Using Population Models to Evaluate Management Alternatives for Gulf Striped Bass

by

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ABSTRACT

Interstate management of Gulf Striped Bass *Morone saxatilis* has involved a thirty-year cooperative effort involving Federal and State agencies in Georgia, Florida and Alabama (Apalachicola-Chattahoochee-Flint Gulf Striped Bass Technical Committee). The Committee has recently focused on developing an adaptive framework for conserving and restoring Gulf Striped Bass in the Apalachicola, Chattahoochee, and Flint River (ACF) system. To evaluate the consequences and tradeoffs among management activities, population models were used to inform management decisions. Stochastic matrix models were constructed with varying recruitment and stocking rates to simulate effects of management alternatives on Gulf Striped Bass population objectives. I used an age-classified matrix model that incorporated stock fecundity estimates and survival estimates to project population growth rate. In addition, I evaluated how combinations of management alternatives (harvest regulations, stocking rates, *Hydrilla* control) influenced population growth rate. Annual survival and mortality rates were estimated from catch-curve analysis and fecundity was estimated and predicted using a linear least squares regression analysis of fish length versus egg number from hatchery brood fish data. Stocking rates and stocked-fish survival rates were estimated from census data. Results indicated that management alternatives would be an effective approach to increasing the Gulf Striped Bass population. Population abundance was highest under maximum stocking effort, maximum *Hydrilla* control and a moratorium and lowest under no stocking, no *Hydrilla* control and the current harvest regulation. Stocking rates proved to be an effective management strategy; however, low survival estimates of stocked fish (1%) limited the potential for population growth.

Hydrilla control increased the survival rate of stocked fish and provided higher estimates of population abundances than maximizing the stocking rate. A change in the current harvest regulation (50% harvest regulation) was not an effective alternative to increasing the Gulf Striped Bass population size. Applying a moratorium to the Gulf Striped Bass fishery increased survival rates from 50% to 74% and resulted in the largest population growth of the individual management alternatives. The results can be used to inform management decisions for other populations of Striped Bass in the Gulf Region.

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INTRODUCTION

Since the 1970s, Gulf Striped Bass *Morone saxatilis* have exhibited population declines due to habitat modification and fragmentation throughout their native range (Frugé et al. 2006). The species has been the subject of a thirty-year cooperative effort involving multiple State and Federal agencies in Georgia, Florida and Alabama that has focused on developing an adaptive framework for conserving and restoring the stock in the Apalachicola, Chattahoochee, and Flint River system (ACF). In order to conserve the depleted population, the Apalachicola, Chattahoochee-Flint Gulf Striped Bass Technical Committee (GSBTC) was formed in 1987 to develop management plans and goals for Gulf Striped Bass in the ACF river system. The GSBTC has managed Gulf Striped Bass populations with a goal to restore a self-sustaining population of Gulf Striped Bass to the "maximum extent possible" (Long et al. 2013). Unfortunately, management has been difficult due to anthropogenic and biologic alterations within the ACF river system. To incorporate a more systematic approach to management of Gulf Striped Bass, the GSBTC used a structured decision making (SDM) process to set management objectives and alternatives each year (Conroy and Peterson 2013). Structured decision making is a transparent, stepwise process for making complex decisions that includes 1) identifying the problem to be solved, 2) determining objectives that will be used to evaluate how management actions address the problem, 3) identifying alternative management actions, 4) estimating consequences on objectives for each management action, and 5) identifying the management alternative that provides the best outcome or combination of consequences (Hammond et al. 1999).

In 2011, the GSBTC used SDM to evaluate impacts of various alternative actions on population, angling and management cost objectives related to Gulf Striped Bass (GSBTC 2012).

The GSBTC recognized that uncertainty of population level responses to management was limiting the prediction of both species response and management effectiveness. Population models have been used to assist fishery managers with decisions related to conservation or management issues and these models have been incorporated into decision analysis (Bain 1987; Peterson and Evans 2003). Constructing a population model (using existing data) for Gulf Striped Bass could assist in evaluation of the effects of management alternatives on population goals in the ACF river system.

Population dynamics of Striped Bass in the Atlantic Ocean and Atlantic Coast drainages have been studied particularly for assessment of impacts of environmental variation and harvest rates on population growth rates (Cohen et al. 1983; Goodyear 1985; Prager et al. 1987). This study describes the use of similar population models to analyze the effects of alternative management practices such as varying stocking rates, *Hydrilla* control and harvest rates on population growth rates for Gulf Striped Bass. Population models were used to analyze the effects of variable stocking, *Hydrilla* control and harvest rates on population growth for Gulf Striped Bass. Through the use of extant data, models (e.g., regression or stochastic matrix models) were developed to help predict Gulf Striped Bass population dynamics in the ACF river system. By incorporating different management alternatives into various models, managers may make better management decisions for Gulf Striped Bass.

The purpose of this study was to apply several modeling approaches to Gulf Striped Bass population data to provide an understanding of population dynamics and ultimately inform management decisions. The specific objectives were to: 1) Construct an age-based stochastic matrix model to simulate population abundance under different alternatives identified by managers, 2) Use existing data from agency monitoring and published literature to estimate model parameters, and 3) Use the models to inform SDM for Gulf Striped Bass management.

METHODS

Study Site

The ACF river system is located in the southeastern portion of the United States along Alabama, Georgia and Florida (Figure 1). The ACF river system is approximately 19,800 mi ^{2}, which begins in Northeastern Georgia and flows down into the Gulf of Mexico at the Apalachicola Bay (Couch et al. 1996). The ACF river system is comprised of two major river systems (Flint River and Chattahoochee Rivers) that converge into Lake Seminole to form the Apalachicola River.

The Chattahoochee River Basin drains 8,770 mi^2 and flows 430 miles to its confluence with the Flint River. There are a total of 16 dams located within the ACF river system; of which 13 hydroelectric dams are located along the Chattahoochee River. There are three main reservoirs located on the Chattahoochee River: Walter F. George Lake, George W. Andrews Lake, Lake Sydney Lanier and West Point Lake. These reservoirs provide electricity, recreational opportunities, flood control, navigation and water supply to the surrounding areas.

The Flint River basin is approximately 350 miles long and 8,460 mi^2 of watershed. There are three major hydroelectric dams along the Flint River: Crisp County Power Dam (Lake Blackshear), Georgia's Power Flint River Dam (Lake Worth) and Jim Woodruff Lock and Dam (Lake Seminole). These reservoirs provide hydroelectric power, navigation, water quality, recreation and flood control to surrounding areas. The Flint River has one of only 42 free-flowing river reaches longer than 125 mi remaining in the contiguous 48 states (Benke 1990). The Flint River is comprised of large tributaries and ground water discharges. Most of the larger tributaries in the ACF river system are located along the Coastal Plain Province part of the Flint River basin (Couch et al. 1996).

The Apalachicola River below Lake Seminole is unimpeded for approximately 112 miles and drains an area of 2600 mi^2 into the Gulf of Mexico. The Apalachicola River is comprised of three major rivers, including the Flint, Chattahoochee and Chipola River and numerous streams and creeks (Wooley and Crateau 1983). The Apalachicola River along with the Chipola River are major sources of nutrients and fresh water to the Apalachicola Bay (Livingston et al. 1974). Water level fluctuations occur seasonally due to underwater discharges and runoff from the Chattahoochee and Flint River watersheds. Eighty percent of the flow in the Apalachicola River is contributed by the Chattahoochee and Flint Rivers, 11 percent from the Chipola River, and less than 10 percent from ground water and overland flow (Elder et al. 1988).

Developing Matrix Models for Gulf Striped Bass

Gulf Striped Bass vital rates were estimated using published literature and existing data from agency monitoring (Long et al. 2013; Table 1; Appendices 1-5). Linear least squares regression analyses were applied to empirical data to estimate survival and fertility rates that would be incorporated into the matrix model (Table 2 and 3).

An age-classified matrix model with specific vital rates and varying age-0 survival of stocked and naturally recruited fish was developed to simulate population growth rates under different management alternatives. Age-classified matrix models were structured following a basic design:

$$\begin{pmatrix} f_0/2 & f_1/2 & f_2/2 & f_3/2 & \cdots & f_{10}/2 & f_{11}/2 \\ S_0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & S_1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & S_2 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & S_3 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & S_{(t-1)} & 0 \end{pmatrix} \tag{1}$$

where S_i is the probability of individuals in age class i surviving one year and f_i is the fertility rate of individuals in age class i. The numbers of age classes were set from zero to the maximum aged brood fish collected in the ACF river system. Fertility rates were applied to fish ≥ 4 years of age because female Gulf Striped Bass mature at age 4 (Berlinsky et al. 1995). Baseline population abundance was assumed to be 10,000 individuals based on expert opinion (GSBTC 2015). The population was projected for 10 years on yearly intervals, so that the population in the following year was the result of the population in the previous year multiplied by the corresponding survival and fertility rates (described below). Population models were constructed using Program R (Development Core Team 2011). Management scenarios were simulated 500 times to reduce uncertainty in model outcomes.

Survival. — Annual survival of each age class was predicted using a weighted catch-curve analysis (Jensen 1985). The catch-curve model was used to relate catch-at-age using a linear least squares regression analysis on Gulf Striped Bass brood fish data. The estimated slope of the regression was interpreted as the instantaneous total mortality rate of age classes that were fully vulnerable to sampling and fishing mortality (Appendix 1; Figure 2). Fish less than the maximum catch-at-age were assumed not fully vulnerable to the sampling gear and fishery (Smith et al. 2012; Appendix 1). Finite annual survival rate was calculated using this equation, $S = e^{-z}$. A major assumption of using a catch curve analysis is that survival is constant across age classes. Survival was assumed constant for all age classes except naturally recruited and stocked age-0 fish. The baseline age-0 stocked fish survival was assumed to be 0.01 based on expert opinion (GSBTC, personal communication), but was also allowed to vary with *Hydrilla* coverage (see description of the relation of fish survival to *Hydrilla* abundance below). Naturally recruited age-0 fish were assigned a maximum survival rate of 0.00006 that did not depend on *Hydrilla* coverage, and was based on estimates of survival rates from eggs to post-larval stage from published studies of Atlantic stocks of Striped Bass (see Dahlberg 1979 for review). The sensitivity of the maximum survival rate of naturally recruited fish was investigated to ensure a stable population structure (i.e., the modeled population did not crash or grow exponentially and/or unreasonably). Age structured matrix models and demographic analyses can be used as tools to identify and check the validity of parameter estimates that are not well understood (Quinlan and Crowder 1999; Gedamke et al. 2007).

A linear least squares regression analysis was used to examine the relation between *Hydrilla* abundance (acres) and corresponding mean catch-per-unit-effort (CPUE) of age-0 fish (stocked and naturally recruited fish) in Lake Seminole, upper Apalachicola River and lower Apalachicola River (Figure 3; Appendix 2). The linear assumptions of normality and constant variance were addressed by evaluating the residuals of catch-per-unit-effort for homogeneity using a histogram plot. I reported a significant negative relation between *Hydrilla* abundance and CPUE of age-0 fish. The slope of the linear least squares regression was used to predict age-0 survival in the matrix model where:

$$S_{s,t} = \left(\frac{b_0 + b_1 * Hydrilla}{b_0}\right) * S_{stocked} \tag{2}$$

$$S_{0,t} = \left(\frac{b_0 + b_1 * Hydrilla}{b_0}\right) * S_{natural} \tag{3}$$

survival rate of stocked fish (S_s) and naturally recruited fish (S_0) in year (t) are equal to the proportional difference ((b_0+b_1**Hydrilla*)/b_0)) that would be observed for catch-per-unit-effort with estimates of *Hydrilla* abundance multiplied by the baseline survival rate of stocked fish ($S_{stocked}$) and naturally recruited fish ($S_{natural}$) without *Hydrilla* present.

The model incorporated stochastic variation in *Hydrilla* coverage (HAC) by drawing random deviates for *Hydrilla* abundance from a normal distribution with mean and standard deviation that was based on observed *Hydrilla* coverage data (Appendix 4). I chose to use a normal distribution because normal distributions are commonly found in nature (Frank 2009). Randomly selected *Hydrilla* abundance values that were >26,537 acres (value where age-0 survival = 0) were adjusted by fixing *Hydrilla* abundance = 26,537 in order to keep predicted age-0 survival rates positive. *Hydrilla* abundances were adjusted to account for the low probability of randomly selecting a *Hydrilla* abundance higher than observed. Ultimately, less than 2 % of randomly selected *Hydrilla* abundances would have been high enough to predict negative survival rates.

Fertility. — Fertility rates for each age class were predicted using the coefficients $\hat{b}_0$(Intercept) and $\hat{b}_1$(slope) from a linear least squares regression analysis of fish length versus number of eggs per individual (Figure 4; Appendix 3). A von Bertalanffy model was used to predict mean length-at-age (l_a) from brood fish age data (Chen 1992; Figure 5), which was then applied to the linear least squares regression analysis (fish length versus number of eggs) to predict the number of eggs-at-age (Figure 6; Table 4). The number of mature ova was divided by 2, assuming that half would be females upon fertilization (Cohen et al. 1983). Age-specific fertility rates (*f*) were assumed constant and did not vary annually. Total age-specific fertility rates were calculated using the following equation:

$$f = \hat{b}_0 + \hat{b}_1 * l_a \qquad (4)$$

Evaluation of Management Alternatives

Stocking. — Stocking rates were incorporated into the matrix model to examine the impacts of different stocking rates on population growth. Included in the model was a maximum stocking rate (1,000,000 age-0 fry), minimum rate (500,000 age-0 fry) and no stocking (0 fish). Stocking alternatives were chosen based on previous stocking rates applied to the ACF river system (Long et al. 2013; Appendix 2). The number of stocked fish that survived was added to the proportion of naturally recruited fish that survived to age-1 where:

$$N_{1,t+1} = \sum_{t-1}^{N_{\geq 4} * f_i} * S_{0,t-1} + N_{s,t-1} * S_{s,t-1} \tag{5}$$

$N_{1,\,t+1}$ denotes the number of age-1 fish (N_1) that would exist in the following year (t+1). The number of age-1 fish is equal to the sum of fertility rates (adults ≥ age 4 * f_i) in the previous year (t-1) multiplied by the survival rate of naturally recruited fish ($S_{0,t-1}$) in the previous year plus the number of stocked fish ($N_{s,t-1}$) in the previous year multiplied by the survival rate of stocked fish ($S_{s,t-1}$) in the previous year.

Hydrilla control. —I simulated three different levels of *Hydrilla* control on the population. Included in the model was a maximum *Hydrilla* control (20% reduction), minimum control (10% reduction) and do nothing (no control; Figure 8). Levels of *Hydrilla* control were based on expert opinion (GSBTC, personal communication).

Harvest regulations. — I was interested in considering the impacts of three different harvest regulations on the Gulf Striped Bass fishery. I used the current bag limit of 15 fish daily (Alabama Striped Bass Regulations 2016; OutdoorAlabama.com), a 50% bag limit reduction (7 Striped Bass daily) and a total moratorium (No harvest; Figure 9). Variable harvest regulations were applied to Gulf Striped Bass populations using estimates of mortality from a catch-curve analysis on brood fish catch-at-age on the Chattahoochee and Flint River system (Figure 2; Appendix 1). Instantaneous mortality rate was predicted using the following equation:

$$Z = F+M \tag{6}$$

where (Z) total instantaneous mortality is equal to the sum of (F) Fishing mortality and (M) natural mortality. Assuming natural mortality estimates from Atlantic stocks (Jiand et al. 2007) were applicable to the Gulf Striped Bass, I was able to calculate fishing mortality. Fishing mortality estimates were used in the following equation:

$$U= FA/Z \tag{7}$$

where exploitation rate (U) is the product of fishing mortality (F) and annual discrete mortality (A) divided by total instantaneous mortality (Z; Hashemi 2012). Annual discrete mortality is calculated as $1-(e^{-Z})$. The exploitation rate (U) would provide the proportion of fish that are removed from the population due to harvest (Cochrane 2002).

Creel survey data were used to estimate the average harvest-per-trip in a given year (Appendix 5). To estimate harvest-per-trip, I used total abundance of fish in that given year and multiplied abundance by the exploitation rate (U) to estimate the predicted harvest (number of fish). I used the estimate of predicted harvest and divided it by the number of trips annually to estimate the average harvest per trip. Effort among anglers was assumed constant.

A Poisson distribution was used to assign probabilities of catching fish in a given trip under a range of values (0 to 25 fish) using average harvest-per-trip as the mean. The catch-per-trip was estimated using a Poisson distribution:

$$P[x|\lambda_j] = \frac{\lambda_j^x}{x!}e^{-\lambda} \tag{8}$$

where $P\left[x \middle| \lambda_j\right]$ denotes the probability of catching exactly x fish on the *j*th trip (Porch and Fox 1990). Catch per trip (*x*) represents the number of fish that could be caught per trip. Lambda (λ) is the average harvest-per-trip. The probability assigned to each individual's catch-per trip-was used to estimate the total catch or harvest under a given bag limit (b_c) using the equation:

$$b_C = T\left(\sum_{x \leq b} xP[x] + b\sum_{x>b} P[x]\right) \tag{9}$$

where P[*x*] is the proportion of the total fishing trips (*T*) that caught *x* fish (Porch and Fox 1990). I assumed that anglers did not harvest any fish over the bag limit. Therefore, this method capped the harvest by accounting for the frequency of trips in which the bag limit would have been filled. Total harvest was used to update a realized exploitation rate ($\widehat{U}$) in the following equation:

$$\widehat{U} = \frac{b_C}{N} \tag{10}$$

where $\widehat{U}$ is the proportion of fish that are harvested under a given bag limit (b_c) using the current population (*N*). $\widehat{U}$ informs a new realized fishing mortality using the following equation:

$$\hat{F} = \frac{\widehat{U} * Z}{A} \tag{11}$$

where $\widehat{F}$ is the change in fishing mortality due to the proportion of fish that are harvested ($\widehat{U}$). Changes in the fishing mortality estimate ($\widehat{F}$) will be incorporated for (F) fishing mortality into (Equation 6) where a new survival rate is estimated under the given bag limit (Equation 12):

$$\hat{S} = e^{-Z} \tag{12}$$

Harvest regulations including the current bag limit and the 50% bag limit reduction were incorporated into (Equation 9) where total harvest would change under different bag limits. Because a moratorium does not include fishing mortality due to harvest, total mortality would be comprised of natural mortality and hooking mortality. Hooking mortality is the proportion of fish that will die due to mortality associated with catch and release practices. Hooking mortality estimates were used from studies conducted on Striped Bass from freshwater environments (Wilde 2000). I applied a hooking mortality estimate (see below) to fishing mortality using the current bag limit to tease out mortality that would occur under catch and release practices (Equation 13).

$$Z = F * (H) + M \tag{13}$$

Consequences of Management Alternatives

Consequences table. — I constructed a consequence table to compare the impacts of alternative management actions on objectives for the Gulf Striped Bass population (Hammond et al. 1999; Gregory et al. 2012). A consequences table is a matrix that enables comparison of alternative actions that influence objectives by assessing the utility of each in order to make better management decisions. Included in the consequences table are objectives (and sometimes their weights by value), direction of response to actions, performance measures and management actions.

Fundamental objectives (i.e., highest level objectives) were elicited from managers using a structured decision making framework focused on restoring and maximizing the Gulf Striped Bass population (GSBTC 2012). Identified fundamental objectives were to maximize population abundance, maximize angler satisfaction and minimize cost. The population objective was achieved through the number of Gulf Striped Bass in the population predicted by the matrix models under management alternatives. Angler satisfaction was achieved through values associated with management alternatives and cost was achieved through the amount of money that would be spent on management alternatives. Directions (maximize, minimize) were used to define the response that was expected for each objective under each management scenario. The population and angler satisfaction objectives were assigned a maximum direction; cost was assigned a minimum direction. Performance targets were used to describe how the objectives were predicted to respond to management. Performance targets are quantifiable, meaningful metrics to capture the essence of each objective and enable the description of consequences more clearly (Hammond et al. 1999). Population abundance was predicted using the matrix model under each management scenario for a 10 year period.

Angler satisfaction was estimated by constructing a utility value that ranged from 3 to 10. Angler satisfaction was determined by assigning values for each management combination based on population abundance, stocking rates, harvest regulations and *Hydrilla* control. Management combinations with a population abundance between 10,000 and 20,000 fish were assigned a value of 1, from 20,001 to 30,000 fish were assigned a value of 2 and estimates of population size > 30,000 fish were assigned a value of 3. No stocking was assigned a value of 1, minimum stocking was assigned a value of 2 and maximum stocking was assigned a value of 3. Current harvest regulation was assigned a value of 1, 50% harvest regulation were assigned a value of -1 and a moratorium was assigned a value of -2. No *Hydrilla* control was assigned a value of 1, minimum *Hydrilla* control was assigned a value of 2 and maximum *Hydrilla* was assigned a value of 3. Scores were summed across population abundance, stocking rates, harvest regulations and *Hydrilla* control to calculate an angler satisfaction utility value for each combination of management. Cost was estimated using a Likert scale (0-5) where 0 was the most expensive alternative and 5 was the most cost effective alternative. Relative cost of management actions was determined based on expert opinion and objectives were weighted based on their importance to the stakeholders (GSBTC, personal communication). The population objective was weighted 60%, angler satisfaction objective was weighted 30% and the cost objective was weighted 10%.

The consequences table included all combinations of management alternatives (Table 5). Using the outcome from each management alternative, weighted scores were applied to each alternative based on a directional linear additive model using the following equations:

$$WeightedScore\ (max) = \left(\frac{a - a_{min}}{a_{max} - a_{min}}\right) * W \tag{14}$$

$$WeightedScore\ (min) = \left(1 - \left(\frac{a - a_{min}}{a_{max} - a_{min}}\right)\right) * W \tag{15}$$

where *a* is the alternative value in question, *min* is the smallest alternative value, *max* is the largest alternative value and W is the corresponding weighted objective. Weighted scores were summed across objectives to achieve a weighted summed score for each alternative. The sum of weighted scores were calculated and used as a utility value for ranking management alternatives.

Because weighted objectives intentionally bias for one objective over another, I also calculated utility values for each management scenario for equally weighted objectives (0.33) to compare differences in management outcomes for weighted and equally weighted objectives (Table 6). The results could allow managers to evaluate changes in management alternative rankings for equal and equally weighted objectives.

RESULTS

Effects of Management Alternatives on Population Abundance

The ACF Gulf Striped Bass population was comprised of fish from age 0 to age-11; 70% of individuals were age 1 or 2. The maximum age represented in the model was 11 years. Estimates of survival rates of older age classes (≥ age 1) ranged from 0.509 to 0.74 (Figure 2; Table 2). Baseline survival rate of age-0 stocked and naturally recruited fish were 0.01 and 0.00006, respectively. Adjusted age-0 survival rates varied according to *Hydrilla* abundance and coefficients ($\hat{b}_0$=5.257; $\hat{b}_1$=-0.0001981) derived from the negative relation of catch-per-unit-effort versus *Hydrilla* aerial counts (HAC = surface area in acres covered by *Hydrilla*; Figure 3; Table 3). Length of fish used for fertility estimates ranged from 609 to 1066mm (Figure 4; Table 2). Predicted length-at-age from a von Bertalanffy model ranged from 692 to 983mm for ages 4-11 (Figure 5; Table 3). Fertility rates of fish ages 4-11 ranged from 181,230 to 464,440 eggs (Figure 6; Table 2 and 4).

Stocking rates — Incorporating the maximum stocking effort over a ten year period resulted in the largest predicted population abundance (23,753) out of the three stocking alternatives (Figure 7). The minimum stocking rate increased the population abundance from 10,000 to 18,172 fish and a “no stocking” action increased the population from 10,000 to 11,877. Stocking alternatives allowed more individuals into the age-0 class however low survival estimates for stocked fish kept stocking initiatives from having an impact on recruitment into the next age class. Stocking of age-0 Gulf Striped Bass resulted in a lower population abundance than *Hydrilla* control or harvest regulations.

Hydrilla control —Maximum *Hydrilla* control over a ten year period, resulted in the largest population abundance (36,014) out of the three *Hydrilla* control alternatives (Figure 8). Incorporating a minimum *Hydrilla* control increased the population from 10,000 to 25,756 fish and “no action” increased the population from 10,000 to 18,172. *Hydrilla* control was estimated to have a larger impact on predicted population abundance than stocking initiatives.

Harvest regulations — Implementing a moratorium increased the population from 10,000 to 160,738 fish in 10 years (Figure 9). Total instantaneous mortality (Z) under a moratorium was 0.302 (Equation 12; Table 2). It was assumed that harvest did not occur under a moratorium and therefore exploitation rate, probability of catching fish, total catch under the bag limit, realized exploitation rate and realized fishing mortality rate were not necessary to estimate adult survival (Equations 7-11; Table 2). Hooking mortality (29%) was applied to fishing mortality, which reduced estimates of fishing mortality from 0.5247 to 0.1521 (Equation 13; Table 2). Survival rate with a moratorium for age classes > 1 year old increased from 0.509 to 0.74 (Equation 12; Table 2). A 50% decrease in harvest regulations increased the population from 10,000 to 18,096 fish. Total instantaneous mortality (Z) with 50% harvest regulation was - 0.674 (Equation 6; Table 2). Exploitation rate (U) with a 50% harvest regulation was estimated to be 0.381(Equation 7; Table 2). Probability of catching 7 fish ranged from 1.60×10^{-7} with 10,000 fish to 7.49×10^{-6} with 18,096 fish (Equation 8; Table 2). Total catch with a 7 bag limit ranged from 3,815 with a population abundance of 10,000 fish and 6,905 with a population abundance of 18,096 fish (Equation 9; Table2). The realized exploitation rate with a population abundance from 10,000 to 18,096 fish was 0.381(Equation 10; Table 2) and the realized fishing mortality rate with a population abundance from 10,000 to 18,096 was 0.524 (Equation 11; Table 2). Realized exploitation rate and realized fishing mortality rate did not change as population abundance grew because probabilities associated with catching 7 fish (1.60×10^{-7} to 7.49×10^{-6}) were low and therfore anglers would not harvest fewer fish under the reduced bag limit. Survival rate with a 50% bag limit was 0.509 (Equation 12;Table 2). “No change” to the harvest regulations predicted that the population would increase from 10,000 to 18,172. Total instantaneous mortality (Z) under the current harvest regulation (15 fish) was -0.674 (Equation 6; Table 2). Exploitation rate (U) was estimated to be 0.381 (Equation 7; Table 2). The probability of catching 15 fish ranged from 2.81×10^{-19} with a population of 10,000 fish to 1.60×10^{-15} with 18,172 fish (Equation 8; Table 2). Total catch with a current harvest regulation ranged from 3,815 with a population abundance of 10,000 fish and 6,934 with a population abundance of

18,172 fish (Equation 9; Table 2). The realized exploitation rate with a population abundance from 10,000 to 18,172 fish was 0.381 (Equation 10; Table 2). The realized fishing mortality rate with a population abundance from 10,000 to 18,172 fish was 0.524 (Equation 11; Table 2). Survival rate with the current harvest regulation was 0.509 (Equation 12; Table 2). There was no difference in survival rates with a current bag limit or a 50% reduction in bag limits. The probability of anglers catching 15 fish or 7 fish per trip were low and therefore anglers were predicted to harvest the same amount of fish because the bag limit was never reached.

Combination of Management Alternatives

A total of 27 management combinations were used in the matrix model to predict population abundance versus management portfolios. The highest population abundance was predicted when the maximum stocking rate, maximum *Hydrilla* control and a total moratorium on the fishery scenario was modeled (Figure 10). The population abundance was estimated to be 365,970 fish in a 10-year simulation. These results suggested that population abundance would be greatest under the maximum effort for each management alternative. However, there was a difference in population abundance when using a moratorium in combination with stocking rates and *Hydrilla* control. Management combinations that included a moratorium predicted more fish (93,077-319,454) than when a moratorium was not included in management scenario. The highest predicted population abundance without a moratorium was a maximum stocking rate, maximum *Hydrilla* control and keeping the current harvest regulation (46,516). These results suggest that management should be geared towards increasing *Hydrilla* control and maximizing the stocking rate if a moratorium is not included.

Consequences — The population abundance predicted for each management alternative was incorporated into a consequences table (Table 5). Population abundance was compared across weighted objectives to calculate a weighted utility value under stakeholder weighted objectives (Table 6). The sum of weighted values suggested that the best management scenario for the weighted objectives was to maximize the stocking rate, maximize *Hydrilla* control and introduce a moratorium on the fishery. The lowest weighted score was management with no stocking, no *Hydrilla* control, and a 50% harvest regulation.

Results from equal weighted objectives indicated that management decisions would be different from current weighted objectives (Table 6). Only one management combination ranked similarly with non-weighted (0.33) and stakeholder weighted objectives. This management alternative included a maximum stocking rate, no *Hydrilla* control and a moratorium. Management alternatives were predicted to be the most effective when used in combinations with one another and the top ranked

DISCUSSION

Management and conservation of fishery stocks usually involves complex socioeconomic factors that make decisions regarding implementation of actions that might benefit populations difficult especially in the face of uncertainty (Irwin et al. 2011; McGowan et al. 2011). Gulf Striped Bass managers have invested 30+ years of effort toward stock recovery with some measurable success (ACF stock not extinct); however, a self-sustaining population does not exist. If stocking programs ceased and harvest continued at the current regulation, my models predicted that the stock would not collapse but achievement of agency population goals was unlikely. Examples of stock recovery are not well documented; however, populations of Striped Bass on the Atlantic seaboard rebounded through aggressive management actions after they were decimated because of overfishing and habitat loss through aggressive management actions (Richards and Rago 1999). Although management of Gulf Striped Bass through stocking and angler regulation in the ACF has reportedly bolstered population numbers, uncertainty exists regarding reasons that population goals have not been met. Demographic models have been employed to inform conservation efforts for taxa from bears (Faust et al. 2004) to sharks (Gedamke et al. 2007), the models for Gulf Striped Bass reported herein could help to predict effects of future management actions and to illustrate sources of uncertainty.

This study provided the opportunity to investigate key uncertainties regarding the influence of proposed management actions on population growth rates to inform decision making. There was a great deal of uncertainty regarding survival of Gulf Striped Bass. Specifically, survival rates of age-0 stocked and naturally recruited fish were not well understood. Estimates of stocked fish survival were lacking. Survival rates of naturally recruited fish were lacking and involved using estimates from other systems in order to inform survival rates. There was uncertainty regarding mortality rates on the Gulf Striped Bass population. Estimates of natural mortality from Atlantic stocks were used to estimate fishing mortality from a catch-curve analysis. Using estimates of natural mortality from Atlantic stocks involves uncertainty because estimates are not specifically from the ACF river system.

The simultaneous assessment of impacts of management actions on multiple objectives provided the management agencies with a framework to examine tradeoffs among single and combination of actions (Runge 2011). Ultimately the agencies have a goal of implementing an adaptive management process to manage the population through reducing uncertainty of effects of management (Irwin et al. 2011).

Stocking of Gulf Striped Bass has been on-going for over 30 years and has reportedly been an effective method for sustaining the fishery (Long et al. 2013). The management committee adopted a structured decision making approach so they could predict the impacts of management strategies (GSBTC 2012). The structured decision making process that the committee implemented predicted that increased stocking, particularly in the upper system, would have a positive impact on their multi-attribute problem. Although I found that stocking rates had the smallest impact on population growth, I also predicted that greater stocking rates would result in higher population abundances. Explanatory reasons for why modeled stocking rates did not result in simulated rapid population growth as was predicted with *Hydrilla* control and harvest regulations, range from low survival rates associated with stocking practices to uncertainty regarding the survival of stocked fish (Brown and Day 2002; Regan et al. 2005). In addition, survival rates of stocked Striped Bass in the ACF are not known. Although studies were conducted on stocked Gulf Striped Bass survival by holding stocked fish in aquaria for 48-72-hours (Long et al. 2013) survival rates from this study were not used for in my model because mortality could only be attributed to stress and handling (Lorenzen 2005) and results from the 48-72 study suggested survival of stocked fish to be 83%.

All combinations of management alternatives that included a harvest moratorium predicted the best population response for the ACF Gulf Striped Bass population. Fishery closures can be an effective way to recover stocks from potential collapse (Richards and Rago 1999). Due to a decline in recruitment, a moratorium was applied to Striped Bass stocks in the Maryland waters of the Chesapeake Bay from 1985 to 1989 (Secor 2000). The effect of the moratorium in restoring Striped Bass stocks has been heralded as one of few recent success stories in fisheries management (Secor, 2000). It was hypothesized using historical data and modeling that recruitment overfishing was a major factor in the decline of the Chesapeake Bay stock (Richards and Rago 1999). Mathematical models predicted that a reduction of high estimated fishing mortality (30%-50%) would increase population numbers (Goodyear 1985;

Richards and Rago 1999). After the imposed moratorium on Striped Bass, female abundance on spawning grounds doubled, recruitment and juvenile indices improved and the moratorium was relaxed to strict fishing and harvest regulations (Goodyear 1985; Richards and Rago 1999). My demographic models (catch-curve analysis) indicated that fishing mortality may have a controlling impact on the ACF Gulf Striped Bass population; annual fishing mortality in the ACF was estimated to be 52.4 %. My modeling results indicated that a moratorium on the Gulf Striped Bass fishery could have a positive impact on population growth likely due to its effectiveness in reducing fishing mortality. I believe that implementing a moratorium on the Gulf Striped Bass fishery could produce results similar to the restoration of Chesapeake Striped Bass stocks. However, the social acceptance of this alternative is thought to limit the feasibility of the action, other restrictive fishing regulations may be options.

My models predicted that reducing the bag limit by 50% from the current harvest regulation would not have an impact on population abundance due to the small probability associated with catch-per-trip on the 50% bag limit. Most fisheries implement a bag limit to reduce the fishing mortality associated with more experienced anglers. However, more often than not anglers do not reach the bag limit (Radomski et al. 2001). I used a Poisson distribution to estimate catch probabilities under different bag limits. Typically, most catch distributions in recreational fisheries follow some sort of compound Poisson distribution or a negative binomial distribution (Porch and Fox 2011). I chose to use a Poisson distribution over a negative binomial distribution because I did not have estimates on the variation in average harvest per trip. Using a Poisson distribution allowed for accounting for variance in the mean by assuming the variance was equal to the mean. To fit a negative binomial distribution, data on the number of fish harvested per trip is needed to account for variation in the mean and estimate K (measure of over dispersion). To justify the use of the simpler model (Poisson distribution), I used different levels of variation from the mean to explore whether the use of a negative binomial would change the survival rate. If variation in the mean (harvest-per-trip) was 1, estimated survival rates for both distributions remained the same. Only when variation in the mean was equal to 2 were there noticeable differences in survival rates equal to 0.50 for the Poisson distribution and 0.53 for the negative binomial distribution. Because the variation in harvest-per-trip was not well documented for this fishery, using a Poisson distribution to estimate catch probabilities was the best method to estimate impacts of different bag limits.

Hydrilla control resulted in increased survival rates of age-0 stocked fish and larger estimates of total population abundance than stocking alternatives. Efforts to control *Hydrilla* abundances could have a significant increase on the survival of stocked Gulf Striped Bass. Unfortunately, *Hydrilla* removal has not been conducted experimentally in Lake Seminole to estimate changes in abundance or growth of young Striped Bass. There have been studies on the successful use of herbicides to control *Hydrilla* and its impact on young Largemouth Bass *Micropterus salmoides* population characteristics in Lake Seminole (Maceina and Slipke 2004). *Hydrilla* removal was reported to have a positive impact on young Largemouth Bass growth in Lake Seminole (Maceina and Slipke 2004) Also, relative weights and food consumption in Largemouth Bass both increased following *Hydrilla* reductions resulting in greater growth (Sammons and Maceina 2006). Estimates of slower growth and low relative weight (Wr) values were reported for age-0 Striped Bass after the expansion of *Hydrilla* into Lake Seminole (Long et al. 2013).

Hydrilla coverage may reduce the amount of available habitat to age-0 Striped Bass which may concentrate fish into limited amounts of habitat resulting in density dependent poor growth, condition and starvation (Long et al. 2013). The concentration of fish in limited areas of suitable habitat may make them more susceptible to predation from other piscivorous fish like Largemouth Bass. However, studies investigating the changes in diet and food consumption following large scale *Hydrilla* removal in Lake Seminole did not report any Striped Bass in the gut contents of Largemouth Bass (Sammons and Maceina 2006). I believe that poor survival of stocked fish is more than likely the result of limited available habitat and food (Welker et al. 1994; Mitro and Zale, 2002). Through the reduction of *Hydrilla* abundances in Lake Seminole, managers might observe an increase in stocked fish survival and population growth of Gulf Striped Bass.

Studies to estimate survival rates of stocked Striped Bass fingerlings were conducted on Smith Mountain Lake, Virginia and post-stock fingerling survival was estimated using back-calculation of cohort survival rates predicted from catch curve analysis (Moore et al. 1991). Stocked fish survival on Smith Mountain Lake ranged from 3.9-54.3%, which was much higher than estimates of Gulf Striped Bass stocked fish survival. Experts believe that Gulf Striped Bass populations would persist but remain stable if stocking practices ceased.

Survival rates for naturally recruited Gulf Striped Bass are not well understood. There are very few studies that have been conducted on the survival rate of natural recruitment in Striped Bass. I used a survival rate of 0.00006, which was chosen based on estimates of survival rates from studies on the Chesapeake Bay, Hudson River, Potomac River and Delaware Canal (Dahlberg 1979). Survival rates from Atlantic stocks were used to inform survival rates of naturally recruited fish. Estimates of naturally recruited survival rates were incorporated into a matrix model that would result in similar estimates of total population abundance that are believed to be in the Apalachicola-Chattahoochee-Flint river system.

Density dependence in year class strength has been demonstrated in other populations of age-0 Striped Bass (Martino and Houde, 2012); however, density dependence was not incorporated into my model. Possible limiting factors (*Hydrilla* abundance, stocking rates) could be responsible for density dependence on catch-per-unit effort of stocked and naturally recruited age-0 Gulf Striped Bass. I did not look for density dependent factors influencing population growth for older age classes of Gulf Striped Bass. Limiting factors including hydrologic variation (Stevens 1977) available thermal refuge (Coutant 1987) and prey abundance (Axon and Whitehurst 1985) are all factors that could influence density dependence. I did not use density dependence in the population model because relations between abundance and limiting factors are not well understood.

Conclusions — Population models were a helpful way to evaluate the effects of management alternatives on population goals. Management combinations were estimated to be more effective at increasing the population abundance than the use of a single management alternative. A moratorium could provide the higher population abundances than would be realized through *Hydrilla* control or increased stocking rates. *Hydrilla* control could result in higher population abundances than increased stocking rates alone. Stocking rates may be necessary to maintain the Gulf Striped Bass fishery but did not prove to be the best single management alternative. Relations between management alternatives and their impact on population abundance could be used inform the structured decision making process and allow better management decisions for Gulf Striped Bass fishery. I would recommend in the future that managers consider implementing a moratorium on the Gulf Striped Bass fishery to maximize population abundance. Otherwise, other management alternatives including *Hydrilla* control, which would provide more suitable habitat and higher survival rates of stocked fish, should be considered. Stocking rates have proven to be vital in sustaining the population of Gulf Striped Bass however population goals will likely not be attained through stocking alone.

REFERENCES

Axon, J. R., and D. K. Whitehurst.1985. Striped bass management in lakes with emphasis on management problems. Transactions of the American Fisheries Society 114:8-11.

Bain, M. B. 1987. Structured decision making in fisheries management: trout fishing regulations on the Au Sable River, Michigan. North American Journal of Fisheries Management 7:475-481.

Benke, A. C. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society 9:77-88.

Berlinsky, D. L., M. C. Fabrizio, J. F. O'Brien, and J. L. Specker. 1995. Age-at-maturity estimates for Atlantic coast female striped bass. Transactions of the American Fisheries Society 124:207-215.

Bettinger J. M., J. R. Tomasso, Jr., and J. J. Isely. 2005. Hooking mortality and physiological responses of striped bass angled in freshwater and held in live-release tubes. North American Journal of Fisheries Management 25:1273-1280.

Chen, Y., D. A. Jackson, and H. H. Harvey. 1992. A comparison of von Bertalanffy and polynomial functions in modeling fish growth data. Canadian Journal of Fisheries and Aquatic Sciences 49:1228-1235.

Cochrane, K.L. 2002. A Fishery Managers Guidebook: Management Measures and their Application. FAO Fisheries Technical Paper No. 424, FAO, Rome

Cohen, J. E., S. W. Christensen, and C. P. Goodyear. 1983. A stochastic age‑structured population model of striped bass (*Morone saxatilis*) in the Potomac River. Canadian Journal of Fisheries and Aquatic Sciences 40:2170‑2183.

Conroy, M. J., and J. T Peterson. 2013. Decision making in natural resource management: a structured, adaptive approach. John Wiley & Sons.

Couch, C. A, E. H. Hopkins, and P. S. Hardy. 1996. Influences of environmental settings on aquatic ecosystems in the Apalachicola-Chattahoochee-Flint River basin. U.S. Geological Survey Water-Resources Investigations Report 95-4278

Coutant, C. C. 1987. Poor reproductive success of striped bass from a reservoir with reduced summer habitat. Transactions of the American Fisheries Society 116:154-160.

Dahlberg, M. D. 1979. A review of survival rates of fish eggs and larvae in relation to impact assessments. Marine Fisheries Review 41:1-12.

Elder, J. R., S. D. Flagg, and H.C. Jr. Mattraw. 1988. Hydrology and ecology of the Apalachicola River, Florida a summary of the river quality assessment. U.S. Geological Survey Water-Supply Paper 2196.

Faust, L. J., R. Jackson, A. Ford, J. M. Earnhardt, and S. D. Thompson. 2004. Models for management of wildlife populations: lessons from spectacled bears in zoos and grizzly bears in Yellowstone. System Dynamics Review 20:163-178.

Frank, S.A. 2009. The common patterns of nature. Journal of Evolutionary Biology 22: 1563-1585.

Fruge, D. J. 2006. The striped bass fishery of the Gulf of Mexico, United States: a regional management plan. Gulf States Marine Fisheries Commission.

Gedamke, T., J. M. Hoenig, J. A. Musick, W. D. DuPaul, and S. H. Gruber. 2007. Using demographic models to determine intrinsic rate of increase and sustainable fishing for elasmobranchs: pitfalls, advances, and applications. North American Journal of Fisheries Management 27:605-618.

Goodyear, C. P. 1985. Toxic materials, fishing, and environmental variation: simulated effects on striped bass population trends. Transactions of the American Fisheries Society 114:107-113.

Gregory, R., L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson. 2012. Structured decision making: a practical guide to environmental management choices. John Wiley and Sons.

Gulf Striped Bass Technical Committee. 2012. Apalachicola-Chattahoochee-Flint (ACF River Basin) Gulf Striped Bass 5-year Management Plan. Draft Report. Panama City, Florida.

Hammond, J. S., R. L. Keeney, and H. Raiffa.1999. Smart choices: a practical guide to making better life decisions.

Hashemi, S. A. R., H. Safikhani, and A. Vahabnezhad. 2012. Growth, Mortality Parameters and Exploitation Rate of Silver Pomfret (*Pampusargenteus euphrasen*, 1788) in Northwest of Persian Gulf (Khuzestan Coastal Waters, Iran). American Eurasian Journal of Agricultural and Environmental Sciences 12: 1095-1101.

Irwin, B. J., M. J. Wilberg, M. L. Jones, and J. R. Bence. 2011. Applying structured decision making to recreational fisheries management. Fisheries 36:113-122.

Jensen, A. L. 1985. Comparison of catch-curve methods for estimation of mortality. Transactions of American Fisheries Society 114:743-747.

Jiang, H., J. M. Pollock, C. Brownie, J. M. Hoenig, R. J. Latour, B. K. Wells, and J. E. Hightower. 2007. Tag return models allowing for harvest and catch and release: evidence of environmental and management impacts on striped bass fishing and natural mortality rates. North American Journal of Fisheries Management 27:387–396.

Livingston, R. J., R. L. Iverson, R. H. Estabrook, V. E. Keys, and J. Jr. Taylor. 1974. Major features of the Apalachicola Bay system physiography, biota, and resource management. Florida Scientist 37:245-271.

Long, E. A., C. L. Mesing, K. J. Herrington, R. R. Weller, and I. I. Wirgin. 2013. Restoration of Gulf Striped Bass: Lessons and Management Implications. American Fisheries Society 80: 25-63.

Lorenzen, K. 2005. Population dynamics and potential of fisheries stock enhancement: practical theory for assessment and policy analysis. Philosophical Transactions of the Royal Society of London B: Biological Sciences 360:171-189.

Martino, E. J., and E. D. Houde. 2012. Density-dependent regulation of year-class strength in age-0 juvenile striped bass (Morone saxatilis). Canadian Journal of Fisheries and Aquatic Sciences 69(3): 430-446.

Maceina, M. J., J. W. Slipke, and J. M Grizzle. 1999. Effectiveness of three barrier types for confining grass carp in embayments of Lake Seminole, Georgia. North American Journal of Fisheries Management 19:968-976.

Maceina, M. J. and J. W. Slipke. 2004. The use of herbicides to control *Hydrilla* and the effects on young largemouth bass population characteristics and aquatic vegetation in Lake Seminole, Georgia. Journal of Aquatic Plant Management 42:5-11.

Mitro, M. G., and A.V. Zale. 2002. Seasonal survival, movement, and habitat use of age-0 rainbow trout in the Henrys Fork of the Snake River, Idaho. Transactions of the American Fisheries Society 131:271-286.

McGowan, C. P., M. C. Runge, and M. A. Larson. 2011. Incorporating parametric uncertainty into population viability analysis models. Biological Conservation 144:1400-1408.

Merriman, D. 1941. Studies of the striped bass (*Roccus saxatilis*) of the Atlantic coast. USFWS Fishery Bulletin 50:1–77.

Moore, C. M., R. J. Neves, and J. J. Ney. 1991. Survival and abundance of stocked striped bass in Smith Mountain Lake, Virginia. North American Journal of Fisheries Management 11:393-399.

Peterson, J. T. and J.W. Evans. 2003. Quantitative decision analysis for sport fisheries management. Fisheries 28: 10-21.

Porch, C. E., and W. W. Jr. Fox. 1990. Simulating the dynamic trends of fisheries regulated by small daily bag limits. Transactions of the American Fisheries Society 119:836-849.

Prager, M. H., J. F. O'Brien, and S. B. Saila. 1987. Using lifetime fecundity to compare management strategies: a case history for striped bass. North American Journal of Fisheries Management 7:403–409.

Quinlan, J. A., and L. B. Crowder. 1999. Searching for sensitivity in the life history of Atlantic menhaden: inferences from a matrix model. Fisheries Oceanography 8: 124-133.

R Development Core Team. 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Radomski, P. J., G. C. Grant, P. C. Jacobson, and M. F. Cook. 2001. Visions for recreational fishing regulations. Fisheries 26:7-18.

Richards R. A., and P. J. Rago .1999. A Case History of Effective Fishery Management: Chesapeake Bay Striped Bass. North American Journal of Fisheries Management 19:356-375.

Runge, M.C. 2011. An introduction to adaptive management for threatened and endangered species. Journal of Fish and Wildlife Management 2:220-233.

Sammons, S. M., and M. J. Maceina. 2006. Changes in diet and food consumption of largemouth bass following large- scale *Hydrilla* reduction in Lake Seminole, Georgia. Hydrobiologia 560:109-120.

Secor, D. H., T. M. Trice, and H. T. Hornick. 1995. Validation of otolith-based ageing and a comparison of otolith and scale-based ageing in mark-recaptured Chesapeake Bay striped bass, *Morone saxatilis*. Fishery Bulletin 93:186-190.

Slipke, J. W., M. J. Maceina, and J. M. Grizzle. 1998**.** Analysis of the recreational fishery and angler attitudes toward *Hydrilla* in Lake Seminole, a Southeastern Reservoir Journal of Aquatic Plant Management 36:101-107.

Smith, M. W., A. Y. Then, C. Wor, G. Ralph, K. H. Pollock, and J. M. Hoenig. 2012 Recommendations for catch-curve analysis. North American Journal of Fisheries Management 32:56–96.

Secor, D. H. 2000. Longevity and resilience of Chesapeake Bay striped bass. Journal of Marine Science 57:808–815.

Stevens, D. E. 1977. Striped bass (*Morone saxatilis*) year class strength in relation to river flow in the Sacramento-San Joaquin Estuary, California. Transactions of the American Fisheries Society 106:34-42.

Welker, M.T., C.L. Pierce, and D. H. Wahl. 1994. Growth and survival of larval fishes: roles of competition and zooplankton abundance. Transactions of the American Fisheries Society 123(5): 703-717.

Wilde, G. R., M. I. Muoneke, P. W. Bettoli, K. L. Nelson, and B. T. Hysmith. 2000. Bait and temperature effects on striped bass hooking mortality in freshwater. North American Journal of Fisheries Management 20:810-815.

Wooley, C. M., and E.J. Crateau. 1983. Biology, population estimates, and movement of, native and introduced Striped Bass, Apalachicola River, Florida. North American Journal of Fisheries Management 3:383-394.

TABLES

Table 1. Sampling data provided by the Florida Fish and Wildlife Conservation Commission (FWC), U.S. Corps of Engineers (USCOE) and the Georgia Division of Natural Resources (GDNR) on the Apalachicola-Chattahoochee-Flint River system. See Appendices 1-5 for descriptions of these data.

Sampling data	Agency	Years sampled
Stocking rates of age-0 fish	FWC	1986-2013
Catch-per-unit-effort (YOY)	FWC	1985-2006
Hydrilla aerial count (HAC)	USCOE	1985-2006
Brood fish data	GDNR	1991-2011
Creel survey data	GDNR	1980-2009

Table 2. Model input parameters used in Gulf Striped Bass management and their baseline values.

Parameter	Baseline value (range)	Definition
M	0.15	natural mortality rate
A	0.490	annual discrete mortality
F	0.524	fishing mortality rate
$\hat{S}$	(0.509 to 0.74)	survival rates predicted from a catch-curve
S	S	Survival rate
0	stochastic	age-0 naturally recruited fish with *Hydrilla*
s	stochastic	age-0 stocked fish with *Hydrilla*
stocked	0.01	age-0 stocked fish without *Hydrilla*
naturally	0.00006	age-0 naturally recruited fish without *Hydrilla*
$\hat{F}$	0.524	realized fishing mortality rate
Z	0.6747	total instantaneous mortality rate
H	0.29	hooking mortality of Striped Bass
U	0.381	exploitation rate
$\hat{U}$	0.381	realized exploitation rate
b_c	(3,815 to 18,172)	total catch under bag limit
P	(2.81x10^{-19} to 1.6x10^{-7})	probability
x	(0 to 25)	catch per trip
j	1	trip
λ	0.382	average harvest-per- trip
e	2.718	exponential term
T	9989	total fishing trips that caught fish
i	(0 to 11)	age classes
f	(0 to 464,440)	fertility rates of individuals in age class i
Hydrilla	(13,400 to 24,000)	abundance of *Hydrilla* (acres)
W	(0.1 to 0.6)	weighted objectives
a	(0 to 323.432)	alternative value
min	0	smallest alternative value
max	323.432	largest alternative value

Table 3. Model output parameters predicted from a von Bertalanffy model and regression analyses.

Parameter	Baseline Value (range)	Definition
l_a	(482 mm to 983 mm)	predicted length at age
L_∞	1059.43	asymptotic length
K	0.23	growth rate
t_0	-0.691	age of fish at 0 length
b_0	5.257	intercept of CPUE-HAC relation
b_1	-0.0001981	slope of CPUE-HAC relation
$\hat{b}_0$	-4.71	intercept of egg-length relation
$\hat{b}_1$	2.67	slope of egg-length relation

Table 4. Estimated age-specific fecundity rates of Gulf Striped Bass. The average number of female eggs laid each year, assuming half would be female upon fertilization (Cohen et al. 1983). Fecundity of mature females was estimated using a regression analysis of fish length versus egg number and estimates of length at age from a von Bertalanffy model.

Age	Fecundity
1	0
2	0
3	0
4	181,230
5	238,057
6	290,547
7	337,218
8	377,621
9	411,930
10	440,652
11	464,440

Table 5: Summary of management alternatives using a consequences table. Population abundance was predicted from the matrix model for each management combination for a 10-year period. Angler satisfaction values were constructed using additive combinations of values* (*satis*) associated with population abundance and each individual management alternative (value = population$_{satis}$ + stocking $_{satis}$ + *Hydrilla* control$_{satis}$ + regulation$_{satis}$); resulting values ranged from 3 to 10. Relative cost was scored using a Likert scale (0-5) based on the estimated cost for each management combination.

Gulf Striped Bass	*Fundamental*	Population	Angler Satisfaction	Cost
Alternative	*Direction:*	Max	Max	Min
	Attribute:	predicted abundance	constructed utility score	relative cost
	Scale:	1,000 x	3 - 10	0 - 5
weights		0.6	0.3	0.1
No stocking + No hydrilla control +Moratorium		139.593	3	0
No stocking + No hydrilla control + 50 % harvest		12.436	2	0
No stocking + No hydrilla control + Current harvest		11.877	4	0
No stocking + Min. hydrilla control + Moratorium		202.032	4	1
No stocking + Min. hydrilla control + 50 % harvest		18.131	3	1
No stocking + Min. hydrilla control + Current harvest		18.09	5	1
No stocking + Max. hydrillla control + Moratorium		269.25	5	2
No stocking + Max. hydrilla control + 50% harvest		25.509	5	2
No stocking + Max. hydrilla control + Current harvest		25.187	7	2
Min. stocking + No hydrilla control + Moratorium		160.738	4	1
Min. stocking + No hydrilla control +50% harvest		18.096	3	1
Min. stocking + No hydrilla control + Current harvest		18.172	5	1
Min. stocking rate + Min. hydrilla control + Moratorium		238.984	5	3
Min. stocking rate + Min. hydrilla control + 50% harvest		26.122	5	3
Min. stocking rate + Min. hydrilla control + Current harvest		25.756	7	3
Min. stocking rate + Max. hydrilla control + Moratorium		323.432	6	4
Min. stocking rate + Max. Hydrilla control + 50% harvest		36.001	7	4
Min. stocking rate + Max. hydrilla control +Current harvest		36.014	9	4
Max. stocking rate + No hydrilla control + Moratorium		186.741	5	2
Max. stocking rate + No hydrilla control + 50% harvest		24.035	5	2
Max. stocking rate + No hydrilla control + Current harvest		23.753	7	2
Max. stocking rate + Min. hydrilla control + Moratorium		271.106	6	4
Max. stocking rate + Min. hydrilla control +50% harvest		34.519	7	4
Max. stocking rate + Min. hydrilla control +Current harvest		34.237	9	4
Max. stocking rate + Max hydrilla control + Moratorium		365.97	7	5
Max. stocking rate + Max hydrilla control +50% harvest		46.416	8	5
Max. stocking rate + Max. hydrilla control +Current harvest		46.516	10	5

**satis* values were: 10,000-20,000 fish = 1, 20,001-30,000 fish = 2, >30,000 fish = 3; No stocking = 1, Min stocking = 2, Max stocking = 3; Current harvest = 1, 50% harvest = -1, moratorium = -2; no *Hydrilla* control = 1, Min *Hydrilla* control = 2, Max *Hydrilla* control = 3.

Table 6. Sum of weighted scores under equal (Population 0.33, Angler Satisfaction 0.33, Cost 0.33) and unequal (Population 0.6, Angler Satisfaction 0.3, Cost 0.2) weighted objectives. The equally weighted scores ranks are reported next to the score to illustrate changes in rank versus the weighted objectives. Management alternatives were: Max stocking (MAS), Min. stocking (MS), No stocking (NS), Max. *Hydrilla* (MAH), Min. *Hydrilla* (MH), No *Hydrilla* control (NH), Moratorium (M), 50% Harvest (50%H), Current Harvest (CH).

Mangement alternatives	**Sum of weighted scores (Population 0.6, Angler Satisfaction 0.3, Cost 0.1)**	**Sum of weighted scores (Population 0.33, Angler Satisfaction 0.33, Cost 0.33)**
MAS,MAH,M	0.788	0.536 2
MS,MAH,M	0.698	0.521 4
MAS,MH,M	0.609	0.472 8
NS,MAH,M	0.609	0.561 1
MS,MH,M	0.537	0.467 9
NS,MH,M	0.477	0.523 3
MAS,NH,M	0.469	0.484 7
MS,NH,M	0.407	0.485 6
MAS,MAH,CH	0.359	0.362 17
NS,NH,M	0.354	0.490 5
MS,MAH,CH	0.323	0.377 15
MAS,MH,CH	0.320	0.375 16
MAS,MAH,50%H	0.284	0.279 26
NS,MAH,CH	0.270	0.416 10
MAS,NH,CH	0.268	0.415 11
MS,MH,CH	0.251	0.351 18
MS,MAH,50%H	0.248	0.294 24
MAS,MH,50%H	0.246	0.293 25
MS,NH,CH	0.203	0.393 14
NS,MH,CH	0.203	0.393 13
NS,MAH,50%H	0.196	0.334 19
MAS,NH,50%H	0.193	0.333 20
MS,MH,50%H	0.177	0.269 27
NS,NH,CH	0.175	0.412 12
NS,MH,50%H	0.128	0.311 22
MS,NH,50%H	0.128	0.311 23
NS,NH,50%H	0.101	0.330 21

FIGURES

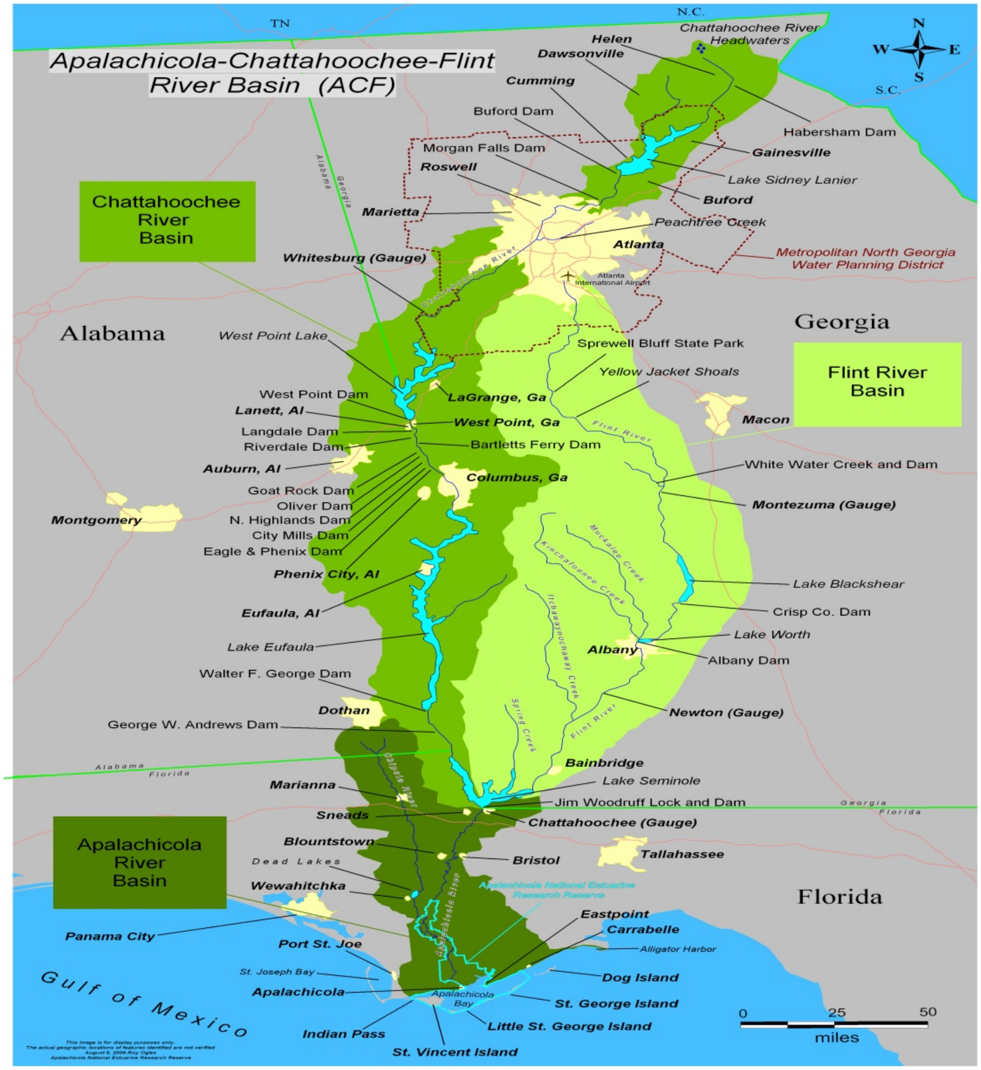

Figure 1. Study Site (Apalachicola-Chattahoochee-Flint River System). The Apalachicola-Chattahoochee-Flint River (ACF) system is approximately 19,800 square miles, which begins in Northeast Georgia and flows down into the Gulf of Mexico. The ACF river system is comprised of two major river systems (Flint River and Chattahoochee River) that converge into Lake Seminole to form the Apalachicola River.

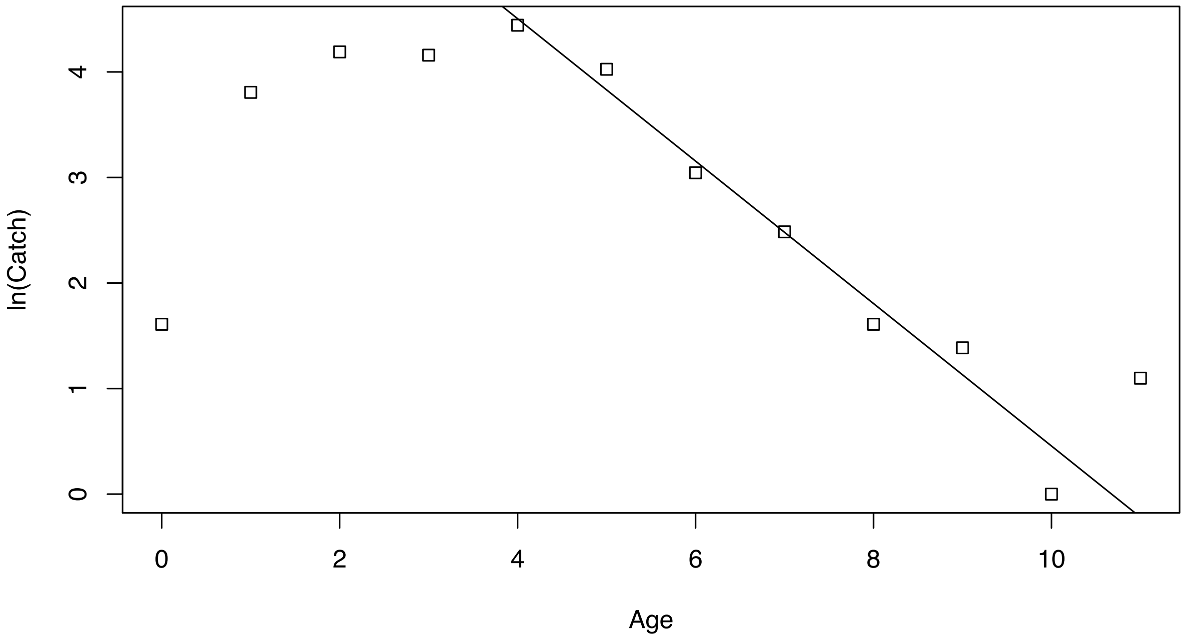

Figure 2. Log catch-at-age relation (catch-curve) of Gulf Striped Bass brood fish collected from the tailrace of the Jim Woodruff Lock and Dam, George Andrews Lock and Dam, and sections of the Flint River. Line represents the linear relation of peak catch-at-age, which was used as an estimation of total instantaneous mortality (Z).

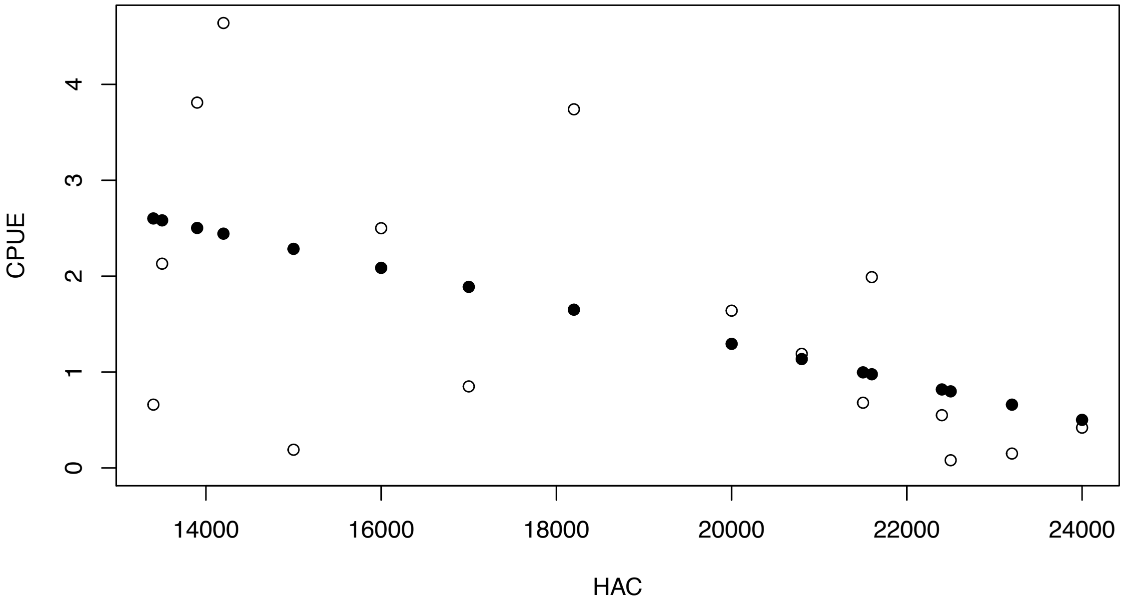

Figure 3. Linear relation between catch-per-unit-effort (CPUE) of age-0 Gulf Striped Bass and *Hydrilla* aerial counts (HAC) in Lake Seminole (P= 0.03; r^2= 0.27). Open circles (○) represent individual catch-per-unit-effort of age-0 Gulf Striped Bass and the corresponding *Hydrilla* aerial counts. Shaded circles (●) represent the linear relation between catch-per-unit effort of age-0 Gulf Striped Bass and *Hydrilla* aerial counts.

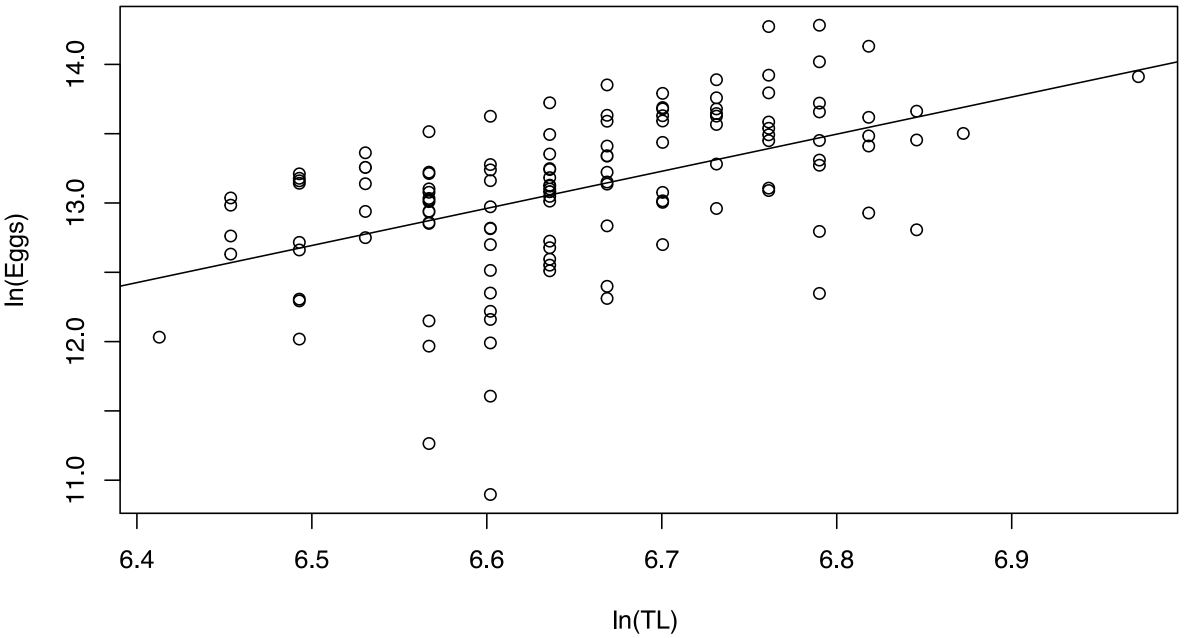

Figure 4. Egg-length relation using a least squares regression analysis of fish length versus egg number from hatchery brood fish data. Open circles represent log-transformed number of eggs at length of individual Gulf Striped Bass. Line represents the linear relation between the numbers of eggs at a given length.

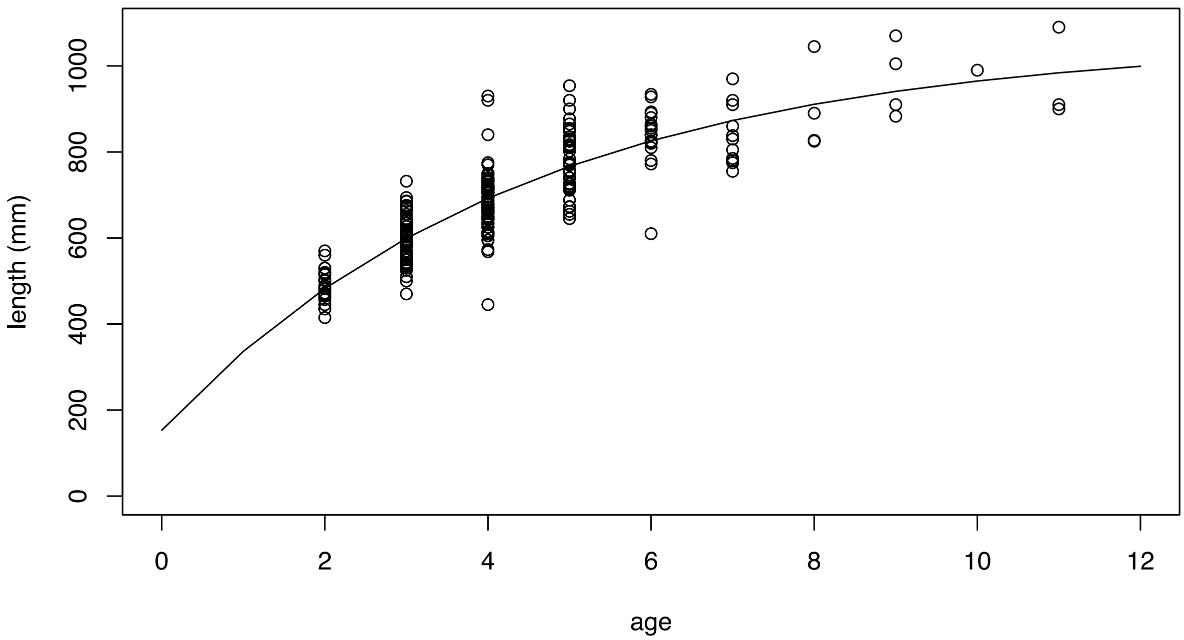

Figure 5: Predicted length-at-age of Gulf Striped Bass brood fish using a von Bertalanffy model. Growth parameters include (L_∞= 1059.43, K= 0.23, t_0= -0.691). Open circles represent collected length-at-age of Gulf Striped Bass. Line represents the predicted length-at-age for Gulf Striped Bass.

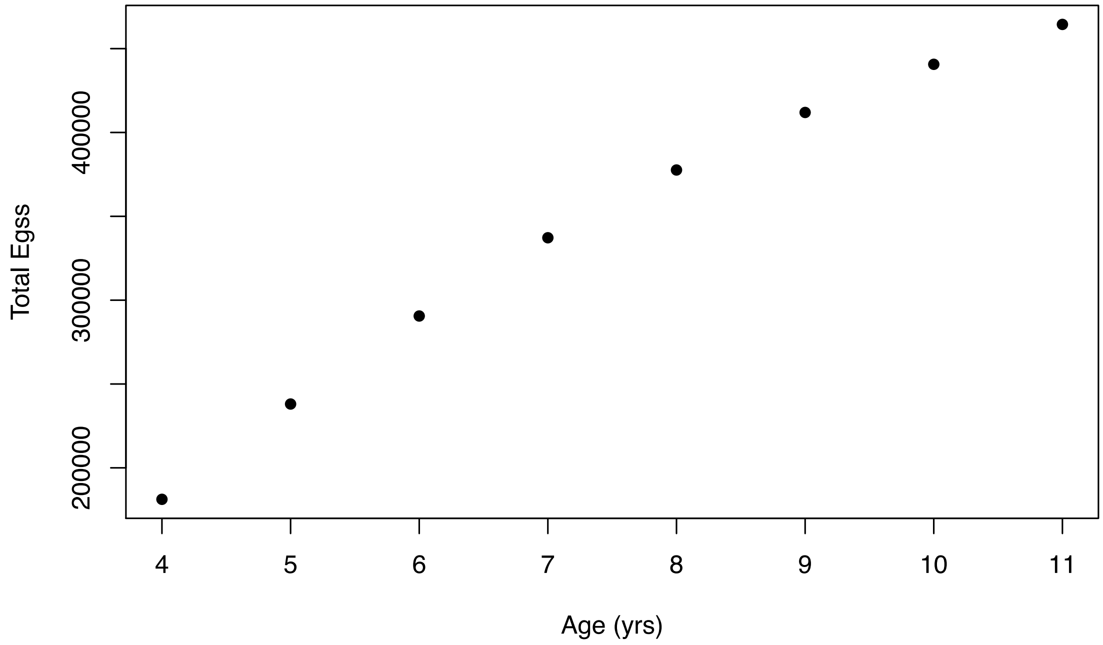

Figure 6: Predicted eggs-at-age using a least squares regression analysis on egg-length relation and estimated length at age (von Bertalanffy model) from brood fish data.

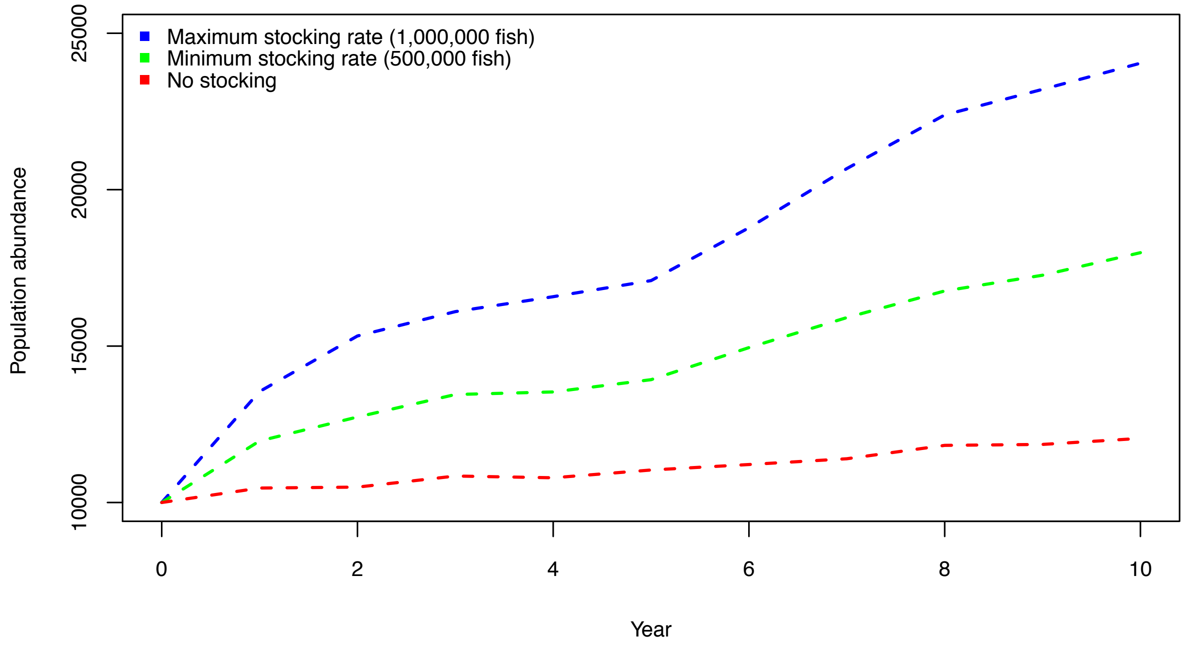

Figure 7. Population abundance of Gulf Striped Bass under three stocking scenarios. The blue dashed line represents the population abundance of Gulf Striped Bass under a maximum stocking rate for 10 years. The green dashed line represents the population abundance of Gulf Striped Bass under a minimum stocking rate for 10 years. The red dashed line represents the population abundance of Gulf Striped Bass under a no stocking rate for 10 years.

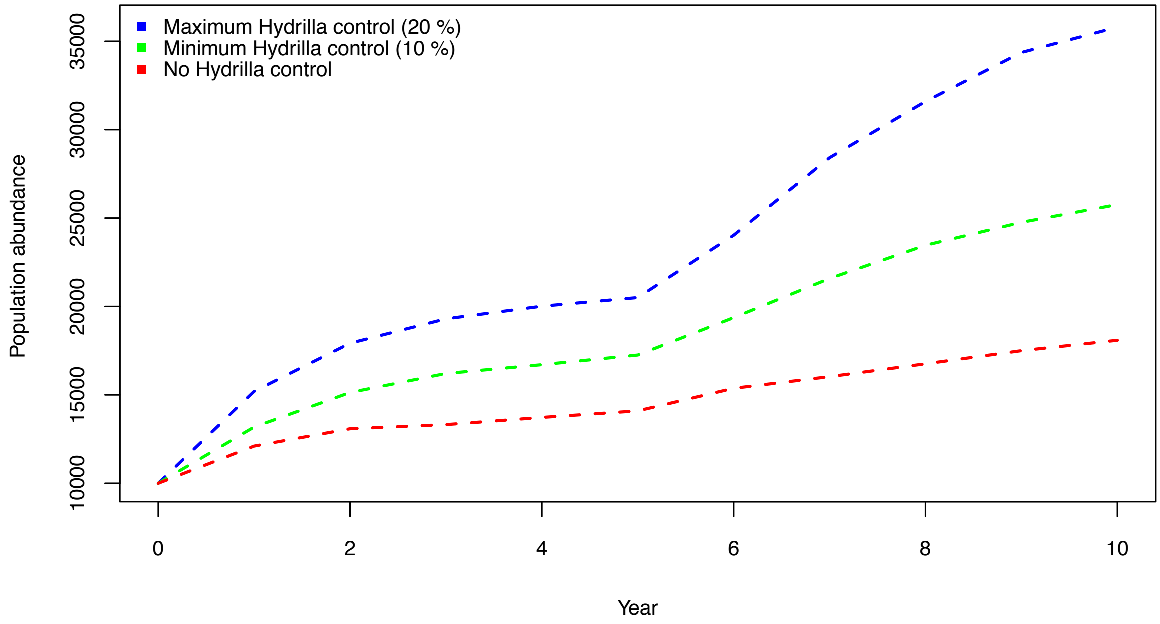

Figure 8. Population abundance of Gulf Striped Bass under three levels of *Hydrilla* control. The blue dashed line represents the population abundance of Gulf Striped Bass under a maximum *Hydrilla* control (20%) for 10 years. The green dashed line represents the population abundance of Gulf Striped Bass under a minimum *Hydrilla* control (10%) for 10 years. The red dashed line represents the population abundance of Gulf Striped Bass under no *Hydrilla* control for 10 years.

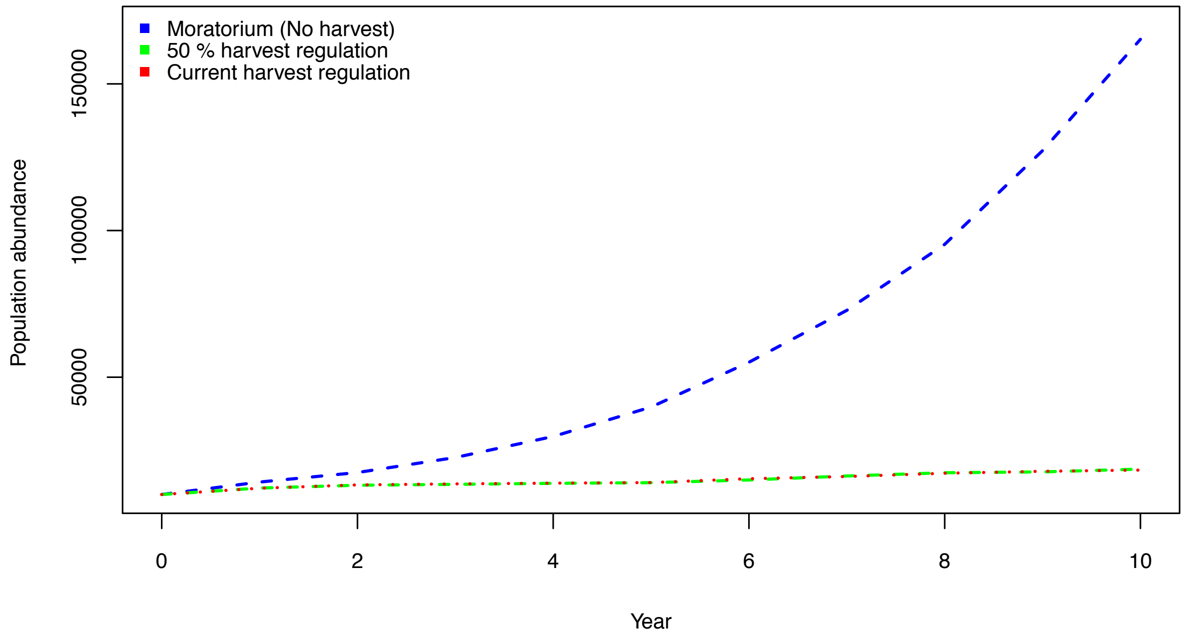

Figure 9. Population abundance of Gulf Striped Bass under three levels of harvest regulations. The blue dashed line represents the population abundance of Gulf Striped Bass under a moratorium for 10 years. The green dashed line represents the population abundance of Gulf Striped Bass under a 50% harvest regulation for 10 years. The red dashed line represents the current harvest regulation of Gulf Striped Bass for 10 years.

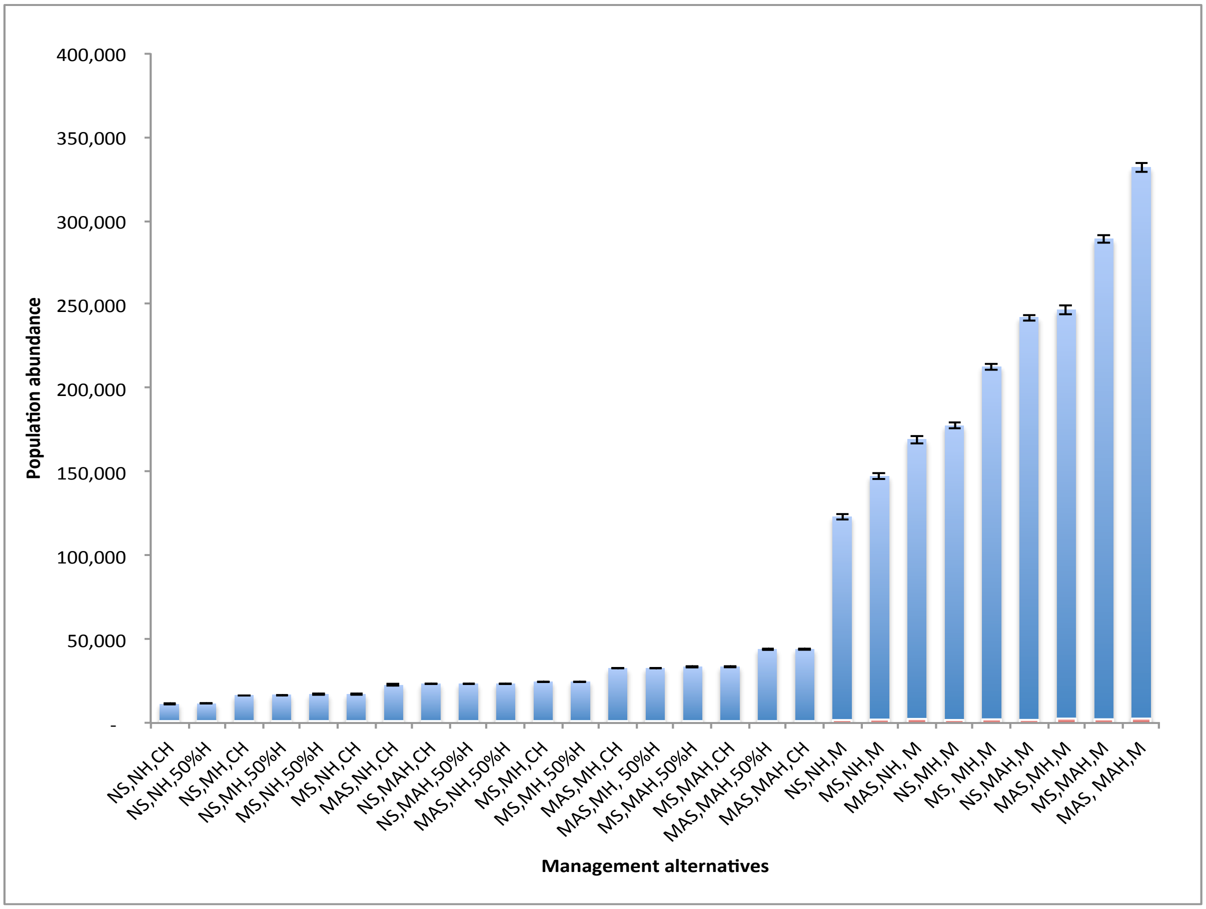

Figure 10. Population abundance under each management alternative. Columns represent the total population abundance under each management combination in 10 years. Management alternatives: Max stocking (MAS), Min. stocking (MS), No stocking (NS), Max. *Hydrilla* (MAH), Min. *Hydrilla* (MH), No *Hydrilla* control (NH), Moratorium (M), 50% Harvest (50%H), Current Harvest (CH).

APPENDICES

Sampling data were provided by various state agencies on Gulf Striped Bass in Apalachicola-Chattahoochee-Flint river system. Data were used to estimate and inform Gulf Striped Bass vital rates that were incorporated into the matrix model.

Appendix 1. Fish data

Brood fish data were collected in several locations in the ACF. These locations included the tailrace of Jim Woodruff Lock and Dam, the tailrace of George Andrews Lock and Dam, and sections of the Flint River (Long et al. 2013) . Brood fish were collected primarily for genetic analysis and hatchery propagation. Fish were sampled using boat electrofishing equipment to estimate CPUE and relative abundance values for adult fish. Sampled fish were measured for total length (mm) and weighed (kg). Fish were aged using sagittal otoliths from fish that died from hatchery propagation or sacrificed at the hatchery for age determination (Long et al. 2013). Brood fish data were used to estimate length at age using a von Bertlanffy model. Brood fish data were also used to estimate mortality rates using a catch-curve analysis.

Appendix 2. Stocking and Catch-per-unit effort of age-0 Gulf Striped Bass.

Since 1986, Gulf Striped Bass have been stocked annually throughout the ACF. Typically, age-0 fish were stocked in the Spring (April- May) and sampled in the Fall (September –November). Catch-per-unit effort (CPUE = #fish/hour) and relative abundance (CPUE/number of fish stocked) values for age-0 stocked fish were estimated yearly by the Florida Fish and Wildlife Conservation Commission from 1986-2013 using electrofishing boats during Fall sampling trips (Long et al. 2013). In 2001, all phase-1 fish were batch marked with oxytetracycline (OTC) to determine relative abundance of naturally recruited and wild fish. Natural recruitment remained low with the majority (75%-100%) of all age-0 fish recaptured in the Fall samples being stocked fish (Long et al. 2013).

Appendix 3. Egg production of Gulf Striped Bass

Egg production data were provided by the Marion Fish Hatchery from 2001 to 2014. The hatchery provided the number of total eggs and initial settled volumes(ml) recorded for each female. Unfortunately, age data associated with egg production were lacking. Using predicted length at age from a von Bertlanffy model, egg production data were used to predict eggs at age through a regression analysis. Predicted number of eggs at age was used for fertility estimates in the matrix model.

Appendix 4. *Hydrilla* abundance in Lake Seminole

Hydrilla aerial counts are conducted yearly by the ACOE using aerial photography along with airboat and GPS surveys (Slipke 1998). *Hydrilla* abundance (acres) was monitored on Lake Seminole from 1985 to 2006. Estimates of *Hydrilla* abundance was used to inform future estimates using a random normal distribution.

Appendix 5. Creel Survey

Creel surveys were conducted from 1985 to 2009 from various locations throughout the ACF river system (Long et al. 2013). Surveys were conducted using randomly stratified and roving creel with non-uniform probabilities. Anglers were monitored for total catch, harvest, effort (hours) and angler success (Striped Bass catch or harvest per hour; Long et al. 2013). Estimates of total annual trips from creel survey data were used to inform catch rates under different bag limits. Peak season creel surveys indicated that after stocking initiatives took place, harvest by anglers increased up to 10-fold (Long et al. 2013)