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EVALUATING ALTERNATE MANAGEMENT STRATEGIES FOR SPOTTED SEATROUT (CYNOSCION NEBULOSUS) IN THE NORTH-CENTRAL GULF OF MEXICO

by

Nathaniel Wallace Jermain

A Thesis
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the College of Arts and Sciences
and the School of Ocean Science and Engineering
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in Partial Fulfillment of the Requirements
for the Degree of Master of Science

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ABSTRACT

Spotted Seatrout (*Cynoscion nebulosus*) receive considerable fishing pressure as the most popular saltwater target species in the north-central Gulf of Mexico. The potential for alternate management strategies, including stock enhancement and reducing discard mortality, to support the sustainability of the stocks and the desires of stakeholders is unknown. The purpose of this study was to provide an objective evaluation of the efficacy of alternate management strategies for Spotted Seatrout in Louisiana, Mississippi, and Alabama. I used a management strategy evaluation (MSE) to measure the performance of 18 alternate management scenarios relative to control scenarios. Scenarios with a high hatchery input exhibited the highest expected benefit to the stock and fishery in each state; reducing discard mortality had a substantially lesser predicted effect. MSE model results indicated that the expected outcome of alternate management strategies was highly variable by state in the north-central Gulf of Mexico. Characteristics of the stock and fishery in the three states provided information to describe the observed geographic variability in MSE model results. States with a large stock size such as Louisiana exhibited the lowest potential benefit from the management alternatives evaluated. Key fishery characteristics included the proportion of fishing mortality due to discarding, and the minimum length limit imposed by managers. Results from this study provide insights regarding the optimal management of Spotted Seatrout in the north-central Gulf of Mexico.

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LIST OF ABBREVIATIONS

GOM	Gulf of Mexico
MSE	Management Strategy Evaluation
MRIP	Marine Recreational Information Program
SPR	Spawning Potential Ratio
SS3	Stock Synthesis 3
SSB	Spawning Stock Biomass
PA3	Proportion of age-three or older individuals

CHAPTER I

INTRODUCTION

Spotted Seatrout (*Cynoscion nebulosus*) are a prized target of the recreational fishery that inhabit inshore parts of the Gulf of Mexico (GOM) and Atlantic coast (Hoese and Moore 1998). In the north-central GOM, Spotted Seatrout receive considerable fishing pressure and are the most popular saltwater target species in the region (Bohaboy et al. 2018, Deegan 1990); stocks in Mississippi and Alabama are considered overfished and experiencing overfishing (Bohaboy et al. 2018; Leaf 2018). Spotted Seatrout are managed by each state in the north-central GOM as region-specific stocks, despite a lack of state-specific delineation of the stock in Louisiana, Mississippi, and Alabama (Somerset and Saillant 2014). In each state, managers use minimum length and bag limits (Table 1) to control effort and maintain sustainable biomass (Blanchet et al. 2001). The status of each stock is assessed using the spawning potential ratio (SPR) and spawning stock biomass (SSB) as limit fishery and biological reference points. SPR is a measure of the reproductive capacity of the fished stock relative to that of the unfished stock and provides a metric to evaluate the impact of fishing (Goodyear 1993). Spawning stock biomass is a measure of the spawning capacity of the stock and may be represented as the number of sexually mature individuals in the stock or the number of eggs among others metrics. Managers aim to restrict fishing mortality to ensure that SPR and SSB values do not decrease below their respective limits. The limit reference points vary for each state (Table 1).

A challenge to fishery managers is to balance the conflicting objectives of maintaining sustainable stock biomass while also satisfying the desires of stakeholders

(Beardmore et al. 2015). The number and length of fish harvested is a critical component of angler satisfaction for those targeting Spotted Seatrout in the north-central GOM (Deegan 1990), so management actions to reduce effort negatively impact stakeholder groups. In response, some management regimes for Spotted Seatrout in the GOM have considered incorporating the practice of releasing hatchery-reared individuals to the wild stock, also known as stock enhancement, into management strategies. Stock enhancement efforts employ hatchery production of fish to supplement the stock in an effort to increase the abundance of spawning capable individuals (Lorenzen 2005; Lorenzen et al. 2012) and has evolved from a research endeavor to a management tool (Lorenzen et al. 2013). Despite the intended application of stock enhancement as a management tool, assessments of enhancement programs have often focused on the effectiveness of aquaculture production rather than achieving fishery-oriented goals (Heppell and Crowder 1998).

An alternative approach to understanding the potential of stock enhancement involves evaluating enhancement options by weighing the expected benefit to the fishery for a given strategy in relation to alternate approaches (Lorenzen et al. 2010). Simulation models are one tool that offers the ability to compare a variety of management, biological, and environmental scenarios (Ye et al. 2005; Camp et al. 2014, 2016). A management strategy evaluation (MSE) is a simulation modeling approach often used to compare fishery management strategies. MSEs employ multiple submodels to represent the stock, fishery, and the management dynamics expected from predefined, realistic scenarios (Smith et al. 1999). Submodels are parameterized in a way that maximizes their overall representation of data collected from the stock and fishery. A major obstacle in constructing a simulation model to evaluate management strategies is identifying realistic parameter values to represent the dynamics of the stock (e.g. growth, mortality, recruitment) and dynamics of the fishery (e.g. fishing mortality and selectivity). Explicitly acknowledging uncertainty in a way that contributes to the structure of the analysis is the hallmark of a MSE (Punt et al. 2016). MSEs mimic the entire management cycle to determine the relative performance of predetermined strategies and use random sampling methods to incorporate the perceived level of imprecision for parameter estimates (Smith et al. 1999). Strategies are evaluated by their ability to achieve specific *a priori* objectives set by stakeholders of the fishery despite the imprecision incorporated in the model. Because stakeholder's objectives of the fishery are often conflicting, (i.e. the desire to simultaneously maintain both harvest and stock biomass), a specific advantage of MSEs is the ability of stakeholders and managers to choose between multiple candidate strategies to understand how objectives can be met and what tradeoffs are necessary (Holland 2010). The utility of evaluating strategies, in simulation, prior to application has allowed the MSE approach to become a popular tool for commercial (Amar et al. 2008, Needle 2008, Kuykendall et al. 2017) and recreational fishery applications (Irwin et al. 2008; Deroba and Bence 2012).

The fundamental components of MSE are an operating model and a model of the management procedure (Figure 1) (Smith et al. 1999). The operating model components simulate the biological characteristics of the stock and the characteristics of the fishery. Multiple sub-models describe essential characteristics of the stock and fishery and include instantaneous fishing mortality, the stock-recruitment relationship, and abundance-at-age. The management procedure component simulates an assessment of the stock and the subsequent determination of regulations. By incorporating specific methods by which the stock is managed, simulations provide estimates of performance indices that are consistent with the prescribed methodology (Rademeyer et al. 2007).

In this work, I use an MSE approach to evaluate the efficacy of two alternative management strategies 1.) stock enhancement and 2.) reduction of discard mortality to achieve predetermined goals for three Spotted Seatrout stocks in the north-central GOM. Specifically, I evaluated the probability of achieving 1.) a 10% increase in the spawning stock biomass (SSB), 2.) a 10% increase in annual harvest, and 3.) a 10% increase in the proportion of age-three or older individuals in the stock for the two strategies. I chose the reduction of discard mortality as an alternate strategy against which to compare stock enhancement because both strategies have a similar enhancement effect; efforts to reduce the discard mortality rate allow a greater percentage of released fish to return to the population without limiting the catch or harvest. Although the discard mortality rate for Spotted Seatrout in the GOM is considered low (10 %) (Stunz and McKee 2006), the magnitude of catch indicates that discard mortality could be a critical source of fishing mortality in the region (National Marine Fisheries Service 2018). Reductions may be achieved through gear adjustments (Carbines 1999; Cooke and Suski 2004) or improving release technique (Ferguson and Tufts 1992; Brownscombe et al. 2017) and are often incorporated into management strategies through regulations. I estimate the predicted outcomes using a MSE model parameterized with results from an *ad hoc* assessment of Spotted Seatrout population dynamics; the assessment was conducted specifically to estimate parameter values for the MSE model. To understand how strategies perform under alternate regulation of the fishery, I evaluate the two enhancement strategies for scenarios where SPR target values deviated from those currently employed by management agencies in the three states.

METHODS

ASSESSMENT OF SPOTTED SEATROUT POPULATION DYNAMICS

Data Sources

I used fisheries-dependent and fisheries-independent data to model the population dynamics of Spotted Seatrout in Louisiana, Mississippi, and Alabama. Fisheries data was unavailable from Louisiana after 2013, so I used a times series of data for each of the three states from 1993 to 2013. I queried fishery-dependent data from the Marine Recreational Information Program (MRIP) to describe the annual recreational catch of Spotted Seatrout in Louisiana, Mississippi, and Alabama using the most recent information after the comprehensive survey design calibration in July of 2018. The data query included the annual numbers of Spotted Seatrout harvested, numbers released, and length frequency of harvested fish (fork length, centimeters). Commercial landings were ignored in the analysis; their magnitude was insignificant relative to recreational landings in the north-central GOM (West et al. 2014; Leaf et al. 2016). Fisheries-independent data was derived from gillnet surveys conducted by state agencies in Louisiana, Mississippi, and Alabama. Survey data included a time series of standardized catch-per-unit-effort (CPUE) and associated annual age composition.

State-specific Catch

I calculated annual catch for each state. Catch was characterized as either harvest or discards that died due to fishing-related injury. Estimates of annual harvest and the number of released Spotted Seatrout was queried directly from the MRIP database (Table

2). I calculated the number of dead discards as 10% of the estimated number of released Spotted Seatrout based on the discard mortality rate estimated by Stunz and McKee (2006) (Table 3). This estimate is consistent with the discard mortality rates used by stock assessments conducted by natural resource management agencies in Louisiana, Mississippi, and Alabama.

The age composition of harvested Spotted Seatrout was determined using MRIP length frequency information and an age-length key. I converted length frequencies (FL, cm) to total length (TL, cm) using parameter estimates provided by the Florida Fish and Wildlife Research Institute (2010):

$$TL = 1.0008\,FL + 0.6306 \text{ , (1)}$$

where TL is total length (cm) and FL is fork length (cm). Using an age-length key developed from fishery-independent samples by the Mississippi Department of Marine Resources (Table 4, MDMR), I converted state- and length-specific catch to catch-at-age (Table 5, Table 6, Table 7). Six age classes represented catch-at-age, bounded by an age one and a six year plus group that included all individuals six years or older. I assumed age-length proportions contained in the key were estimated without error and were temporally invariant. No data on the length or age composition of released Spotted Seatrout were available.

Abundance Indices

I used one time series of index data from fisheries-independent gillnet sampling conducted in each state. Indices were based on catch per unit effort (CPUE) from gillnet panels and were standardized using generalized linear models to reduce unexplained variability. Generalized linear models described the relationship between predictor variables such as mesh size, station number, month, and the response variable CPUE. CPUE predicted by the model was used as the observed index of abundance. CPUE for Alabama and Mississippi surveys was calculated using multiple panels (10.2 to 16.5 cm and 6.35 cm to 10.16 cm mesh respectively). CPUE for the Louisiana survey was derived from a single 2.54 cm mesh panel. Age composition was included for each index; sex-specific composition was available for the Alabama index only.

Life-History Characteristics

I assumed that Spotted Seatrout in Louisiana, Mississippi, and Alabama shared the same natural mortality, fecundity, maturity, length-at-age, and weight-at-length relationships. I used von Bertalanffy growth parameters (Equation 4) derived from Alabama fisheries-independent samples to define the length-at-age relationship. The von Bertalanffy growth equation used was:

$$L_t = L_\infty(1 - e^{-k(t-t_0)}) \text{ , (2)}$$

where L_t is the expected total length (cm) at age t (years), L_∞ is the average maximum length (cm), k is the growth rate coefficient (y^{-1}) , t_0 is the hypothetical age (years) when total length is zero. I defined the weight-at-length relationship using:

$$W = P_1 L^{P_2} \text{ , (3)}$$

where P_1 and P_2 are sex-specific parameters estimated from fisheries-independent samples caught in Alabama, W is weight (kg), and L is total length (cm).

Estimates of natural mortality-at-age followed the Lorenzen inverse linear length to mortality relationship:

$$M_L = \frac{M_1}{L} \text{ , (4)}$$

where M_L is the length-specific natural mortality, L is the total length (cm), and M_1 is the natural mortality rate at length. I used equation one and sex-specific lengths associated with each age class to determine sex-specific natural mortality-at-age.

Fecundity estimates followed Brown-Peterson and Warren's (2001) relationship of batch fecundity to length for female Spotted Seatrout and an estimated average of 37.5 batches of eggs per year. The annual mean number of eggs (E) produced per mature female Spotted Seatrout as a function of total length (TL) was determined using Equation 5:

$$E = -3.50 \times 10^6 + 1.47 \times 10^5 \, TL \, . \text{(5)}$$

Brown-Peterson and Warren (2001) estimated at 34 centimeters total length, 50 percent of female Spotted Seatrout are sexually mature (L_{50}). I used Brown-Peterson and Warren's L_{50} estimate as the inflection point for a logistic function to determine the proportion of individuals at a given length that were sexually mature:

$$Prop_{mat} = (1 + e^{-0.5(TL-34)})^{-1} \text{ , (6)}$$

where $Prop_{mat}$ is the proportion of Spotted Seatrout mature at a given length and TL is the total length (cm).

Assessment Model

I employed Stock Synthesis 3 (SS3) version 3.24u, a peer-reviewed and widely applied forward projecting age-structured model (Methot and Wetzel 2013) to estimate parameter values used in the MSE operating model. Six fleets were included in the analysis; one fleet represented the recreational harvest of Spotted Seatrout, and one fleet accounted for dead discards for each state. Each fleet was assigned to one of three regions in the assessment model corresponded to the three Gulf states. I assumed that Spotted Seatrout did not move among states.

I used a Beverton-Holt stock-recruitment relationship to describe the number of recruits (age-zero individuals) as a function of spawning biomass:

$$R_y = \frac{4hR_0S_{y-1}}{S_0(1-h)+S_{y-1}(5h-1)}e^{-0.5R_0\sigma_R^2+R_y}\text{ , (7)}$$

where R_y is the number of recruits at year y, R_0 is virgin recruitment, h is steepness, S_0 is virgin spawning biomass (number of eggs), and S_y is the spawning biomass at year y. Virgin recruitment was the sole parameter estimated using the stock-recruitment relationship; I fixed the remaining parameters representing steepness and the variance of recruitment at .89 and 0.3 respectively. The steepness and variance of recruitment values match those employed by the most recent assessment of Alabama’s Spotted Seatrout stock (Bohaboy et al. 2018). SS3 aggregates spawning biomass among states included in the model prior to calculating a global recruit abundance. Each state receives a proportion of global recruit abundance; to account for variable recruitment patterns, I allowed the proportion of recruits received by each state to vary over time. Recruits were assumed to be born on July 1.

Age-, fleet-, and year-specific fishing mortality (F_{agy},y^{-1}) was calculated as the product of selectivity (S_{ag}) and a fishing mortality multiplier ($FMult_{gy}$):

$$F_{agy} = S_{ag}FMult_{gy}\text{. (8)}$$

I estimated age- and fleet-specific selectivity (S_{ag}) using a two-parameter logistic function:

$$S_{ag} = \frac{1}{(1+e^{-\beta(a-a_{50})})}\text{ , (9)}$$

where β is a parameter describing the steepness of the curve, a is age (years) and a_{50} is the age at 50 percent selection. No length information was available from MRIP for released Spotted Seatrout, so selectivity for dead discard fleets was fixed at the inverse relationship of the selectivity for harvest-associated fleets in each state.

Annual state-specific total mortality-at-age (Z_{ajy}) was calculated as the sum of aggregate fishing morality (F_{ajy},y^{-1}) for fleets assigned to state j and natural mortality-at-age (M_a,y^{-1}) using the equations:

$$F_{ajy} = \sum_g (F_{agjy}), \text{ (10) and}$$

$$Z_{ajy} = F_{ajy} + M_a \text{ . (11)}$$

SS3 models state-specific abundance-at-age (N_{ajy}) as:

$$N_{ajy} = N_{a-1,j,y-1} e^{-Z_{a-1,j,y-1}}, a < A, \text{ (12), and}$$

$$N_{ajy} = N_{A-1,j,y-1} e^{-Z_{A-1,j,y-1}} + N_{A,j,y-1} e^{-Z_{A,j,y-1}}, a = A \text{ , (13)}$$

where A is the oldest age class included in the model.

Annual state-specific catch-at-age (C_{ajy}) is calculated using the equation:

$$C_{ajy} = \frac{N_{ajy} \sum_g (F_{agjy})(1 - e^{-Z_{ajy}})}{Z_{ajy}} \text{ . (14)}$$

SS3 calculates indices of abundance (G_{ajy}) for each state as:

$$G_{ajy} = q_{ind} \sum_a N_{ajy} S_{ind,a} \text{ , (15)}$$

where q_{ind} is the catchability coefficient for each index, N_{ay} is the year-specific numbers-at-age, and $S_{ind,a}$ is survey selectivity-at-age. I used a four-parameter double logistic function to represent survey selectivity-at-age:

$$S_{ind,a} = \frac{T_1}{(1+e^{-\beta_1(a-\beta_2)})(1+e^{\beta_3(a-\beta_4)})} \text{ , (16)}$$

where β_1, β_2, β_3, and β_4 are parameters estimated by the model, a is age (years), and T_1 is a scaling factor. Parameter values for β_1, β_2, β_3, and β_4 were fixed at values that fit the data and were consistent with estimates from previous assessments. Age composition for surveys was modeled as:

$$\frac{G_{ajy}}{\sum_a G_{ajy}}, (17)$$

where G_{ajy} is the age-, state-, and year-specific index value.

I estimated 180 parameters describing the population dynamics of Spotted Seatrout in the north-central GOM with the SS3 model. Estimated parameters included two time-invariant recruitment distribution coefficients, 42 annual deviations for recruitment distribution, virgin recruitment, initial fleet-specific fishing morality, 21 annual fleet-specific fishing mortality parameters, and two selectivity parameters for each harvest-associated fleet. Initial values for virgin recruitment, initial fleet-specific fishing morality, and selectivity parameters were derived from stock assessments of Spotted Seatrout in Louisiana, Mississippi, and Alabama.

Two identical SS3 models were fit to the data using different methods; I used maximum likelihood estimation (MLE) to estimate parameter values for one model and fit an additional SS3 model using Markov Chain Monte Carlo (MCMC). The model fit using MCMC employed 1,000,000 iterations for a single chain, and a thinning interval of 1000. Parameters estimated by the SS3 model fit using MLE were incorporated in the MSE simulation, while those estimated using MCMC were used for a diagnostic comparison with the MLE model. Convergence of the model fit with maximum likelihood estimation was determined by assessing the final gradient value calculated by a gradient decent algorithm. I assessed MCMC model convergence with Heidelberger and Welch's diagnostic, and Geweke's statistic. I diagnosed model output by comparing parameter estimates from the two fitting techniques, evaluating the standard deviations or posterior distributions associated with each parameter, and plotting the model predictions relative to the data.

EVALUATION OF ALTERNATE MANAGEMENT STRATEGIES

Simulation Design

I evaluated 18 alternate management scenarios that differed by the magnitude of hatchery releases, discard mortality rates, and target SPR values (Table 8). Three sets of scenarios included an annual release of hatchery-raised Spotted Seatrout into the wild at one, two, and five million individuals. An additional three sets of scenarios included decreases in the discard mortality rate to nine, eight, and five percent. Fishing intensity varied within each set of scenarios; one scenario was evaluated for the current state-specific SPR target value (SPR_T) and two five percent deviations. I computed 1,000 simulations for each scenario to incorporate uncertainty inherent to the MSE model.

Operating Model Structure

I constructed an age-structured operating model to represent the Spotted Seatrout population and fishery in each state in the north-central GOM. State-specific fisheries included a fleet associated with harvest and a fleet for dead discards. The model represented growth and mortality of Spotted Seatrout from the approximate size of release by hatcheries (30 mm) to recruitment at age-1, and subsequent adult stages. I assumed Spotted Seatrout were born on July 1 and join the age-1 year class the following

July 1. Growth of age-0 individuals during the first six months was represented with a linear equation developed by Powell et al. (2004):

$$L_t = -10.56 + .8834\,t\ , (18)$$

where L_t is standard length (mm) and t is age in days. I converted standard length (SL, mm) for age-0 individuals to total length (TL, mm) using the equation developed by Hein et al. (1980):

$$TL = \frac{SL+2.0520}{0.8369}\ . (19)$$

The growth of Spotted Seatrout after 6 months was represented using equation 2 with parameter estimates L_∞, k, and t_0 derived from fisheries-independent sampling in Alabama. Mortality prior to recruitment was calculated on a weekly basis using equation 4. I converted the rate of natural mortality (15 y^{-1}) for a one cm individual estimated by Lorenzen (2005) to a weekly rate (0.29 w^{-1}) to accommodate the approximately 21 week period between release and age-1 recruitment. Based on the number of hatchery fish to be released for a given management strategy, I used equations 7, 8, and 9 to calculate the number of individuals that survive from 30 mm in length to join age-1 adults on January 1st.

State-specific total mortality-at-age was modeled as the sum of age-, fleet-, and state-specific fishing mortality (F_{agjy}, y^{-1}) and natural mortality-at-age (M_a, y^{-1}) using equations 10 and 11. Male and female mortality rate estimates were combined. I used the mean male and female length-at-age values derived from Alabama fisheries-independent samples to describe the length-at-age relationship used in the operating model. Natural mortality-at-age for recruited individuals was calculated using equation 20 with M_1 parameter value (15 y^{-1}). Natural mortality was temporally and spatially invariant.

I represented age-, fleet-, and state-specific fishing mortality (F_{agjy},y^{-1}) as the product of selectivity (S_{agjy}) and a fishing mortality multiplier ($FMult_{jg}$) using equation eight. I determined fishing mortality multiplier values ($FMult_{jg}$) for the operating model using the average of the terminal five $FMult_{jg}$ values estimated by my initial assessment of Spotted Seatrout population dynamics. Age- and fleet- specific selectivity values were inferred based on specific minimum length limits (Table 9) consistent with estimates by Fulford and Hendon (2010). Selectivity estimates assumed that anglers comply with regulations and there is no undersized harvest. Selectivity for fleets associated with dead discards was the inverse of selectivity for fleets representing the harvest of Spotted Seatrout. Over the time series in each simulation, selectivity varied based on the minimum length limit imposed for a given year.

I addressed the lack of an informative stock-recruitment relationship for Spotted Seatrout by treating recruitment as a random variable. I used bootstrap resampling to select year- and state-specific recruitment values from those estimated by the initial assessment of the stock. To provide consistency in comparisons of alternate management strategies, I used the same 1,000 time series of state-specific recruitment values used in base scenario simulations for the 18 alternate scenarios.

For the first year of the simulation, numbers at age were calculated for each state using the exponential decay equation:

$$N_{a+1,g,y+1} = N_{ajy}e^{-Z_{ajy}} \text{, (24)}$$

where N_{ajy} is age-, state-, and year-specific numbers-at-age and Z_{ajy} is age-, state-, and year-specific total mortality. Numbers-at-age for subsequent years were calculated using equations 12 and 13. State- and fleet-specific catch-at-age (C_{agjy}) was calculated using equation 14. Catch for discard fleets was interpreted as the number of dead discards.

The enhancement effect associated with reducing the discard mortality rate was determined by calculating the number of released Spotted Seatrout at age (R_{ajy}) from the number of dead discards prior to the rate adjustment (C_{ajy}):

$$R_{ajy} = \frac{C_{ajy}}{0.1}, (28)$$

and the number of dead discards after the rate adjustment (NDD_{ajy}) using the new discard mortality rate (DM):

$$NDD_{ajy} = R_{ajy} \times DM. (29)$$

I subtracted the difference between the number of dead discards before the rate adjustment from those after the rate adjustment, and added them to the numbers-at-age.

Estimation and Assessment Model

Estimation and assessment components of the simulation determined the annual fishing regulations in the operating model. I used SPR as a reference point for monitoring the magnitude of fishing mortality for each state-specific stock. Data used by the assessment model included state-specific annual catch, an index of abundance, and age composition for both the catch and index. Because I evaluated management strategies that were independent of stock size, estimation components of the MSE collected the necessary data from the operating model without error. State-specific annual abundance indices (I_{jy}) were calculated by summing state-specific numbers-at-age (N_{ajy}):

$$I_{jy} = \sum N_{ajy}. (30)$$

Annual catch (AC_{jy}) was calculated by summing state-specific catch-at-age (C_{ajy}):

$$AC_{jy} = \sum C_{ajy}. \quad (31)$$

Numbers-at-age, sourced directly from state-specific values in the operating model, represented age composition for state-specific fleets and abundance indices.

I used SS3 to assess state-specific stocks every third year of the 30 year projection. Few stock assessments have been conducted for Spotted Seatrout in the three states in the past decade, so I determined the frequency of assessments in the operating model to insure a balance between consistent monitoring of the resource and computation efficiency. The assessment model included a single fishing fleet and abundance index. The fishing fleet included in the assessment model represented the mortality associated with the state-specific fishing fleet simulated in the operating model. Submodels describing stock-recruitment and life-history relationships including natural mortality, fecundity, maturity, length-at-age, and weight-at-length used in each assessment were identical to the initial assessment conducted at the beginning of this study. I used initial parameter values for each state-specific assessment that were consistent with true parameter values contained in the operating model. Assessment models were fit to the data using maximum likelihood estimation and convergence was assessed using the final gradient value calculated by a gradient decent algorithm.

Fishing regulations were allowed to vary after each assessment of state-specific stocks. Adjustments to regulations were made provided that terminal SPR was substantially above or below the target value and was not exhibiting a self-correcting pattern. To evaluate for a self-correcting pattern, I used linear regression fit with ordinary least squares (OLS) estimation to determine the slope of terminal five SPR values. The minimum length limit was increased by one inch if the terminal SPR value for a given state was less than five percent below the state-specific target SPR value and the terminal five SPR values had a slope less than 0.005. The opposite occurred if the terminal SPR value was larger than five percent above the state-specific target SPR value and the terminal five SPR values had a slope greater than -0.005. Each simulation began with the same state-specific minimum length regulations that were in place during the 2017 fishing season.

Model Output

Eighteen alternate management scenarios were compared to a base scenario based on the terminal annual values of three metrics including harvest, proportion of age-3 or older individuals in the stock (PA3), and spawning stock biomass (SSB). Base scenarios simulated management strategies without enhancement. Comparisons were conducted for scenarios where the state-specific SPR target values were equal. I subtracted terminal values of the three metrics associated with a single simulation of an alternate scenario from a single simulation associated with a base scenario. Each comparison was conducted for simulations with the same time series of bootstrapped recruitment. I reported the number of simulations that exhibited a 10 percent increase in the three metrics as a proportion of the total simulations I conducted for each alternate management scenario.

Scenario Analysis

The parameter estimate for M_1 (15 y^{-1}) used to describe natural mortality as a function of length is an estimate derived from metanalyses of stocking experiments (Lorenzen 2000) and has considerable uncertainty in its accuracy to describe the natural mortality of Spotted Seatrout. The mortality of age-0 Spotted Seatrout is particularly uncertain. As limited information exists to inform the development of probability density functions that could be used to incorporate uncertainty in M_1 into the MSE, I evaluated the change in model results associated with changes in the M_1 parameter for age-0 individuals. Two alternate M_1 parameter values were selected based on the associated survival of age-0 Spotted Seatrout; M_1 at 10 y^{-1} corresponded to 49% survival and M_1 at 20 y^{-1} corresponded to 24% survival. I conducted 100 trials for a stock enhancement program releasing two million individuals each year and a two percent reduction in discard mortality at M_1 values of 10 and 20 y^{-1}. Results were compared to those measured for scenarios without stock enhancement and a discard mortality rate of 10% at M_1 values of 10 and 20 y^{-1}. The difference in model results given the change in M_1 indicated the expected outcome under alternate values of the parameter estimate.

RESULTS

ASSESSMENT OF SPOTTED SEATROUT POPULATION DYNAMICS

The SS3 model fit using MLE exhibited a good fit to the data. Standard error for catch was set very low (0.01), so the predicted catch values deviated very little from observed catch (Figure 2, Figure 3). The model fit the indices of abundance for each state moderately well (Figure 4), with no obvious patterns (sequences of positive and negative values) to the residuals. The indices for Mississippi and Louisiana exhibited a decrease in values throughout the time series, however the index for Alabama increased over time. The predicted age composition of the fishery in each state matched the observed values, with the exception of the age composition from Louisiana (Figure 5). Two-year-old Spotted Seatrout constitute the majority of the landings in the three states and those older than age-four comprise a very small percentage of the landings.

Instantaneous fishing mortality (F, y^{-1}) for fleets associated with harvest in Louisiana, Mississippi, and Alabama exhibited similar temporal trends; an increase during the time series (Figure 6). Spotted Seatrout in Mississippi and Louisiana experienced the greatest fishing mortality within the terminal two years of the analysis. Louisiana exhibited the highest F y^{-1} values during the time series and Alabama exhibited the lowest. The mean terminal five-year fishing mortality rates in Louisiana, Mississippi, and Alabama were F = 1.69, 1.45, and 0.99 y^{-1} respectively. Fishing mortality for fleets associated with discard mortality was very low relative to mortality rates associated with harvest; mean terminal five-year rates for Louisiana, Mississippi, and Alabama were F = 0.03, 0.04, and 0.05 y^{-1} respectively (Figure 7). The discard fleet in Alabama exhibited the highest variability in annual F values and the highest mean F value. During the period of 2011 to 2013, the fishing mortality associated with discard mortality increased in all three states.

SPR estimates followed the pattern of increasing fishing mortality through the time series. I estimated terminal SPR in Louisiana, Mississippi, and Alabama at 14%, 26%, and 25% respectively. Estimates for Louisiana and Alabama were below their respective state’s limit reference point value (Table 1), indicating that in 2013, both stocks were experiencing overfishing.

The model predicted a decline in stock biomass in Louisiana from 1993 to 2002, and from 2006 to 2013 because of the increase in fishing mortality in the region (Figure 8). Predicted stock biomass in Alabama increased during the period of 1993 to 1999 and 2004 to 2010, peaking in 2010. The periods of increasing stock biomass in Alabama parallel a similar increase in the predicted abundance of age-0 recruits that occurred over the same period of time (Figure 9). Predicted stock biomass in Mississippi exhibited a gradual increase over the time series, peaking in 2008 (Figure 8), the same year that exhibits a peak in the abundance of age-0 recruits. The correlation between stock biomass and recruit abundance was relatively high in Alabama ($r = 0.83$) compared to Mississippi ($r = 0.69$) or Louisiana ($r = 0.53$). Recruit abundance in Alabama was also more variable (CV = 0.34) over the time series than in Mississippi (CV = 0.24) or Louisiana (CV = 0.06).

EVALUATION OF ALTERNATE MANAGEMENT STRATEGIES

I compared terminal year measurements of harvest, SSB, and PA3 for scenarios of alternate strategies and a base scenario. For each comparison, I summarize model output below by reporting the predicted mean increase of each performance metric and the predicted probability of increasing each metric by 10%. Results indicate the expected efficacy of each alternate strategy.

Base Level Target SPR Scenarios

Trials for scenarios at base level SPR target values indicated that stock enhancement had a greater predicted probability of increasing the performance metrics harvest, SSB, and PA3 by 10% than did reducing the discard mortality rate. In general, stock enhancement was more effective in increasing harvest and SSB in simulations than PA3 (Table 10, Table 11). The reverse was true for reducing discard mortality. Reduction of discard mortality resulted in a higher probability of increasing PA3 than harvest or SSB. The MSE model predicted that the maximum reduction in discard mortality rate had a less than seven percent chance of increasing performance metrics by 10% in any state. In contrast, maximum hatchery input was predicted to increase performance metrics in some states by 10% with near 100% probability. However, the anticipated efficacy of stock enhancement and reducing discard mortality was geographically variable. Both strategies were most effective in increasing performance metrics in Alabama and least effective in Louisiana. Model results for the increase in performance metrics expected given each alternate management strategy exhibited greater variability in Alabama and Mississippi than Louisiana. Despite observed variability in efficacy, stock enhancement and reductions in discard mortality resulted in increases in the mean value of each of the performance metrics in every state.

Model results for Alabama predict improvements to the stock and fishery with annual hatchery input from one to five million individuals. Simulations that released one million individuals annually had a 51% probability of increasing harvest by 10% (Table 10). For simulations with annual releases of two and five million individuals, the model predicted a very high probability of increasing all three metrics by 10%. Scenarios that employed hatchery input exhibited roughly the same probability of increasing harvest by 10% as SSB. Only at release levels greater than one million did hatchery input scenarios result in an increase of the predicted PA3 with a probability greater than 50%. The mean values for the increase in harvest, SSB, and PA3 expected for annual releases of one million were 10%, 10%, and 6% respectively; the predicted mean increases in the three metrics for scenarios with stockings of two and five million were roughly two and five times the former values respectively. The interquartile range of the expected proportional change in harvest, SSB, and PA3 increased with increasing magnitude of hatchery input (Figure 11). At annual releases of five million individuals, the predicted mean increase in harvest was dramatically higher than at lower hatchery input scenarios. Reducing the discard mortality rate by one percent resulted in a zero predicted probability of increasing harvest by 10%, and a one percent predicted probability of increasing the remaining metrics by the same margin (Table 10). Only a reduction in the discard mortality rate of five percent was expected to have a greater than two percent probability of increasing the three metrics by 10% and a mean increase in any of the three metrics greater than one percent. The interquartile range observed for the proportional change in harvest, SSB, and PA3 was very small relative to that for stock enhancement (Figure 11). Reducing discard mortality by five percent resulted in a predicted mean increase in the three metrics between three and four percent.

In Mississippi, only scenarios that employed high annual hatchery input were expected to have a high probability of improving the stock and fishery. Simulations for scenarios that released one million individuals annually predicted an eight percent probability of increasing harvest by 10% and roughly the same probability of increasing SSB and PA3 by the same margin (Table 11). The MSE model predicted a mean increase in harvest, SSB, and PA3 of seven, eight, and six percent respectively at annual releases of one million. Scenarios that released two and five million individuals annually had a higher predicted probability of increasing harvest and SSB by 10% than at one million individuals. The mean values for the predicted increase in each metric at two and five million individuals were proportionally larger than the mean values associated with stocking one million individuals. The predicted probability of increasing PA3 by 10% was less than 50% for all stock enhancement scenarios with annual releases less than five million. The interquartile range for the proportional change expected in harvest, SSB, and PA3 increased with the magnitude of the annual release of Spotted Seatrout (Figure 12);

at an annual release of five million, the interquartile range for the proportional change in PA3 was over four times that for an annual release of one million. Simulations that reduced the discard mortality rate by one percent predicted a zero probability of increasing harvest by 10%, and a one percent probability of increasing the remaining metrics by the same margin (Table 11). At a two and five percent reduction in the discard mortality rate, model results exhibited an anticipated one and two percent probability of increasing all three metrics respectively. The maximum mean increase in each of the three performance metrics predicted by the MSE model was between one and two percent. The interquartile range for the proportional change in each of the three metrics for scenarios at a reduced discard mortality rate was very low (Figure 12). Outliers were present in the boxplot of the proportional change in metrics for all scenarios; the most distinct groups were observed for the change in PA3.

Stock enhancement and reducing discard mortality exhibited minimal impacts on harvest, SSB, and PA3 for simulations in Louisiana. The MSE model predicted a zero probability of increasing any performance metric by 10% for any of the scenarios evaluated. Only simulations for stock enhancement scenarios with annual releases of five million resulted in a predicted mean increase in the three metrics greater than two percent. The predicted benefits of reducing discard mortality were similar in magnitude to the benefits of stock enhancement in Louisiana as the other two states. The MSE model predicted greater increases in harvest and SSB for a five percent reduction in discard mortality than for scenarios that released one million hatchery-reared individuals (Figure 13). The predicted mean increase in the three metrics for a reduction in discard mortality of five percent was the lowest of the three states from one to a half percent. The interquartile range for the proportional change in the three metrics was much smaller for Louisiana than for Mississippi or Alabama. Additionally, in contrast to Mississippi and Alabama, no outliers were present in a boxplot of the proportional change in the three metrics.

The predicted proportional change in harvest, SSB, and PA3 exhibited by the MSE model was temporally invariant except for scenarios with the highest levels of stock enhancement and reduction in discard mortality. At annual releases of five million individuals, the predicted mean annual change in PA3 increased over time in Mississippi, but decreased over time in Alabama (Figure 14). The mean annual change in SSB predicted for both states remained static, indicating that the benefit of stocking on the age composition of the stock changed over time irrespective of SSB. At a reduction in the discard mortality rate of five percent, the predicted change in SSB and PA3 in Alabama increased through the time series (Figure 15). In contrast, the expected change in PA3 values in Mississippi peaked in the middle of the time series.

Stock assessments conducted every three years during the MSE projection estimated SPR values that were used to inform regulatory changes. Predicted catch, age composition, and indices of abundance from each state-specific assessment matched the simulated data from the operating model. Annual minimum length regulations imposed by each state for the base scenario varied among simulations (Figure 10). In Louisiana, minimum length limits always increased through the projection. Simulations in Alabama exhibited minimum length limits greater than or equal to the starting limit of 14 inches, and the largest variability in length limits among the three states. Among the three states, minimum length limits only decreased from the starting value in Mississippi. The majority of simulations in the state exhibited a constant 15-inch minimum length limit. Annual minimum length limits employed by each state for scenarios with enhancement strategies rarely deviated from those in place during the base scenario, except for scenarios that exhibited the largest magnitude of enhancement. The mean annual deviation in minimum length limits did not vary from zero for any scenario in each of the three states, but the standard deviation of minimum length limit deviations was highest for annual releases of five million.

Alternate Target SPR Scenarios

Scenarios where the target SPR values were five percent higher or lower than those employed by natural resource management agencies in the three states exhibited very similar results as scenarios with base level target SPR values (Table 10, Table 11). At low target values, stock enhancement scenarios predicted a slightly higher probability of increasing SSB and PA3 by 10% than at high or base target values in both Mississippi and Alabama. The difference in the predicted probability of increasing each of the three metrics by 10% was within two percent for scenarios where the discard mortality rate was reduced.

Management scenarios evaluated with alternate target SPR values and no enhancement exhibited a high predicted probability of altering SSB and PA3, or harvest when compared to the scenario at base target values, but not all three simultaneously. By reducing the target values by five percent, model results predicted a 43% and 64% probability of increasing harvest by 10% in Mississippi and Alabama respectively, but a zero probability of increasing the remaining metrics by the same margin (Table 12). The MSE model predicted a very low probability of a 10% increase in harvest by reducing the

SPR target value in Louisiana. In contrast, increasing target values by five percent yielded a very high expected probability of increasing SSB and PA3 by 10% in Louisiana. Mississippi and Alabama exhibited a 65% and 51% predicted probability of increasing SSB and PA3 by 10% respectively. Model results predicted a zero probability of increasing harvest by 10% in any state by increasing the target SPR values.

Scenario Analysis

The anticipated increase in annual harvest, SSB, and PA3 associated with hatchery input of two million individuals was moderately sensitive to a change in the M_1 parameter value for age-0 individuals. In Alabama, the mean increase in harvest and SSB measured during stock enhancement simulations was 20% and five percent lower respectively at high M_1 than low M_1 (Figure 16). In contrast, the expected mean increase in PA3 was 30% higher at a high M_1 value than low M_1. Model results for Mississippi were sensitive to the M_1 values with a similar magnitude (Figure 17); the mean increase in harvest and SSB measured during stock enhancement simulations was seven percent and 13% lower respectively at high M_1. The mean increase in PA3 expected with hatchery input was also three percent higher for high M_1 in Mississippi. In Louisiana, the predicted mean increase in harvest and SSB was 10% lower at high M_1 than low M_1, but the mean increase in PA3 was 10% higher (Figure 18).

The increase in the three metrics expected by reducing discard mortality by two percent was also moderately sensitive to a change in the M_1 parameter. In Alabama, the predicted mean increase in harvest and SSB was 22% and 9 percent lower respectively at high M_1 values than low M_1 values. The mean increase in harvest and SSB was the largest for Louisiana (25%) and was lower for Mississippi (12%). PA3 measurements were the most sensitive in Louisiana and Mississippi.

DISCUSSION

Understanding the expected benefits of management strategies is critical for effective management (Holland 2010). The purpose of this study was to provide an objective evaluation of the efficacy of alternate management strategies for Spotted Seatrout in Louisiana, Mississippi, and Alabama. I present a quantitative assessment of Spotted Seatrout population dynamics in the region and a comparison of performance metrics that allow the estimation of anticipated benefits of changes to management strategies. The efficacy of management strategies varied substantially by technique and geographic region. Scenarios with a high hatchery input exhibited the highest expected benefit to the stock and fishery in each state; reducing discard mortality had a substantially lesser predicted effect. MSE model results indicate that the expected outcome of alternate management strategies is highly variable by state in the north-central Gulf of Mexico. Characteristics of the stock and fishery in the three states described during the assessment of Spotted Seatrout population dynamics provided information to describe the observed geographic variability in MSE model results. States with a large stock size such as Louisiana exhibited the lowest potential benefit from the management alternatives evaluated. Key fishery characteristics included the proportion of fishing mortality due to discarding, and the minimum length limit imposed by managers. Discrepancies observed between model results from the assessment of Spotted Seatrout population dynamics conducted in this study, and model results from state-specific stock assessments, provides insight into the effect of contrasting model structure and the inclusion of revised data. The differences in assessment modeling methods that I used included assuming a single unit stock, allowing recruitment allocation among states to vary over time, and using the best available data.

Model results for comparisons of scenarios with contrasting target SPR values without enhancement illustrated the advantage of employing alternate management strategies alongside effort control; simply adjusting the SPR target values was unable to cause an increase in both harvest and SSB. All strategies that included hatchery input or a reduction in discard mortality increased the annual harvest, SSB, and PA3 relative to the base scenario. The magnitude of benefits expected from each strategy have implications for management of Spotted Seatrout in each of the three states.

The high probability of increasing harvest and SSB in Mississippi and Alabama expected by releasing more than one million individuals implies that stock enhancement programs in the two states should set annual production goals accordingly. It is possible that a stock enhancement program releasing one million annually in Alabama would increase harvest and SSB by 10%, but at releases of two million individuals, nearly every trial increased the two metrics by the same margin. The high predicted probability of increasing performance metrics in Mississippi and Alabama given the release of five million individuals indicates that without density-dependence in the growth or mortality of the stock, the strategy offers substantial benefits to the fishery and stock. Density-dependent growth and mortality are central processes in assessing the potential gain associated with hatchery input to wild stocks, but are poorly understood (Lorenzen 2005). Assessment methodology for enhancement strategies developed by Lorenzen (1995, 2000) uses information from the stock-recruitment relationship to imply the degree of density-dependent influence on growth and mortality of early juvenile stages. In these simulations, density-dependent impacts were omitted because assessment scientists assume a minimal relationship between SSB and recruitment for Spotted Seatrout and state-specific stock biomass estimates are low relative to a virgin state (West et al. 2014; Bohaboy et al. 2018; Leaf 2018). At high hatchery input, especially for annual releases of five million individuals, the assumption of density-independent growth and mortality may not be accurate, so the performance measures of high input stock enhancement programs should be used with caution.

Louisiana did not realize the benefits in the proportional increase in performance metrics from stock enhancement in equal magnitude to those realized by Mississippi and Alabama. However, the magnitude of the absolute increase in harvest caused by stock enhancement was greatest in Louisiana. Louisiana exhibited the highest fishing mortality rate and the lowest minimum length limit of the three states that allowed the large representation of hatchery input in harvest. The very small proportional increase in the three metrics observed in Louisiana implies that potential stock enhancement programs should pursue annual production goals much larger than five million individuals. The observed efficacy of stock enhancement strategies in each state was largely driven by the magnitude of the number of hatchery-reared individuals released annually relative to the number of wild age-0 recruits in each state’s stock. Stock enhancement had the largest impact on performance metrics in Alabama that exhibited the lowest annual recruitment of the three states. One million individuals released annually in Alabama was approximately 15% of the mean recruitment of 6.53 million individuals. The high predicted probability of increasing the three performance metrics with annual releases of two million individuals in Mississippi and Alabama corresponds to roughly a 22% to 30% increase in age-0 individuals through stocking. To achieve a similar percent increase in age-0 recruitment through stocking in Louisiana, annual hatchery input would need to be between 19 and 26 million individuals. The minimal impact of stock enhancement in the increase of performance metrics for Louisiana was likely due to such a high mean annual recruitment of 89 million individuals.

Reducing discard mortality offered benefits to the stock and the fishery by allowing a greater percentage of released catch to return to the stock than at base discard mortality. Even at the maximum reduction in discard mortality evaluated, very few trials increased performance metrics by 10% in any of the three states. In contrast to stock enhancement programs, the abundance of recruits was an unlikely driver of the efficacy of reducing discard mortality. The magnitude of fishing mortality associated with discarding had a large impact on the effectiveness of reducing discard mortality. Managers in Mississippi and Alabama regulate the respective stocks with greater minimum length limits than Louisiana, so the fishing mortality due to discarding in the two states was a higher percentage of the total fishing mortality than in Louisiana. The effects of minimum length limits on discarding and the benefits of reducing the discard mortality rate were evident in the roughly two-fold increase in mean performance metrics in Mississippi and Alabama relative to Louisiana. Reducing discard mortality was better able to increase PA3 than harvest or SSB; this result illustrates an advantage of mitigating mortality in the fishery over increasing recruitment abundance by stock enhancement. Released individuals were already recruited to the fishery, so they were not subject to the high natural mortality expected at a smaller length (Lorenzen 2005). Despite a large percentage of released individuals that survived due to lower discard mortality were able to be caught by the fishery or contribute to the spawning stock, the estimated magnitude of individuals added to stock and fishery was low relative to the magnitude added by stock enhancement. The model predicted reductions in discard mortality from one to five percent resulted in increases to the abundance of the age-one year class between 28,000 and 144,000 thousand individuals in Mississippi and Alabama. In Louisiana, the model predicted increases to the abundance of the age-one class between 171,000 and 862,000. In contrast, the model predicted stock enhancement contributed between 352,000 and 1,760,000 individuals to the age-one class in each state. The positive correlation between minimum length limits and the efficacy of reducing discard mortality indicates that if managers impose higher length limits to restrict fishing effort in the future, reducing discard mortality would be a more effective strategy than observed in this analysis.

I observed minimal temporal variation in performance metrics in this study. Because the stock-recruitment relationship is not strong for Spotted Seatrout, the design of the MSE model limits the ability of increased SSB to cause an increase in recruit abundance. Any temporal variability observed was likely due to the adjustment of fishing regulations by the MSE model that allowed minimum length limits to change based on annual SPR estimates. Fluctuations in the mean annual change of PA3 in Mississippi and Alabama followed the average trend of respective decreasing and increasing minimum length limits. The change in minimum length limits over the simulated time series reflected the relationship between estimated fishing mortality, and the target SPR value. In Louisiana, where terminal SPR estimated at the beginning of this study exceeded the state’s target value of 18%, minimum length limits increased in all trials. Mississippi was the only state that exhibited a terminal SPR estimate above the state-specific target value, so minimum length limits never increased from the starting value. In Alabama, where the stock was estimated to be experiencing over fishing, minimum length limits increased in most simulations, exhibiting high variability. The high variability in recruitment expected in Alabama may have resulted in large fluctuations in SPR estimates over time despite the fixed fishing mortality multiplier used in the model. Minimum length limits determined from SPR estimates then exhibited the same variability in the state. The patterns of minimum length limits exhibited by each state in the based simulations show that reactive effort control results in far more adjustments to the minimum length limits than observed under current management regimes.

Minimum length limits rarely changed between the base scenario and scenarios under alternate management, indicating that benefits from stock enhancement or reducing discard mortality were not sufficient to allow less restrictive effort control. The high variability in changes to the minimum length limit observed for strategies with high hatchery input was a likely driver of the high variability of associated performance metrics. Despite the variation in minimum length limits, the flexibility of the length limits over the simulated time series had minimal impact on the relative efficacy of each strategy.

The efficacy of stock enhancement and reducing discard mortality did not vary substantially at alternate SPR target values. A reduction in SPR target values allowed slightly higher increases in SSB and PA3 by imposing higher minimum length limits that insured a smaller percentage of mature individuals were exposed to fishing mortality than at high SPR target values. The limited effect that the variation in SPR values had on the model results suggests that the biological characteristics of the stock may play a more crucial role in determining the efficacy of stock enhancement and reducing discard mortality than the fishery reference points established by decision-makers. Model results showed that reference point selection could have a substantial impact on the stock and fishery (Table 12), but under management regimes that employ contrasting reference points, alternate management strategies were not more or less effective.

The observation that model results were sensitive to the M_1 parameter value for age-0 individuals identifies a source of uncertainty in the estimates for the anticipated benefit of stock enhancement or reducing discard mortality. By altering the M_1 parameter for only age-0 individuals, I changed the shape of the power function describing the relationship between length and natural mortality; at high M_1 values, a greater percentage of smaller individuals died than at low M_1 values. Increasing the M_1 parameter reduced the expected benefit of stock enhancement on harvest and SSB by limiting the proportion of hatchery-reared to wild individuals that recruit to the age one year class. In contrast, I observed a higher increase in PA3 estimates at high M_1 parameters because older individuals made up a larger percentage of the stock. The sensitivity of model results in each state was positivity correlated with the mean age composition of each state-specific stock. Despite the uncertainty associated with model results that are sensitive to the M_1 parameter value, at a high estimate of M_1 I observed a considerable increase in the SSB and harvest for stock enhancement in Mississippi and Alabama.

I assumed hatchery-reared Spotted Seatrout exhibit the same natural mortality and growth as wild individuals; in some cases, hatchery-reared individuals show genetic and behavioral adaptations to the hatchery environment that are deleterious in the wild (Olla et al. 1998; Lorenzen 2000). While Hendon (2013) demonstrated that hatchery-reared Spotted Seatrout in Mississippi were able to transition to wild prey, their survival relative to wild individuals has not been evaluated. Due to a lack of knowledge of the relative survival of hatchery-reared Spotted Seatrout, the efficacy of stock enhancement reported in this study may overestimate the results expected in practice given current hatchery-rearing practices. Improvements to the release procedure, hatchery environment, and rearing techniques can substantially improve post-release survival of hatchery-reared fish (Patten 1977; Naslund 1992; Brown and Day 2002; Olla et al. 2004). To achieve results from stocking to a similar magnitude reported in this study, stock enhancement programs for Spotted Seatrout should make concerted efforts to ensure maximizing post-release survival as a priority.

Stock assessments for Spotted Seatrout in the three states use a Beverton-Holt steepness parameter value close to one based on the life-history characteristics of the species (West et al. 2014; Bohaboy et al. 2018; Leaf 2018); Spotted Seatrout grow rapidly (Dippold et al. 2016), mature sexually at a young age, and exhibit high fecundity (Brown-Peterson and Warren 2001). The parameter represents the proportion of virgin recruitment expected when SSB is 20% of its virgin state (Mangel et al. 2010). A steepness value close to one suggests little relationship between spawning stock biomass and annual recruitment (Lee et al. 2012) and implies density-independent mortality in early life stages. By bootstrapping annual recruitment at age-0 for each year in the operating model, I assumed that steepness never varies from one and density-independent factors such as environmental conditions drive annual recruitment entirely. Steepness probably varies over time, especially at very low stock sizes (Lee et al. 2012), but the extent to which steepness varies for Spotted Seatrout is unknown. Because mortality events that cause steepness to be one were assumed to influence the abundance of individuals joining the age-0 year class, hatchery-reared Spotted Seatrout released at 30 mm (estimated at 38 days old) were not subject to the same variability in survival. The operating model assumed hatchery-reared fish were large enough to avoid the mortality events that cause a high steepness parameter, but the specific early life stage at which such mortality events occur is unknown. Identifying the optimal size-at-release is a critical consideration for stock enhancement programs (Ray et al. 1994; Leber et al. 2005); the assumptions necessary in this study illustrate the critical nature to which age-0 mortality dynamics play in the efficacy of stock enhancement for Spotted Seatrout. I recommend assigning a high priority to understanding the growth and mortality of early life stages of Spotted Seatrout for future assessments of enhancement strategies.

The results of the assessment of population dynamics describe the difference in model results from state-specific assessments using an alternate model structure and revised data. The objective of the assessment I conducted was to estimate parameter values that could be used in a simulation model of the Spotted Seatrout stock and fishery. The objective was not to conduct a comprehensive stock assessment, so I did not evaluate derived quantities with retrospective or sensitivity analyses, nor did I insure model structure was consistent with previous studies. Alternate approaches in modeling techniques from state-specific assessments were based on the biological characteristics of the stock, rather than the structure of current management regimes. Derived quantities estimated during the assessment additionally offer insight into possible drivers of MSE results.

State-specific annual recruitment and *F* values estimated during the assessment of Spotted Seatrout population dynamics were consistently higher than estimates from state-specific stock assessments for the period of 1993 to 2013 (West et al. 2014; Bohaboy et al. 2018; Leaf 2018). The discrepancy in parameter estimates may be attributed to the difference in the magnitude of estimated catch caused by the comprehensive survey design change by MRIP. Estimated annual landings after the design change were on average 2.89 times larger in each state than those prior to the change due to increased efficiency of sampling anglers under the revised sampling plan. I adjusted the initial equilibrium catch to match the revised catch estimates from the first year of the time series, so the estimated number of individuals in the stock was substantially larger by including the new data. The estimates of spawning stock biomass were also impacted by the inclusion of the new MRIP data; estimates were much larger in each state when the new MRIP data were used. This analysis is the first published assessment of Spotted Seatrout in the north-central GOM using the revised MRIP data. Because the status of the Spotted Seatrout stocks is in part assessed using spawning stock biomass as a biological reference point and target reference points were established prior to the MRIP survey design change, decision-makers in the three states may need to revise target reference point values to reflect the newly available data. Estimated annual fishing mortality in each state was also larger on average than estimates from state-specific stock assessments, especially in Louisiana. Because the initial equilibrium catch was adjusted for the revised MRIP data, and the age composition for catch was unchanged, the inclusion of revised data was unlikely to have caused larger fishing mortality estimates. The number of recruits allocated to Mississippi and Alabama increased over time relative to Louisiana, so the relative decline in recruitment in Louisiana may explain the high fishing mortality estimates in the state. Temporal variation in recruitment allocation to each state allowed by the SS3 model was necessary to model the change in recruit abundance over time given a single stock structure. I assumed a single stock structure because although results from tagging studies show Spotted Seatrout in the region do not typically make substantial migrations (Hendon et al. 2002), a significant genetic delineation across the three states does not exist (Somerset and Saillant 2014). Additionally, the proximity of fishing grounds in each of the three states suggests a portion of the Spotted Seatrout caught in one state may be landed in another. The SS3 model fit the data well from six fleets, and three surveys in three areas; the flexibility of the SS3 model (e.g. variable recruitment allocation, inclusion of multiple areas) over the Age Structured Stock Assessment Program (ASAP) used by assessment scientists in Mississippi and Louisiana is an advantage for stock with a large spatial extent. Results suggest that fishing mortality and SSB estimates were sensitive to changes in model structure and catch data, and demonstrate the expected implications given similar changes to state-specific assessment methodology.

The magnitude of SSB is assumed to be a poor predictor of recruitment for Spotted Seatrout, but given the short life span of the species, recruitment may be a critical determinant of stock size in some states. In Alabama, the high correlation between estimates for recruitment and stock biomass relative to the other two states indicates that the abundance of early life stages of Spotted Seatrout may be more critical in supporting the sustainability of the stock than in Louisiana where the correlation was poor. Estimated landings nearly tripled in Alabama over the time series, so the above average recruitment experienced after 2005 played a crucial role in supporting the sustainability of such high landings. The observed benefit of above average recruitment on the stock and fishery is analogous to the effect expected from stock enhancement. The disproportionately high efficacy of hatchery input strategies in Alabama may in part be due to the expected role of recruitment in governing stock size. The critical role of recruitment in Alabama suggested by this study is corroborated by the results of Bohaboy et al. (2018) who reported that above average recruitment was a critical determinant of observed increases in stock size. Bohaboy et al. also found that the strong recruitment-stock size relationship was consistent after 2013, indicating that the pattern was not restricted to a short period. The correlation between estimates of recruitment and stock biomass in Mississippi was not high, however, the peaks in stock biomass and recruitment align, suggesting that years with very high recruitment support high stock biomass. The low correlation between recruitment and stock biomass in Louisiana points to another potential factor limiting the efficacy of hatchery input in the state; the abundance of age-0 recruits is a lesser predictor of stock size. Recruitment strength in estuarine fishes has been reported to be highly influenced by density-independent and environmental factors (Allen L.D. 1990; Martinho et al. 2009, 2012). Given the likely influence of environmentally driven effects on recruitment and uncertainty in the steepness parameter for the Beverton-Holt stock-recruitment relationship, improving the understanding of the recruitment dynamics of Spotted Seatrout is a critical area for future research. Should landings remain high, understanding the pattern of recruit abundance will be integral in the effective management of the fishery and understanding the potential efficacy of stock enhancement practices.

Table 1 *Fishing Regulations and Reference Point Values*

State	Minimum Length (in)	Bag Limit	Target SPR (%)
LA	12	25	18
MS	13	15	20
AL	14	10	30

Fishing regulations and the fishery reference points employed by natural resource management agencies for Spotted Seatrout in Louisiana (LA), Mississippi (MS), and Alabama (AL) during the period of 1993-2013.

Table 2 *Harvest Estimates*

	State		
Year	LA	MS	AL
1993	9367056	443783	324097
1994	13499091	350017	85599
1995	14143894	569400	179661
1996	13052565	719111	154221
1997	12960071	623962	186282
1998	13142399	827193	206971
1999	18491301	1130536	461277
2000	19337611	558718	623896
2001	16233366	811997	698668
2002	11175267	897643	622122
2003	12138716	537622	702241
2004	11612386	1656700	377325
2005	12117325	777775	531878
2006	15611145	1169155	610539
2007	13392951	668677	747758
2008	17832509	1788941	750577
2009	17958898	2215372	814252
2010	15582001	1421464	1576484
2011	19035440	1563166	1454975
2012	19410132	1394636	1395534
2013	16267462	1985166	1299327

Annual harvest estimates (numbers of individuals) of Spotted Seatrout in Louisiana, Mississippi, and Alabama.

Table 3 *Dead Discard Estimates*

	State		
Year	LA	MS	AL
1993	960598	74696	13540
1994	1030499	53028	5816
1995	952152	55192	13815
1996	1055136	142638	22815
1997	1325408	87844	26695
1998	1189923	98189	14376
1999	1606953	115033	65430
2000	1381987	114339	125101
2001	982951	146673	129852
2002	791897	132611	59065
2003	1239907	138262	92890
2004	1161582	225448	27431
2005	1206281	211121	59329
2006	1353854	257129	119944
2007	1109282	174587	100175
2008	1485878	264114	244463
2009	1520319	214535	199658
2010	1018647	164515	115196
2011	1096095	121809	257194
2012	1405536	207112	202976
2013	1915319	235376	200907

Annual dead discard estimates (numbers of individuals) of Spotted Seatrout in Louisiana, Mississippi, and Alabama.

Table 4 *Age-Length Key*

	Age					
TL (in)	1	2	3	4	5	6+
6	1.00	0.00	0.00	0.00	0.00	0.00
7	1.00	0.00	0.00	0.00	0.00	0.00
8	1.00	0.00	0.00	0.00	0.00	0.00
9	0.88	0.12	0.00	0.00	0.00	0.00
10	0.81	0.18	0.01	0.00	0.00	0.00
11	0.86	0.14	0.00	0.00	0.00	0.00
12	0.68	0.28	0.03	0.00	0.00	0.00
13	0.41	0.56	0.02	0.01	0.00	0.00
14	0.27	0.70	0.03	0.01	0.00	0.00
15	0.15	0.72	0.12	0.01	0.00	0.00
16	0.07	0.70	0.20	0.03	0.01	0.00
17	0.06	0.54	0.33	0.07	0.00	0.00
18	0.02	0.53	0.41	0.04	0.01	0.00
19	0.01	0.31	0.58	0.09	0.00	0.01
20	0.00	0.22	0.53	0.23	0.00	0.03
21	0.02	0.09	0.39	0.41	0.09	0.00
22	0.04	0.07	0.32	0.54	0.04	0.00
23	0.00	0.07	0.21	0.50	0.07	0.14
24	0.00	0.00	0.00	0.00	1.00	0.00
25	0.00	0.00	0.00	0.00	0.00	1.00
26	0.00	0.00	0.00	1.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00	1.00
28	0.00	0.00	0.00	0.00	0.00	1.00

Age-length key describing the proportions of Spotted Seatrout in each age class for a given length bin.

Table 5 *Harvest-At-Age in Louisiana*

	Age					
Year	1	2	3	4	5	6+
1993	28.19	57.69	11.10	2.92	0.31	0.17
1994	27.97	56.55	11.89	3.31	0.45	0.16
1995	26.38	57.35	12.27	3.49	0.49	0.44
1996	24.46	57.68	14.17	3.51	0.30	0.26
1997	26.88	57.13	12.22	3.15	0.46	0.50
1998	26.15	58.37	12.70	2.79	0.23	0.08
1999	25.37	55.84	13.86	4.10	0.76	0.42
2000	24.12	57.23	14.76	3.72	0.31	0.25
2001	23.56	55.91	15.16	4.49	0.74	0.54
2002	23.21	56.96	14.96	4.27	0.63	0.40
2003	26.30	57.41	12.47	3.42	0.43	0.31
2004	27.75	57.00	11.77	2.90	0.37	0.50
2005	28.00	58.76	10.92	2.36	0.24	0.09
2006	24.89	58.35	13.77	2.89	0.33	0.10
2007	25.90	57.50	13.10	3.23	0.44	0.20
2008	25.00	59.25	12.75	2.89	0.34	0.20
2009	27.12	58.61	11.36	2.56	0.41	0.31
2010	26.02	59.16	11.73	3.07	0.36	0.11
2011	20.84	59.32	15.39	4.12	0.50	0.30
2012	23.66	57.42	14.63	3.90	0.64	0.19
2013	25.68	59.19	12.13	2.88	0.29	0.25

Estimates of annual harvest-at-age of Spotted Seatrout in Louisiana.

Table 6 *Harvest-At-Age in Mississippi*

	Age					
Year	1	2	3	4	5	6+
1993	19.84	57.89	16.87	4.77	0.77	0.34
1994	26.40	54.12	14.80	4.20	0.30	0.45
1995	13.91	56.14	23.04	6.16	1.00	0.26
1996	17.16	58.00	19.28	5.31	0.62	0.17
1997	14.47	54.46	22.52	7.33	0.62	0.32
1998	18.65	63.08	13.64	3.74	0.39	1.09
1999	21.23	47.65	19.19	10.29	1.05	0.92
2000	14.66	58.36	19.25	5.98	1.75	0.56
2001	15.33	55.02	21.02	7.57	0.83	0.69
2002	14.14	54.37	23.25	7.31	0.68	0.70
2003	10.51	58.45	23.57	6.03	0.60	1.41
2004	19.55	61.23	15.24	3.11	0.26	0.98
2005	11.99	58.61	23.72	5.47	0.59	0.18
2006	11.86	58.87	23.35	5.22	0.64	0.60
2007	11.73	59.99	23.27	4.55	0.89	0.23
2008	20.00	57.29	18.35	4.13	0.39	0.27
2009	15.99	57.72	19.63	5.37	1.27	0.51
2010	15.16	52.03	21.56	7.92	0.90	2.86
2011	12.00	59.48	22.39	5.48	0.66	0.56
2012	17.91	54.67	21.54	5.60	0.43	0.29
2013	19.86	61.28	15.58	3.12	0.35	0.13

Estimates of annual harvest-at-age of Spotted Seatrout in Mississippi.

Table 7 *Harvest-At-Age in Alabama*

	Age					
Year	1	2	3	4	5	6+
1993	8.51	50.70	28.77	8.70	2.50	1.36
1994	25.42	59.41	11.13	4.04	0.40	0.05
1995	19.97	62.33	14.40	3.41	0.44	0.00
1996	10.14	51.18	27.25	5.92	5.67	0.45
1997	13.35	62.15	16.86	5.70	1.85	0.75
1998	13.10	48.05	24.04	9.70	1.05	4.48
1999	16.56	60.08	18.16	4.91	0.53	0.29
2000	11.74	53.28	27.66	7.00	0.59	0.30
2001	10.10	53.99	26.50	8.23	0.93	0.79
2002	7.45	51.19	29.80	9.48	0.98	1.65
2003	7.00	47.79	30.42	10.50	1.55	3.25
2004	7.76	53.88	27.31	9.52	0.99	1.11
2005	9.69	53.78	26.55	9.20	0.97	0.35
2006	9.02	51.84	29.30	8.63	0.76	1.05
2007	10.33	52.91	26.77	7.09	1.87	1.56
2008	9.98	56.13	23.86	9.09	1.25	0.36
2009	6.33	50.91	30.35	10.01	1.34	1.66
2010	6.90	49.64	29.74	11.18	2.42	0.77
2011	7.92	55.03	27.17	8.13	1.15	1.15
2012	7.68	53.91	28.15	8.76	1.32	0.79
2013	5.83	48.61	30.51	12.27	1.35	1.84

Estimates of annual harvest-at-age for Spotted Seatrout in Alabama.

Table 8 *Simulation Design Matrix*

Hatchery Input	Discard Mortality	Δ SPR	Trials
1 Million	10%	Base	1,000
2 Million	10%	Base	1,000
5 Million	10%	Base	1,000
None	9%	Base	1,000
None	8%	Base	1,000
None	5%	Base	1,000
1 Million	10%	-5%	1,000
2 Million	10%	-5%	1,000
5 Million	10%	-5%	1,000
None	9%	-5%	1,000
None	8%	-5%	1,000
None	5%	-5%	1,000
1 Million	10%	5%	1,000
2 Million	10%	5%	1,000
5 Million	10%	5%	1,000
None	9%	5%	1,000
None	8%	5%	1,000
None	5%	5%	1,000

Matrix design for the number of simulations to be conducted in the management strategy evaluation where enhancement is achieved through hatchery releases or decreasing the discard mortality rate, and fishing is controlled using contrasting SPR target values (SPR_T).

Table 9 *Age-Specific Selectivity*

		Minimum Length Limit (in)					
		11	12	13	14	15	16
	0	0	0	0	0	0	0
	1	1	0.9	0.8	0.6	0.3	0.1
Age (years)	2	1	1	1	1	0.9	0.7
	3	1	1	1	1	1	0.9
	4	1	1	1	1	1	1
	5	1	1	1	1	1	1
	6	1	1	1	1	1	1

Age-specific selectivity values associated with minimum length regulations.

Table 10 *Probability of Increasing Metrics in Alabama*

Hatchery Input	Discard Mortality	Δ SPR	Harvest	SSB	PA3
1 Million	10%	Base	51%	52%	4%
2 Million	10%	Base	97%	96%	61%
5 Million	10%	Base	100%	100%	89%
None	9%	Base	0%	1%	1%
None	8%	Base	0%	2%	2%
None	5%	Base	2%	4%	6%
1 Million	10%	-5%	52%	55%	7%
2 Million	10%	-5%	95%	100%	70%
5 Million	10%	-5%	100%	100%	99%
None	9%	-5%	0%	0%	0%
None	8%	-5%	0%	0%	1%
None	5%	-5%	0%	2%	3%
1 Million	10%	5%	51%	57%	7%
2 Million	10%	5%	92%	100%	66%
5 Million	10%	5%	99%	100%	100%
None	9%	5%	0%	1%	1%
None	8%	5%	0%	2%	2%
None	5%	5%	2%	4%	5%

Probability of increasing harvest, spawning stock biomass (SSB), and the proportion of age-three or older individuals (PA3) by 10% or more for each alternate management strategy evaluated in Alabama.

Table 11 *Probability of Increasing Metrics in Mississippi*

Hatchery Input	Discard Mortality	Δ SPR	Harvest	SSB	PA3
1 Million	10%	Base	8%	6%	6%
2 Million	10%	Base	90%	93%	46%
5 Million	10%	Base	99%	100%	93%
None	9%	Base	0%	1%	1%
None	8%	Base	1%	1%	1%
None	5%	Base	2%	2%	2%
1 Million	10%	-5%	4%	11%	9%
2 Million	10%	-5%	90%	100%	57%
5 Million	10%	-5%	100%	100%	100%
None	9%	-5%	0%	0%	0%
None	8%	-5%	0%	0%	0%
None	5%	-5%	0%	0%	0%
1 Million	10%	5%	6%	1%	0%
2 Million	10%	5%	99%	92%	35%
5 Million	10%	5%	100%	100%	85%
None	9%	5%	0%	0%	0%
None	8%	5%	0%	0%	0%
None	5%	5%	0%	1%	1%

Probability of increasing harvest, spawning stock biomass (SSB), and the proportion of age-three or older individuals (PA3) by 10% or more for each alternate management strategy evaluated in Mississippi.

Table 12 *Probability of Increasing Metrics using Alternate SPR Target Values*

State	Δ SPR	Harvest	SSB	PA3
LA	-5%	1%	0%	0%
MS	-5%	43%	0%	0%
AL	-5%	64%	0%	0%
LA	5%	0%	100%	100%
MS	5%	0%	65%	65%
AL	5%	0%	51%	51%

Probability of increasing harvest, spawning stock biomass (SSB), and the proportion of age-three or older individuals (PA3) by 10% or more using alternate SPR target values.

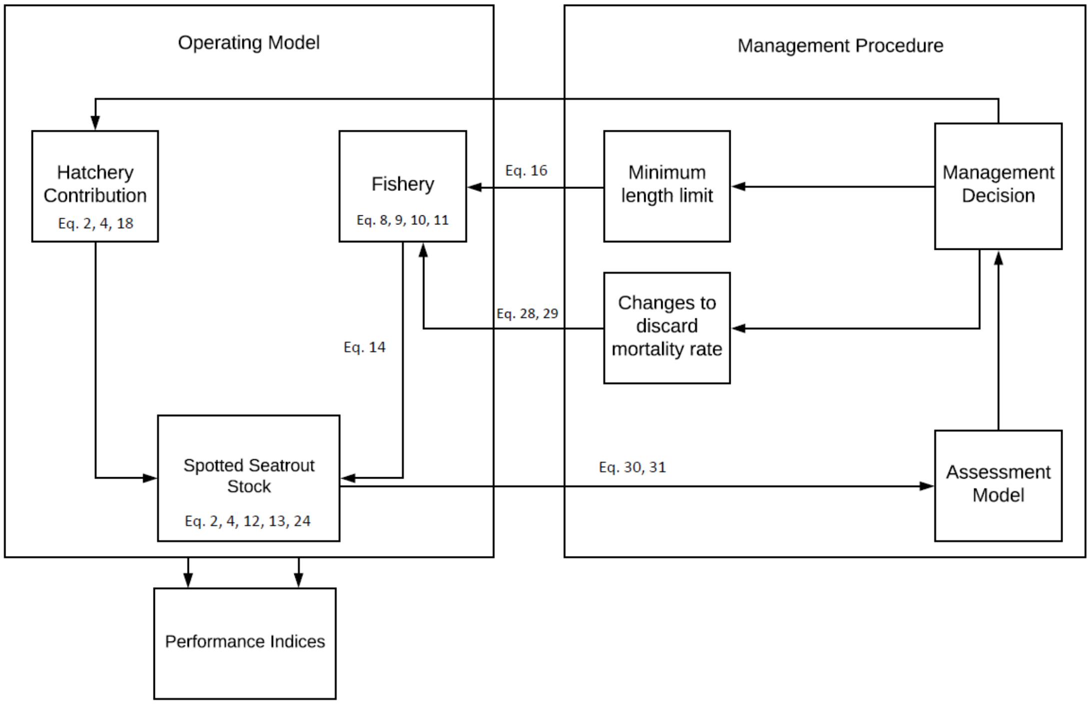

Figure 1. MSE Simulation Cycle

The MSE simulation cycle that describes the interaction of components of the operating model and the management procedure, including key equations used in the construction of each submodel.

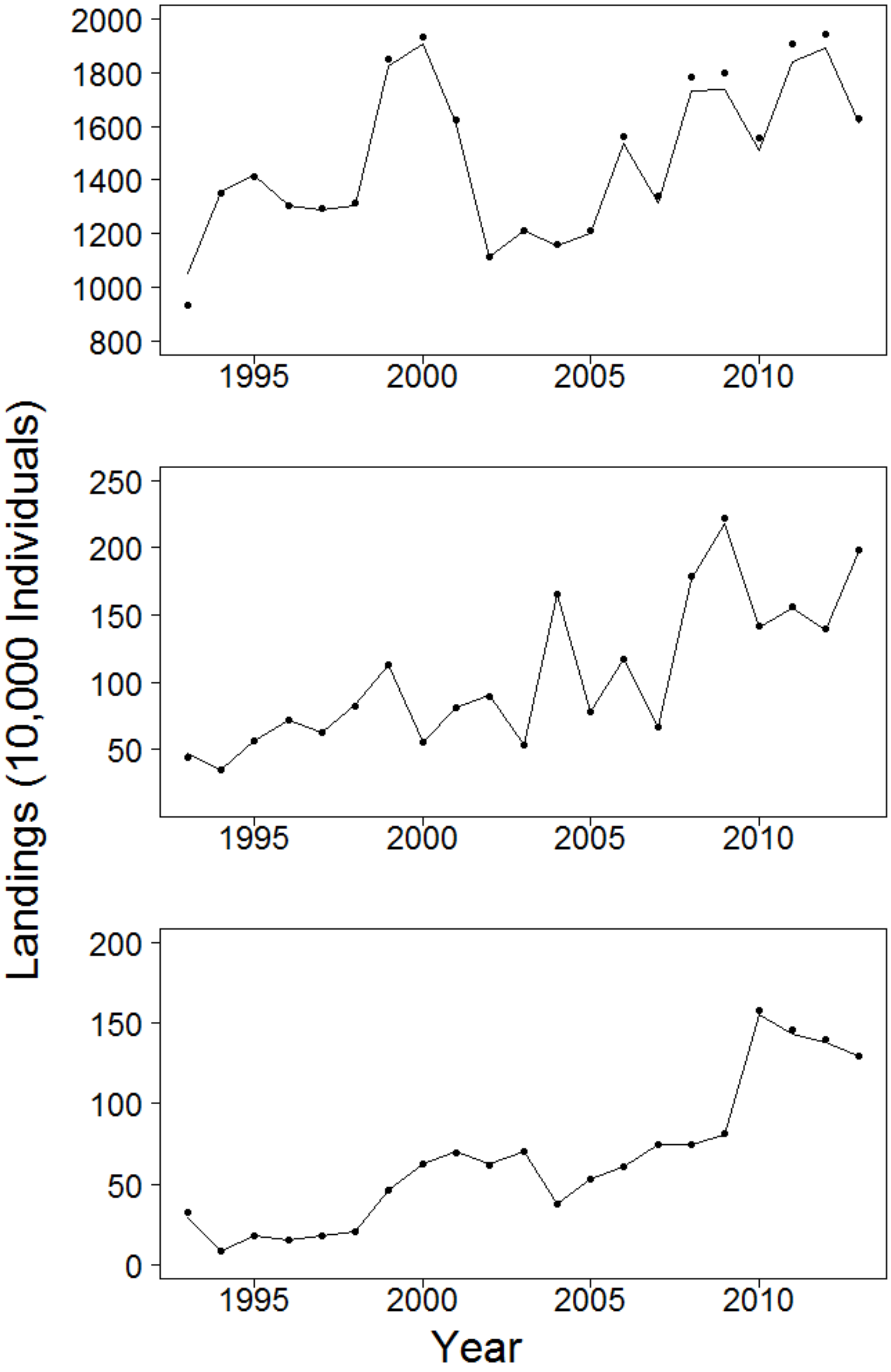

Figure 2. Landings for Harvest Fleets

Observed (points) and predicted (lines) landings for fleets associated with harvest in Louisiana (A), Mississippi (B), and Alabama (C).

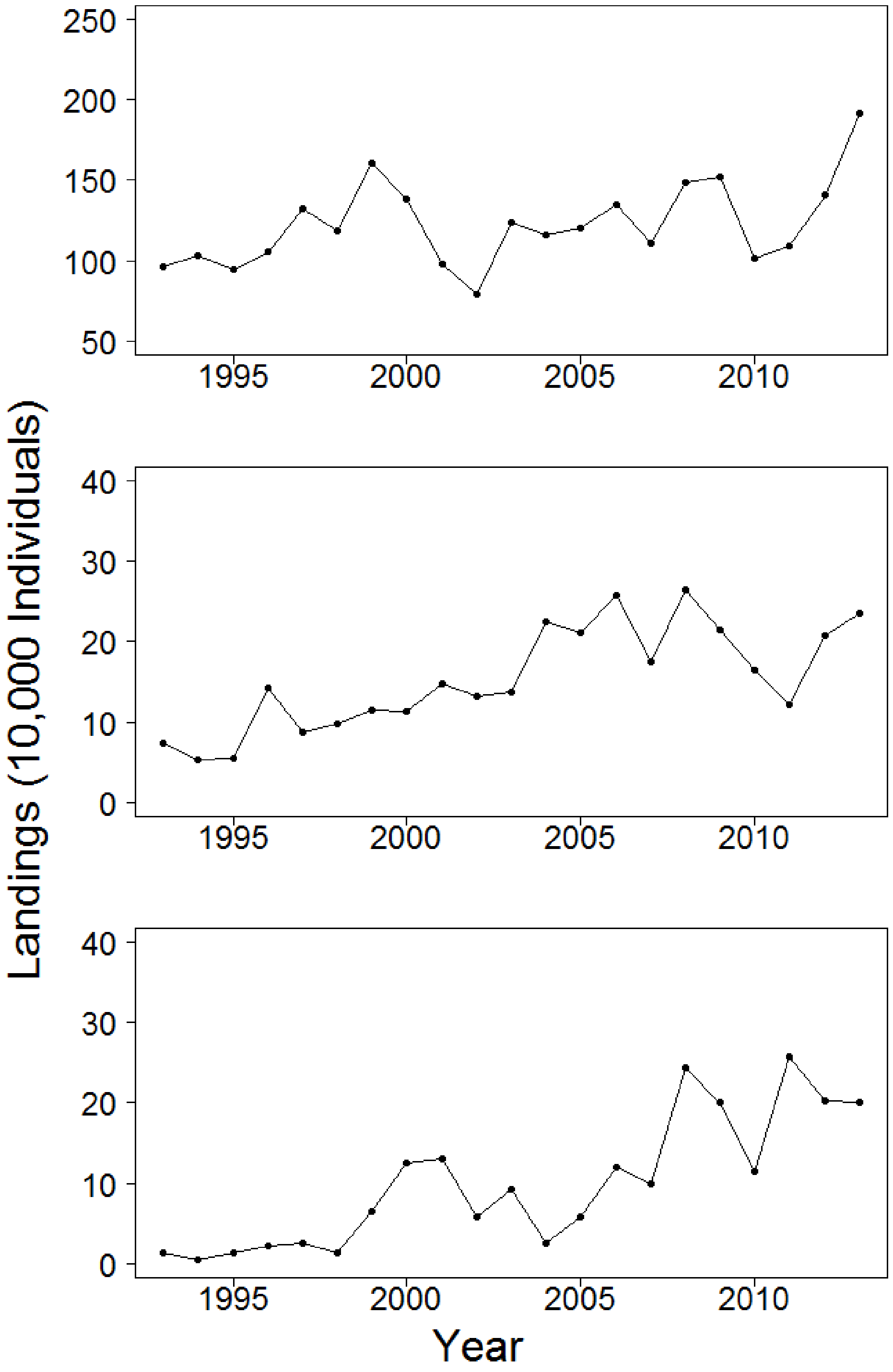

Figure 3. Landings for Discard Fleets

Observed (points) and predicted (lines) landings for fleets associated with discards in Louisiana (A), Mississippi (B), and Alabama (C).

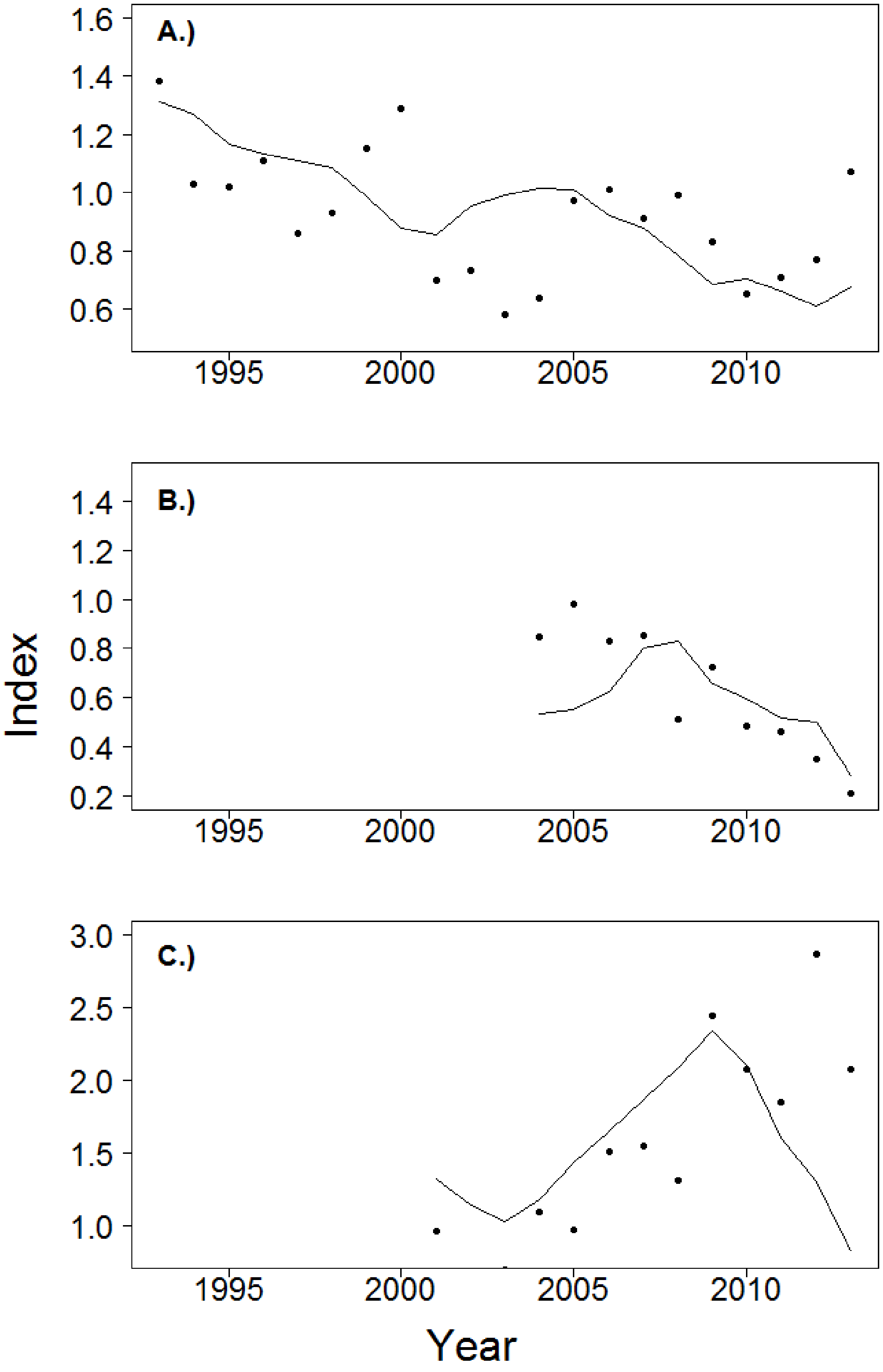

Figure 4. Indices of Abundance

Observed (points) and predicted (line) index of abundance for Spotted Seatrout in Louisiana (A), Mississippi (B), and Alabama (C).

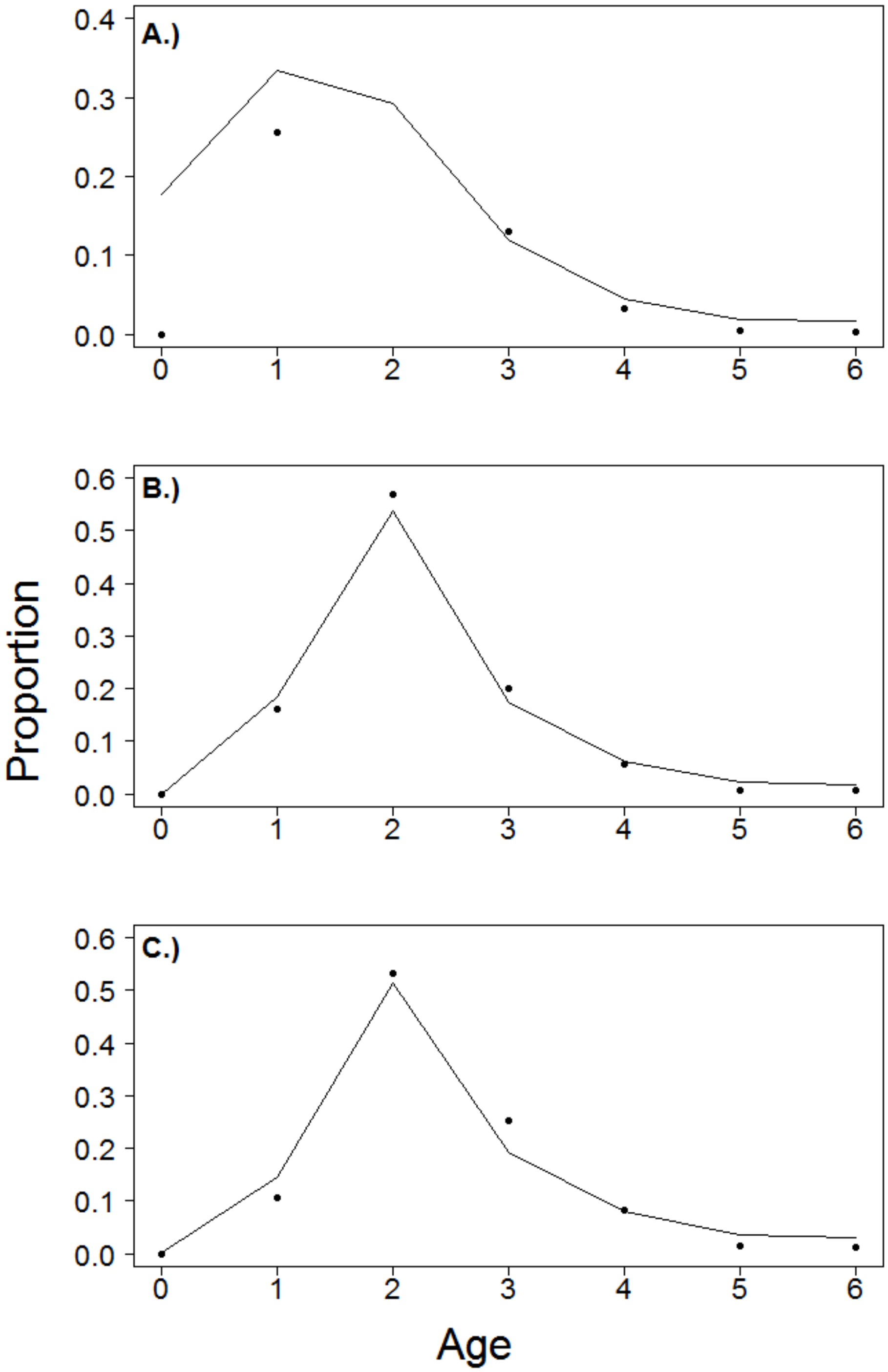

Figure 5. Age Composition

Observed (points) and predicted (lines) age composition for fisheries in Louisiana (A), Mississippi (B), and Alabama (C).

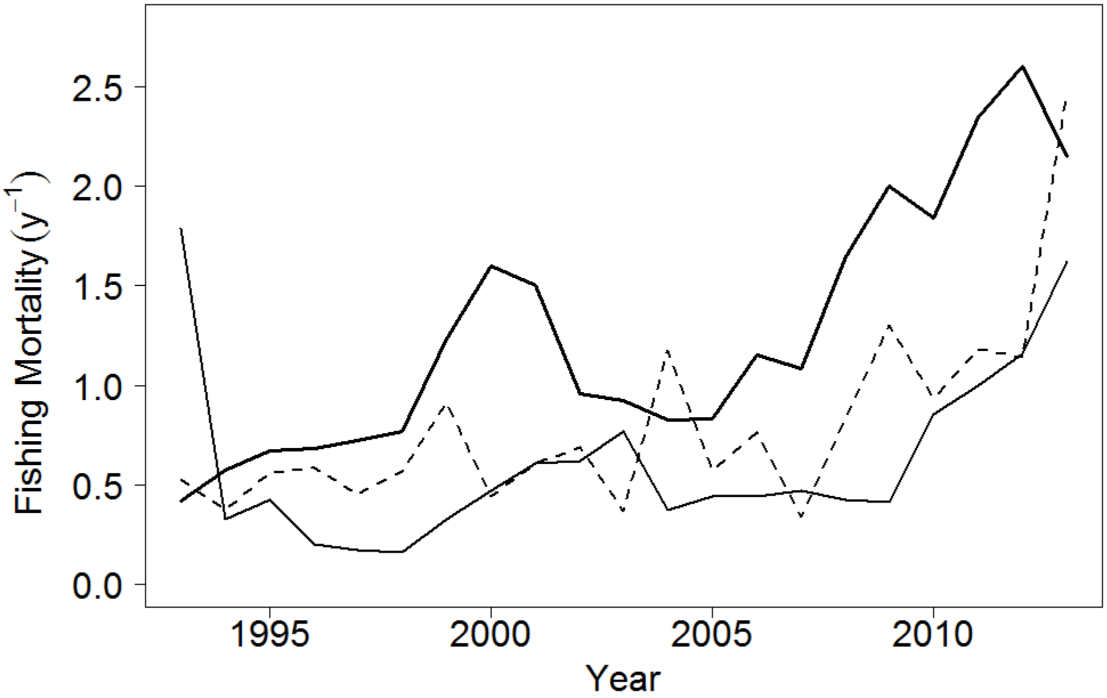

Figure 6. Fishing Mortality from Harvest

Fishing mortality (y^{-1}) for fleets associated with harvest in Louisiana (thick), Mississippi (dashed), and Alabama (thin).

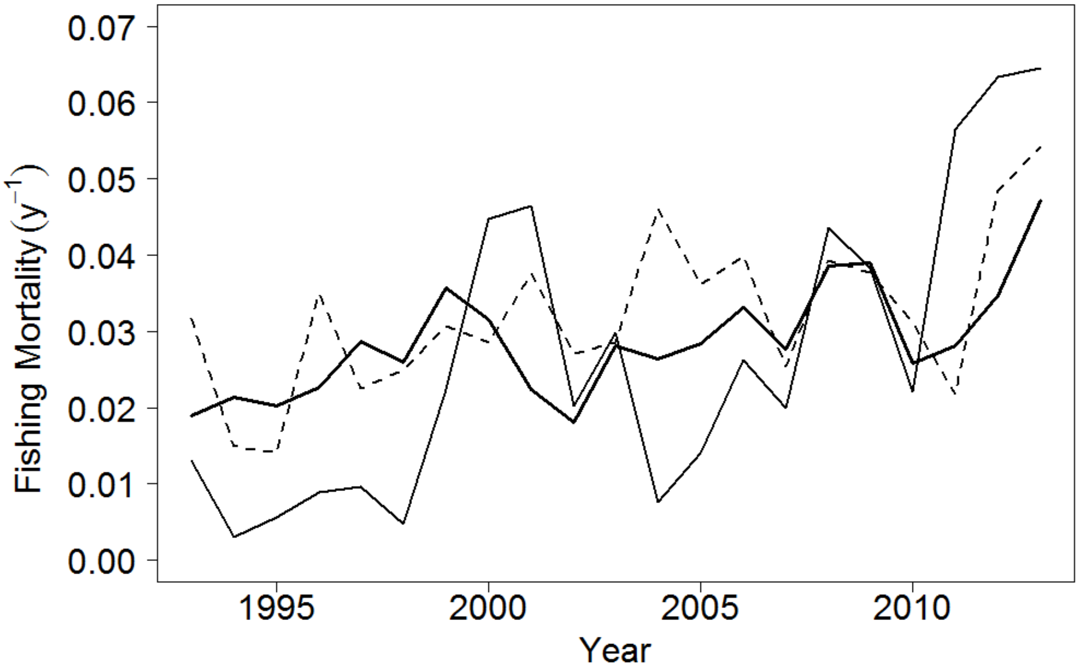

Figure 7. Fishing Mortality from Discarding

Fishing mortality (y^{-1}) for fleets associated with discard mortality in Louisiana (thick), Mississippi (dashed), and Alabama (thin).

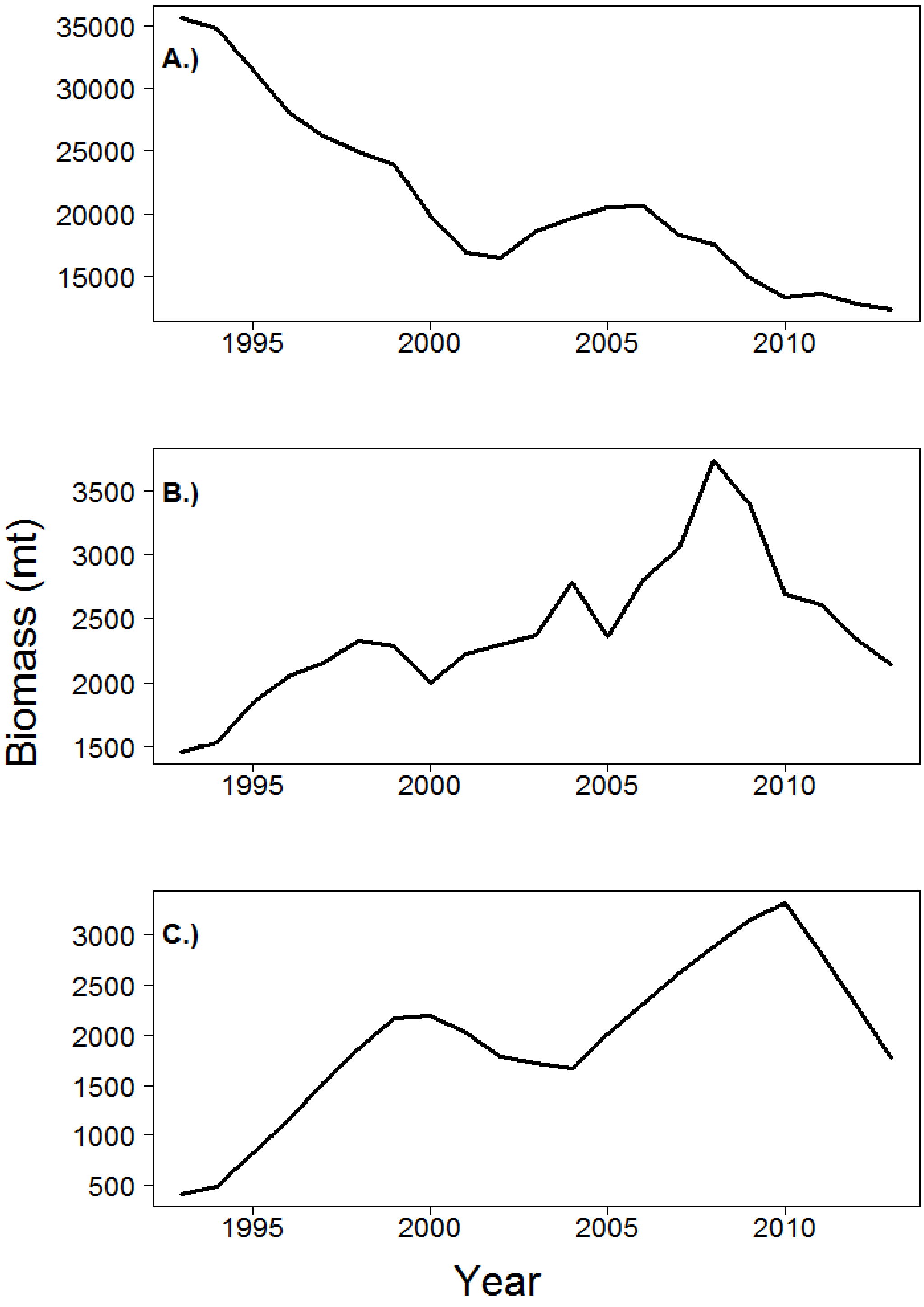

Figure 8. Stock Biomass Estimates

Stock biomass (mt) for Spotted Seatrout in Louisiana (A), Mississippi (B), and Alabama (C) over the time series assessed.

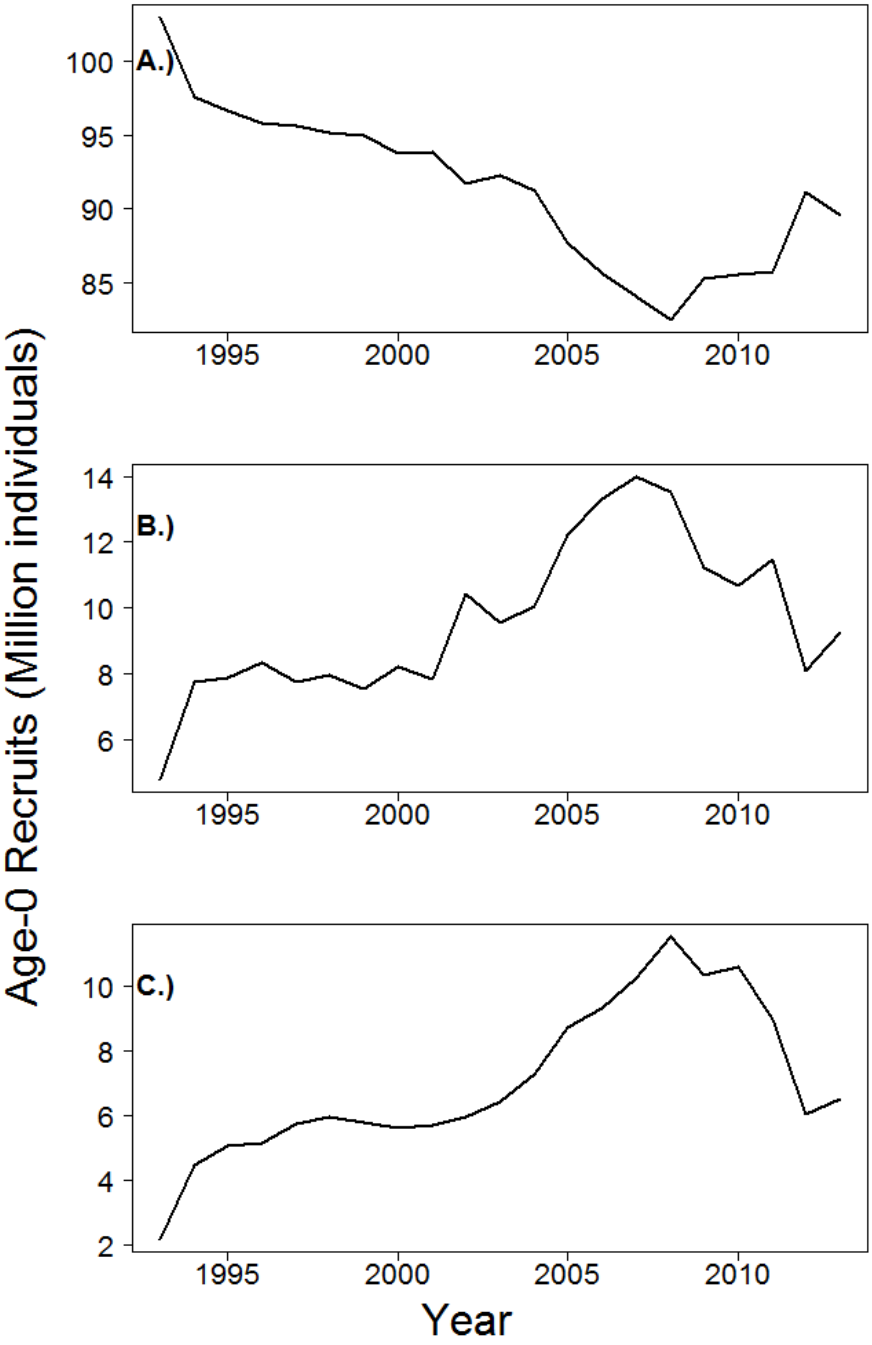

Figure 9. Recruit Abundance Estimates

Age-0 recruitment (Million individuals) of Spotted Seatrout in Louisiana (A), Mississippi (B), and Alabama (C) over the time series assessed.

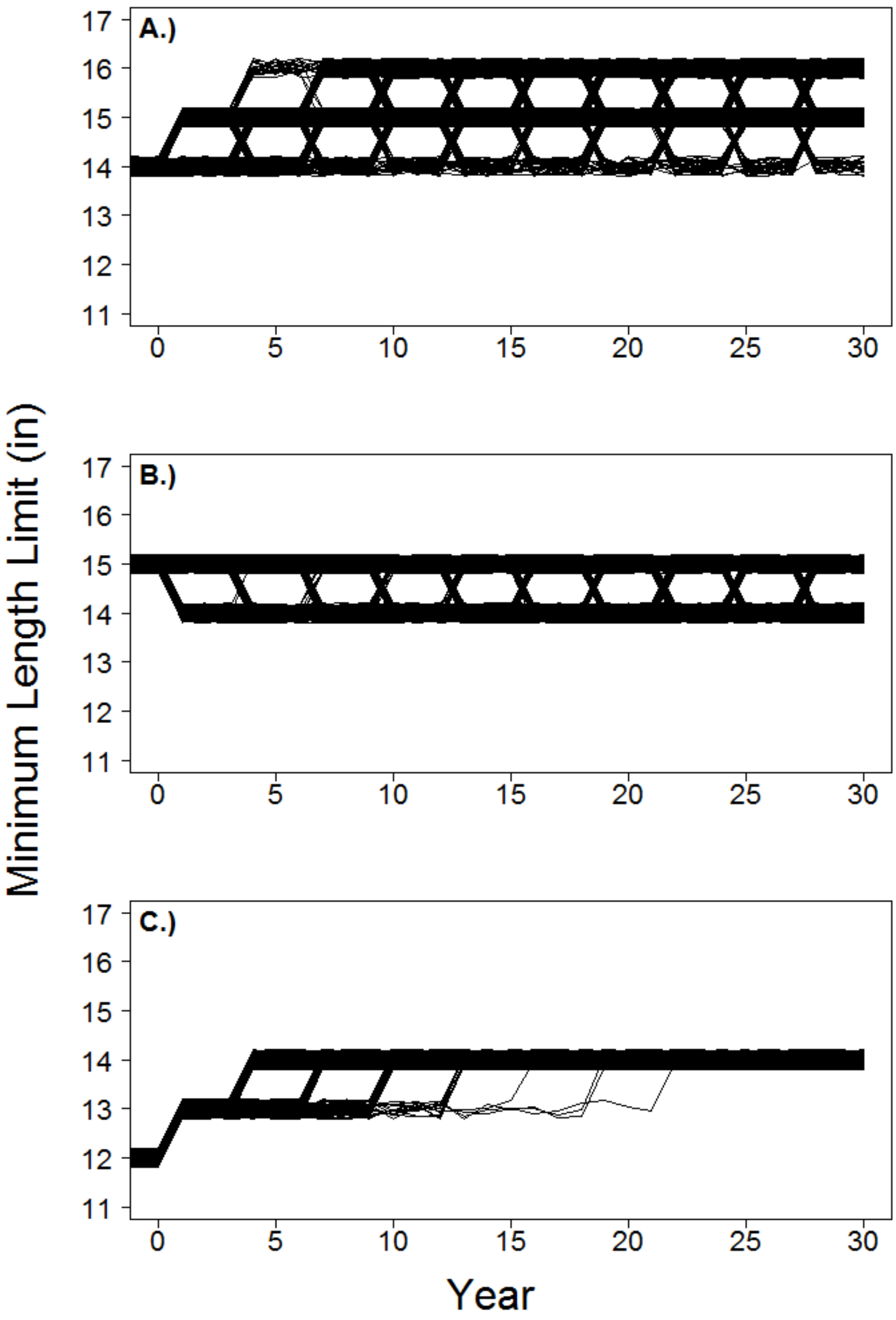

Figure 10. Minimum Length Limit Fluctuations

Minimum length limits overlaid for each trial of the base scenario at base SPR target values in Alabama (A), Mississippi (B), and Louisiana (C). A jitter function was applied to distinguish between overlapping time series.

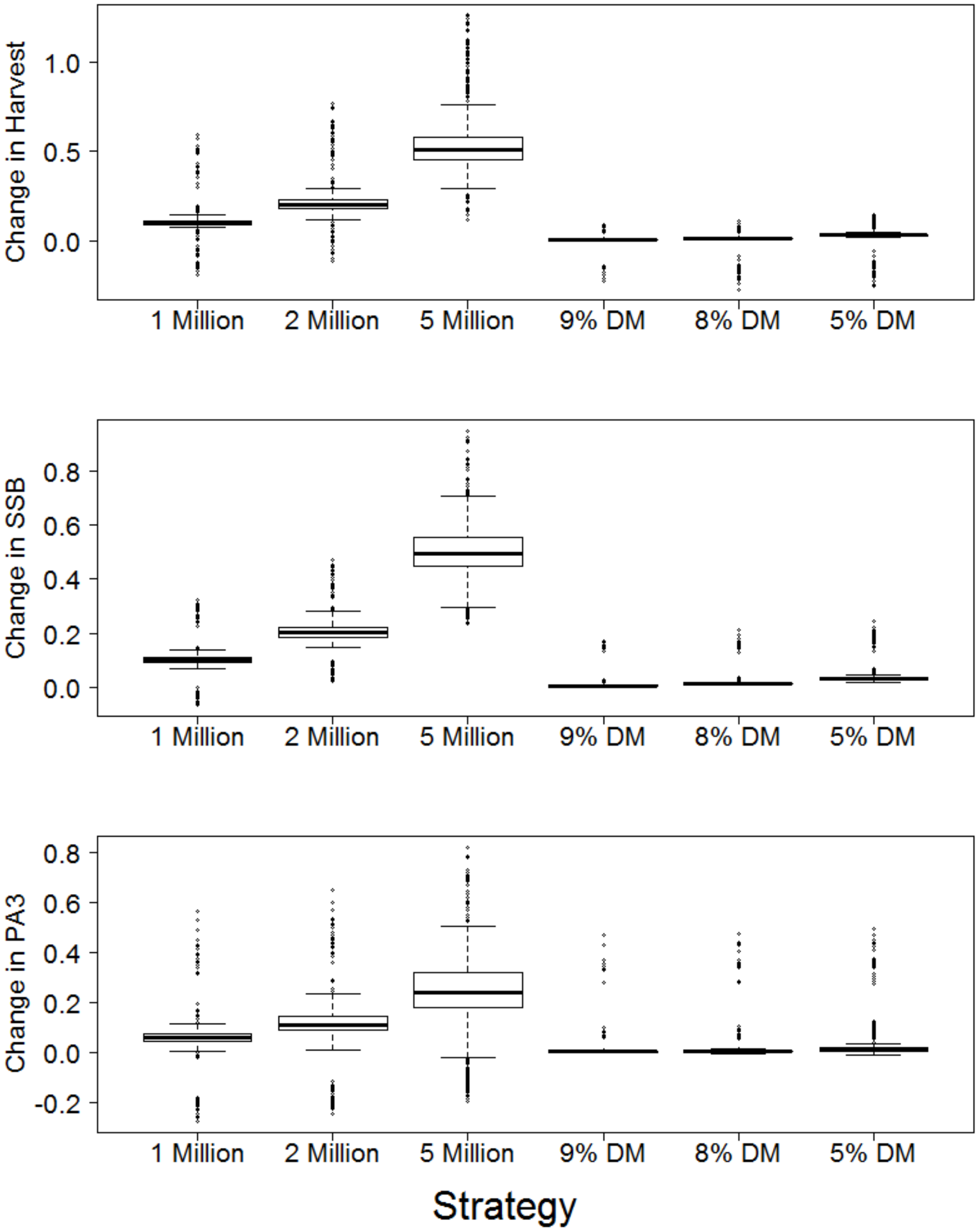

Figure 11. Metric Comparisons in Alabama

Proportional change in harvest, spawning stock biomass (SSB) and the proportion of age-three or older individuals (PA3) in Alabama for each candidate management strategy. Boxes represent the interquartile range (IQR), whiskers signify the range of the data (1.5 times the lower and upper IQR), and dark lines mark the median values. Points outside each box represent data outside the range of the whiskers.

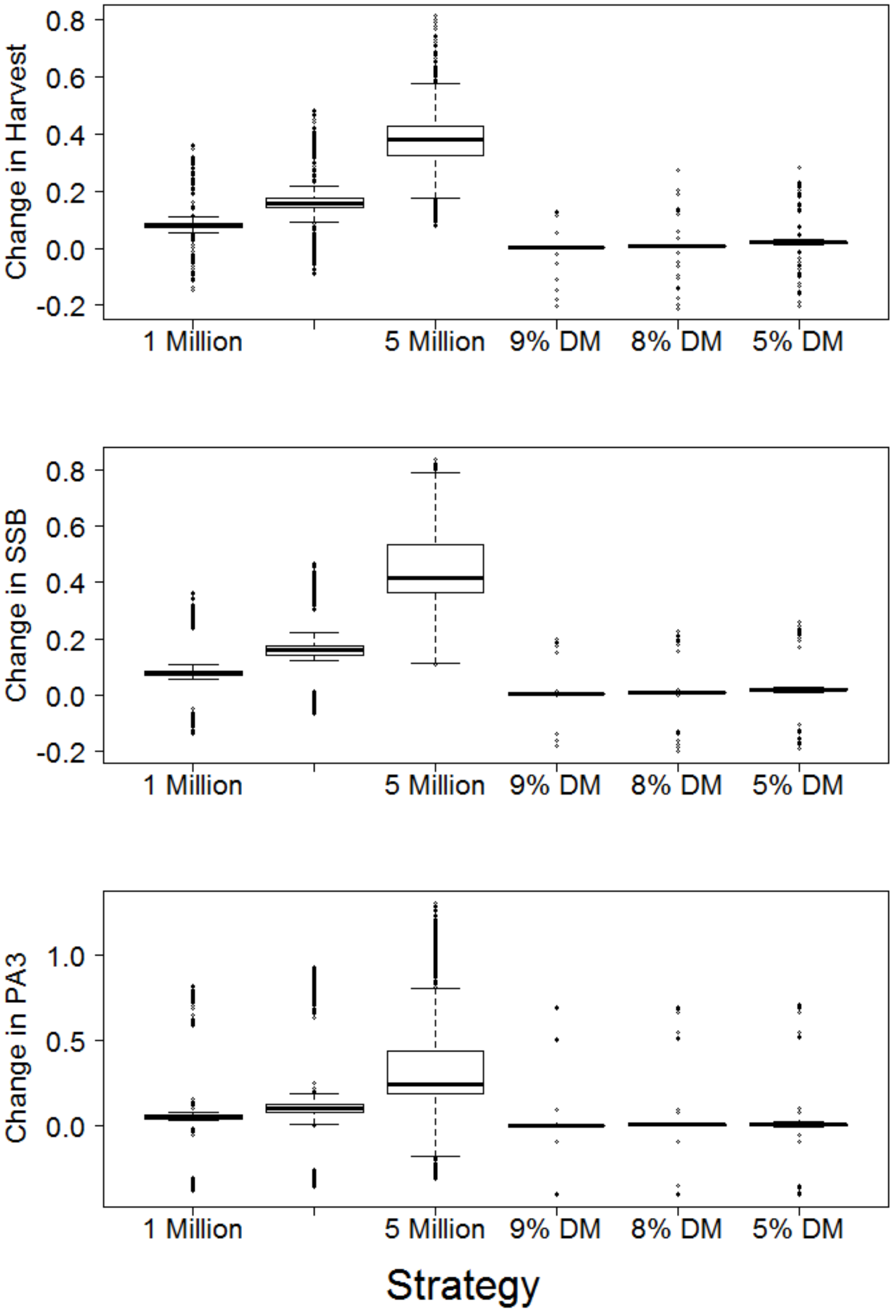

Figure 12. Metric Comparisons in Mississippi

Proportional change in harvest, spawning stock biomass (SSB) and the proportion of age-three or older individuals (PA3) in Mississippi for each candidate management strategy. Boxes represent the interquartile range (IQR), whiskers signify the range of the data (1.5 times the lower and upper IQR), and dark lines mark the median values. Points outside each box represent data outside the range of the whiskers.

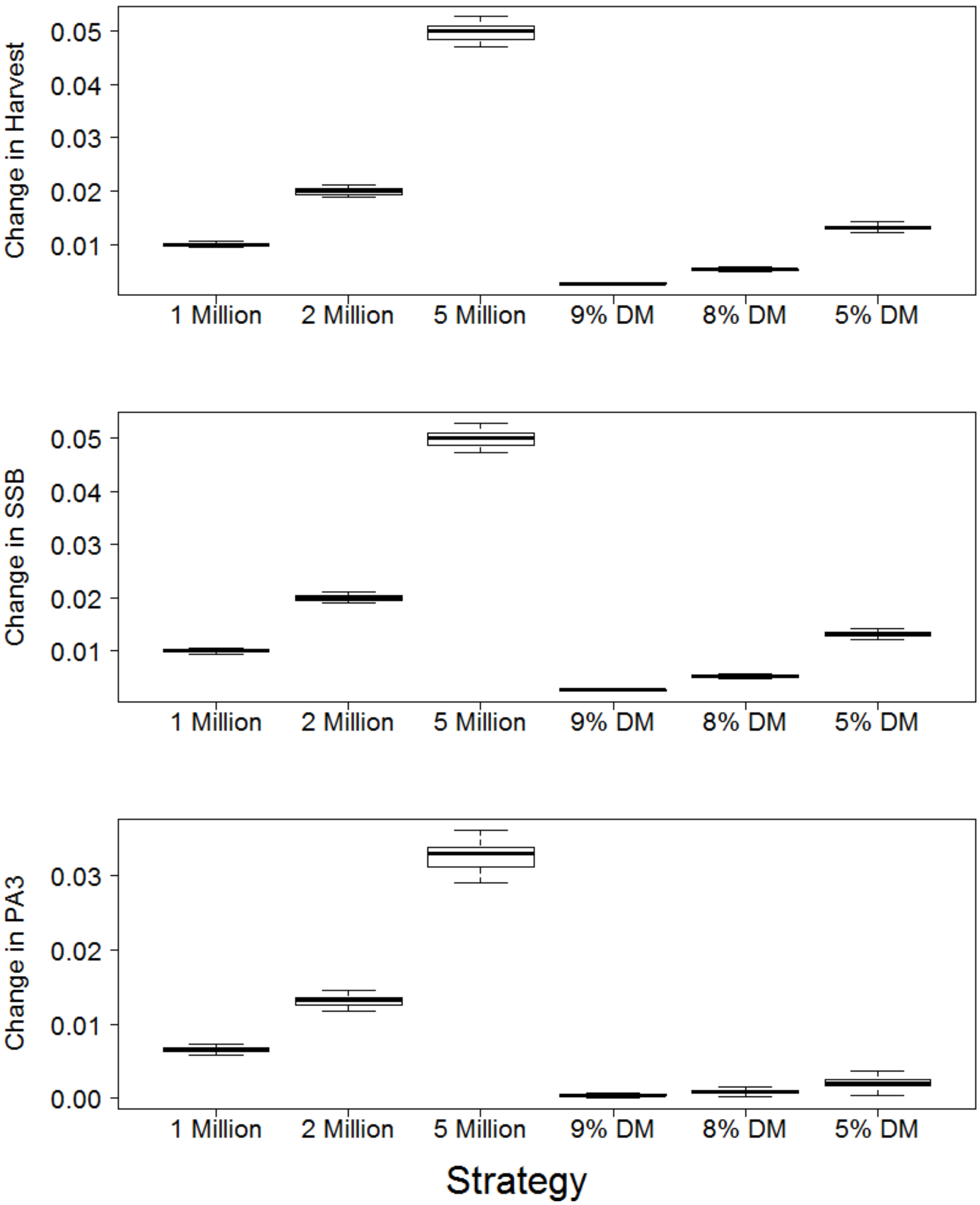

Figure 13. Metric Comparisons in Louisiana

Proportional change in harvest, spawning stock biomass (SSB) and the proportion of age-three or older individuals (PA3) in Louisiana for each candidate management strategy. Boxes represent the interquartile range (IQR), whiskers signify the range of the data (1.5 times the lower and upper IQR), and dark lines mark the median values. Points outside each box represent data outside the range of the whiskers.

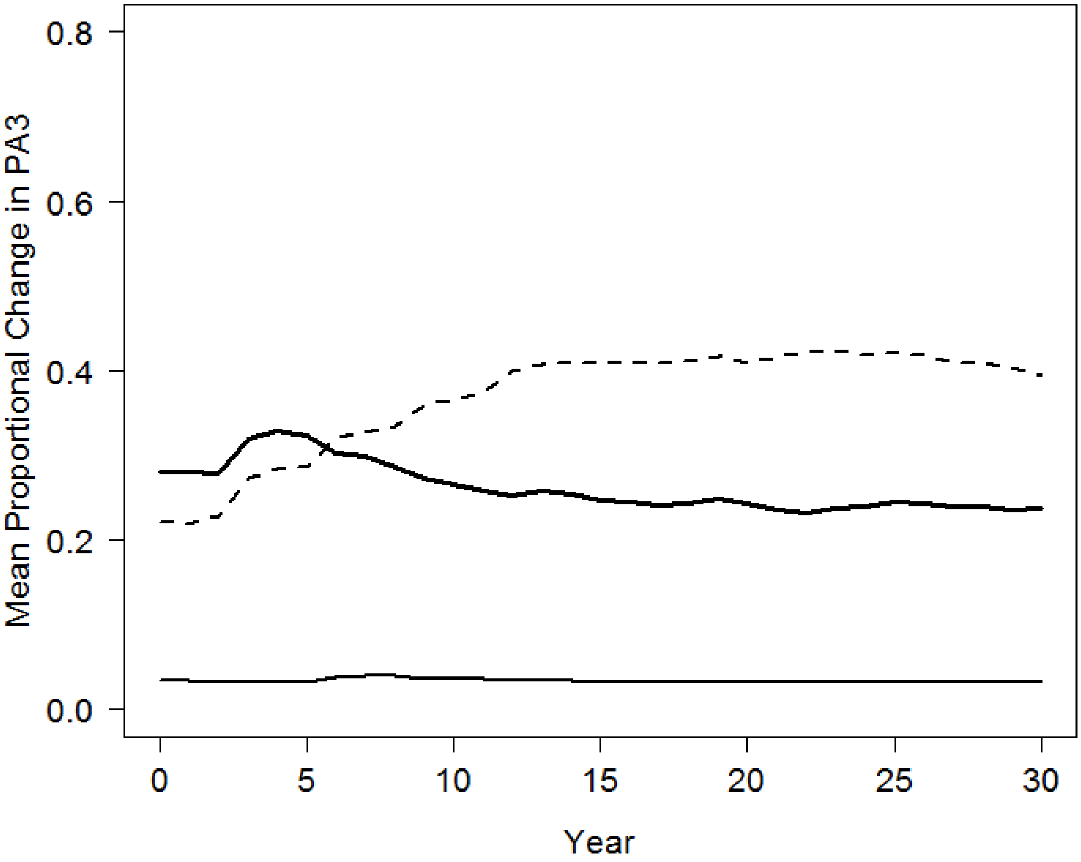

Figure 14. Temporal Change in PA3 given Stock Enhancement

Temporal variability of the mean proportional change in the proportion of age-three or older individuals for scenarios with annual releases of five million in Louisiana (thin), Mississippi (dashed), and Alabama (thick).

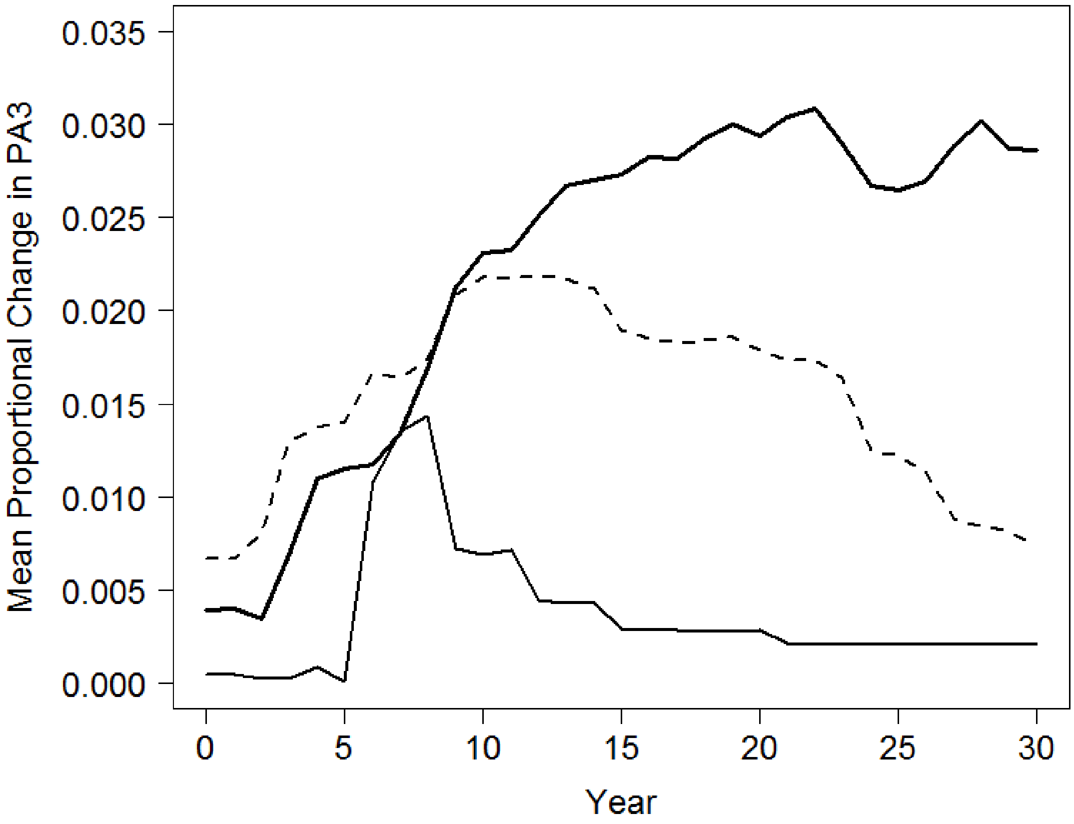

Figure 15. Temporal Change in PA3 by Reducing Discard Mortality

Temporal variability of the mean proportional change in the proportion of age-three or older individuals for scenarios with a five percent reduction in discard mortality in Louisiana (thin), Mississippi (thin), and Alabama (thick).

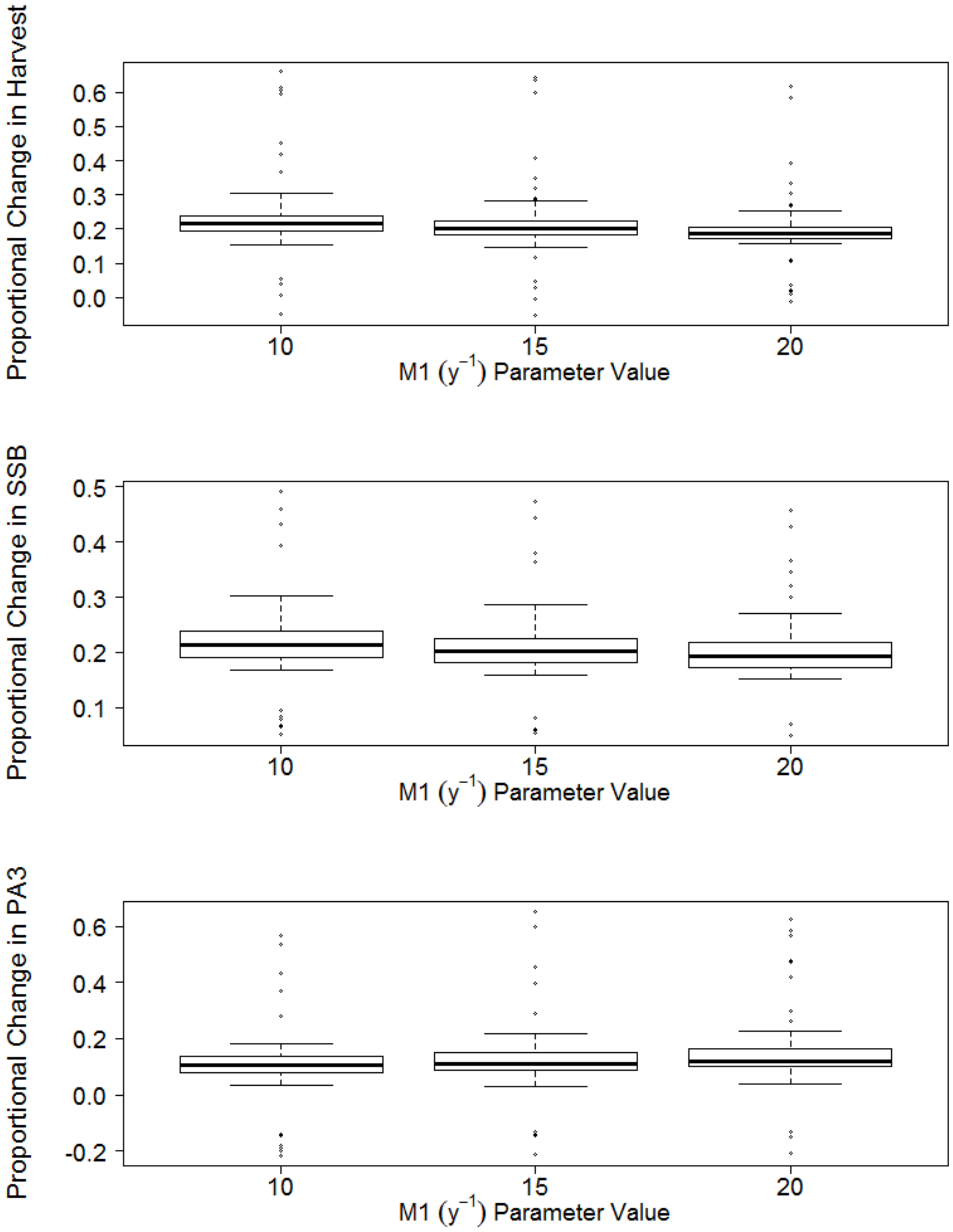

Figure 16. Metric Sensitivity in Alabama

Sensitivity of the change in harvest, spawning stock biomass (SSB), and the proportion of age-3 or older individuals in the stock (PA3) to low (10 y^{-1}) and high (20 y^{-1}) M_1 parameter values for stock enhancement of two million individuals in Alabama.

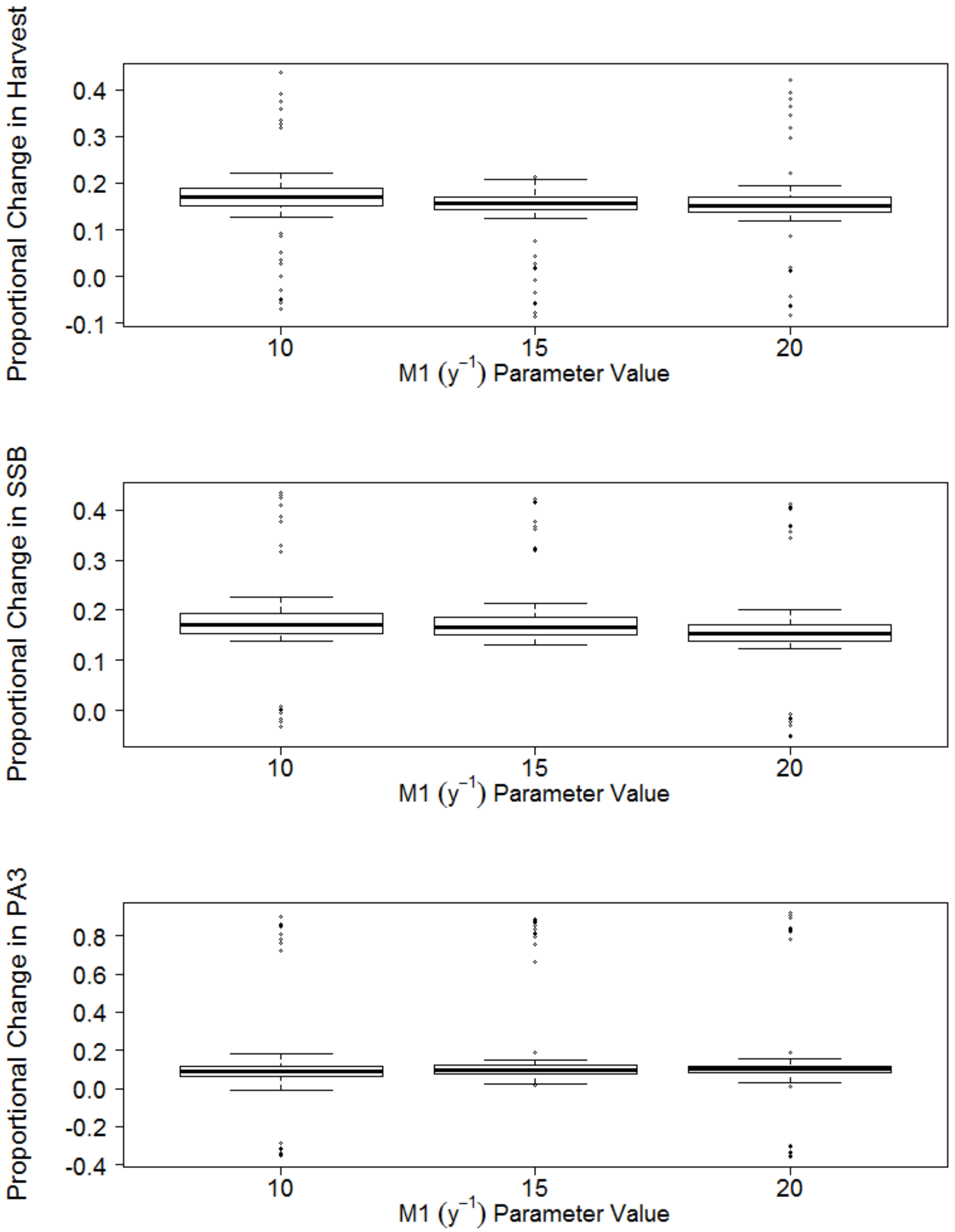

Figure 17. Metric Sensitivity in Mississippi

Sensitivity of the change in harvest, spawning stock biomass (SSB), and the proportion of age-3 or older individuals in the stock (PA3) to low (10 y^{-1}) and high (20 y^{-1}) M_1 parameter values for stock enhancement of two million individuals in Mississippi.

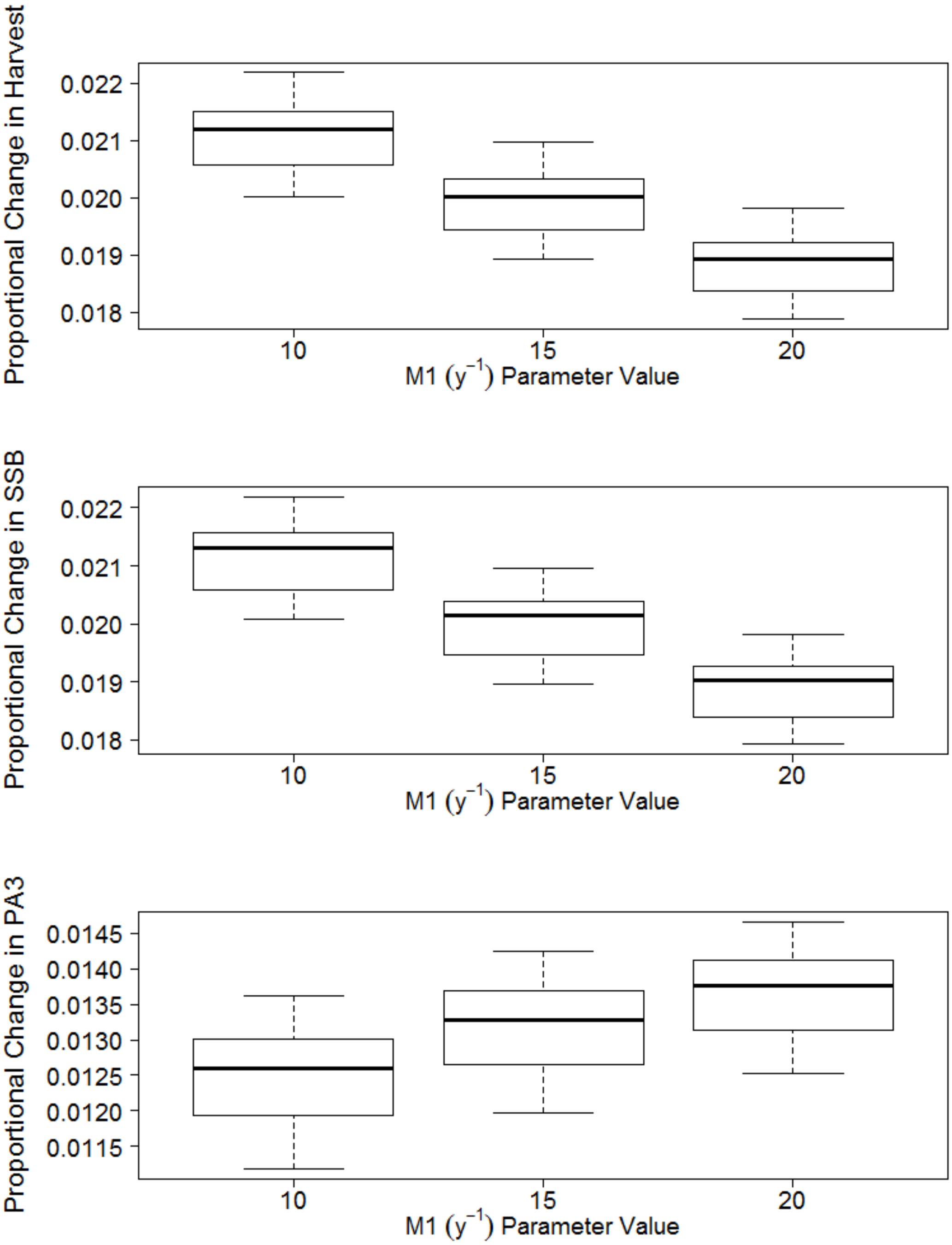

Figure 18. Metric Sensitivity in Louisiana

Sensitivity of the change in harvest, spawning stock biomass (SSB), and the proportion of age-3 or older individuals in the stock (PA3) to low (10 y^{-1}) and high (20 y^{-1}) M_1 parameter values for stock enhancement of two million individuals in Louisiana.

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