Effects of size-selective catch-and-release angling on population size structure of two Black Bass (Micropterus spp.) species in an Alabama Reservoir

By

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Abstract

The potential for size-selective catch-and-release angling to affect the size distributions of black bass (Micropterus spp.) populations is not well understood. Angling is highly size-selective, and competitive fishing events, may be particularly size-selective by incentivizing the capture of large fish. These competitive events (i.e., tournaments) are increasing in popularity which leads to more angling effort that might be size-selective. We conducted research on Largemouth and Alabama Bass at Neely Henry reservoir in Alabama to assess the potential for size-selective angling to affect population size structure. This system is characterized by high fishing effort and a high proportion of fish captured in tournaments. Size-selectivity of tournament and non-tournament angling was estimated from a high reward tagging study. Size-specific vulnerability estimates from angler tag returns revealed that vulnerability of 300 mm Largemouth Bass was 0.75 and vulnerability of the same size class of Alabama Bass was 0.66.

Variation in growth among individual fish was estimated by ageing samples of fish from the creel and from standardized electrofishing surveys. A pairwise comparison between gears for each age class was conducted for both Alabama Bass and Largemouth Bass. Alabama Bass collected from tournaments were on average 55 mm longer at age 1, 19 mm longer at age 2, and 25 mm longer at age 3 than fish from electrofishing surveys. Largemouth Bass collected from tournaments were on average 28 mm longer at age 1 and 13 mm at age 2. A Bayesian hierarchical growth model was fit to age samples to estimate von Bertalanffy growth parameters for individuals. The mean posterior growth parameters estimated from electrofishing samples of Largemouth Bass estimated from electrofishing samples were 563 (95% CI: 561 - 565), 0.279 (95%CI: 0.277 – 0.282), and -0.348 (95% CI: -0.359 – -0.336) for L_∞, k, and t_0, respectively. For Alabama Bass the mean posterior growth parameter estimates across individuals collected via electrofishing were 566 (565 – 567) for L_∞, 0.25(0.248 – 0.252) for k, and -0.25(-0.26 – -0.23) for t_0. An age- and size-structured equilibrium model was used that accounted for individual variation in growth within these populations under encounter rates developed from Neely Henry. The Ricker stock-recruitment model and Beverton-Holt model, along with variation in natural mortality, and maximum lifetime reproductive rate were modeled to assess influence on the abundance of quality (≥305 mm) and memorable (≥508 mm) fish of both species. Under high encounter rates the model predicted angling could reduce the abundance of quality sized Largemouth and Alabama Bass by 6% and 12% relative to the unfished condition, respectively. A decline of 48% in memorable size Largemouth Bass abundance and 79% in memorable size Alabama Bass abundance was predicted relative to the unfished condition. This study provides information on the level of impact that catch-and-release angling can have on population size structure in a reservoir system.

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Introduction

Catch-and-release angling is defined as the live release of fish back into the water after being captured (Policansky, 2002). Size and bag limit regulations necessitate the mandatory release of fish in accordance with statutes to prevent overharvesting. This mandatory release is known as regulatory catch-and-release (Policansky, 2002). Conversely, the purposeful release of fish that could have been harvested is known as voluntary release. Black bass fisheries have become increasingly oriented toward voluntary catch-and-release over the last 30 years. The impact of catch-and-release angling on black bass populations is an important topic considering the popularity of these fisheries in the United States.

Voluntary release angling for black bass arose out of concern for maintaining high fishing quality in the face of increases in the number of fishing tournaments. Voluntary catch and release was heavily promoted by an insurance salesman from Alabama named Ray Scott who loved bass fishing and had an idea to start a tournament tour in 1967. The following year he founded the Bass Anglers Sportsman Society (B.A.S.S) which has become the most popular platform for competitive bass fishing. Ray Scott saw the potential for the sport but knew that it could flourish only if the fishery resource was protected by releasing tournament-captured fish. He started the “Don’t Kill Your Catch” campaign in 1972 which required anglers to release their fish alive at the end of the day (Precht, 2019). The first catch and release tournament in B.A.S.S. was the Florida Invitational in 1972. Anglers were required to have aerated live wells to keep fish alive (Precht, 2019). The growing popularity of competitive angling further shifted angler’s views of harvesting fish.

The goals of catch and release are to improve fishing quality in the form of angler catch rates, population size structure, and trophy potential (Sass & Shaw, 2020). It appears that these goals are species-specific and for Black Bass, there is a trade-off between angler catch rates and trophy potential. The increase in catch-and-release by anglers has resulted in a gradual increase in catch rates but has had the opposite effect on population size structure (Hansen et al. 2015; Rypel et al. 2016; Sass & Shaw, 2020). Sass and Shaw (2020) found increases in Largemouth Bass *Micropterus nigricans*, abundance contributed to the decline in size structure observed in Wisconsin lakes. Sass and Shaw (2020) found that catch and release also negatively impacted the growth rates and maximum growth potential of Largemouth Bass. Although catch and release angling may increase population abundance relative to harvested stocks, the unintended mortality of released fish may be an underappreciated source of mortality especially for species that experience very high rates of capture.

Catch-and-release by anglers has become increasingly prevalent for all size classes of black bass, especially Largemouth Bass. A study done by Myers et al. (2008) assessed voluntary release rates at popular bass fishing lakes and reservoirs in Florida and Texas. They compiled creel survey data from 1975 to 2006 to assess the voluntary release rates by anglers on different water bodies. They found an increase in voluntary release rate across all lakes, with the smallest increase (0.16 to 0.58) at Toledo Bend Reservoir and the largest increase (0.24 to 0.83) at Sam Rayburn Reservoir (Myers et al., 2008). They found that at Lake Fork Reservoir and Lake Monticello Reservoir, the voluntary release rates had reached functional ceilings (>.95), meaning they were effectively operating as entirely catch-and-release fisheries (Myers et al., 2008). Voluntary release of legal-size bass has increased similarly across the U.S. While catch and release may decrease overall fishing mortality, it is evident that catch-and-release fishing has the potential to deplete fish populations under higher post-release mortality rates (Policansky, 2002).

Rising voluntary catch-and-release rates present a challenge for managers in that typical management options such as length and bag limits are less likely to influence primarily catch-and-release fisheries (Miranda et al. 2017). Miranda et al. (2017) found that changes in length limits failed to restructure Black Bass population size structure given a lack of harvest by anglers. Despite changes in length limits over a 28-year period, there was no significant change in population size structure that could be accredited to the changes in regulations (Miranda et al. 2017). The population size-structure changes that were seen by Miranda et al. (2017), were thought to have been because of a lack of Black Bass harvest and the aging of Ross Barnett Reservoir.

The increase of voluntary release rates has increased the number of studies on angling tournaments as most tournaments are live-release events. Tournament mortality or prerelease mortality is defined as the death of the tournament-captured fish before it can be released after weigh-in. Post-release mortality is defined as the death of the fish that is released alive after capture but subsequently dies thereafter due to stress and environmental conditions associated with the capture and release event. Post-release mortality has been studied significantly as voluntary release by anglers has become increasingly common. Estimates of post-release mortality rates are highly variable depending on the time of year, duration of the fight, live well containment, handling techniques, and other factors (Driscoll et al. 2007, Plumb et al.1988, Schramm et al. 1987, Siepker et al. 2007). During the tournament catch, transportation, and weigh-in process, fish experience prolonged air exposure, increased anaerobic energy expenditure, crowding, and metabolic waste accumulation (Suski et al. 2011). It is hypothesized that the combination of these sublethal stressors is responsible for the increases in mortality rates seen from tournament angling (Schram et al. 1987 and Suski et al. 2011). Wilde (1998) conducted a meta-analysis of the results of numerous studies and found post-release mortality to range from 0 to 52% in black bass. These rates were estimated from 130 fishing tournaments with a range in number of anglers and weigh-in procedures (Wilde 1998). Schramm Jr. et al. (1985) looked at the survival of tournament caught Largemouth Bass in Florida by collecting data from 18 large tournaments held on two lakes. They concluded that there was a 14% total mortality rate for fish weighed in at a tournament and found no significant relationship between mortality, catch per team, air temperature, and water temperature (Schramm et al., 1985). However, Meals and Miranda (1994) conducted a study to test size-related mortality of Largemouth Bass concerning water temperature and the mean number of fish per boat in Black Bass tournaments. They found that water temperature and mean fish per boat had a compensatory relationship on Largemouth Bass prerelease mortality (Meals and Miranda, 1994). They also saw that increases in water temperature and mean number of fish per boat had a greater impact on the survival of larger individuals compared to smaller individuals (Meals and Miranda, 1994). They found that the prerelease mortality rate for small individuals ranged from 3 to 12% and from 11 to 57% for large individuals (Meals and Miranda, 1994). The small Largemouth were between 12 and 14 inches and the large individuals were 18 inches or greater (Meals and Miranda, 1994). They hypothesized that fish outside of the two size classes they evaluated would likely experience direct increases in mortality with increases in fish size (Meals and Miranda, 1994). Estimating post-release mortality rates can be challenging due to limitations of study design. Specifically, it is difficult to produce control treatments to assess background mortality rates, handling effects, or caging effects. Kerns et al. (2016) conducted a study to assess the components of mortality through a combination of dart tags and radio transmitters. Their study system (Lake Sante Fe, FL) was unique in that their estimated harvest rate was relatively high with an instantaneous rate from 0.17 to 0.60, and they noted this could have affected the post-release mortality rates (Kerns et al. 2016). Kerns et al. (2016) speculated the increase in harvest rate may have been influenced by word spreading of the use of high-reward dart tags, resulting in increased angler effort. The increase in harvest rates would decrease post-release mortality rates as more fish are harvested, they are not susceptible to post-release mortality.

Since competitive Black Bass fishing has become popular, investigators have attempted to estimate the number of tournaments. Shupp (1979) took an early look into the B.A.S.S. tournaments, as they were the largest organization for competitive bass fishing. Shupp (1979) conducted a nationwide survey to assess tournament activity. He found that 44 out of 50 states had Black Bass tournaments occurring on waters within each state and a total of 12,369 tournaments occurring across these states at that time (Shupp 1979). In 1984 the same survey was conducted by Duttweiler (1985) to assess if the tournament numbers had changed over the six-year period. Duttweiler's (1985) survey was slightly modified to include competitive angling of multiple species in addition to black bass. He found that Black Bass tournaments outnumbered tournaments for all other species by ten times (Duttweiler 1985). Interestingly he observed a reported decrease in the number of competitive Black Bass events from 12,369 events in 1978 to 7,419 events in 1983 (Duttweiler 1985). In 1989, Schramm et al (1991b) conducted a survey across the United States, Puerto Rico, Virgin Islands, and Canada to estimate the status of competitive fishing in North America. They reported 14,055 Black Bass tournament events from their survey but noted this number was an underestimate due to state agencies underreporting the number of events occurring in their state (Schramm et al. 1991b). For example, they pointed out that Texas reported more bass fishing clubs than tournaments and some states only reported the known larger events on their water bodies (Schramm et al. 1991b). Other studies such as Kerr and Kamke (2003) and Schramm Jr and Hunt (2007) reported increases in competitive fishing events in the United States but did not distinguish between species for these events.

The Southeastern region of the United States is home to some of the top Black Bass fisheries in the country, which generates many tournaments on the waters of the region. Like much of the United States, the Southeastern part of the country has experienced increases in the number of black bass tournaments. A study done by Driscoll et al (2012) conducted a survey similar to Schramm and Hunt (2007) but modified it to only include black bass tournaments. Of the 15 Southeastern states, 14 responded to the survey with South Carolina being the only non-respondent (Driscoll et al 2012). In 6 of the 14 responding states, they found increases of ≥10% in Black Bass tournament occurrences from 2005 to 2012 (Driscoll et al 2012). Overall, the 2005 Schramm and Hunt (2007) study of all inland tournaments estimated a total of 32,321 events with 18,736 of those occurring in the Southeast region across all species. Driscoll et al (2012) estimated 41,939 Black Bass tournaments occurred in the Southeastern states, and this is a conservative estimate.

The increase in tournament effort on reservoirs can come with some adverse effects but also potential positive impacts. A survey conducted by Driscoll et al (2012) included a series of questions to gauge “adverse-impact factors” of Black Bass tournaments. The main concerns from fishery managers were “resource overuse”, “user group conflicts”, and “concentrating fish at tournament release sites” (Driscoll et al., 2012). The perceived benefits of tournaments were “generate revenue for my agency”, “reduce harvest by stimulating live-release ethic among anglers”, and “collect fishery assessment data to supplement current agency efforts” (Driscoll et at., 2012). There is no doubt the increase in Black Bass tournaments is going to continue to influence Southeastern fisheries and the way they are managed. It will be important as tournament pressure increases to better monitor tournament occurrences and the potential impacts they have. Fishery managers should be encouraged to use tournaments and the data generated from them to their advantage to assess Black Bass populations in their reservoirs (Driscoll et al., 2012). Studies like Driscoll et al. (2012), Kerr and Kamke (2003), Schramm et al. (1991b), and Schramm Jr and Hunt (2007) are biologically and economically valuable and provide direction for future studies.

The continuing popularity of live-release Black Bass tournaments has caused concern about the impact of tournament and post-release mortality on Black Bass populations. Extensive research has been conducted on all aspects of fishing tournaments, including how they might influence Black Bass populations. Studies assessing tournament and post-release mortality have come to mixed conclusions on the impacts of these sources of mortality on population size structure and abundance (Allen et al., 2008, Chong et al., 2021, Driscoll et al., 2007, Hysmith et al., 2014, Meals and Miranda, 1994, Plumb et al., 1988, Schramm Jr. et al., 1985, Schramm Jr. et al., 1987, Suski et al., 2011, Sylvia et al., 2021, Weathers and Newman, 1997, Wild et al., 1998). The impacts of fishing tournaments have generally been greater in smaller reservoirs that have higher per-hectare fishing effort (Hysmith et al., 2014). Greater impacts on population size structure and abundance is also likely when a larger proportion of the angling effort occurs in fishing tournaments (Hysmith et al. 2014). Driscoll et al. (2007), Plumb et al. (1988), Schramm Jr. et al. (1985), and Sylvia et al. (2021) all found that tournaments were likely to have little effect on the Black Bass population. They found that there was a low impact of tournaments on their respective reservoirs but under other conditions, there could be a cause for concern. Kerns et al. (2016) also found a low population level effect for tournaments based on their estimates of instantaneous post-release mortality for tournaments and instantaneous catch-and-release mortality. Their estimates ranged from 0.04 to 0.07 and 0.03 to 0.05 for tournament post-release mortality and catch-and-release mortality, respectively. Other studies such as Allen et al. (2008), Meals and Miranda (1994), and Schramm Jr. et al (1987), could not make definitive conclusions from their studies but suggested tournaments could impact populations under different circumstances. For example, if reservoirs had higher catch rates, high tournament activity, and poor tournament weigh-in organization, compared to the ones included in their studies, there could be a higher post-release mortality and a greater impact on population dynamics (Allen et al. 2004, Meals and Miranda, 1994, and Schramm Jr. et al., 1987, Weathers and Newman, 1997).

Many studies focusing on tournament angling evaluate tournament effects on an individual fish basis as opposed to a population-level assessment (Siepker et. al., 2007). For example, studies have evaluated the dispersal of fish released at tournament weigh-in sites. Typically, fish will be tagged using external tags, passive integrated-transponder tags, or telemetry tags and then attempted to be recaptured via electrofishing. Ricks and Maceina (2008) observed steep decreases in tagged fish density 3 months after being released from a fishing tournament while Gilliland (1999) observed that 64% of tournament caught Largemouth Bass remained within 1.6km of the release site up to one year after release. Another study by Hunter and Maceina (2008) observed that 53% of displaced Black Bass stayed within 2 km of the release site after two weeks and 38% remained after one month. Results for studies evaluating the dispersal of Black Bass vary between both extremes of very little dispersal, to most fish dispersing within a short time frame.

Assessing population size structure and the factors that influence it, including catch and release angling, is an important research topic. A study done by Sass et al. (2018) found a decrease in population size structure during a catch-and-release angling experiment at Little Rock Lake South over four years. Little Rock Lake South was closed during the experimentation period to recreational angling and was only angled by members of the research project (Sass et al. 2018). Catch-and-release angling events using conventional hook-and-line angling with artificial lures of various sizes were conducted once a week (Sass et al. 2018). They found that proportional size distribution (PSD) of quality size fish and PSD of preferred size fish decreased from 75% in 2001 to 29% in 2005 and 23% in 2001 to 6% in 2005, respectively. They attributed the decrease in size structure to an increase in recruitment and not catch-and-release mortality due to an increase in Largemouth Bass density (Sass et al. 2018). However, they hypothesized that under higher rates of catch-and-release mortality for larger individuals a shift in the population size structure could occur to be comprised of higher counts of smaller individuals (Sass et al. 2018). On Amon G. Carter reservoir in North Texas, Hysmith et al. (2014) used T-Bar tags and a roving creel survey to estimate tournament and non-tournament catch. Using an age-structured model they estimated a 6% and 9% increase in the abundance of bass ≥ 356 mm and ≥457 mm, respectively, when tournament catch was reduced by 50% (Hysmith et al. 2014). This suggests tournament capture did affect the population by reducing the abundance of these two-size classes.

There is a lack of additional research on Black Bass population size structure and how it might be influenced by catch-and-release angling. A potential mechanism that affects size structure that needs further research is the size-selectivity of recreational angling. Size-selective angling refers to the active targeting by anglers of particular size classes of fish in the population. It is most common for anglers to target larger individuals in the population for recreation or competitive sport. There is considerable evidence that size-selective fishing in commercial fisheries influences size structure, life history traits, and potentially behavioral traits (Heino and Godø, 2002). There have been efforts at quantifying population size structure (Gablehouse and Willis, 1986) but little has been done to assess if angling can shift the size structure of Black Bass populations. Sutter et al. (2012) assessed associations between individual fitness and vulnerability to angling and found that Largemouth Bass with increased vulnerability exhibit more aggressive behavior, better parental care, and higher reproductive fitness (Sutter et al. 2012). Vulnerability as it relates to the selectivity of angling has been reported in Black Bass (Binder et al. 2012, Philipp et al. 2009, Sutter et al. 2012), but researchers have neglected to draw a connection with high fishing mortality. Not all Black Bass populations are influenced by high fishing mortality, but more effort is needed to quantify the effects of selective angling pressure on populations. The combination of high fishing effort, high fishing mortality, and angler selectivity towards larger bass, has the potential to impact these types of systems.

Despite extensive research on catch-and-release angling there is a need for further study on the effect of size-selective angling on Black Bass populations. Knowing which size and age classes are most vulnerable to be weighed in at tournaments or released outside of tournaments will increase awareness of which size classes have the potential to be affected. The size-based vulnerability an individual fish to angling is a product of the individual's growth trajectory and the selective properties of the fishing method. Individual growth trajectories in Black Bass have not been analyzed extensively and thus requires additional investigation. The variability of growth trajectories between faster and slower-growing individuals could influence an individual’s survival. Fish with faster growth rates become vulnerable to angling at an earlier age than an individual of the same year class but with slower growth rates. Thus, faster-growing fish may potentially experience higher cumulative mortality, which could negatively impact the size structure of a population by the selective removal of the faster-growing fish.

This study will fill the knowledge gaps and provide supplemental research for tournament angling in the Southeast. The study will address gaps in size-selective angling, growth trajectories, vulnerability, and the effects of catch-and-release angling on Black Bass population size structure. The purpose of this study is to evaluate the effects of size-selective catch-and-release angling on population size structure of two Black Bass species in Alabama. My objectives are: (1) estimate variability in growth trajectories among individual Black Bass; (2) estimate size-based vulnerability to mandatory catch-and-release, voluntary non-tournament catch-and-release, and tournament catch-and-release; (3) simulate the effects of size-selective catch-and-release angling on Largemouth Bass and Alabama Bass *Micropterus henshalli* using a size-and-age structured model.

Materials and methods

Study site

Neely Henry Reservoir is a 4546.6-ha reservoir located in Northeast Alabama. It is part of the mainstem of the Coosa River chain of reservoirs. It is located below Weiss Lake and above Logan Martin Lake. Neely Henry dam was built in 1966 and is operated by the Alabama Power Company for hydroelectric power. It has 547 km of shoreline and a maximum depth of 16 meters. It has 1.7 million hectares of watershed flowing into the reservoir. Neely Henry Reservoir is a public recreational reservoir used by many for boating and fishing. This reservoir has high fishing effort and high voluntary release with a large percentage of capture in competitive angling events. Neely Henry offers an array of fish for angling, but the effort is primarily focused on the Largemouth and Alabama Bass.

Study design

Research was conducted on Largemouth and Alabama Bass to assess the potential for size-selective angling and its effects on the population. Size-selectivity was assessed from tournament and non-tournament angling over a wide size distribution of both species. Size-selectivity was estimated using a high reward tagging study. Growth trajectories of individual fish were estimated by aging fish from tournament creel samples and electrofishing surveys. This took place over two years with the same approach and methods for both years (2022 & 2023). Tagging took place in the late winter and creel sample collections occurred continuously throughout the year. Estimates of growth trajectories of individual Largemouth and Alabama Bass along with estimates of angling size-selectivity were used to parameterize a simulation model that predicted the abundance of two size classes of these species as a function of the angling encounter rate (i.e., the number of times each fish is captured on an annual basis).

Objective 1: Estimate variability in growth trajectories among individual black bass

Tournament creel samples

Creel samples were collected from fishing tournament weigh-ins when tournaments were known to occur during the week or weekend. Tournaments occurred primarily from February to November, with the majority from March to June. Sampling trips predominantly occurred on Saturdays due to when most tournaments were held. Permission by tournament directors was obtained before attending any tournament to collect fish. When given permission, up to 10 Largemouth Bass and 10 Alabama Bass were collected from each tournament. Anglers were encountered after the tournament weigh-in and randomly selected to be asked whether they would like to donate their fish to our study. Fish from participating anglers were euthanized by being placed in an ice bath and transported back to the lab. I attempted to age a maximum of 10 fish per centimeter length interval per species per year from tournaments. In addition to the 20 fish per tournament collected for ageing, an additional maximum of 50 were measured for total length and released alive at each tournament. These additional measurements created a more robust length distribution for the sampled tournament events. All euthanized fish were taken back to the E.W. Shell Fisheries Center for data collection. Total length, wet weight, and sex were collected, and the sagittal otoliths were extracted for later aging.

Electrofishing collection

Electrofishing surveys were conducted to increase sample size and to compare the size structure and size-at-age of electrofishing captures to Black Bass collected from tournaments. Electrofishing collections occurred once per quarter using pulsed DC electrofishing with one person netting off the bow. Twenty-five Largemouth and Alabama Bass were collected during the winter, summer, and fall electrofishing events and euthanized for aging. Sampling occurred within 3 km of 3 different boat ramp locations at the north, middle, and south end of the reservoir to spread out samples. The spring collection was conducted using the Alabama Department of Conservation and Natural Resources methods for standardized sampling. The methods consisted of collecting and euthanizing all available Black Bass within ten randomly selected 1km sections sampled for 30 minutes each.

Otolith processing

Otoliths were extracted and aged by two independent readers. An independent third reader was brought in for age discrepancies between the first two readers. Otoliths were cleaned and placed into scintillation vials once extracted and assigned an identification number unique to each individual. All otoliths collected were sectioned transversely to ensure otoliths were read equally from the same viewing method. The otolith was mounted into a two-part epoxy resin and left to cure for a minimum of 24 hours before sectioning. The mounted otolith was then cut on a low-speed isometric saw using two circular Isomet diamond wafering blades. Two cuts were made simultaneously, with the blades being placed on either side of the otolith's nucleus. The sectioned piece was cut at 0.7 mm thick and mounted on a glass microscope slide using crystal bond for later viewing under a microscope. All slides were viewed under a Q Imaging Micropublisher camera on a compound microscope. When viewing the slides, pictures were taken of the otoliths for record-keeping and to be later used for measuring the distribution of annuli. The annuli distribution was measured using the Nikon NIS-Elements Advanced Research software to then use the measurements to back-calculate length-at-age using the direct proportion method.

Growth Analysis

I tested the hypothesis that faster growing fish were more vulnerable to capture at tournaments than electrofishing, where the size of fish captured by electrofishing to represent the broader population of Alabama Bass and Largemouth Bass in the reservoir. I hypothesized that the tournament creel sampled individuals would on average have a higher mean length-at-age, particularly for younger age classes, than the fish collected via electrofishing due to stronger size-selection for faster-growing individuals by tournament anglers. The rationale is that the fish in the population targeted by tournament angling are the faster growing individuals because Black Bass must be greater than 305 mm to be weighed in at most tournaments. We used the back-calculated lengths-at-age to first conduct a marginal increment analysis to determine when annuli were formed on the otolith. Our analysis showed high variability in the growth of Black Bass at Neely Henry, and we could not conclude when annuli are formed. Without being able to determine an accurate time for annuli formation we decided to exclude the length at capture and use the length at the last known age. This is the back-calculated length at the outermost identifiable annuli. We did this to control for the time of year when a fish was collected and not introduce error when assigning ages. The back-calculated lengths at the last known age were used to estimate mean length at age (MLA) for Largemouth and Alabama Bass. This hypothesis was tested by fitting an ANOVA that modeled mean length at age as a function of age, collection method, and their interaction.

The back calculated lengths were used to create growth trajectories for individuals that are used in simulating the population in our size-and-age-structured model (Figure 1). The growth trajectories for all collected fish were compared across sampling methods, to test for potential difference in growth rates. I used a Bayesian hierarchical model (Helser and Lai, 2004; de Zarate and Babcock, 2016) that incorporates random effects of individual fish on growth parameters such that the model estimates individual growth parameters (L_∞, k, t_0) that are assumed drawn from an overarching distribution of growth parameters across individuals in the population. The model also included three fixed affects (one for each growth parameter) for collection method to account for potential differences in each parameter between collection methods (tournaments vs. electrofishing). These estimates of individual growth trajectories were used to inform within-population variation in growth parameters for the simulation in Objective 3, below. The Bayesian model was run using Markov chain Monte Carlo (MCMC) simulation of 2 independent chains each initialized with unique starting values. The model was simulated for 100,000 iterations, with a burn-in period of 20,000, while thinning every 100th posterior sample.

We used the Gelman-Rubin statistic to ensure convergence of the MCMC chains by ensuring every parameter had achieved convergence. Convergence was determined by a convergence diagnostic value (R) of less than 1.2 for each parameter. From the posterior samples, I calculated the posterior mean of each individual growth parameter for each species for fish collected via electrofishing, because I suspected these would provide more representative growth trajectories than fish collected at tournaments. I also estimated the variance-covariance matrix of the growth parameters to facilitate simulation of growth trajectories in Objective 3, below, that account for correlation among growth parameters across individuals in the population.

Objective 2: Estimate size-based vulnerability to mandatory catch-and-release, voluntary non-tournament catch-and-release, and tournament catch-and-release

Black Bass tagging

Electrofishing outings took place in the winter to tag Largemouth and Alabama Bass on Neely Henry Reservoir. Black Bass were collected during the day using pulsed DC electrofishing with one person netting off the bow of the boat. Collection sites were randomly selected 1.6-kilometer transects of shoreline. Total length (mm) and species were collected for the fish sampled at each site and tallied into 25 mm length bins. Only fish 300 mm and longer were tagged with external dart tags. I aimed to tag 400 Largemouth Bass and 400 Alabama Bass per year.

Angler tag returns

Anglers who caught a tagged fish were instructed by text on the tag to call a phone number to receive a reward. The reward value ($100-300) was printed on the tag, so the angler knew the reward value upon capture. Instructions on how to report angler captured fish were also communicated by high visibility signs at all public boat ramps. I collaborated with local tournament organizers and the Neely Henry Lake Association to advertise the reward tagging program. The angler reporting hotline was monitored from 8 am to 8 pm central time 7 days a week. If anglers called after hours, they were instructed to leave a voicemail and were called back the next day. Anglers that called the hotline were asked to complete a brief phone survey. Information recorded included: the tag number of the fish, the date, time, and location of capture, if the fish was kept or released, the reason for releasing or harvesting the fish, if the fish was caught in a tournament or non-tournament, and if the fish was weighed in at a tournament. After completing the phone survey anglers were emailed detailed instructions on how to claim their reward. Anglers were instructed to mail the tag(s) to Auburn University prior to payment. Anglers who caught fish with two external dart tags were asked to remove both tags.

Analysis

The tagging data paired with the tag return data allowed me to calculate size-based vulnerability for different angling sectors within the reservoir. This was done by examining the proportion of tags returned for fish across 25 mm length bins. For this analysis, I only used tags returned by June 1 of the year of tagging to minimize the possibility of fish growing out of the size class in which they were tagged. Also, only fish 300 mm or greater were used as we didn’t tag fish under this threshold. Vulnerability was estimated as the proportion of tags returned by angers in a length bin divided by the maximum proportion returned across length bins. This approach scaled the vulnerability estimates to a maximum of 1.0 across length bins. Vulnerability was estimated separately for each species and fishery sector (tournament vs. non-tournament). A species-specific logistic regression model was fitted to the vulnerability estimates with fish length and fishery sector, and their interaction as covariates. The interaction term indicated whether vulnerability differed between sectors.

Objective 3: Simulate the effects of size-selective catch-and-release angling on Largemouth Bass and Alabama Bass using a size-and-age structured model.

Simulation modeling

I used a size- and age-structured population model to evaluate fishery responses to size-selective angling. The model simulated an age-structured simulation for each of 1,000 different von Bertalanffy (Bertalanffy 1938) growth trajectories (i.e., growth types) for each species. These growth trajectories were specified by drawing growth parameters from a multivariate normal distribution with the mean and covariance of the growth parameters drawn from the posterior estimates for the Bayesian growth model described above. The model tracked the survival of and capture of Largemouth and Alabama Bass individuals. The variability in growth trajectories allowed for the evaluation of size-specific angling mortality and vulnerability, to account for the possibility that faster-growing individuals may experience higher cumulative fishing mortality rates by reaching catchable sizes earlier in life.

Abundance at age for each growth type was estimated by multiplying the survivorship estimate at each age to the equilibrium recruitment (Table 1). The model generated new recruits to the population via Beverton-Holt or Ricker spawner-recruit models. I incorporated uncertainty in the functional form of recruitment by running all model scenarios under each of the two recruitment models. Recruitment was modeled as a function of spawning stock biomass, which was predicted as a function of abundance, mean weight-at-age, and age-specific maturity (Table 1). In addition to uncertainty in the functional form, I also assessed the influence of spawner-recruit productivity by running the model across three levels (low, medium, high) of the maximum lifetime reproductive rate parameter (alpha_hat; i.e., the maximum lifetime replacement spawners per spawner at low spawning stock; Table 2). Weight-at-age was estimated as a function of fish length, the length-weight constant, and allometric parameter, which were obtained from Neely Henry Reservoir length-weight observations for both species from my electrofishing samples. Maturity parameters were obtained from the literature and were assumed to follow a logistic form and modeled as a function of fish length (Laarman and Schneider 1931, Miranda and Muncy 1987, and Nieman et al. 1979). Thus, faster growing individuals in these simulated populations were allowed to also mature at a younger age. Two different lengths were used evaluate uncertainty in the length at which fish start to become vulnerable to angling (i.e., length at first capture). A difference in the length at first capture was modeled using 200 mm and 250 mm as the assumed lengths at which fish start to become vulnerable to capture. Preliminary model runs indicated that the model was insensitive to changes in the assumed length at first capture, therefore I selected 200 mm as the length at first capture.

Survival was modeled as a function of the instantaneous total mortality which is comprised of natural mortality and fishing mortality. Fishing mortality is the sum of tournament release mortality, non-tournament release mortality, non-tournament harvest mortality, and release mortality of sub-legal fish (<305 mm). Fishing mortality was generated by modeling the vulnerability of fish to capture, a probability of release or harvest, and if released, some probability of succumbing to post release mortality. Rates of fish capture of fish by tournament and non-tournament anglers, and post release mortality rates were obtained from a concurrent modeling effort by fellow graduate student Max Rubino, who estimated these parameters from a combined analysis of reward tag returns and radio tag detections. Natural mortality rates were estimated by taking the average across multiple methods for estimating natural mortality. Uncertainty in natural mortality and encounter rates were assessed by running the model across a range of each parameter to assess predicted population responses. Instantaneous encounter rates varied incrementally from 0.0 to 1.5/yr, and species-specific natural mortality was incorporated at three levels (low, medium, high). Length-based vulnerability of fish greater than 305 mm was estimated from the tag return data as described under Objective 2. Vulnerability of fish less than 305 mm was obtained by linear interpolation from the length at first capture to the predicted vulnerability of 305 mm fish.

The outputs of the model were two measures that would be expected to influence fishing quality. The fishery performance was based on the abundance of quality and memorable size Black Bass. This is equivalent to the abundance of fish 305 mm and greater and 508 mm and greater, respectively. Fishing quality was assessed by obtaining model predictions of the abundance of memorable size fish and fish legal to be weighed-in at tournaments. There is no legal minimum length limit for harvesting bass on Neely Henry, however the majority of tournaments used a 305 mm minimum length limit, which is why the abundance of this size class was a measure of fishing quality. The memorable size class of fish represents a large Black Bass that would be desired by anglers. I scaled the predicted size-specific abundance of each species under each encounter rate scenario to the unfished condition (encounter rate = 0.0/yr) to place the results in terms of the population impacts relative to the unfished state.

Results

Objective 1: Estimate variability in growth trajectories among individual Black Bass

Growth Analysis

Mean length at age (MLA) of fish collected from tournament weigh-ins differed significantly from MLA of fish collected via electrofishing (Figures 2 & 3). The interaction between gear and age was also significant indicating that gear differences were not consistent across age classes. Pairwise comparisons of each age class by gear indicated that MLA differed by gears for ages one, two, and three for Alabama Bass and ages one and two for Largemouth Bass but not for the remaining age classes. Specifically, Alabama Bass collected from tournaments were on average 55 mm longer at age 1, 19 mm longer at age 2, and 25 mm longer at age 3. Largemouth Bass from tournaments were 28mm longer at age 1 and 13mm longer at age 2 on average than fish from electrofishing samples.

The mean posterior growth parameters for Largemouth Bass estimated from electrofishing samples were 563 (95% CI: 561 - 565), 0.279 (95%CI: 0.277 – 0.282), and -0.348 (95% CI: -0.359 – -0.336) for L_∞, k, and t_0, respectively (Table 3). For Alabama Bass the mean posterior growth parameter estimates across individuals collected via electrofishing were 566(565 – 567) for L_∞, 0.25(0.248 – 0.252) for k, and -0.25(-0.26 – -0.23) for t_0 (Table 4). The L_∞ and k parameters exhibited a correlation coefficient of 74% across individual fish in the population. The correlation coefficient for L_∞ and t_0 was 15% and 5% between t_0 and k among individuals (Figure 4). I also included a parameter representing the effect of gear type on each growth parameter. This allowed the model to predict differences in L_∞, k, and t_0 for tournament fish vs non-tournament fish. The credible intervals for the parameter representing the difference in L_∞ between gears contained zero, meaning the model did not predict a difference in L_∞ between gears. Zero was not contained in the credible intervals for the difference parameters for k and t_0 meaning it predicted higher values for both parameters for fish from tournaments. The model was also able to predict back calculated lengths on an individual fish basis (Figure 5)

Objective 2: Estimate size-based vulnerability to mandatory catch-and-release, voluntary non-tournament catch-and-release, and tournament catch-and-release

Analysis

Estimates of size-specific vulnerability from angler tag returns did not differ between tournament and non-tournament tag returns ($P = 0.285$). After pooling data across gear types, the analysis revealed that vulnerability of 300 mm Largemouth Bass was 0.75 and vulnerability of the same size class of Alabama Bass was 0.66 (Figures 6 & 7). Both species were fully vulnerable at 350 mm and beyond.

Objective 3: Simulate the effects of size-selective catch-and-release angling on Largemouth Bass and Alabama Bass using a size-and-age structured model.

Simulation modeling

The baseline scenario for the model was ran under a recruitment productivity value (alpha_hat) of 10 and 200 mm as the length at first capture for both species. The simulation model estimated a 6% decline in abundance of quality size Largemouth Bass relative to the unfished condition under the baseline scenario, 70% of the Largemouth Bass were captured annually, a Ricker spawner recruit model, and a natural mortality of 0.38 (Figure 8). Alabama Bass experienced higher estimated encounter rates of 120% per year, which means that fish will be encountered more than once. The model predicted that the abundance of quality size Alabama bass would be 12% lower relative to the unfished condition under a natural mortality value of 0.46 and the baseline scenario (Figure 8). The predicted abundance of 508 mm Largemouth Bass and Alabama Bass was more sensitive to the baseline encounter rates. Largemouth Bass abundance was 48% lower and Alabama Bass 79% lower than the unfished condition at the baseline encounter rates of 70% and 120% for each species, respectively (Figure 9).

Model predicted size class abundance was sensitive to the assumed functional form of the spawner-recruit relationship. Under the Beverton-Holt spawner-recruit function, declines in size class abundance were greater than under the Ricker model. The Beverton-Holt recruitment model on average predicted 36.5% larger declines for Largemouth Bass and 56% larger declines for Alabama Bass compared to the Ricker recruitment model across both size classes. For example, under baseline model settings but with the Beverton-Holt model, the simulation predicted a 29% decline in the abundance of quality size class Largemouth Bass as compared to the unfished population whereas the Ricker model predicted a 6% decline. Similarly, the simulation predicted a 60% decline in memorable size Largemouth Bass under the Beverton-Holt model and an 86% decline in memorable Largemouth Bass under the Ricker.

Perhaps a more valuable way of evaluating changes in abundance is to evaluate the effects of encounter rates. We wanted to evaluate the additional impact an increase in fishing pressure would have on a system that already has moderately high encounter rates. First, we estimated results under the Ricker stock-recruitment model, an alpha_hat value of 10, and a moderate population encounter rate of 45% for both species. This resulted in a 4% decline in relative abundance of quality size Largemouth and Alabama Bass relative to the unfished population. If there was a 50% increase in the capture of both species, there would only be a 2% estimated additional decline in relative abundance for this size class. For the memorable size class, the moderate encounter rate estimates a 34% decline for Largemouth Bass and a 40% decline for Alabama Bass relative to the unfished condition. Again, a 50% increase in capture this would result in an additional 14% decrease in abundance for both Largemouth and Alabama Bass. We also evaluated this scenario using the Beverton-Holt spawner recruit model and median alpha_hat value. This resulted in 19% estimated declines for both species relative to the no-fishing scenario for all fish able to be weighed in at tournaments. There would be an estimated 10% additional decline for Largemouth Bass and an 8% additional decline in Alabama Bass relative abundance if there was a 50% increase in capture. For the memorable size class under 45% capture, the model estimates a 45% and 49% decline in the relative abundance of Largemouth and Alabama Bass, respectively. An additional 50% increase in capture results in a 15% additional decline in the abundance of the memorable size class for both species.

Size class abundance was also sensitive to the assumed spawner-recruit productivity parameter. Under the median natural mortality estimate and length at first capture of 200 mm the quality size class was more sensitive than the memorable size class. Under the Ricker model, the abundance of quality size Largemouth bass showed a 12% variation from the low alpha_hat and high alpha_hat values, and Alabama bass abundance varied by 19% between the low and high alpha_hat. Under the Beverton-Holt model the abundance of quality size Largemouth Bass varied by 7% and 11% for Alabama Bass. The memorable size class showed less variation with an average of 4.5% difference due to changes in the alpha_hat value.

Beverton-Holt models were more influenced by changes in natural mortality than the Ricker spawner-recruit models. The assumed natural mortality rate had a modest influence on the abundance of both size classes of Largemouth and Alabama Bass. Changes in natural mortality had the greatest effect on the abundance of quality size, as compared to little or no influence on the memorable size class. Size class abundance was also less influenced by natural mortality under the Ricker spawner-recruit model than the Beverton-Holt model. The low alpha_hat spawner-recruit scenario under both recruitment models showed the most variation in the abundance estimate for quality size fish. For Largemouth Bass under the Beverton-Holt models, the abundance of the quality size class varied by up to 6% between high and low assumed M values. The average change in estimates for Alabama Bass was slightly higher, averaging an 8% difference in abundance of the quality size class between the upper and lower natural mortality values.

Discussion

Quantifying population-level impacts of size-selective angling is important to understanding its effects on Black Bass populations and fisheries. Previous studies have evaluated the effects of catch-and-release angling; however, they have not explicitly accounted for the potential for size-selective angling to remove faster-growing fish at higher rates than slower-growing fish. Taking this factor into consideration our model predicted reductions in the abundance of two size classes of Black Bass across scenarios. For some scenarios, particularly for memorable size classes modeled under Beverton-Holt recruitment, reductions in abundance relative to an unfished condition were substantial and could affect fishing quality in systems with high fishing effort. Estimates of angling encounter rates are quite high for these two species at Neely Henry Reservoir, likely due to high angling effort. Under high fishing effort, catch-and-release mortality has the potential to negatively impact these fisheries. Several studies have suggested that the impacts of catch-and-release angling, in particular tournament angling, on Black Bass populations is likely negligible but that under high effort or high catch-and-release mortality rates the impact has the potential to be substantial (Driscoll et al. 2007, Plumb et al.

1988, Schramm Jr. et al. 1985, and Sylvia et al. 2021). My simulation model suggests that fishing effort and angling encounter rates of Largemouth and Alabama Bass at Neely Henry Reservoir are likely high enough to raise concerns about the impacts on fishing quality at this reservoir.

My study revealed two lines of evidence for the size-selectivity of angling for these two species. First, I found that mean length-at-age for younger age classes of each species was higher for fish collected from tournaments than for fish collected via electrofishing. Growth parameter bias due to gear size-selectivity is a well-known phenomenon (Taylor et al, 2006). Although electrofishing is not an unbiased sampling gear, the gear is likely more effective at capturing fish less than 250 mm than angling (Bayley and Austen 2002). Furthermore, fish weighed in at tournaments are required to be greater than 305 mm for most tournaments, which placed a strict lower bound on the length-based vulnerability of fish to being weighed-in at a tournament at Neely Henry Reservoir. Mean length-at-age from electrofishing was generally less than 200 mm. If these estimates are relatively unbiased, then only the fastest growing age-1 fish would be vulnerable to tournament weigh-in and its associated mortality. Other studies have compared electrofishing length-at-age samples with tournament creel samples (Ebbers, 1987; Isaak et al., 1992; and Sylvia and Weber 2022). Ebbers (1987) compared length and age-frequency data and von Bertalanaffy growth parameter estimates from fish collected from two tournaments occurring each year in June from 1981-1983 to electrofishing collections. He used scale samples from both collection methods and the frequency histograms and growth curves were similar between collections. Gwinn et al. (2010) described the bias in von Bertalanaffy growth parameter estimates due to size-selective sampling methods. They pointed out that for a short-lived species with an asymptotic vulnerability curve, the smaller fish of each age class have a reduced vulnerability to sampling which results in negative bias in t0 and k estimates. This mechanism was likely at play in my study as t0 and k estimates for tournament fish from the hierarchical growth model were lower than estimates from electrofishing.

The second line of evidence for size-selectivity from my study was the tagging-based vulnerability analysis. The vulnerability estimates from this analysis were asymptotic with both species approaching full vulnerability at around 350 mm total length. Other investigators have found asymptotic (Schultz et al. 2004; Smith 2006) or dome-shaped (Miranda and Dorr 2000; Bacheler et al. 2010; Myers et al. 2014) size-based angling vulnerability curves for recreationally exploited species. Few estimates for Largemouth or Alabama Bass exist but Kerns et al (2015) found that tag return rates of Largemouth Bass >500 mm were less than return rates of smaller size classes, suggesting vulnerability as either a dome-shaped or declining function of fish length, which differs from my finding of asymptotic vulnerability at Neely Henry Reservoir. The lack of decline in vulnerability with increasing fish length in my study suggests that angling mortality likely continues to affect Black Bass in the population even as they achieve large body size, which could reduce the abundance of larger size classes. Conversely, under a dome-shaped vulnerability curve, fish would experience a reduction in angling encounters and thus mortality once they grew out of smaller more vulnerable size classes, which could serve to support higher abundance of large size classes of fish.

The functional form of the assumed spawner-recruit relationship had the most effect on predicted reduction in abundance as a function of increasing angling encounter rates. Unfortunately, no studies have empirically tested for Ricker or Beverton-Holt recruitment dynamics in the Black Basses. Clearly, size class abundance was much more sensitive to the effects of fishing mortality under the Beverton-Holt model. This finding is likely due to the fact that under the overcompensatory Ricker model, recruitment is highest under intermediate fishing mortality rates, which supports abundance of younger age classes. In contrast, the Beverton-Holt function is asymptotic which results in decreasing recruitment with increasing fishing mortality. In addition to uncertainty about the form of the spawner-recruit model, there are no published estimates of the maximum lifetime reproductive rate (alpha_hat; maximum replacement spawners per spawner at low stock sizes) for these species. There is a need for research on the shape of the spawner-recruit relationship for the Black Basses to support better predictions regarding the impacts of catch-and-release angling on these populations.

Including variability in recruitment through multiple models and varying levels of alpha_hat simulates the unpredictable nature of recruitment in a real system. Through our model, we are not able to determine which model is best, Beverton-Holt or Ricker, as we did not collect or include factors important for assessing recruitment. Recruitment in Black Bass is often related to environmental variation, especially throughout the spawning season (Siepker and Michaletz 2013). It can even vary geographically within a single body of water as well as across the United States. Different parts of a reservoir can experience different water temperatures typically related to water depth and rainfall events (DeVries et al. 2009). Because recruitment is environmentally specific it is difficult to apply a recruitment model or determine a suitable alpha_hat value and have certainty that it best represents the modeled population. In previous studies, it has been shown to be difficult to study recruitment in freshwater sport fishes as there are complex environmental, biological, and angling components to consider (Siepker and Michaletz 2013).

Changes in natural mortality only significantly impacted our measures of fishing quality under a limited set of scenarios. Scenarios of low alpha spawner-recruit value when using the Ricker recruitment model and all alpha levels when using the Beverton-Holt model showed sensitivity to natural mortality. Only the ≥305mm size class experienced variation due to natural mortality and the ≥508mm size class saw very little influence if any at all. In the scenarios most impacted by natural mortality, the case with high natural mortality estimated lower abundance declines compared to the base M and lowest M value. This is due to the early age classes being targeted by natural mortality the most, which causes fewer fish to die due to fishing mortality. This results in observing less impact due to fishing, which is reflected in the results when assessing fishing quality.

An important assumption of the simulation model is that growth rate is not heritable. Substantial evidence exists for the heritability of growth rates in fishes and the ability of size-selective fishing mortality to remove fast or slow-growing genotypes (eg. Conover and Munch 2002). Conover and Munch (2002) experimentally exposed populations of Atlantic silversides *Menidia menidia* to size-selective harvest and found decreases in growth rate in populations in where large fish were selectively harvested. It stands to reason that such heritability of growth rates also occurs in Black Basses, yet little research has been done on this topic as other traits such as aggressiveness and vulnerability to angling have been found to be heritable (Philipp et al 2009). Further work should include developing a modeling framework that allows for growth heritability and assesses the effects of selective catch-and-release on metrics of fishing quality. I speculate that the lack of growth heritability in my simulation model may have underestimated the potential effects of size-selective mortality on the abundance of memorable size classes. Although my simulation allowed for the reduction in the abundance of fast-growing individuals due to higher cumulative mortality, my model disallowed the permanent removal of fast-growing genotypes from the population over time.

Another important assumption is that that vulnerability to angling is based on fish length only. While fish length is a common metric for estimating vulnerability, it is a simplification that negates other factors contributing to vulnerability. Behavior and genetics are other factors that have been found to impact vulnerability for Black Bass. Suski and Philipp (2004) demonstrated the increase in aggressive behavior of brood guarding male Black Bass, which increased their vulnerability to angling. They also concluded that selective catch-and-release angling can select for less aggressive and less vulnerable males. Philipp et al. (2009) and Garrett (2002) also found vulnerability to be a heritable trait in Largemouth Bass.

My simulation model also made an assumption regarding the size at first capture, which is the length at which fish started becoming vulnerable to angling. No published studies exist regarding the size at first capture for angling of Largemouth and Alabama Bass and I was not able to tag fish less than 300 mm for fear of high tagging mortality on these size classes. Thus, I tested multiple values and decided on 200 mm because preliminary simulations indicated that the model was not sensitive to this assumption. However, size at first capture does influence our vulnerability estimates for the smaller size classes. Varying size at first capture changes the slope of our extrapolated vulnerability for fish <300 mm.

Conclusion

The goals of my study were to estimate the variability of growth trajectories among individual black bass, estimate size-based vulnerability for different sectors of the fishery, and evaluate the effects of size-selective catch-and-release angling. This study contributed to the understanding of catch-and-release angling and its potential effects on black bass populations. My study concluded that the growth of individual black bass was highly variable among individuals and that angling, especially in tournament events, can potentially select for the faster growing individuals in the population as there was a significant difference between the mean length-at-age of tournament and non-tournament fish. Vulnerability to capture was sigmoidal and was similar between tournament and non-tournament sectors. My simulation model indicated that angling selectivity combined with high encounter rates can cause declines in black bass population size structure and abundance that could explain some of the perceived decline in angling quality in high-effort Black Bass fisheries.

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Tables

Table 1. Equations in the size-and-age structed model

Description	Equation
Von Bertalanaffy length estimation	length=L∞*(1-exp(-K*(age-t0)))
Von Bertalanaffy weight estimation	weight=a_wt*length^b_wt
Estimating maturity at age	maturity=1/(1+exp(-h_mat*(length-L50_mat)))
Instantaneous tournament capture rate	Fc_t=F0*vuln_h*P_t
Instantaneous non-tournament capture rate	Fc_nt=F0*vuln_h*(1-P_t)
Instantaneous encounter rate of non-legal fish	Fc_nl=F0*vuln_mr
Number of legal fish captures at age	Nc_l=(N_a*((Fc_t+Fc_nt)/Z)*A)
Number of memorable size fish captured at age	Nc_500=(Nc_l*Pc_500)
Total capture of all fish	Nc_tot=sum(Nc)
Total capture of legal fish	Nc_l_tot=sum(Nc_l)
Total capture of fish 500 mm and up	Nc_500_tot=sum(Nc_500)
Proportion of all fish caught	Prop_c=(F0/mean(Z))*mean(A)
Instantaneous tournament release mortality rate	F_t=Fc_t*d_t
Instantaneous non-tournament release mortality rate	F_nt_cr=Fc_nt*r*d_nt
Instantaneous non-tournament harvest rate	F_nt_h=Fc_nt*(1-r)
Instantaneous mortality rate for non-legal fish	F_nl=Fc_nl*d_nt
Total fishing mortality	F=F_t+F_nt_cr+F_nt_h+F_nl
Total mortality	Z=M+F
Annual mortality	A=1-exp(-Z)
Exploitation	U=F/Z*A
Ricker recruitment in fished condition	Rf=max(0,log(alpha*EPRf)/(beta*EPRf))
Beverton-Holt recruitment in fished condition	Rf=max(0,(alpha*EPRf-1)/(beta*EPRf))
maximum recruitment given spawner abundance	alpha=alpha_hat/EPR0
Ricker relationship between spawner abundance and recruitment	beta=log(alpha_hat)/(R0*EPR0)
Beverton-Holt relationship between spawner abundance and recruitment	beta=(alpha_hat-1)/(R0*EPR0)
Proportion of population that is quality size	P305=1-pnorm(305,length,cv_tl*length)
Proportion of population that is memorable size	P500=1-pnorm(508,length,cv_tl*length)
Survivorship in unfished condition	l_a_0=exp(-M)
Survivorship in fished condition	l_a_f=exp(-F)
Spawning stock biomass in unfished condition	EPR0=sum(l_a_0*weight*maturity)
Spawning stock biomass in fished condition	EPRf=sum(l_a_f*weight*maturity)

Table 2. Parmeters for Largemouth and Alabama Bass in the size-and-age structed model

Symbol	Description	LMB	ALB
fage	First age	1	1
lage	Last age	12	12
a_wt	Intercept coefficient between length and weight relationship	4.12x10^-6	3.73x10^-6
b_wt	Power coefficient between length and weight relationship	3.2	3.2
h_mat	How quickly fish mature	0.05	0.05
L50_mat	Length at 50% maturity	300	300
alpha_hat	Maximum lifetime reproductive rate	5, 10,15	5, 10,15
R0	Recruitment in unfished condition	1	1
MLL	Minimum length limit	305	305
MLL_12	Size at first capture	200, 250	200, 250
F0	Instantaneous encounter rate	0 - 2	0 - 2
P_t	Proportion of capture in tournament	0.43	0.43
d_t	Proportion of fish released in tournaments and die	0.27	0.27
d_nt	Proportion of fish released in non-tournaments and die	0.05	0.05
r	Voluntary release rate	0.92	0.92
M	Natural mortality	0.30, 0.38, 0.45	0.37, 0.46, 0.55
mean_linf	Mean $L\infty$	546	494
L50c	Length at 50% capture	158	299
h	Vulnerability steepness	0.009	0.771
cv_linf	Variation in $L\infty$	0.15	0.15
vuln_h	Vulnerability to harvest	Estimated quantity	Estimated quantity
vuln_c300	Vulnerability to capture of 300 mm size class	Estimated quantity	Estimated quantity
vuln_c	Vulnerability to capture	Estimated quantity	Estimated quantity
vuln_mr	Vulnerability to mandatory release	Estimated quantity	Estimated quantity

Table 3. Results for the estimates of L_∞, k, and t_0 for Largemouth Bass with 95% credible intervals in parentheses

Description	Value
L∞ Range	480 to 665
L∞ Median	562
L∞ Mean	563(561 - 565)
k Range	0.2 to 0.4
k Median	0.277
k Mean	0.279(0.277 – 0.282)
t0 Range	-0.93 to 0.29
t0 Median	-0.346
t0 Mean	-0.348(-0.359 – -0.336)

Table 4. Results for the estimates of L_∞, k, and t_0 for Alabama Bass with 95% credible intervals in parentheses

Description	Value
L∞ Range	512 to 619
L∞ Median	565
L∞ Mean	566(565 – 567)
k Range	0.16 to 0.38
k Median	0.25
k Mean	0.25(0.248 – 0.252)
t0 Range	-0.98 to 0.35
t0 Median	-0.25
t0 Mean	-0.25(-0.26 – -0.23)

Figures

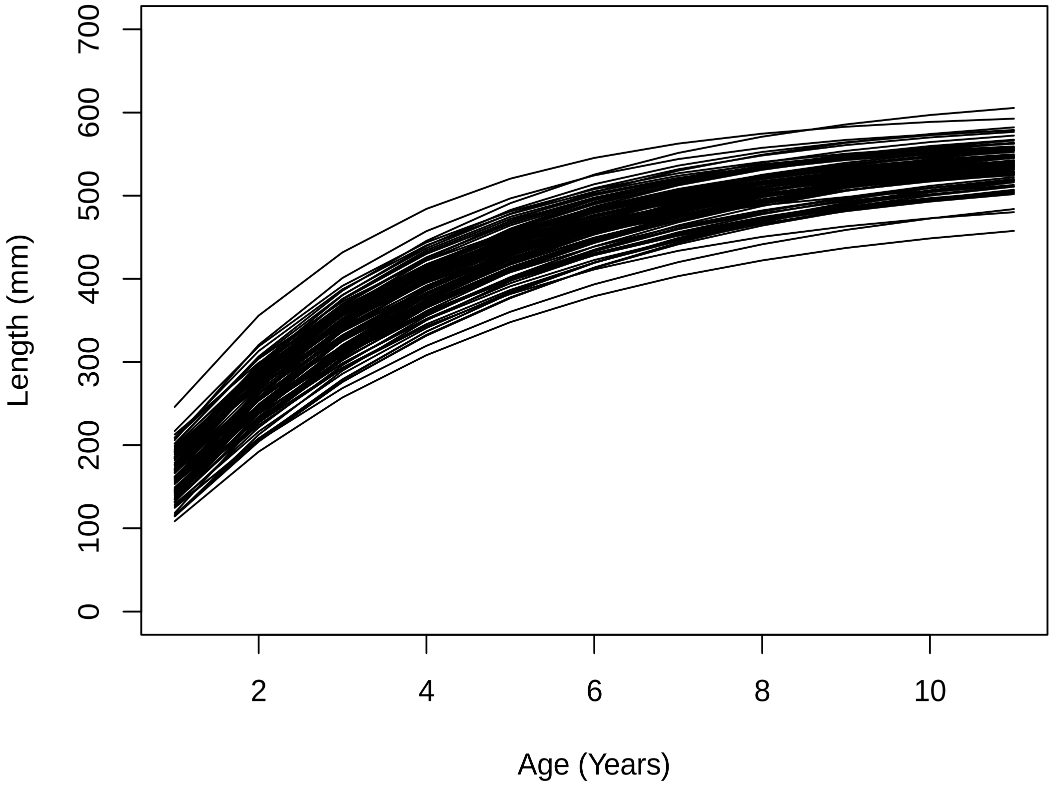

Figure 1. Sample of 100 individual growth trajectory estimates from the Bayesian hierarchical growth model.

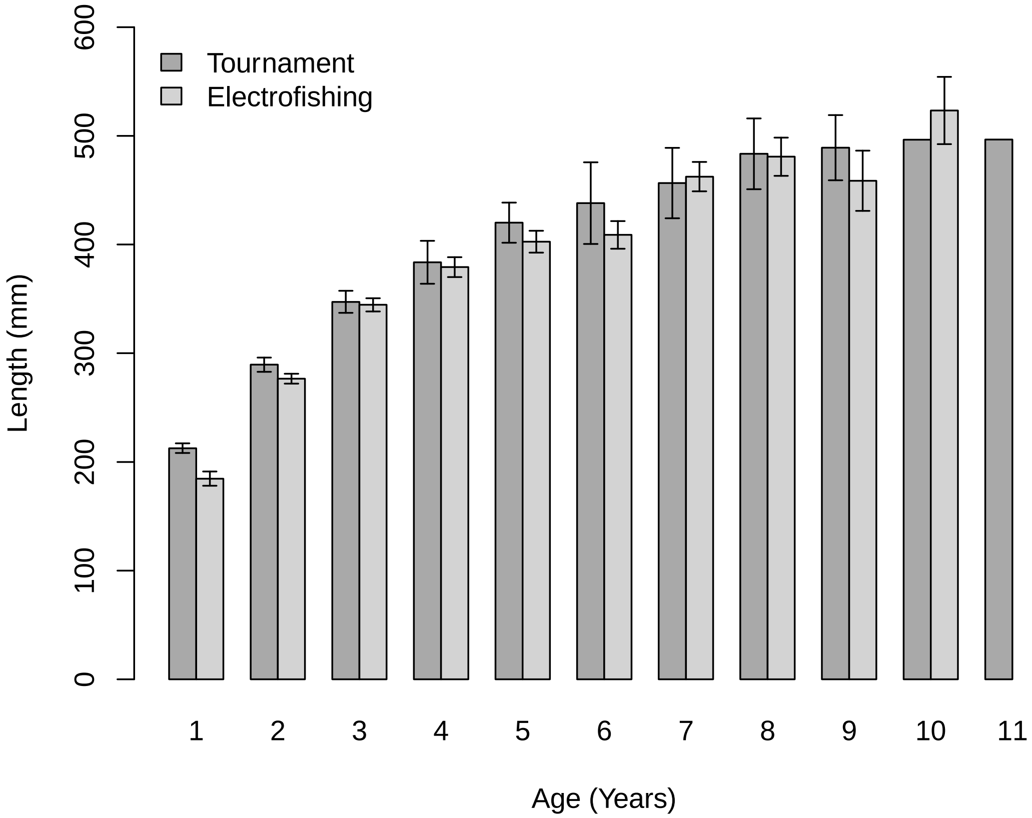

Figure 2. Mean length at age of Largemouth Bass with 95% credible intervals.

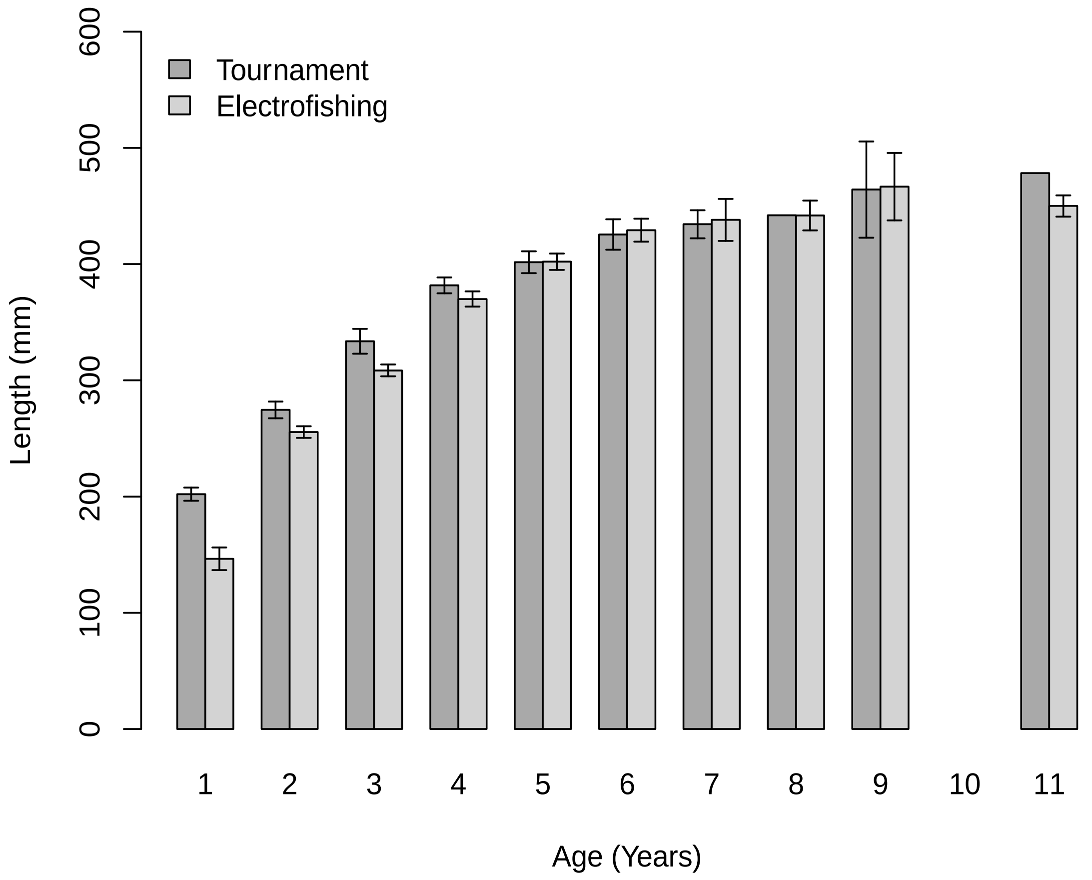

Figure 3. Mean length at age of Alabama Bass with 95% credible intervals.

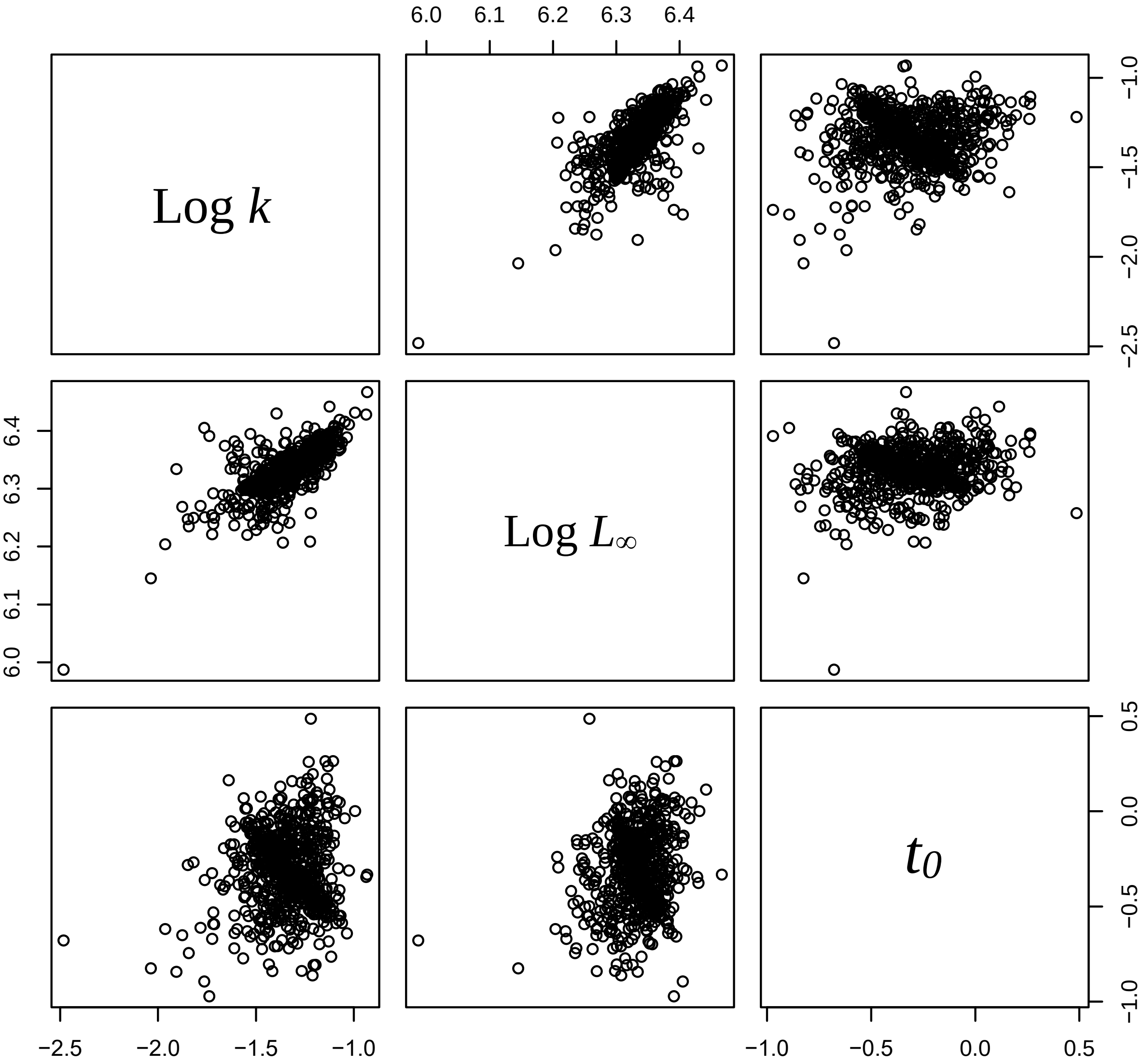

Figure 4. Correlation relationship between growth parameters L_∞, k, and t_0.

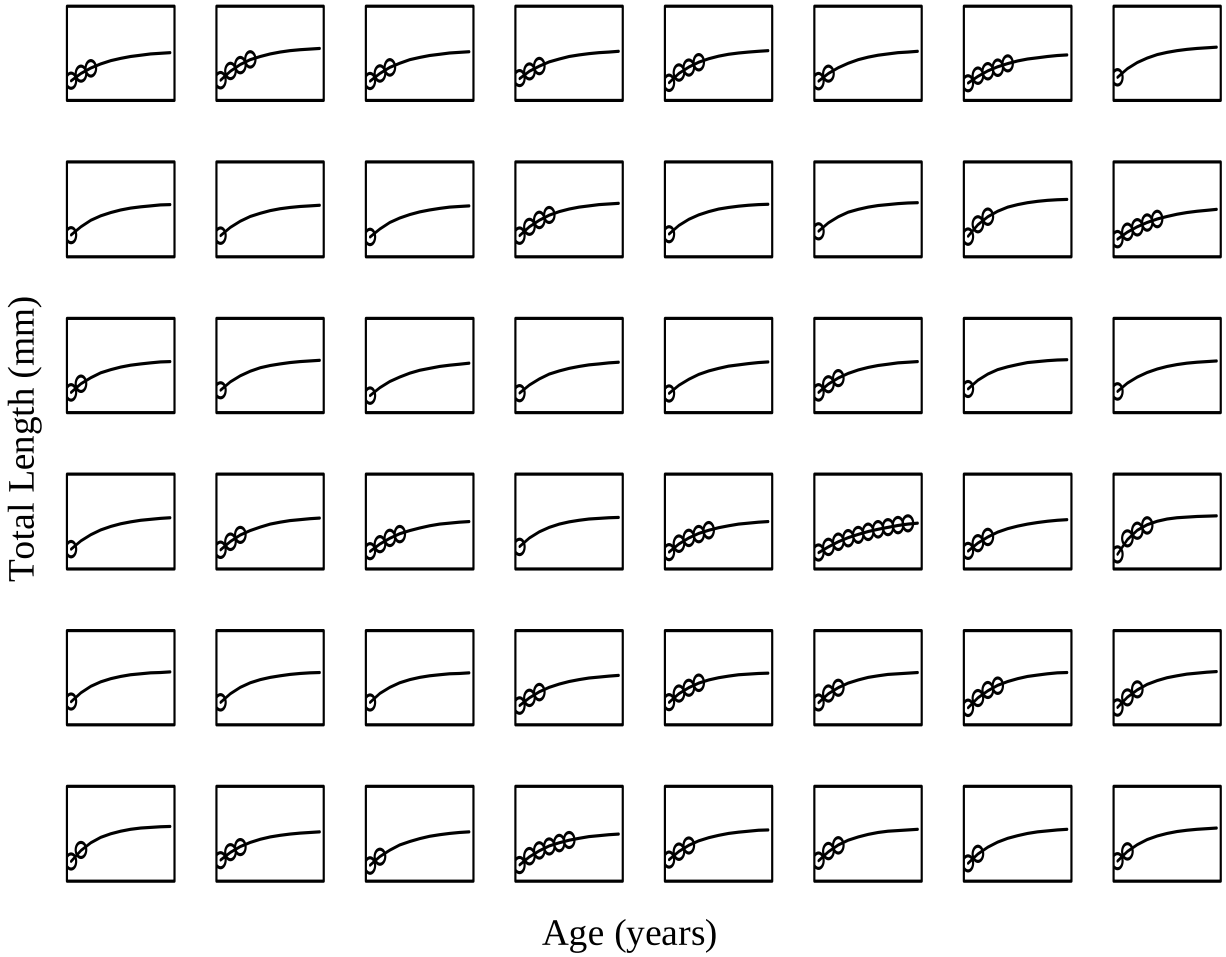

Figure 5. Representative sample of 48 individual fish and their observed (circles) and modeled (lines) predicted back calculated lengths at age.

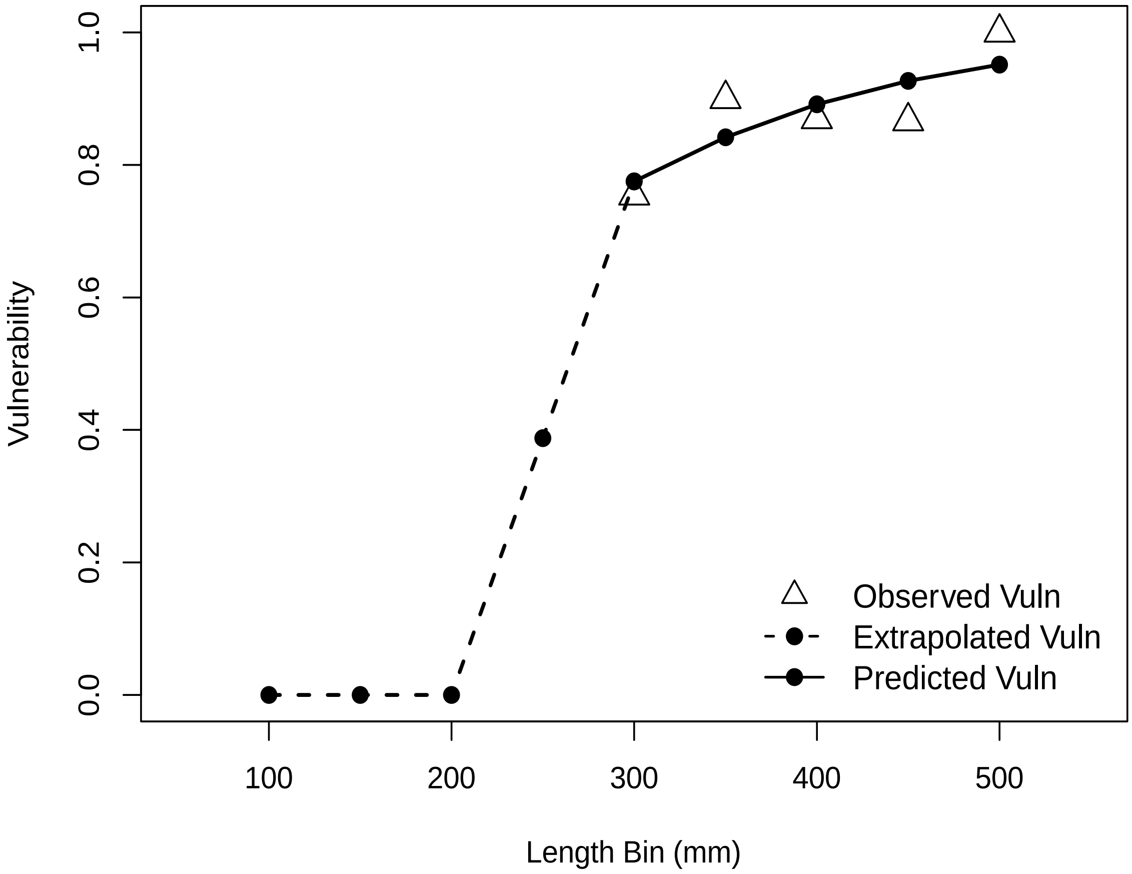

Figure 6. Observed, predicted, and extrapolated vulnerability estimates for Largemouth Bass.

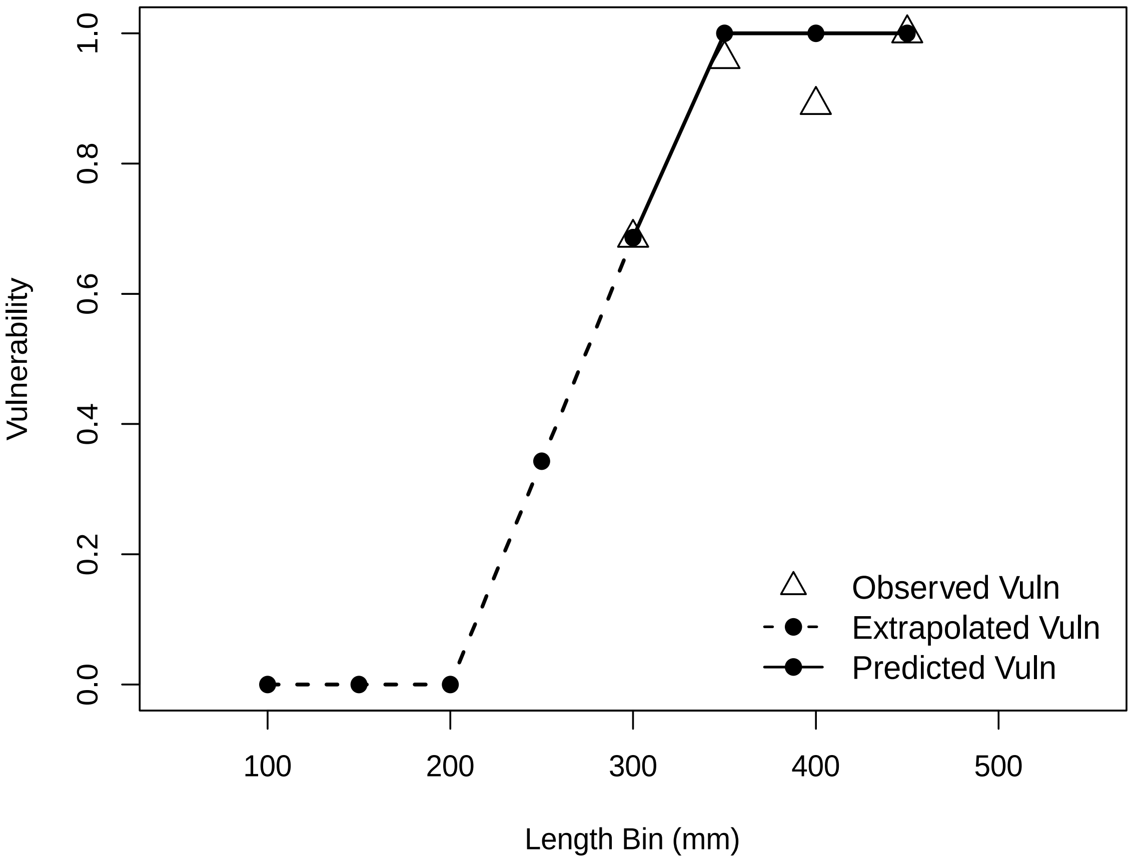

Figure 7. Observed, predicted, and extrapolated vulnerability estimates for Alabama Bass.

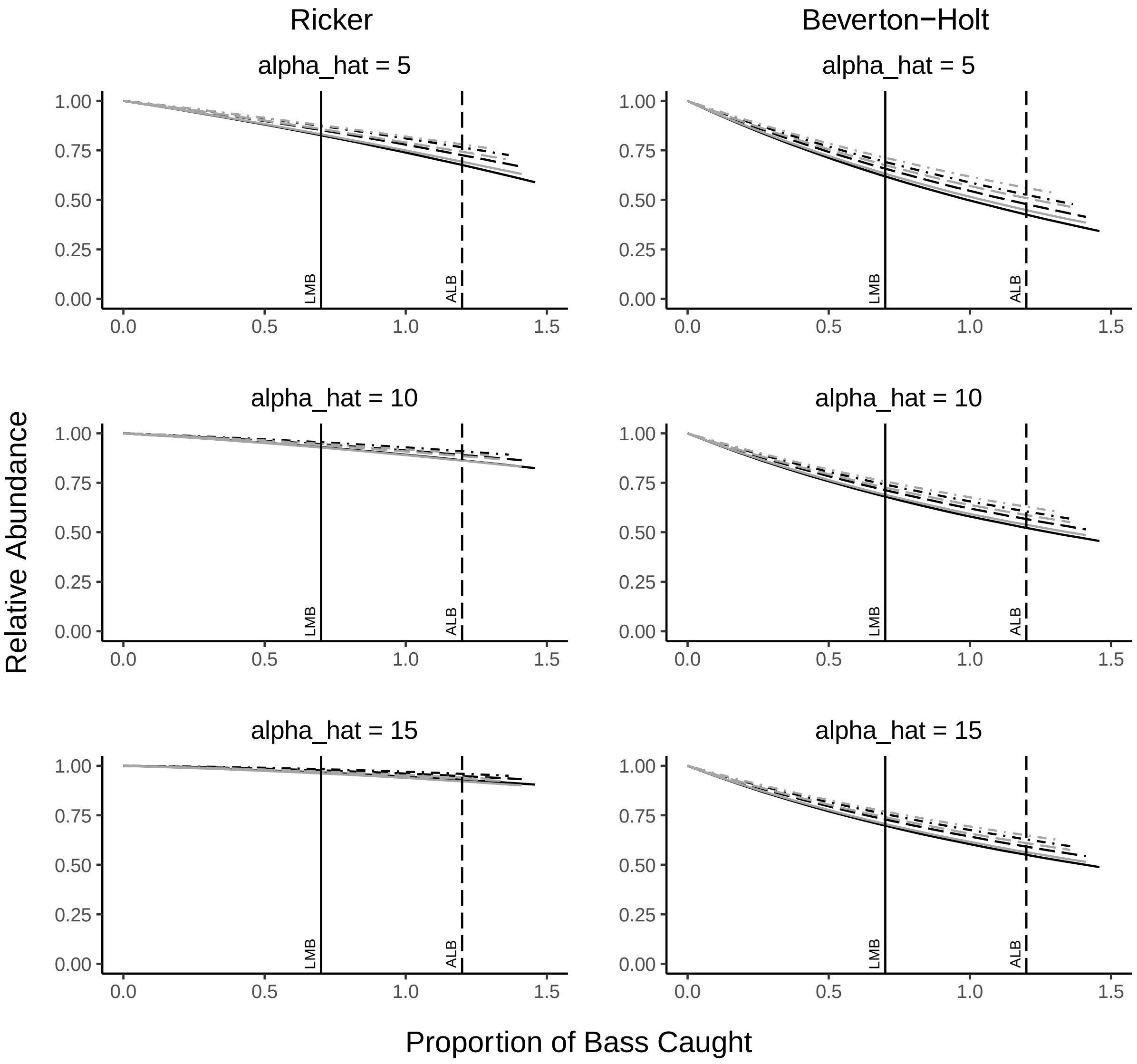

Figure 8. Effect of capture on quality sized Largemouth Bass (black) and Alabama Bass (grey) under different recruit models, alpha_hat values, and low (solid), medium (dashed) and high(dot-dashed) values of natural mortality. Graphs are shown under a length at first capture of 200mm.

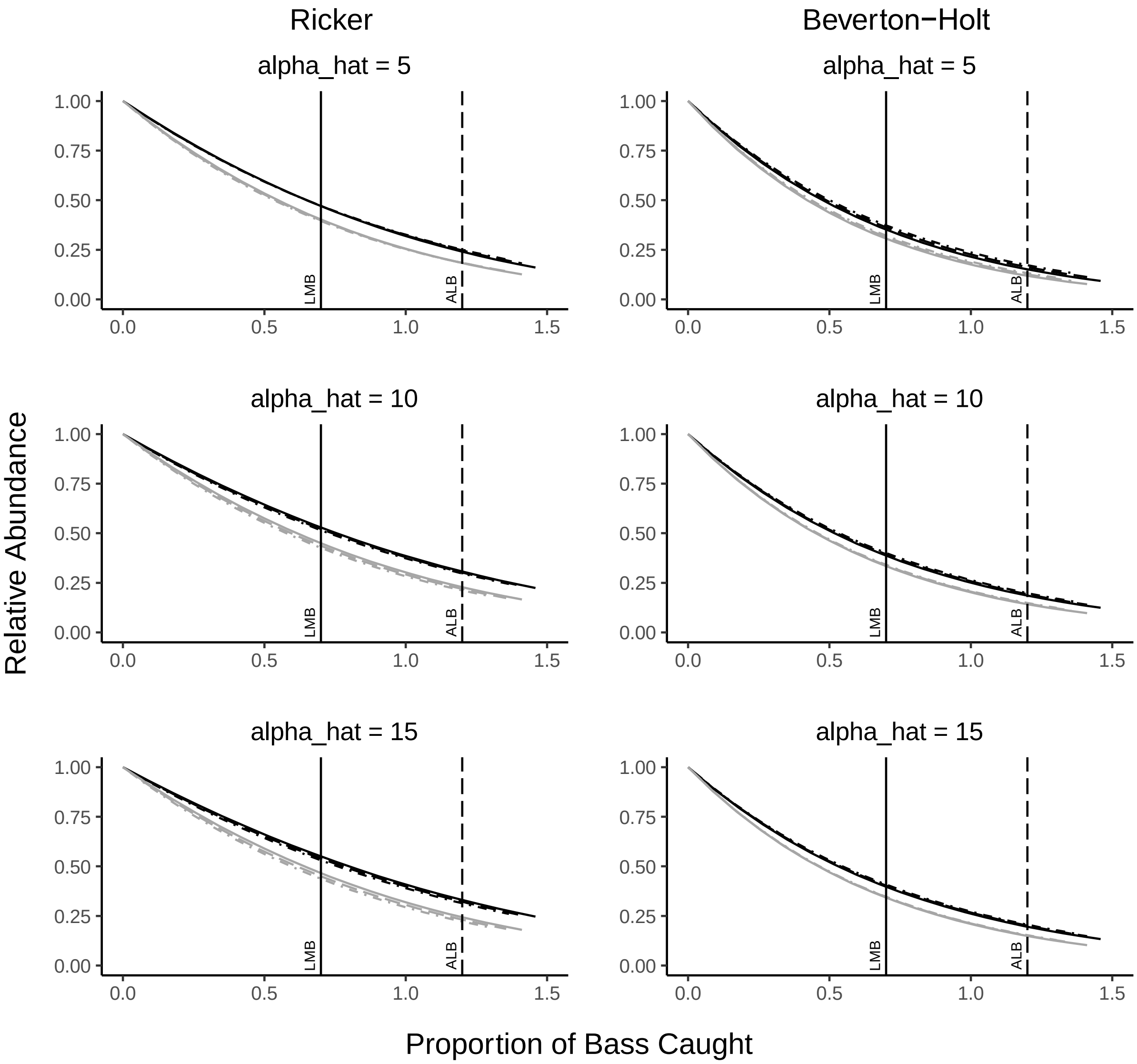

Figure 9. Effect of capture on memorable sized Largemouth Bass (black) and Alabama Bass (grey) under different recruit models, alpha_hat values, and low (solid), medium (dashed) and high(dot-dashed) values of natural mortality. Graphs are shown under a length at first capture of 200mm.