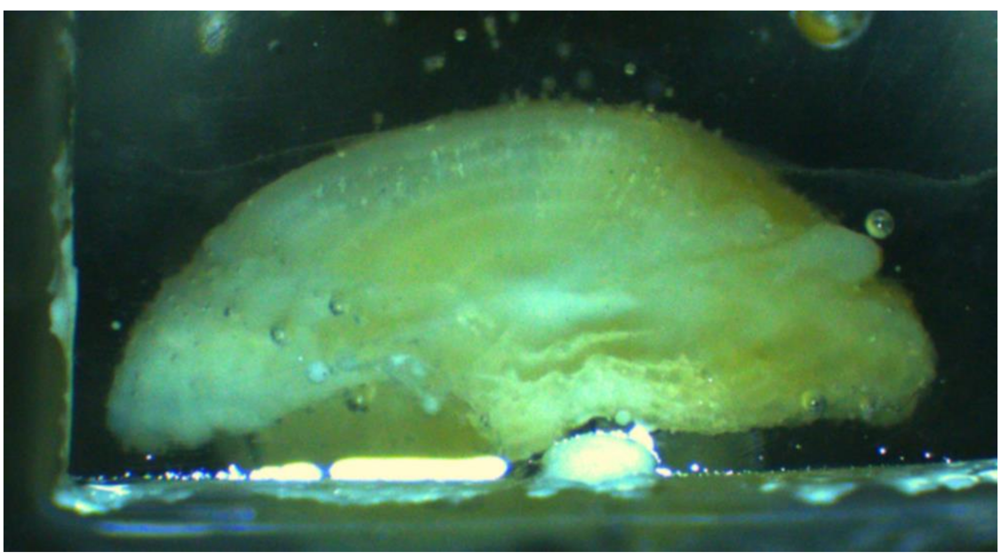


Figure 5. An example of a lapilli otolith cut to expose the core and annuli projecting from the core were counted to estimate age. The wider, tan space is associated with warming water temperatures and increased growth. The thinner, white rings are associated with reduced growth or spawning periods. This hybrid catfish was 6 years old.

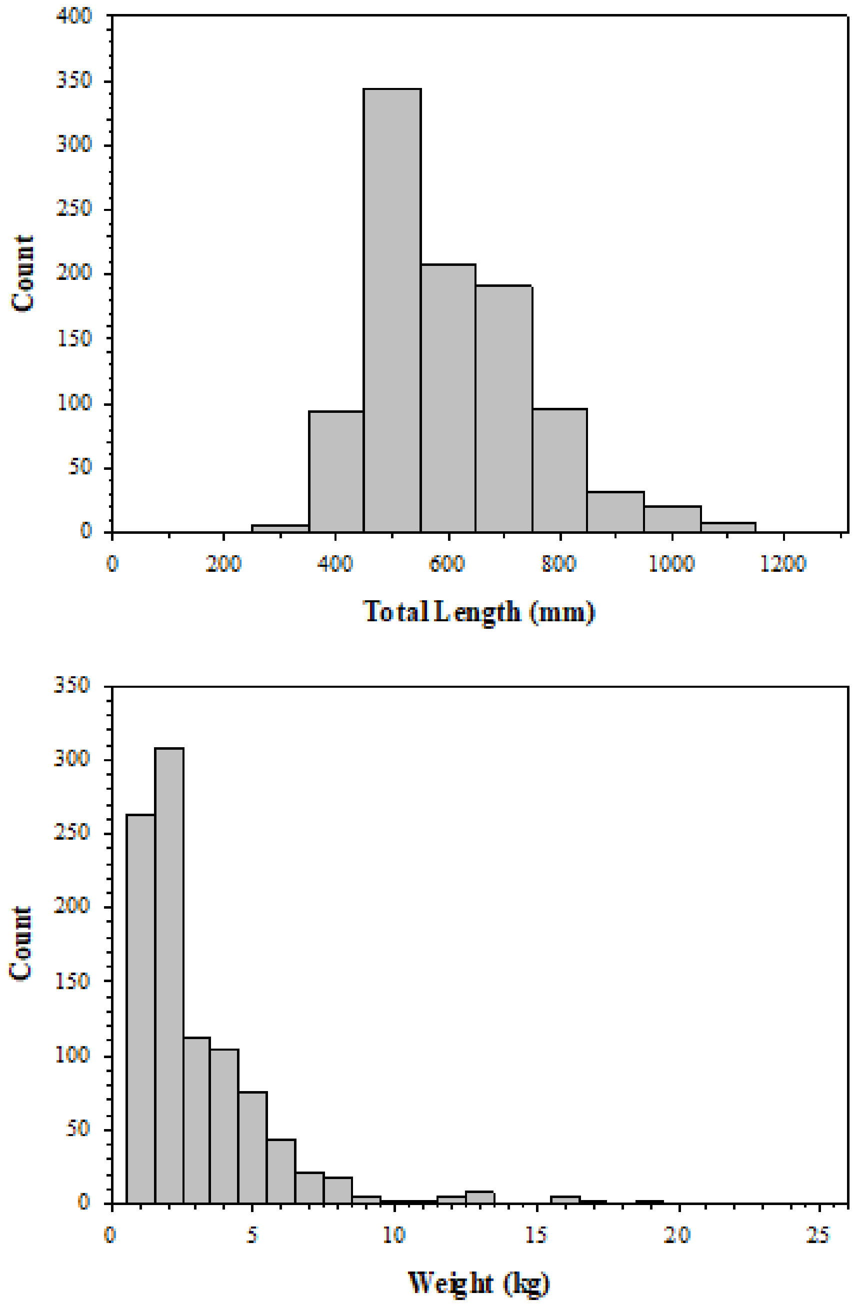


Figure 6. Total length (100 mm bins) and weight (1 kg bins) distributions for sampled hybrid catfish from twelve commercial hybrid catfish ponds in west Alabama that were used in age and growth analyses (*N* = 996).

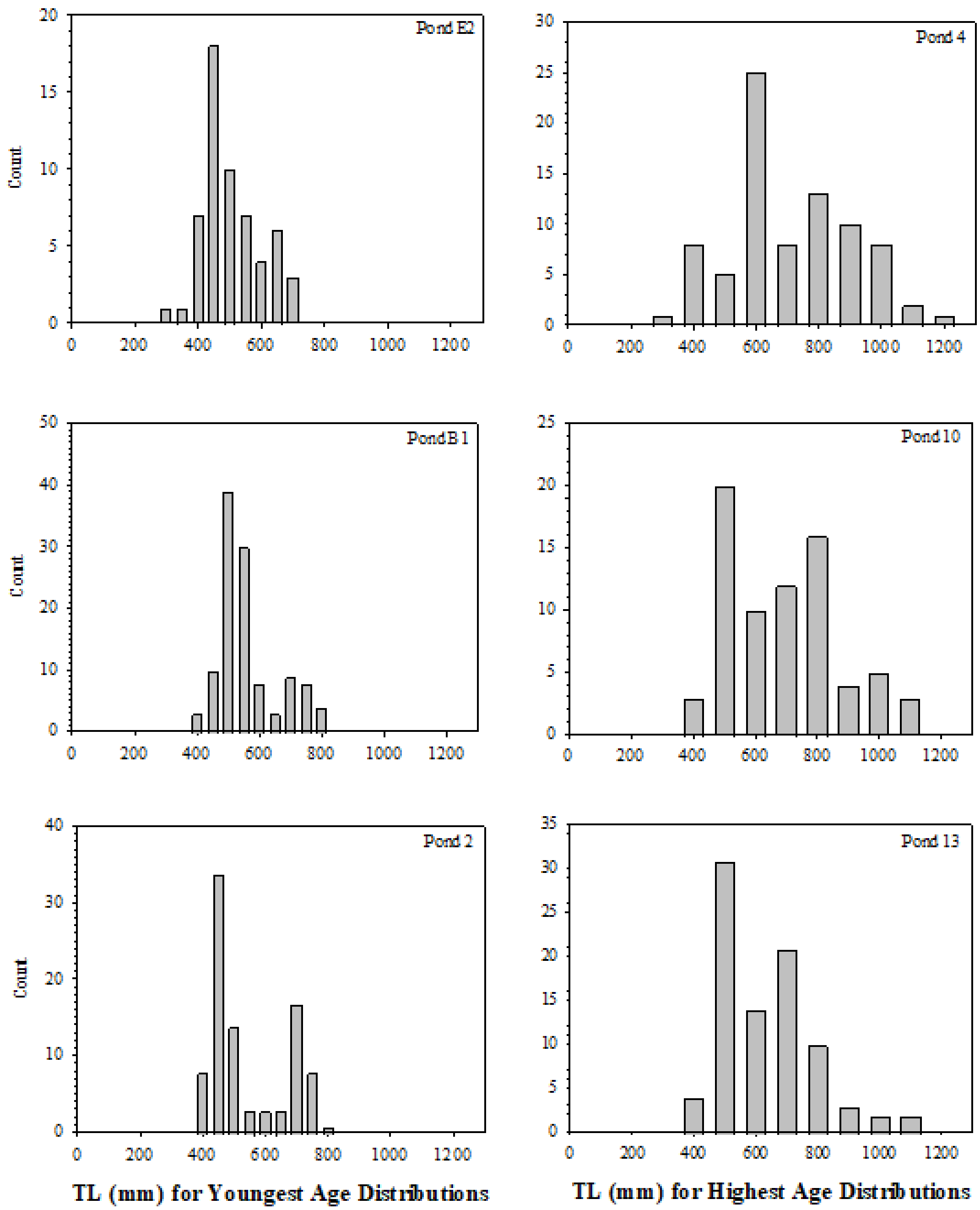


Figure 7. Total length frequencies of ponds for the three youngest age distributions compared to the three highest age distributions. On the x-axis is a range for total length (TL, mm). The y-axis represents the count for each bin. Higher-age class ponds appropriately have catfish that fall in larger total length categories.

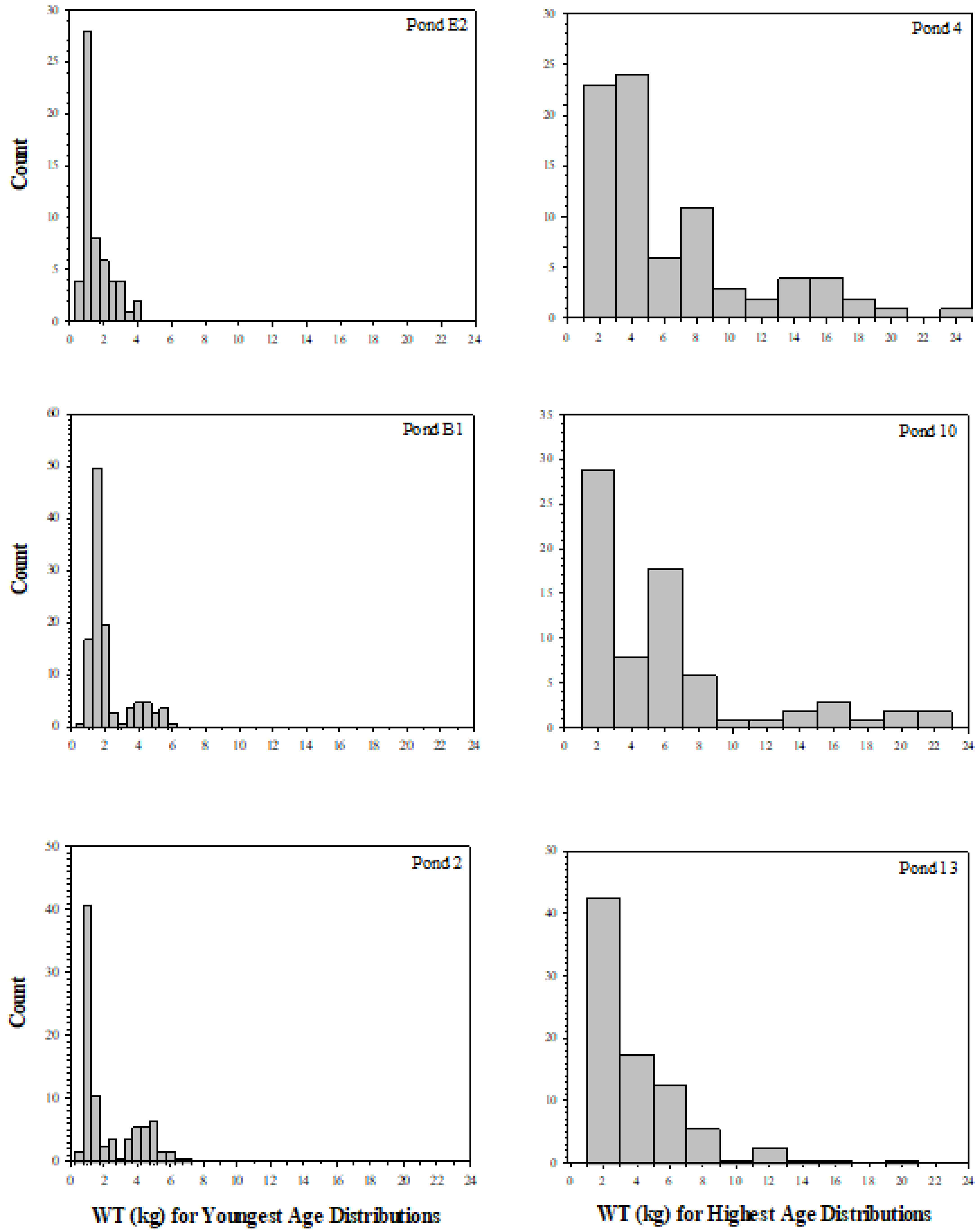


Figure 8. Weight frequencies of ponds for the three lowest age distributions compared to the three highest age distributions. On the x-axis is a range for the weight (WT, kg). The y-axis represents the count for each bin. Higher-age class ponds appropriately have catfish that fall in larger weight categories.

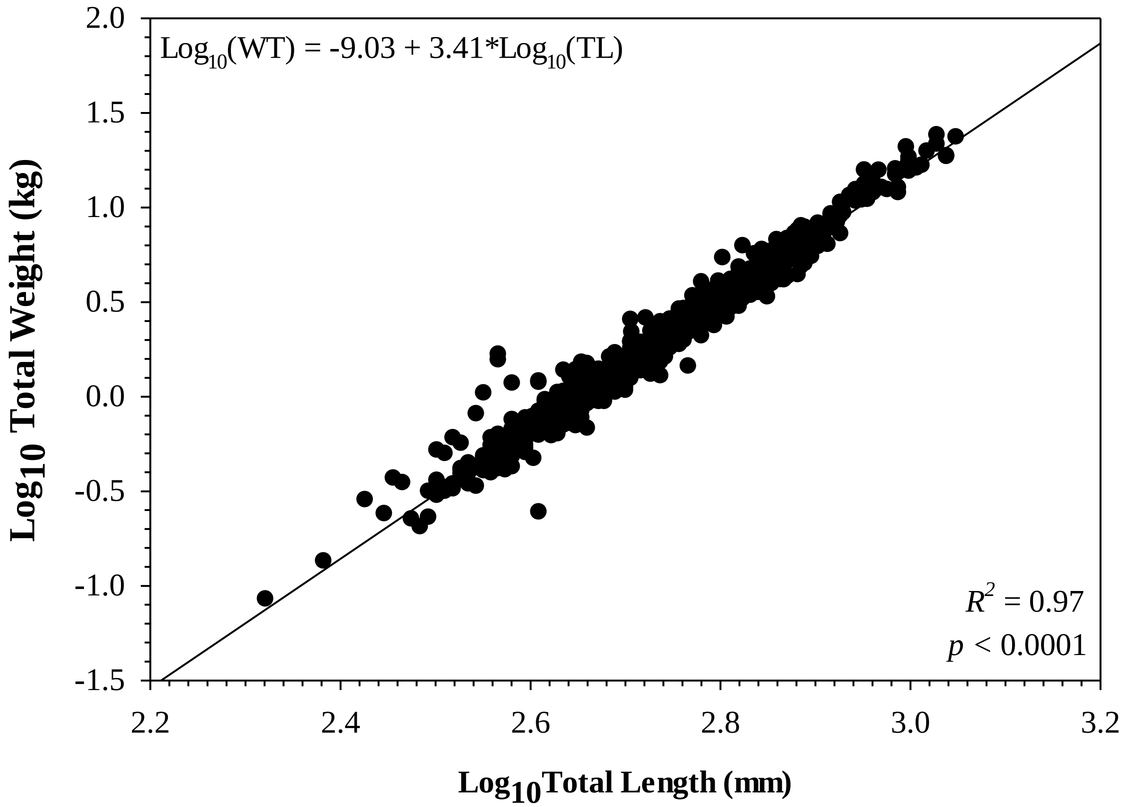


Figure 9. Log-transformed relationship between the two variables, total length (mm) and weight (kg) of hybrid catfish from twelve commercial catfish ponds in west Alabama ($p < 0.0001$).

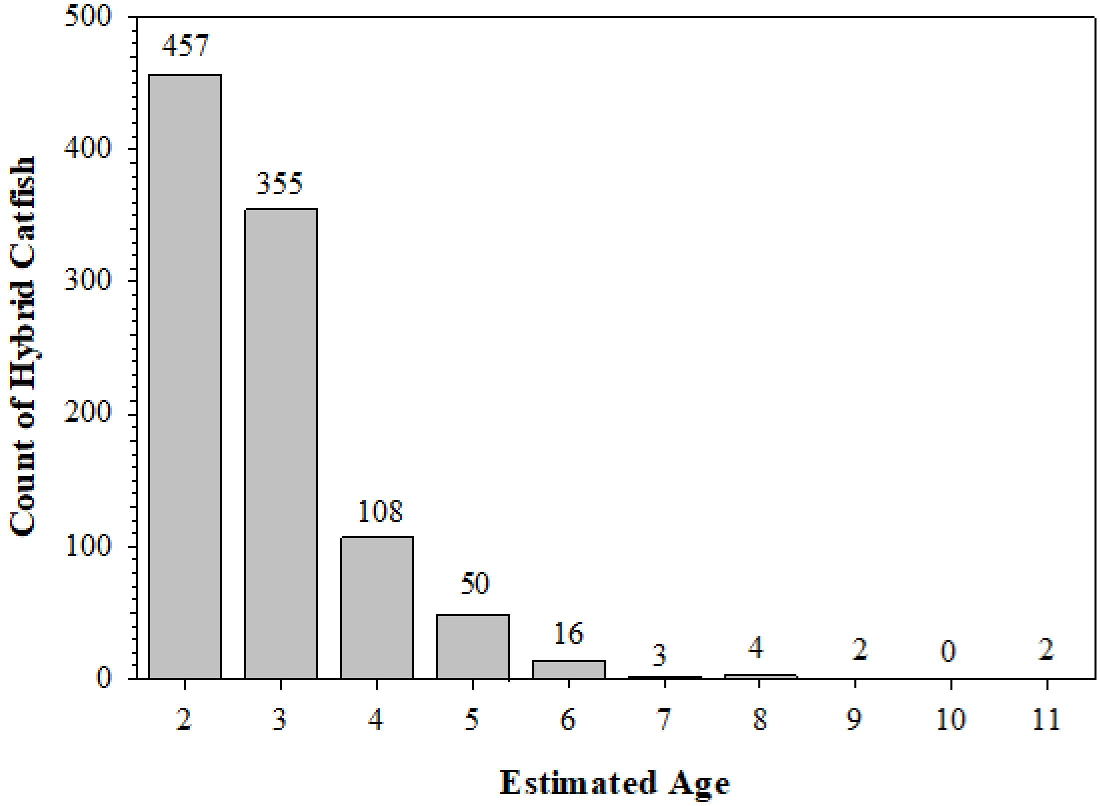


Figure 10. Age histogram (1-year bins) for hybrid catfish collected from twelve west Alabama commercial ponds. The number of catfish found in each age class is labeled at the top of the bin. Hybrid catfish were not found in age class 10, and age class 1 was excluded.

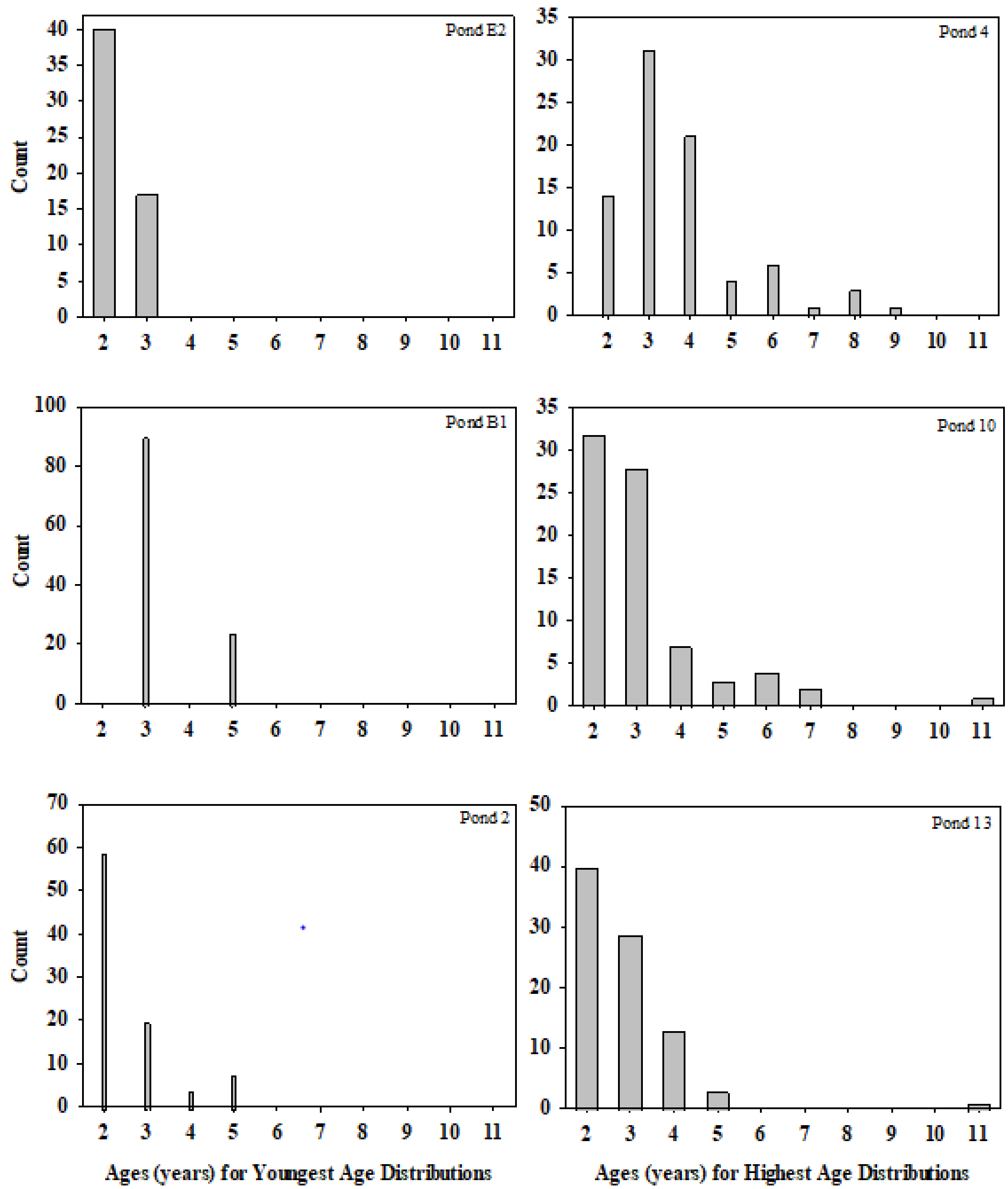


Figure 11. Age structures of ponds for the three youngest age distributions compared to the three highest age distributions. On the x-axis is a range for age (years). The y-axis represents the count for each bin.

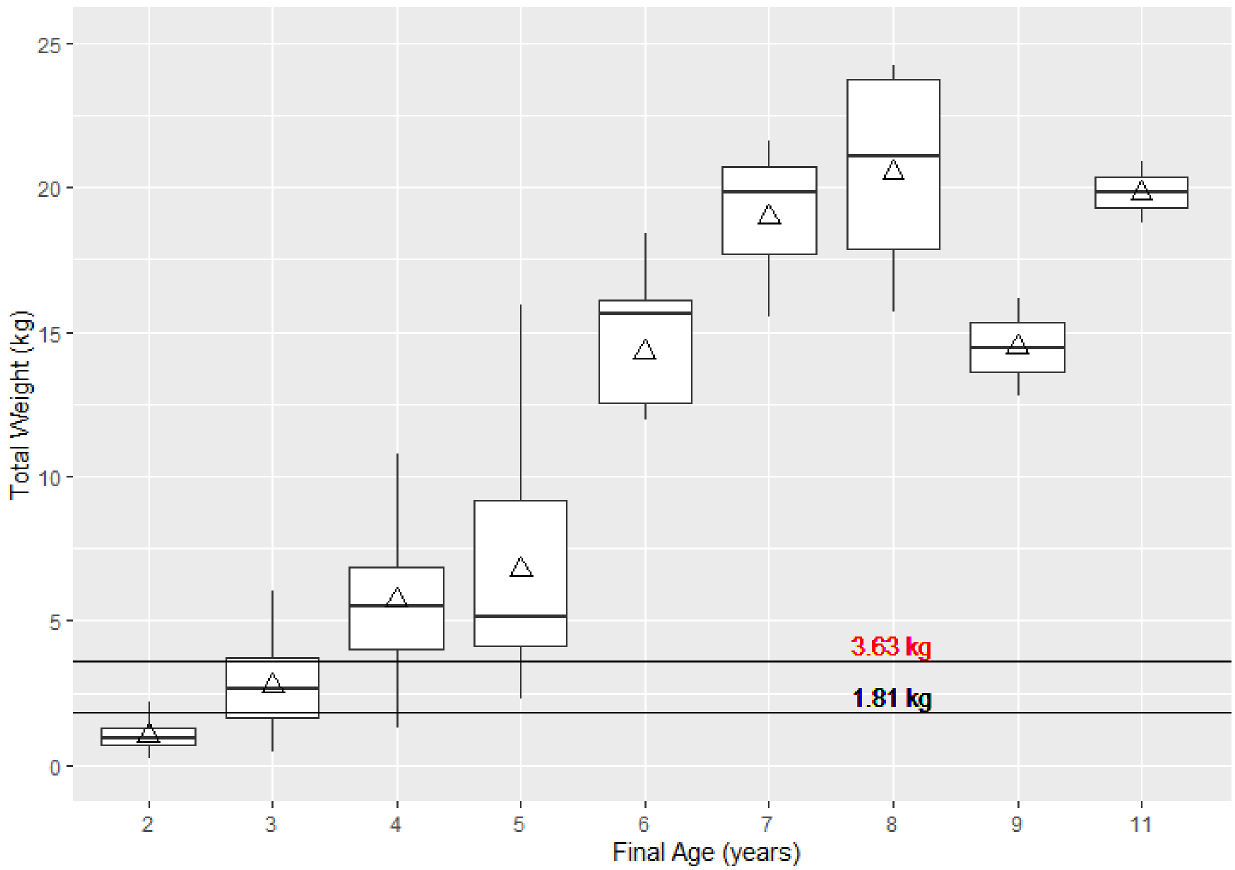


Figure 12. Boxplot graph displaying the minimum, first quartile, mean (triangle symbol), median (black horizontal line), third quartile, and maximum weight at age for hybrid catfish sampled in twelve commercial ponds in west Alabama (*N* = 1,001). No catfish were collected in the age class 10. Note: Commercial catfish hatcheries surveyed by the research team stated that hybrid catfish are typically an average of 10 months old (0.83 years old) when stocked into commercial grow-out ponds.

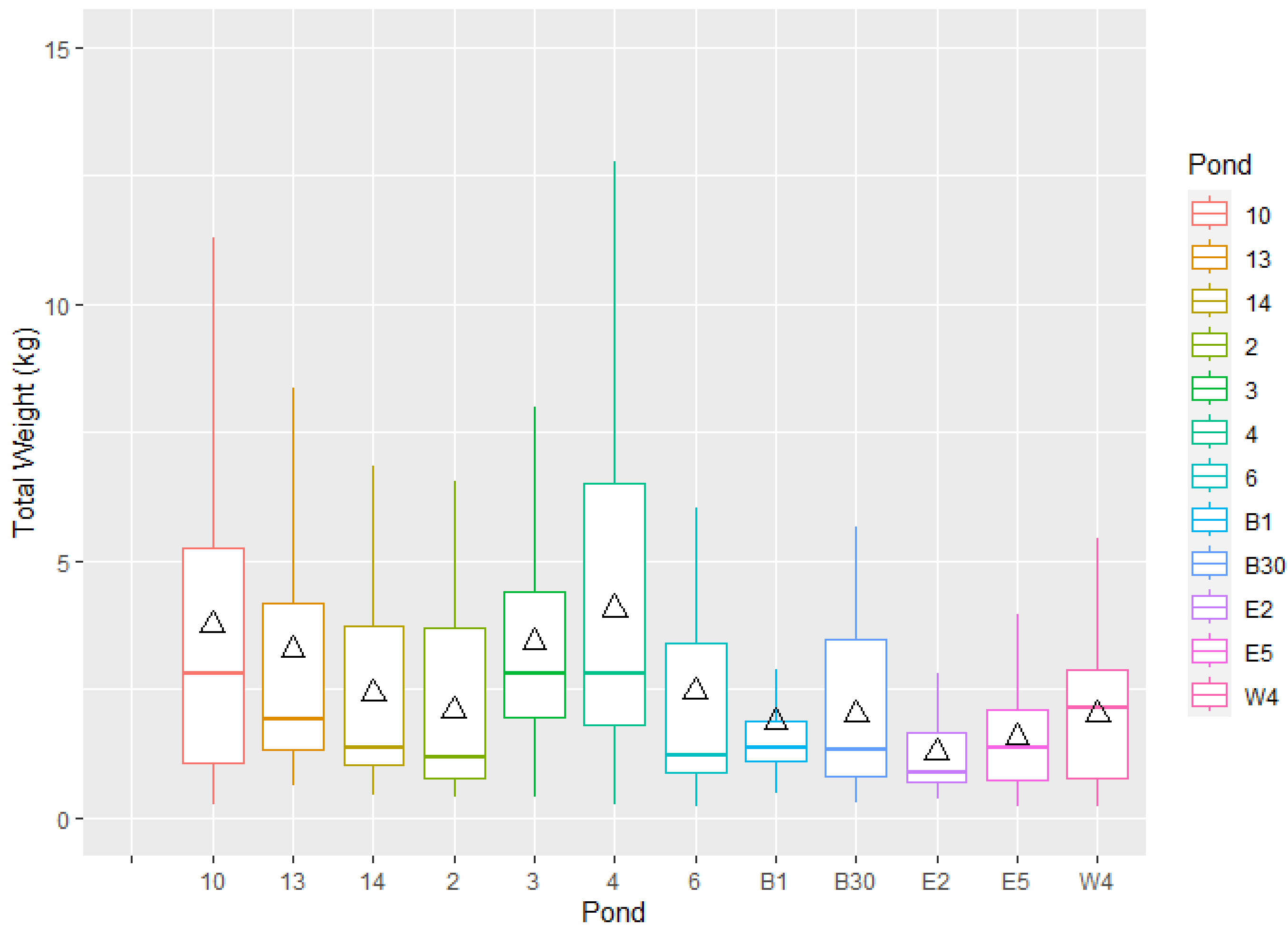


Figure 13. Boxplot graph displaying the first quartile, mean (triangle symbol), median (black horizontal line), and third quartile of the average weight per fish across the twelve ponds and seven farms sampled.

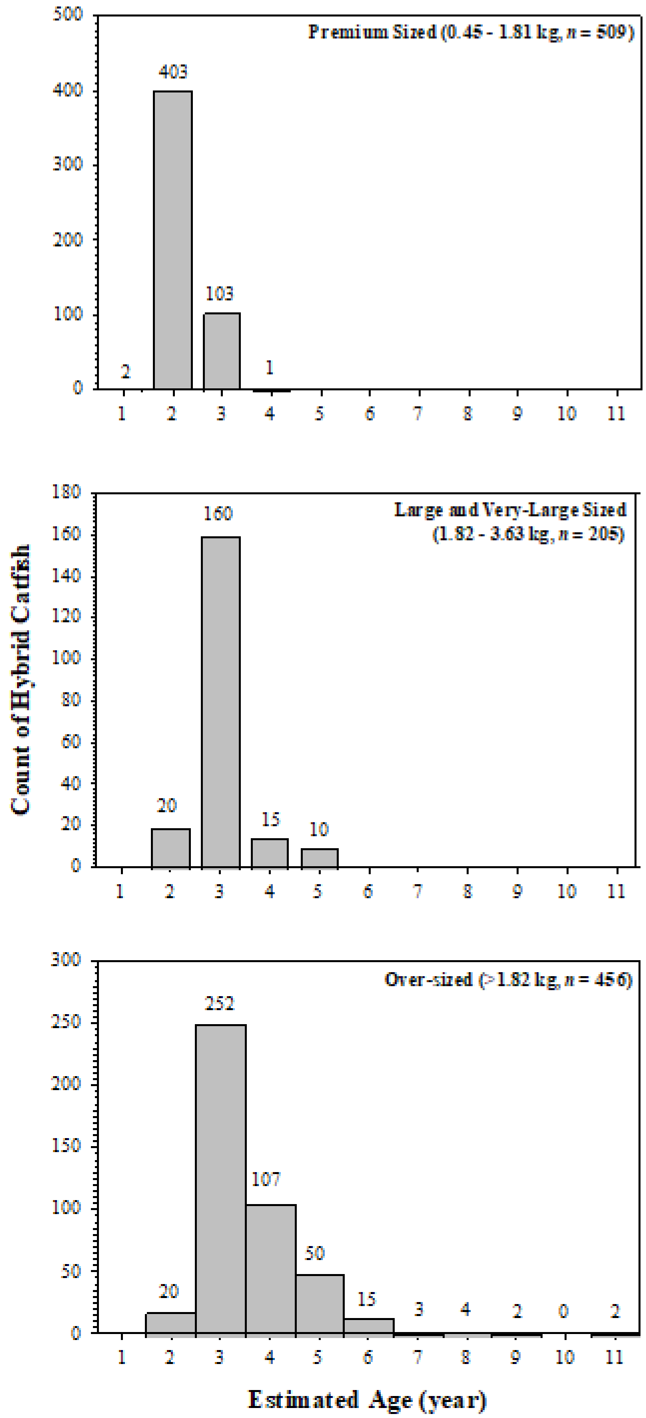


Figure 14. Age structure for hybrid catfish that fell into the various size criteria according to catfish processors.

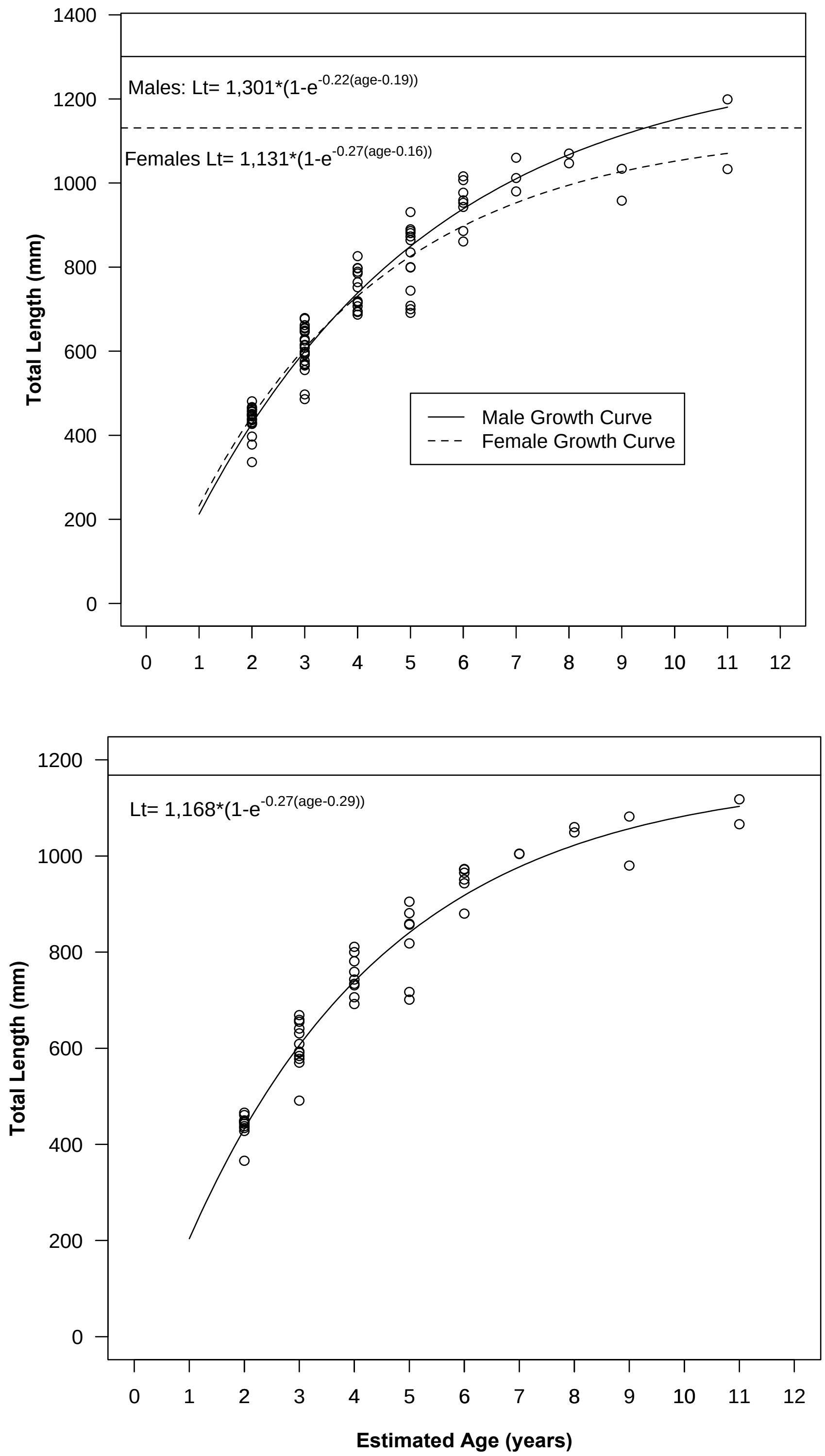


Figure 15. Von Bertalanffy length at age models for male and female hybrid catfish collected in the study, separated (top) and for all hybrid catfish combined regardless of sex (bottom). Data points collected for these graphs came from the predicted mean lengths at each age from

individual ponds. Note: separation in predicted mean TL separated by sex becomes more apparent around age 5.

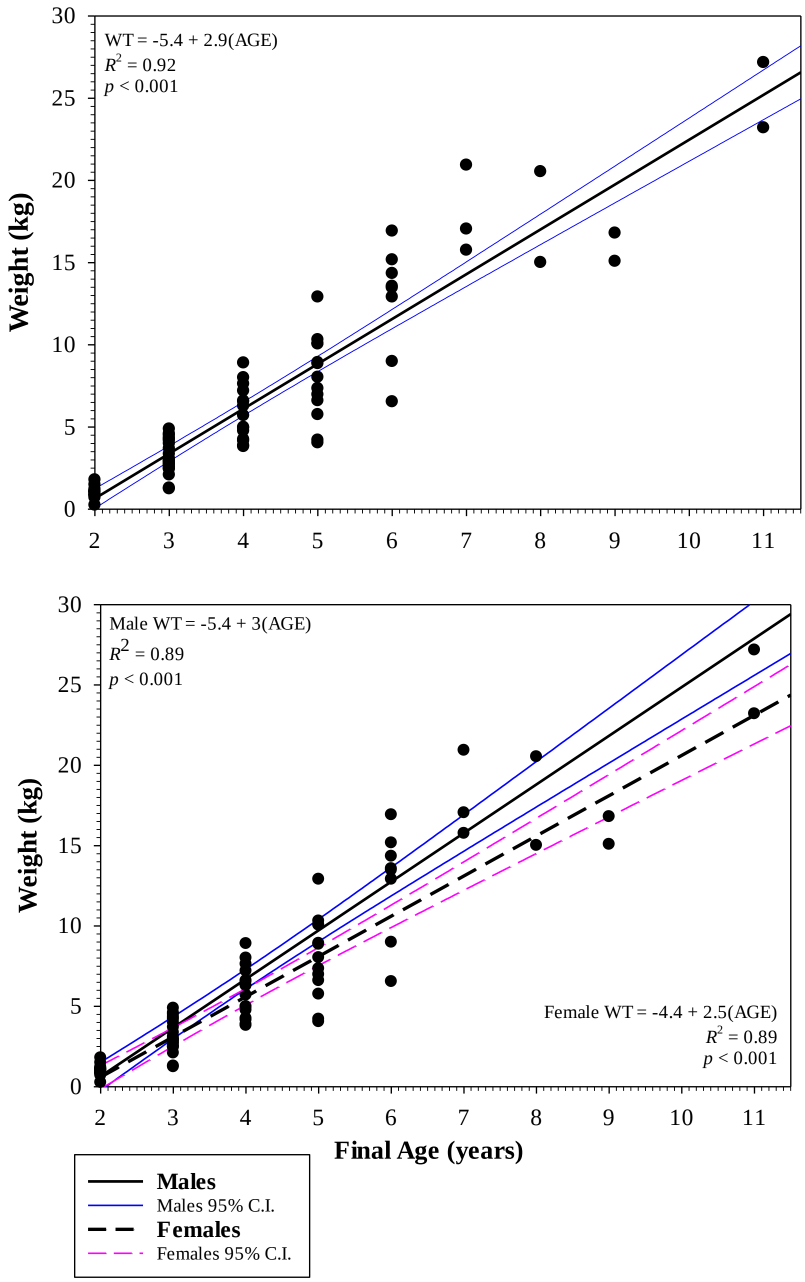


Figure 16. Weight-at-age models for all hybrid catfish combined, regardless of sex (top) and separated by males and females (bottom). Data points collected for these graphs came from the predicted mean weights at each age from individual ponds.

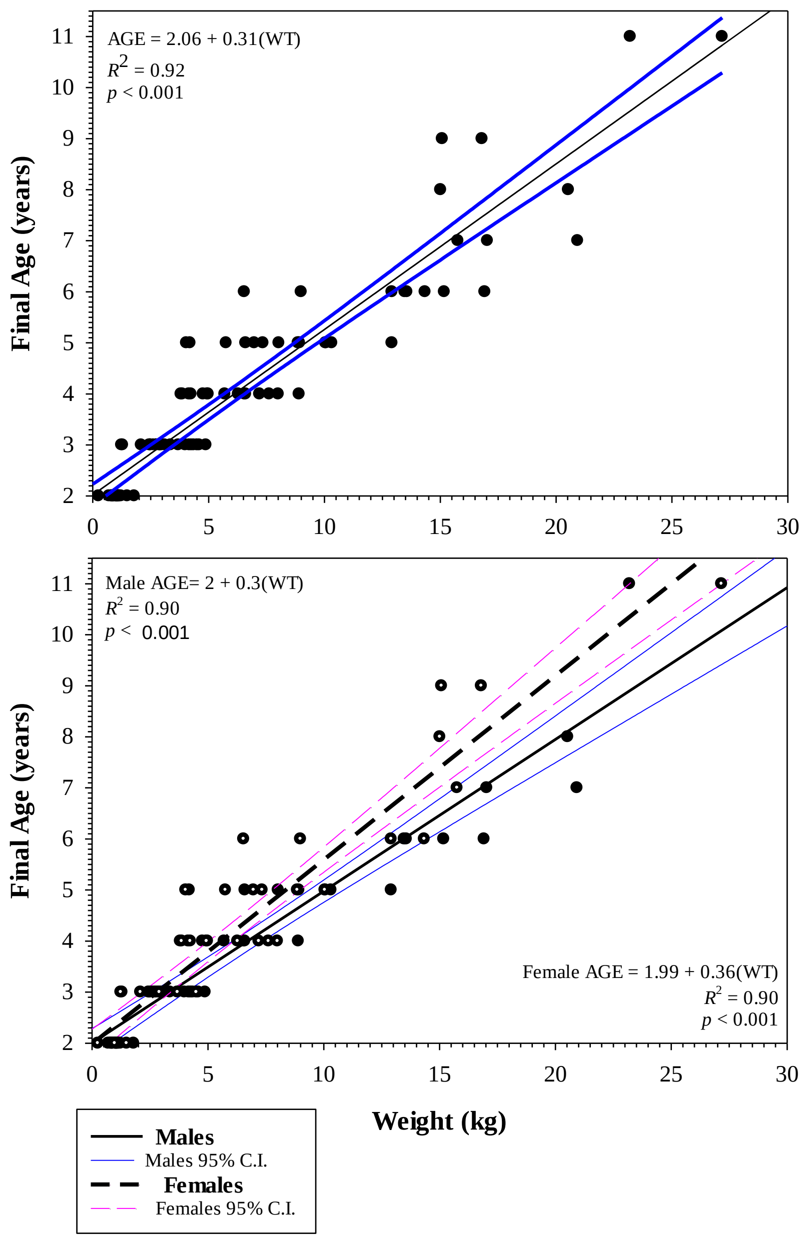


Figure 17. Age-at-weight models for all hybrid catfish combined (top) and for males and females separated (bottom). Data points collected for these graphs came from the predicted mean weights at each age from individual ponds.

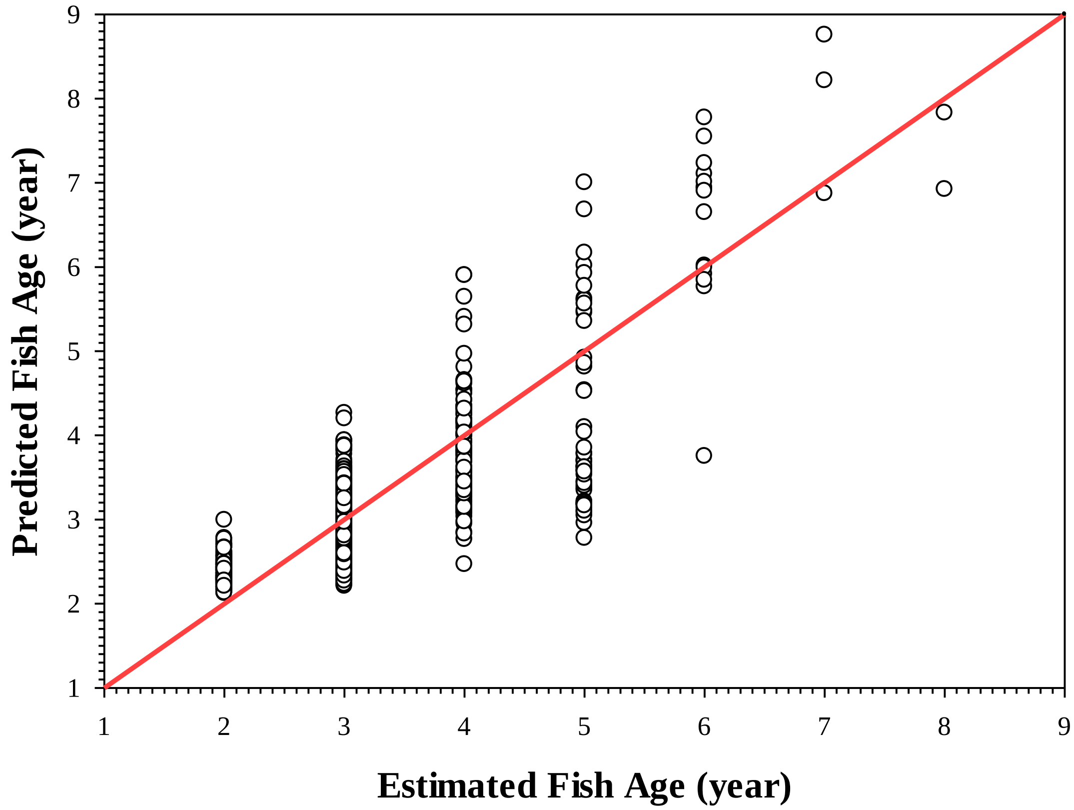


Figure 18. Estimated age versus predicted age allowed us to see how well our weight-at-age model predicted the age of hybrid catfish.

Figure 19. Example of a premium-sized fish (far left) next to several oversized fish sampled from a commercial catfish pond in west Alabama.