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Using Harvest Slot Limits to Promote Stock Recovery and Broaden Age Structure in Marine Recreational Fisheries: a case study

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< A >Abstract

Fish populations with broad age distributions are expected to have higher reproductive capacity than age-truncated populations because of the disproportionate contributions of older fish. Harvest slot limits, an expected means of ameliorating age truncation, are modeled for Tautog *Tautoga onitis* in an overfished population subunit that is experiencing overfishing. Tautog, currently managed by a 40 cm minimum size limit (MSL), is a candidate species for slots because it is relatively long-lived, slow-growing, with low discard mortality. We evaluated changes in biomass and abundance-at-age relative to management with the current MSL regulations using a forward population simulation model for four slots: 35–45 (small-wide), 38–42 (small-narrow), 40–50 (large-wide), and 43–47 (large-narrow) cm, inclusive. Angler behavioral responses were evaluated at 0%, 10%, and 20% noncompliance with the upper slot limit. The biomass and number of fish removed are reduced with harvest slot limit management, relative to the MSL, but because the harvest is redirected to smaller fish the reduction in numbers removed is not as large as the reduction in biomass removed. Slot limits broadened the age structure within 10 years by reducing fishing mortality on extant fish. Median spawning stock biomass (SSB) recovered more quickly in three of the slots than with MSL regulation (three to six years to reach $SSB_{Threshold}$ as compared to nine years with MSL management). We concluded that harvest slot limits can broaden age structure and restore biomass in overfished fisheries, but should be evaluated when managing coastal fisheries as a reduction in biomass removed is required.

< A >Introduction

Fishing truncates fish population size structure and age structure due to increased mortality rates on larger and older individuals. This is a global pattern; 61 of 63 fished populations displayed a decreased proportion of individuals in the oldest age classes (Barnett et al. 2017). While fisheries theory predicts some positive effects of size and age truncation, for example, reduced intraspecific competition and increased individual growth rates (Silliman and Gutsell 1958; Arlinghaus et al. 2010; Kindsvater and Palkovacs 2017), truncation can have long-lasting negative impacts. Offspring quantity may be reduced in populations with truncated size/age structure because, on a per-weight basis, larger females produce more offspring than smaller females (e.g. LaPlante and Schultz 2007). Offspring quality may also be reduced in populations with truncated size/age structure, as older fish in some species produce faster

growing and more provisioned offspring than younger fish (maternal effects, Berkeley et al. 2004; Sogard et al. 2008; Carr and Kaufman 2009; but see Marshall et al. 2010). Populations with truncated size/age structure have exhibited reduced resilience (i.e. the buffering capacity in response to environmental change) and increased recruitment variability (Anderson et al. 2008; Cooper et al. 2013). Thus, even when biomasses are equivalent, stocks composed of younger fish may be less resilient (to fishing and environmental fluctuation) and have lower recruitment than stocks composed of older fish (Wright and Trippel 2009; Rouyer et al. 2011; Botsford et al. 2014; Hixon et al. 2014; Barneche et al. 2018). Conversely, if a truncated age structure is broadened, then recruitment variability may decrease and resilience may increase. Methods to reverse age truncation have been proposed but there remains a dearth of case studies that evaluate species-specific strategies to broaden age structure in the context of actionable management measures.

Truncated age structures can be broadened by reducing fishing mortality on larger/older individuals through modifying fishery selectivity (age-specific vulnerability). Various means of modifying selectivity include: marine reserves (Palumbi 2004; Berkeley 2006), gear modifications (Fauconnet and Rochet 2016; Garner et al. 2017), and harvest length regulations (Berkeley 2006; Cooper et al. 2013; Hixon et al. 2014; Gwinn et al. 2015; Le Bris et al. 2018). Here we focus on harvest length regulations because of their widespread and effective use in recreational fisheries management (van Poorten et al. 2013). Typically, harvest length regulations consist of minimum size limits (MSL, producing an asymptotic selectivity curve) which can reduce the abundance of the largest/oldest fish. When additional harvest reduction is required the minimum size is often increased, focusing the harvest on an ever-decreasing pool of larger, older, fish. In contrast, harvest slot limits—where only fish within a prescribed size range

may be harvested and the others must be released— disproportionately select fish within the slot (producing a dome-shaped selectivity curve). Harvest slot limits should protect older individuals and could also be effective at achieving management objectives.

Harvest slot limits have been implemented in limited marine commercial (Le Bris et al. 2018) and marine recreational fisheries (Armstrong et al. 1996; Pierce 2010; Powers et al. 2012; ASMFC 2013; Muller et al. 2015; Schmidtke et al. 2017; FL FWCC 2019; MD DNR 2019; NYS DEC 2019; WA DFW 2019; GMFMC 2020). In some marine recreational fisheries, harvest slots have been implemented and, apparently, not evaluated. While in other marine recreational fisheries, harvest slot limits have been evaluated, but not implemented (Leaf et al. 2008; Dippold et al. 2016; Morson et al. 2017). These case studies, however, did not explicitly explore the effects of broadening age structure on the population. A case study of Red Drum *Sciaenops ocellatus*, which was managed by slot limits, estimated the daily bag limit required to meet the management target but did not project the changes in the population dynamics as a result of such regulatory changes (Vaughan and Carmichael 2002). Other contributions modeled the impact of harvest slot limits on the age structure of Black Rockfish *Sebastes melanops* and simulated species (Berkeley 2006; Gwinn et al. 2015, respectively). In these examples, harvest slot limits are predicted to protect older age classes (Berkeley 2006) and increase the catch of trophy fish (Gwinn et al. 2015). These studies, however, did not evaluate the use of harvest slot limits as a tool to simultaneously rebuild spawning stock biomass (SSB) and broaden age structure in overfished-age-truncated stocks currently in need of directed management.

Here we provide a case study simulating the implementation of harvest slot limits on a species regionally popular among marine recreational anglers, Tautog *Tautoga onitis*. Tautog is cooperatively managed through the Atlantic States Marine Fisheries Commission (ASMFC);

individual states (NC to MA) have the authority to implement specific management measures, so long as they meet the overall ASMFC management objective. The most recent stock assessment concluded that Tautog in the Long Island Sound component of the coastwide population is overfished and experiencing overfishing in the terminal year (ASMFC 2016). The recreational sector accounts for 90% of the harvest (ASMFC 2016) and Tautog has a low discard mortality rate of 2.5% (Simpson 1999). Tautog egg production on a per-gram basis increases hyperallometrically with length; in one season, 50 cm females produced 24–86 times as many eggs as 25 cm females (LaPlante and Schultz 2007) whereas the difference would be only eight times were the scaling isometric. Tautog is relatively long-lived (maximum recorded age is 34 years) and slow-growing (Cooper 1967) compared to other recreationally exploited species in the Northwest Atlantic, making them particularly vulnerable to age size/truncation. In fact, the median size of female Tautog caught in the Connecticut Long Island Sound Trawl Survey declined 20 mm between 1984 and 2005 (LaPlante and Schultz 2007). Despite increasingly strict regulations (increased minimum size, decreased bag limits, and shortened season), Tautog SSB in the region has not recovered (ASMFC 2016). Restoring the abundance of larger/older individuals may promote stock recovery and enhance angler experience (Gwinn et al. 2015).

The objectives of this study were to 1) evaluate the age structure of Tautog in Long Island Sound, 2) develop and parameterize a population dynamics model to evaluate the effect of varying length limits, and 3) evaluate the sensitivity of results to varying levels of angler noncompliance. Four slot types were analyzed: a two by two combination of median size (small and large) and slot breadth (narrow and wide). We tested the hypothesis that harvest slot limits will broaden age structure and restore SSB in an overfished region. Spawning stock biomass was used as the metric of stock size rather than total egg production; it is more widely employed in

stock assessments because it can be more readily quantified. To estimate these changes appropriately, we reparametrized the Long Island Sound region stock assessment. Using the new assessment, harvest slot limits were evaluated using scenario-specific removal quantities and selectivity curves in forward population simulations. Finally, sensitivity analyses were performed to estimate the impact of angler noncompliance with the upper slot limit.

< A >Methods

Data.—Data used in this study are similar to data used for other species managed with statistical catch-at-age stock assessments. Tautog in Long Island Sound (CT and NY north shore of Long Island) are assessed and managed as a subunit of the coastwide stock. CT, NY, the US federal government, and the American Littoral Society maintain long-term databases describing the biological and fishery characteristics in the region (Figure 1, Table 1, ASMFC 2016). Fishery-independent surveys, fishery-dependent surveys, and biological studies were used to parameterize the stock assessment model (Figure 1). The stock assessment model quantified current SSB, biological reference points, recruitment, age structure, and fishing mortality. These derived quantities were used to perform forward population simulations under different management scenarios. Removals (biomass and numbers) and selectivity curves were predicted for each potential management scenario evaluated from angler catch-at-length data. Forward population simulations were used to forecast changes in SSB and abundance-at-age under conditions of constant removals and selectivity curves within each management scenario.

Fishery-independent surveys provided abundance indices, length-at-age observations, and length-weight relationships (Figure 1, Table 1). An independent index of Tautog abundance (numbers per tow) was developed using the CT Long Island Sound Trawl Survey, a stratified-random survey (CT Department of Energy and Environmental Protection 2016), using a negative

binomial generalized linear model (GLM) with a formula including abundance ~ year + month + stratum, an approach that is consistent with that used for the stock assessment (ASMFC 2016). Additionally, and also consistent with the stock assessment, age-1 abundance indices (numbers per tow) were developed from the Peconic Bay Small Mesh Trawl Survey (McCandless and Grahn 2014) and the Western Long Island Sound Juvenile Abundance (seine) Survey using GLMs: the Peconic survey formula used, abundance ~ year; the Western Long Island sound formula used, abundance ~ year + temperature (ASMFC 2016). Fish from these three surveys were aged (opercular bones), measured for total length in millimeters, and in the case of the CT survey, weighed and sexed (ASMFC 2016).

Fishery-dependent programs characterized the fishery (Figure 1, Table 1). National Marine Fisheries Service's Marine Recreational Fisheries Statistics Survey and Marine Recreational Information Program (personal communication from the National Marine Fisheries Service, Fisheries Statistics Division 2016) provided the fishing effort index, estimated the numbers of fish caught/harvest, and contributed to the harvest/discards-at-length observations. The NY party (head) boat survey, the CT Marine Volunteer Angler Survey Program, and the American Littoral Society tagging program contributed length-at-age (NY survey) and additional harvest- and discard-at-length observations (see Table 1 for specifics, ASMFC 2016). Detailed descriptions of the data preparation are provided (Appendix 1).

Stock characteristics and assessment.—The CT survey was used to evaluate changes in female age structure in Long Island Sound (Figure 1). A one-way analysis of variance (ANOVA) was used to test for changes over time in female catch-at-age. We aggregated years into four selectivity blocks (period of relatively consistent regulations) for this test; the same aggregation of years into selectivity blocks was used in both the management assessment (ASMFC 2016) and

the assessment detailed below. Differences in mean catch-at-age were identified with the post-hoc Tukey's honest significant difference test.

The stock assessment developed for this analysis covers the same years (1984–2015) and applies the same datasets as the Tautog stock assessment (ASMFC 2016) that is currently used for management. Table 2 provides details of the symbols and parameter estimates, and Appendix 2 indicates how this model differs from the ASMFC model. Both assessments were performed using the NOAA Fishery Toolbox Age Structured Assessment Program version 3.0.17 (ASAP, NOAA Fisheries Toolbox 2014). ASAP is a statistical catch-at-age model that uses observed catches and indices of abundance to estimate population size and age structure (Legault and Restrepo 1999). Following Legault and Restrepo (1999), SSB at time (*t*) was calculated as the summation across ages (*a*) of the product of the abundance-at-age (N_a), the proportion mature-at-age (P_{MA}, Chenoweth 1963), the weight-at-age (W_a), and survivorship, which is the product of the proportion of fish that survive to the spawning period (P_{SSB}, Cooper 1967) and total mortality-at-age, Z_a:

$$SSB_t = \sum_a N_{t,a} \cdot P_{MA,a} \cdot W_{t,a} \cdot e^{-P_{SSB} \cdot Z_{t,a}}. \quad (1)$$

As spawning does not occur on January 1, total mortality was adjusted for the proportion of the year that occurred prior to spawning. Abundance for age 1 fish was the product of expected recruitment (*R*) and lognormal recruitment deviations (*log_Rdev*):

$$N_{t,1} = R_t \cdot e^{\log\_Rdev_t}. \quad (2)$$

Recruitment in ASAP was calculated with a Beverton–Holt stock-recruitment relationship. Here the steepness was fixed at 1.0 (expected recruitment was constant) so recruitment was the

quotient of unexploited spawning stock biomass (SSB_0) and unexploited spawners per recruit (SPR_0):

$$R_t = \frac{SSB_0}{SPR_0}. \tag{3}$$

Abundance for ages 2 to the age class younger than the plus group (A) was the product of the abundance of the same cohort in the previous year and survivorship:

$$N_{t,a} = N_{t-1,a-1} \cdot e^{-Z_{t-1,a-1}}. \tag{4}$$

Abundance for the plus group was the summation of the number of fish that survive to the plus group and the survivorship of the previous year's plus group:

$$N_{t,A} = N_{t-1,A-1} \cdot e^{-Z_{t-1,A-1}} + N_{t-1,A} \cdot e^{-Z_{t-1,A}}. \tag{5}$$

Total mortality was the sum of natural mortality (ASMFC 2015) and fishing mortality (F_a) for each age and year:

$$Z_{t,a} = M + \sum F_{t,a}. \tag{6}$$

Fishing mortality was the product of a year effect (*Fmult*) and selectivity-at-age (S_a):

$$F_{t,a} = Fmult_t \cdot S_{b,a}. \tag{7}$$

As in the ASMFC assessment (2016), fishery selectivity was a single logistic curve calculated independently for each of four selectivity blocks (b):

$$S_{b,a} = \frac{1}{1 + e^{-(a - \alpha_b)/\beta_b}} \tag{8}$$

where the midpoint (α_b) and the slope (β_b) describe the ascending portion of the function. Fishery selectivity was estimated separately and held constant for each selectivity block (b = 1 for years 1984–1986, b = 2 for years 1987–1994, b = 3 for years 1995–2011, b = 4 for years

2012-2015). Finally, after initial model parameterization, effective sample sizes were reweighted (Francis 2011) before the final stock assessment model run. The reweighted model was then run using Monte Carlo Markov Chain (MCMC) with 1,000 iterations and a thinning factor of 200 (200,000 MCMC calculations) to characterize uncertainty in parameter estimates. Fishing mortality reference points were based on spawners per recruit estimated in ASAP; F_{Target} = $F_{40\%SPR}$ and $F_{Threshold}$ = $F_{30\%SPR}$. Further, SSB_{Target} and $SSB_{Threshold}$ were the median of terminal SSB values when the stock was managed with F_{Target} or $F_{Threshold}$ for 55 years in the forward population simulation (detailed below).

Population simulations.—SSB and abundance-at-age for Tautog in the Long Island Sound region were forecasted for each year in a forward population simulation model (Figure 1). Simulations were performed in the Age Structured Projection Model version 4.3 Beta 11 (AgePro, NOAA Fisheries Toolbox 2018) which was integrated with the output from the ASAP model. AgePro is a discrete-time model with an annual time step. Fifty population simulations were performed for each of 1,000 initial population abundance-at-age vectors calculated in the terminal year of the ASAP MCMC model (detailed above); thus each projection consisted of 50,000 simulated population trajectories (Brodziak 2009). These trajectories were used to calculate median and 5th/95th percentiles (hereafter referred to as median and confidence limits) of the SSB and abundance-at-age distribution for each of the harvest slot scenarios, relative to MSL management.

Simulations for each scenario were run for 55 years—with this timeframe, equilibrium (annual SSB change <1%) was reached for scenarios in which SSB did not crash. Relative changes in abundance-at-age were analyzed after 10 and 55 years of constant removals and selectivity. The 10-year benchmark was selected because preliminary analyses indicated a peak

of relative change around this time. The 55-year benchmark was chosen as it is representative of equilibrium population dynamics. Removals and fishery selectivity were constant over time and unique to each scenario evaluated (detailed below). Life history parameters (P_{MA}, W_a, P_{SSB}, and M) were averaged over selectivity block four of the assessment model, thus we assumed no change in growth parameters in the forecast model. Removal values were the sum of the number harvested and the discard mortality predicted from the catch in the last selectivity block (detailed below). Recruitment was based on random draws from the empirical values estimated in ASAP and was independent of spawning biomass and time. Abundance-at-age in each year was predicted for ages 2 to 15 and for the age plus group with equations (4 and 5), respectively. Finally, SSB was predicted with equation (1).

Scenario evaluation.—Thirteen management models—the current management strategy using an MSL of 40 cm and four harvest slots, each with three different upper slot limit noncompliance rates—were evaluated. The four slots consisted of two different slot breadths (5 cm and 11 cm, inclusive of lower and upper length limits) each of which was centered on 40 cm or 45 cm lengths. The narrow breadth of 5 cm was selected because a slot narrower than 2 inches seemed unlikely to be implemented. The wide breadth of 11 cm was employed after preliminary analysis indicated broader slots results in population crash. The 40 cm slot median (the "small" slots) was chosen to match the current MSL. The 45 cm median (the "large" slots) was selected as it would enhance the opportunity for anglers to harvest larger fish. We evaluated each of the four slots–35–45 (small-wide), 38–42 (small-narrow), 40–50 (large-wide), and 43–47 (large-narrow) cm, inclusive–assuming 0%, 10%, and 20% noncompliance rates with the upper slot limit size. The noncompliance rates were informed from other fisheries with harvest slot limits: Common Snook

Centropomus undecimalis (5–17%, Muller et al. 2015) and Northern Pike *Esox lucius* (13–19%, Pierce and Tomcko 1998).

Harvest slot limit removals.—Removals (the sum of harvest and discard mortality) were fixed rather than time-dependent. Removals and selectivity curves for each scenario were calculated based on the mean harvest- and discards-at-length observations which informed the regional stock assessment for the years 2012–2015, the most recent selectivity block. The MSL scenario was evaluated as if it were a harvest slot limit, but without an upper limit on the slot. All scenarios included a 20.3% harvest reduction to evaluate performance of these options relative to the required management changes implemented in 2018 (ASMFC 2017). Noncompliance below the minimum size (lower bound of a slot or the MSL) and discard mortality were included in removals (detailed below). Removals in biomass were calculated for each of the 12 slot scenarios and the MSL for use in the forward simulation.

The number of fish removed for each scenario was the summation over lengths of harvest and discard mortality. Harvest was the product of the catch-at-length (C_L) and the proportion harvested-at-length ($P_{H,L}$). Discard mortality was the product of C_L, the discard mortality rate (F_D), and the proportion discarded (1 - $P_{H,L}$):

$$R_N = \sum_{L=11}^{76} C_L \cdot P_{H,L} + C_L \cdot F_D \cdot (1 - P_{H,L}). \tag{9}$$

Similarly, the biomass removed in each scenario was the product of the number removed in each length class and the weight-at-length (W_L):

$$R_B = \sum_{L=11}^{76} C_L \cdot P_{H,L} \cdot W_L + C_L \cdot F_D \cdot W_L \cdot (1 - P_{H,L}). \tag{10}$$

Weight-at-length was estimated using the same approach implemented in the stock assessment (Appendix 1). Proportion removals-at-length was estimated in three stanzas: fish smaller than the lower slot limit (the sum of the noncompliant harvest and dead discards), fish within the slot (the sum of the compliant harvest and dead discards), and fish larger than the upper slot limit (the sum of noncompliant harvest and dead discards). *For fish smaller than the slot*: the catch-at-length data used in the last four years of the stock assessment model included noncompliant harvest of fish below the legal minimum size of 40 cm: 11.3% of the total harvest in numbers were 22 to 39 cm in length. We assumed that below-slot noncompliance behavior would be the same as noncompliance with the MSL. The proportion of noncompliant harvest ($P_{H,L}$) for these 13 length increments (Table A.3) was applied to the 13 length increments below the minimum size limit of each harvest slot and the MSL. *For fish within the slot:* Compliant removal-weight-at-length in the harvest slot was reduced by 20.3% ($P_{H,L} = 0.797$), as justified above. *For fish larger than the slot*: proportion harvested ($P_{H,L}$), in this case noncompliance, was 0.0, 0.1, or 0.2.

Fishery selectivity.—Selectivity-at-age was parameterized independently for each of the 13 scenarios. Removal-at-length (R_L) were calculated by modifying efquation (9) for each length increment using the same data used for the harvest slot limit removal calculation:

$$R_L = C_L \cdot P_{H,L} + C_L \cdot F_D \cdot (1 - P_{H,L}). \tag{11}$$

The $R_L$vector was converted to removal-at-age (R_a) using the multinomial age-length-key approach (Gerritsen et al. 2006) developed with the nnet package in R (Venables and Ripley 2002). The multinomial approach, also implemented in our stock assessment (Appendix 1), accounts for highly variable ages within length intervals as well as small sample sizes and missing length intervals. Length-at-age observations (in years 2012–2015) from the CT and NY

trawl survey as well as the NY head (party) boat survey were used to fit the multinomial model. The resulting coefficients (Table A.1) were used to predict the probability of length-at-age with the predict function in R. Scenario-specific R_a is, therefore, the probability of length-at-age multiplied by the $R_L$vector. The proportion of removals-at-age (P_a) is R_a divided by the total removals (R_N):

$$P_a = \frac{R_a}{R_N}. \tag{12}$$

Selectivity-at-age (S_a) was estimated by fitting the P_a vector to the double logistic equation

$$S_a = \frac{1}{1 + e^{-(a - \alpha_1)/\beta_1}} + \frac{1}{1 + e^{-(a - \alpha_2)/\beta_2}} \tag{13}$$

using nonlinear least squares (nls function in R). As with equation (8), α and β were the midpoint and the slope of the ascending (subscript 1) and descending (subscript 2) portion of the curve, respectively. Starting values were visually estimated from the P_a vector. The S_a vector for each scenario was then scaled to a maximum selectivity of one. In a similar manner the P_a vector for the MSL scenario was fit to a single logistic equation (8), but omitting the subscript. Selectivity for the MSL scenario was recalculated for two reasons: (1) to maintain consistency in the parameterization of across all scenarios and (2) to account for the change in selectivity due to the previously mentioned 2018 regulatory changes.

< A >Results

<B>Stock characteristics

The mean age of female Tautog captured in the Long Island Sound Trawl Survey declined over the last three selectivity blocks and the maximum age of females was the lowest in the most

recent selectivity block, indicating that the population is age-truncated (Figure 2). The reparametrized stock assessment characterized the SSB and fishing effort in the region in a similar manner as the ASMFC assessment, despite differences in the approach. Tautog was overfished in the terminal year: $SSB_{Terminal}$ (1,937 mt) was lower than SSB_{Target} (3,397 mt) and $SSB_{Threshold}$ (2,549 mt). Additionally, overfishing occurred in the terminal year—$F_{Terminal}$ (0.75) was higher than F_{Target} (0.29) and $F_{Threshold}$ (0.54). A comparison of biological reference points, $SSB_{Terminal}$, and $F_{Terminal}$ between the two approaches is provided (Table A.4).

<B>Population simulations

Harvest slot limit yield.—Changes in slot breadth, slot location, and noncompliant harvest modified removals. Removals decreased relative to MSL regulations in the large slots and small-narrow slot (Table 3). The magnitude of removals was larger with each small slot (small-wide or small-narrow) than with the corresponding large slot (large-wide or large-narrow) of the same breadth. Furthermore, removals were larger with wide slots than with the narrow slot. The small-narrow and large-wide slots generated the smallest change in the number of fish removed compared to MSL. As expected, noncompliance with the upper slot limit increased the estimated removals. The change in removals due to noncompliance was smaller with larger upper slot sizes because abundance decreases with age (Table 3).

Fishery selectivity.—Modified length limits changed removals and fishery selectivity. When managed with slot limits, dome-shaped selectivity curves were highest at ages 6 and 7 (Figure 3). In contrast, when managed with an MSL, selectivity increased asymptotically to age 10 and remained high. The selectivity curves for the broad slots are slightly wider than their corresponding narrow slots. Noncompliance with the upper slot limit increased the selectivity of older fish in the narrow slots more than in the wide slots.

Scenario evaluation (SSB).—Harvest slot limits promoted SSB recovery more quickly and to larger magnitudes than MSL management. Spawning stock biomass recovered with harvest slot management in all but the small-wide slot scenario (Table 4). With the narrow slots, median SSB was larger than with the MSL for the duration of the forward population simulation (Figure 4). The large-wide slot rebuilt to SSB_{Target} and $SSB_{Threshold}$ more quickly than with MSL management. Interestingly, the median SSB with this slot was larger than the median SSB with MSL for the first 31 years of the projection, after which the MSL maintained larger median SSB. Even when noncompliance is considered, only one scenario (large-wide with 20% noncompliance) took longer to reach the SSB_{Target} than with MSL management (Table 4).

Scenario evaluation (N-at-age).—Harvest slot limits broadened the age structure of Tautog in the Long Island Sound region by increasing the abundance of older fish (Figure 5). Relative to MSL management, the abundance of older fish increased with slot management. The change in the relative abundance of older fish was more pronounced after 10 years of management than after 55 years of management, owing to the slower stock recovery when managed by MSL. The median relative abundance for ages five to about ten years (depending on scenario and noncompliance) were depressed with harvest slot management due to the redirected fisheries selectivity. This reduction is more pronounced after 55 years than 10 years of management. Noncompliance decreased the relative abundance of older fish in all models. The small-wide slot is not included as SSB analysis indicated that the stock would not recover with this management approach.

< A >Discussion

Managing with harvest slot limits broadens age structure and rebuilds SSB more quickly and to larger magnitudes than managing with MSL (Table 3 and Figure 4). Slot limits reduce

removal biomass, relative to management with MSL, but the biomass reduction does not necessitate an equally large reduction in the number of fish removed. Harvest slots are more effective at broadening age structure than MSL. Finally, biological reference points are reached more quickly with slots than MSL management.

Spawning stock biomass rebuilds more quickly with the harvest slots than with MSL management and potentially to larger magnitudes. Rebuilding to $SSB_{Threshold}$ and SSB_{Target} is faster in three of the compliant scenarios than with MSL management (small-wide being the exception). Harvest slots tolerate noncompliance as only the large-wide with 20% noncompliance scenario took longer to rebuild to SSB_{Target} than with MSL management. Based on median SSB values, the small-narrow slot rebuilt to $SSB_{Threshold}$ and to SSB_{Target} five and fifteen years faster, respectively, while simultaneously broadening age structure. While Tautog is not managed by the Magnuson-Stevens Fishery Conservation and Management Act (MSA) and the Sustainable Fisheries Act (SFA), we considered the stock rebuilding requirements therein. Under federal management, overfished stocks must be rebuilt within 10 years (Sustainable Fisheries Act of the Magnuson-Stevens Fishery Conservation and Management Act 1996). Had this stock been managed by MSA/SFA, a larger stock reduction (27% instead of 20.3%, Appendix 3) would have been required to rebuild to SSB_{Target} in 10 years with MSL management. This larger reduction would have been achieved by the large-narrow slot (Figure A1) but was less effective at broadening age structure (Figure A2). Such profound population-level changes make harvest slots a more attractive management measure than traditional approaches for fisheries with low discard mortality rates.

Management with harvest slot limits broadens truncated age structure by protecting young–extant–individuals and allowing them to grow older, rather than relying on *de novo*

recruitment to rebuild the stock. This is evidenced by the finding that within 10 years of slot limit management the abundance of fish older than 10 years increases relative to management with MSL. In the current study, the predicted rapid increase in the relative abundance of older fish indicates that harvest slots are a powerful tool to modify age structure. This recovery is within one or two benchmark stock assessment cycles, which may garner support for these alternative management measures.

We assumed density independence in recruitment. Our model fixed the initial steepness of the stock-recruitment relationship, a notoriously difficult parameter to estimate (Conn et al. 2010; Lee et al. 2012). While preliminary analysis estimated the steepness of the stock-recruitment relationship, the parameters were not used because the initial steepness and unexploited SSB were highly correlated (data not shown). Fixing initial steepness renders recruitment independent of SSB which may seem contradictory to the goal of increasing SSB. This is nonetheless a common practice in stock assessments (Mangel et al. 2013), and is resolved by implementing spawning potential ratio based reference points. Incorporating density dependence in recruitment would reduce the estimated rate of recruitment when SSB is below the target or threshold, and could delay the recovery in SSB. Incorporating density-dependent recruitment would not impact the extent to which age structure broadens in the short term (e.g., would not affect the proportion of fish older than 10 years after only 10 years of management) but could affect predicted age structure over a longer timeframe. Experimental studies suggest that density dependence in recruitment has a relatively modest effect: in freshwater systems that could be expected to impose density dependence in recruitment, harvest slot regulations are effective at broadening age structure (Pierce 2010; Tiainen et al. 2017).

For general applicability, we chose to assess reproductive capacity with SSB rather than egg production. This metric aligns our study with traditional stock assessment approaches and provides utility for fisheries managers to apply our methods to other species (which are mostly managed by SSB). For example, the ASMFC measures reproductive capacity with total egg production for only Atlantic Menhaden *Brevoortia tyrannus* (SEDAR 2020). Additionally, Tautog—like many marine species—exhibit asynchronous oocyte development (White et al. 2003) making annual fecundity estimates challenging, expensive, and error-prone (McBride et al. 2015). As such, despite the availability of annual fecundity estimates for Tautog in this region (LaPlante and Schultz 2007), we chose to evaluate with SSB. Measuring reproductive capacity with SSB rather than egg production may underrepresent the impact of harvest slot limits. On a per-gram basis, larger Tautog produce disproportionally more eggs than smaller individuals. As the age structure broadens, stocks with more older (larger) fish are likely to have higher reproductive capacity. The narrow slots rebuilt SSB to the largest equilibrium values and were the most effective at broadening age structure. Were reproductive capacity measured in total egg production we would expect the reproductive capacity of the narrow slots to be even larger relative to MSL management than reported.

Management with narrow slots was the most effective strategy for increasing SSB and the abundance of older fish. This may translate into increased population fecundity and, subsequently, resilience. In other species, broad age structures are associated with increased population fecundity (Mehault et al. 2010; Cooper et al. 2013). Increased population fecundity is associated with increased resilience (Le Bris et al. 2018) and truncated age structures with decreased reliance (Stewart 2011; Rouyer et al. 2011). Yet, increased egg production does not predict increased resilience in all species (e.g. Atlantic Cod, *Gadus morhua*, Stige et al. 2017).

Thus, species-specific analyses are needed to determine which of these metrics is most representative of reproductive capacity for a given species. Despite not evaluating resilience, we report other benefits of harvest slot limits.

Harvest slot limits facilitate achieving one of the goals of recreational fisheries management: maintaining sustainable harvest levels (biomass) while maximizing catch rates and sustainable harvest levels (Tetzlaff et al. 2013). There is a tradeoff between the narrow slots: while both allow similar magnitudes of removals in biomass, the large-narrow permits the harvest of fewer larger fish (52% reduction in number harvested) and the small-narrow (19% reduction in number harvested) increases the opportunity for anglers to harvest more smaller fish. Here the objective of the fishery is important to consider in making management decisions: Should managers permit a larger harvest of smaller fish or a smaller harvest of larger fish? On the other hand, while the large-wide scenario allows the largest biomass removal of the slots in which SSB recovered and resulted in only a 10% reduction in the number harvested, it was the least effective slot for broadening age structure and equilibrium biomass was reduced relative to MSL. Despite the reduction in terminal SSB, biomass rebuilds to SSB_{Target} and $SSB_{Threshold}$ more quickly than with MSL management, and age structure broadens. This management approach could be implemented in the short term, allowing stocks to recover, and then modified before the relative abundance decreases. Finally, broadening age structure also is likely to maximize the catch rates of larger/older fish, improving fishing quality which may increase angler satisfaction (Arlinghaus 2006; Gwinn et al. 2015).

While changes in daily bag limits, season length, and harvest length limits can reduce harvest, modification to length limits are more effective. Angler behavior responds unpredictably to changes in bag limits and season length. For example, in an Atlantic Salmon *Salmo salar*

fishery, angler effort did not respond linearly to changes in bag limits (Veinott et al. 2018) but did in a Walleye *Sander vitreus* fishery (Cox et al. 2002). In a Red Snapper *Lutjanus campechanus* fishery, a 75% reduction in season length resulted in a 26% harvest reduction (Powers and Anson 2016) due to changes in angler behavior. Length limits, in general, are a more effective management tool: a meta-analysis concluded that changing length limits produced greater harvest reductions than bag limits (van Poorten et al. 2013). Finally, recent studies in the region demonstrate angler support for slot limits in Tautog (Schultz et al. 2020) and Striped Bass *Morone saxatilis* (Murphy et al. 2015) fisheries.

The inclusion of noncompliant behavior incorporates one aspect of a complex suite of potential angler behavioral responses. The varying noncompliance rates we incorporated, informed from other fisheries managed by harvest slot limits (Pierce and Tomcko 1998; Muller et al. 2015), are suggestive of the degree of noncompliance that could be tolerated. Even at 20% noncompliance (slightly larger in magnitude than reported in other fisheries), SSB recovers and age structure broadens in two of our scenarios. But, directed surveys of angler satisfaction, a topic we are currently investigating (Schultz et al. 2020), are more informative of future behavior and could be used for further evaluation. Finally, an unintended consequence of implementing harvest slot management could be a reduction in high-grading, a practice that in the Red Snapper recreational fishery accounts for 84% of all discarded fish (Garner and Patterson 2015). While Tautog is robust to discards, the practice of high-grading is likely to increase discard mortality.

The degree to which harvest slot limits are effective at broadening age structure and rebuilding biomass is dependent on fishery and biological traits. These traits need consideration to generalize our results. Implementing slot limits may not be as effective if age-specific fishing mortalities differ between recreational and commercial sectors due to different regulations or

discard mortalities. Life-history traits are also important to consider in light of management goals. For example, in Summer Flounder *Paralichthys dentatus*, a sexually dimorphic species in which females grow faster and are larger than males (Morse 1981), slot limits are predicted to reduce females' fishing mortality and meet multiple management goals (Morson et al. 2017). On the other hand, slots could increase female fishing mortality in protogynous hermaphrodites (e.g. serranids, such as Black Sea Bass *Centropristis striata*) which may decrease the probability of achieving management goals. Another life history trait to consider is age-at-maturity; generally, it is advisable to allow individuals to spawn at least once to try to avoid growth overfishing (Froese 2004). As previously mentioned, harvest slot limits are used in managing multiple marine recreational fisheries, but seemingly, in many cases, without an appropriate level of prior analysis. The value of our case study is not in providing a prescription for reversing age truncation in coastal fisheries, but rather in demonstrating the methods necessary to evaluate this management technique as a potential solution.

Our results are constrained by the parameterization of constant removal biomass and constant fishery selectivity in the forward population simulations. These are reasonable assumptions as the stock is managed with a target removal value and with size limits which define the selectivity curve. As the stock recovers, fishing mortality will decrease if removals are constant. But as older fish become more abundant, the number that die due to discard mortality and noncompliant harvest is expected to increase. An alternative to our approach of constant removals in the forecast model would be to maintain constant fishing mortality and predict future changes in removals. If fishing mortality were constant, the biomass of removals would increase, particularly in the scenarios for which the strongest recoveries are predicted. The increase in removals would ultimately dampen the terminal SSB estimates and may reduce the broadening

of the age structure. Either of these approaches, constant removals or constant fishing mortality, are an approximation of a future scenario; in practice, stock assessments are updated every five years and the management is modified to reflect changes in removals, fishing mortality, and selectivity.

In this study, removal biomass varied among the scenarios analyzed. Estimated removal biomass is influenced by slot breadth, slot location, angler behavior, and discard mortality. Recreational fisheries are generally not managed by total allowable catch, thus setting a target removal biomass and estimating the performance of a slot would not be relevant to the current management infrastructure. By allowing the removal biomass to vary with each slot, angler behavior, and discard mortality, we have incorporated a level of management-relevant realism into the analysis.

Modifying fishery selectivity with harvest slot limits can broaden the age structure and restore the SSB of a species that is age truncated and overfished more quickly than with MSL management. The recovery is realized, in part, by reduced harvest biomass, but the number of fish harvested need not be reduced by a similar magnitude. For species with a recreational harvest component, the opportunity to harvest can be preserved (albeit at a lower biomass and redirected to a prescribed size range of fish). We have shown that the actual ability to restore SSB depends on the median size of harvest slot and slot breadth, but can be robust to high levels of noncompliance. The largest relative increases in the abundance of old fish occurred within the first 10 years of harvest slot management, owing to the slower recovery with MSL management. Harvest slot limits belong in the coastal fisheries manager toolbox and the modeling capacity (data and code) to evaluate slots exists for many fisheries (as evidenced by our example). Case studies are important for evaluating alternative management strategies: we provide new methods

to parameterize projection models with harvest slot removals, fisheries selectivity, and noncompliance and show that slot removals alone is not a sufficient predictor of management success. Thus, implementing harvest slots without projecting their efficacy may not rebuild SSB. Perhaps not surprisingly, harvest slots are unlikely to be 'set it and forget it' management tools but deserve more real-world evaluation and experimentation with actively managed fish stocks.

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TABLE 1: Data sources and their contribution to the Tautog stock assessment model for Long Island Sound. Surveys were either fishery-independent (I) or fishery-dependent (D). Survey names are abbreviated: Long Island Sound Trawl Survey (LISTS), Peconic Bay Small Mesh Trawl Survey (PBSMTS), Western Long Island Sound Juvenile Abundance Survey (WLISJAS), Marine Recreational Fisheries Statistics Survey (MRFSS), Marine Recreational Information Program (MRIP), New York party (head) boat survey (NYHB), Connecticut Marine Volunteer Angler Survey Program (CTVAS), and the American Littoral Society (ALS).

Source	Years	Survey Type	Harvest Length	Discard Lengths	Length	Age	Weight	Sex	Catch (N)	Abundance Index	Effort Index
LISTS	1984–2015	I			✓	✓	✓	✓		✓	
PBSMTS	1987–2015[a]	I			✓	✓				✓	
WLISJAS	1995–2015[b]	I			✓	✓				✓	
MRFSS	1984–2003	D	✓						✓		✓
MRIP	2004–2015	D	✓	✓					✓		✓
NYHB	1995–2014[c]	D	✓	✓		✓					
CTVAS	1997–2015	D	✓	✓							
ALS	1987–2015	D		✓							

[a]except years 2005, 2005, 2008; [b]except years 1985, 1994, 2009; [c]except years 2000–2007

TABLE 2: Model parameters and derived quantities, description, and value (when appropriate) used in the stock assessment and population simulation model for Tautog in Long Island Sound. The single logistic model was indexed by selectivity block (*b* = 1-4) for the stock assessment and was constant (no subscript) for the minimum size limit (MSL) scenario used in the population simulations.

Parameter/derived quantities	Description	Value (s)
B	Selectivity block	1, 2, 3, 4
F_D	Discard mortality rate	0.025
M_a	Natural Mortality	0.15
$P_{MA,a}$	Proportion maturity-at-age	0,0,0.8,1,…1
P_{SSB}	Proportion of year prior to spawning	0.42
A	Maximum age (years)	16
A	Age (years)	
T	Time (years)	
C_L	Catch-at-length	
$P_{H,L}$	Proportion harvested-at-length	
P_a	Proportion of removals-at-age	
R_a	Removals-at-age	
R_B	Removal biomass	
R_L	Removals-at-length	
R_N	Number of fish removed	
W_L	Weight-at-length	
α	single logistic midpoint, subscripted with values of *b* for stock assessment or no subscript in the population simulation of MSL	
β	single logistic slope, subscripted with values of *b* for stock assessment or no subscript in the population simulation of MSL	
α_z	ascending (*z* = 1) and descending (*z* = 2) of the midpoint of the double logistic	
β_z	ascending (*z* = 1) and descending (*z* = 2) of the slope of the double logistic	
$F_{t,a}$	Fishing mortality	
$Fmult_t$	Fully selected fishing mortality	
log_Rdev_t	Lognormal recruitment deviations	

$N_{t,a}$	Population abundance-at-age
R_t	Expected recruitment
$S_{b,a}$	Selectivity-at-age
SPR_0	Unexploited spawners per recruit
SSB_0	Unexploited spawning stock biomass
SSB	Spawning stock biomass
$W_{t,a}$	Weight-at-age
$Z_{t,a}$	Total mortality-at-age

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TABLE 3: Management scenarios for Tautog in Long Island Sound. Each slot scenario was evaluated with full compliance and 10% or 20% noncompliance (NC) with the upper slot limit. Removals in biomass (B), 1,000s of fish (N), and the percent change compared to minimum size limit (MSL) management. Removals were constant in the forward population simulations and based on past fishery performance.

Scenario	B (mt)	N (1,000s)	Percent change (B)	Percent change (N)
MSL	418	236		
Small-narrow				
Compliant	220	191	53%	81%
10% NC	257	208	61%	88%
20% NC	294	224	70%	95%
Small-wide				
Compliant	450	401	108%	170%
10% NC	477	412	114%	175%
20% NC	503	422	120%	179%
Large-narrow				
Compliant	188	113	45%	48%
10% NC	207	120	49%	51%
20% NC	225	127	54%	54%
Large-wide				
Compliant	348	213	83%	90%
10% NC	357	216	85%	92%
20% NC	366	219	88%	93%

TABLE 4: Time (years) to reach spawning stock biomass (SSB) biological reference points ($SSB_{Threshold}$ and SSB_{Target}) for each management strategy (slot or minimum size limit, MSL) for Tautog in Long Island Sound. Slot scenarios include compliance with the upper slot limit as well as 10% and 20% noncompliance (NC) with the upper slot limit. The year that SSB is largest relative to SSB with MSL management (max relative difference) and the year in which SSB reaches equilibrium are also included. Median and 5th/95th percentiles (confidence limits) are provided. Scenarios in which SSB crashed are indicated (-).

Scenario	Year SSB ≥ $SSBB_{Target}$	Year SSB ≥ $SSB_{Threshold}$	Year equilibrium	Year max relative change
MSL	22 (9, -)	9 (2, 23)	26 (22, 31)	-
Small-narrow				
Compliant	7 (4, 11)	4 (2, 6)	20 (19, 21)	12 (12, 13)
10% NC	8 (4, 14)	4 (2, 7)	19 (19, 20)	12 (11, 13)
20% NC	10 (5, 23)	5 (2, 9)	19 (19, 20)	10 (10, 11)
Small-wide				
Compliant	- (-, -)	- (3, -)	- (-, -)	- (-, -)
10% NC	- (-, -)	- (4, -)	- (-, -)	- (-, -)
20% NC	- (-, -)	- (-, -)	- (-, -)	- (-, -)
Large-narrow				
Compliant	6 (4, 9)	3 (2, 5)	21 (19, 22)	14 (14, 14)
10% NC	6 (4, 9)	3 (2, 6)	21 (19, 22)	14 (14, 14)
20% NC	7 (4, 10)	4 (2, 6)	21 (19, 22)	14 (14, 14)
Large-wide				
Compliant	16 (6, -)	6 (2, 16)	19 (18, 21)	9 (8, 10)
10% NC	19 (7, -)	7 (2, 19)	19 (18, 21)	8 (8, 8)
20% NC	25 (7, -)	7 (2, 24)	19 (17, 21)	7 (7, 7)

Appendix 1: Data

Catch-at-length.—Gamma distributions were fit to both the harvest-at-length and discard-at-length observations for each selectivity block using a Bayesian model and a random year effect variable. Gamma distribution was selected after fitting harvest and discard length observations independently to log-normal, normal, and gamma distributions using the fitdistr function in the MASS package (Venables and Ripley 2002). Resulting models were tested for goodness of fit using a one-sample Kolmogorov-Smirnov (ks.test). For harvest lengths, the gamma distribution had the lowest D value. While the normal distribution had the lowest D value for discard lengths, the gamma distribution (which had the second-lowest D value) was selected to avoid predicting negative lengths with the normal distribution. This analysis was performed in R using the R2jags package (Su and Masanao Yajima 2015). Posterior distributions were estimated with JAGS (Plummer 2003) using a Gibbs sampler. Vague priors were used and checked against posterior distributions to ensure that priors were flat in the region of the posterior estimate. Estimates were drawn from 15,000 iterations, using a burn-in period of 5,000 and 3 chains.

Model code:

```
("model {
      for(j in 1:4){
      b.year[j] ~ dnorm(mu.year, tau.year)
      }
for(i in 1:n.obs) {
      y[i] ~ dgamma(a[i], b[i])
      a[i] <-((mu[i])^2) / sigma^2
      b[i] <-(mu[i]) / sigma^2
      log(mu[i]) <- b.block[block[i]]
}
      sigma ~ dgamma(0.001, 0.001)
      mu.block ~ dnorm(0, 0.001)
      tau.block ~ dgamma(0.0001, 0.0001)
}")
```

In the last selectivity block, harvest of undersized fish represented 8% of the observed harvest while the release of fish over the minimum size represents 0.3% of the observed discards.

As such, sampling from gamma distributions allowed for the harvest of undersized fish, but not for the release of fish over the minimum size.

Catch length-at-age.—The last major modification in data preparation was the procedure to estimate catch length-at-age. The ASMFC assessment borrowed aging data from neighboring states, as there were not enough Long Island Sound-specific age samples to develop a robust age-length key. This assessment implemented a multinomial approach (Gerritsen et al. 2006) developed with the nnet package in R (Venables and Ripley 2002) to facilitate the use of Long Island Sound- and selectivity block-specific samples (Table 1). The multinomial coefficients (Table A.1) were used to predict the probability of length-at-age using the predict function in R. Removals-at-age was the probably of length-at-age multiplied by the catch-at-length. Length-at-age was estimated independently for each selectivity block, using a maximum age of 16 years.

Weight-at-length.—Catch-weight-at-length was estimated independently for each selectivity block (Table A.2). Weight-at-length was calculated by fitting a linear model to log-transformed observations from the CT Long Island Sound Trawl Survey and correcting for back-transformation bias (Sprugel 1983) using the FSA package in R (Ogle et al. 2020; R Core Team 2020) when estimating the weight-at-age for the mean catch-length-at-age. Spawning stock biomass-weight-at-age was estimated with the von Bertalanffy growth model (Table A.2) using the growth function in the FSA package (Ogle et al. 2020). Weight-at-age was then estimated for mean length-at-age using the same procedure as for the catch-weight-at-length.

Commercial harvest.— Commercial harvest was treated in this assessment as it was treated in the ASMFC Tautog stock assessment for Long Island Sound (ASMFC 2016). In brief, the commercial harvest was included in the total removals because it is a relatively small proportion

of the harvest (~10% annually) and because commercial regulations are similar to recreational regulations.

Appendix 2: Stock characteristics

Model Parameterization.—Several modifications were made to how these data were prepared for this stock assessment versus the ASMFC assessment (ASMFC 2016). The age-plus group for the current analysis was changed to ages 16+ from the 12+ age group used in the ASMFC assessment. This change was made to incorporate all ages of growth and to minimize the loss of reproductive potential in a 12+ age group, which would underestimate the impact of harvest slots. As with the ASMFC assessment, this assessment used for fishery selectivity blocks. Length-at-age and weight-at-length were estimated independently for each selectivity block because some years had small sample sizes, preliminary analysis indicated changes in growth over time, the previously reported size-truncation (LaPlante and Schultz 2007) and age truncation reported herein.

Some parameters were modified from the ASMFC assessment while others remained the same. The following parameters were not modified: years of assessment (1984-2015), number of fleets (1), number of surveys (4), the number of weight-at-age matrices (2, one for catch weight-at-age and one for spawning stock biomass-weight-at-age), start age of average F calculation (8), and estimating selectivity as a single logistic. The following parameters were recalculated because the age plus group was expanded from 12 in the ASMFC assessment to 16 in the current contribution: catch-at-age, weight-at-age matrices, removals-at-age, total weight of removals. The last major departure from the ASMFC assessment was that the stock-recruit relationship was not estimated (fixed at 1), so biological reference points are spawning biomass per recruit (SPR) based. Here, $F_{40\%SPR}$ is the F_{Target} and $F_{30\%SPR}$ is the $F_{Threshold}$.

Appendix 3: Magnuson-Stevens Act recovery

<A>Methods

The removal biomass that results in the median SSB to be equivalent to SSB_{Target} after 10 years of management was estimated through reiterative calculations, in the forward population simulation model used for all other projections, using the MSL fishery selectivity curve. This benchmark was chosen for compliance with stock rebuilding criteria under federal fisheries management legislation (Sustainable Fisheries Act of the Magnuson-Stevens Fishery Conservation and Management Act 1996). The removal value estimated by the reiterative process was then utilized in the forward population simulation model.

<A>Results

A harvest of 352 metric tons (27% harvest reduction, compared to the current management which targets a 20.3% harvest reduction) would rebuild the stock within 10 years. When managed with the MSA required reduction, SSB recovers relative to the current management approach (Figure A1) and age structure broadens (Figure A2). But this management approach is not as effective at broadening age structure as harvest slot limits.

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TABLE A.1 Multinomial coefficients used to estimate length-at-age for Tautog in the Long Island Sound stock assessment. Length-at-age was estimated independently for each of the four selectivity blocks (period of relatively consistent regulations) using fish sampled in both fishery-dependent and independent surveys (Table 1).

Selectivity Block	Age (years)	Intercept	Slope	Selectivity Block	Age (years)	Intercept	Slope
1	2	-162.669	10.230	3	2	-3.089	0.281
1	3	-173.181	10.742	3	3	-9.847	0.613
1	4	-182.976	11.133	3	4	-15.645	0.830
1	5	-194.465	11.508	3	5	-21.871	1.027
1	6	-206.062	11.840	3	6	-28.572	1.209
1	7	-217.696	12.136	3	7	-35.250	1.373
1	8	-226.105	12.329	3	8	-42.197	1.532
1	9	-233.617	12.495	3	9	-46.471	1.618
1	10	-241.921	12.668	3	10	-53.729	1.764
1	11	-247.378	12.771	3	11	-56.494	1.811
1	12	-252.481	12.866	3	12	-62.957	1.931
1	13	-255.774	12.919	3	13	-66.842	2.002
1	14	-265.918	13.109	3	14	-68.362	2.022
1	15	-265.930	13.093	3	15	-71.806	2.081
1	16	-269.592	13.187	3	16	-79.435	2.229
2	2	-2.874	0.273	4	2	-2.587	0.250
2	3	-14.189	0.845	4	3	-12.137	0.729
2	4	-20.509	1.101	4	4	-20.847	1.054
2	5	-27.991	1.348	4	5	-31.684	1.399
2	6	-33.946	1.518	4	6	-36.226	1.523
2	7	-39.864	1.667	4	7	-46.729	1.775
2	8	-45.775	1.807	4	8	-55.479	1.966
2	9	-50.922	1.914	4	9	-62.063	2.099
2	10	-57.317	2.045	4	10	-73.189	2.316
2	11	-64.076	2.176	4	11	-83.274	2.503
2	12	-66.309	2.216	4	12	-90.806	2.632
2	13	-67.336	2.231	4	13	-83.826	2.497
2	14	-72.748	2.332	4	14	-91.547	2.644
2	15	-74.334	2.359	4	15	-89.283	2.587
2	16	-81.890	2.509	4	16	-350.977	7.132

TABLE A.2. Life history parameters, description, and value calculated for the Long Island Sound Tautog stock assessment. Weight-length relationships were estimated independently for each selectivity block (period of relatively consistent regulations) as preliminary analysis indicated changes in this relationship during the assessment period.

Parameter	Description	Selectivity Block	Value
	Von Bertalanffy growth parameters		
L_∞	Asymptotic length (cm)		58.7
K	Growth coefficient		0.171
t_0	Time at zero length (year)		-0.08
	Weight-length relationship		
α_1	Length-weight coefficient	1	1.80E-05
β_1	Length-weight exponent (cm to kg)	1	3.07
ε_1	Bias correction factor	1	1.007
α_2	Length-weight coefficient	2	1.40E-05
β_2	Length-weight exponent (cm to kg)	2	3.13
ε_2	Bias correction factor	2	1.009
α_3	Length-weight coefficient	3	2.00E-05
β_3	Length-weight exponent (cm to kg)	3	3.02
ε_3	Bias correction factor	3	1.011
α_4	Length-weight coefficient	4	2.10E-05
β_4	Length-weight exponent (cm to kg)	4	2.99
ε_4	Bias correction factor	4	1.016

TABLE A.3 Length-specific noncompliance rates for fish smaller than the current minimum size limit for Tautog harvested in Long Island Sound from 2012–2015. These rates were applied in stanza 1 of the harvest slot limit removal estimates.

Length (cm)	Noncompliance rate
27	0.0000130
28	0.0000473
29	0.0001557
30	0.0004905
31	0.0010862
32	0.0026338
33	0.0058760
34	0.0129561
35	0.0250747
36	0.0454834
37	0.0806935
38	0.1340782
39	0.2041256

TABLE A.4. Comparison of biological reference points estimated in the 2016 ASMFC Tautog Long Island Sound stock assessment and the assessment developed for the current study.

Reference point	ASMFC assessment	Current study assessment
$SSB_{Terminal}$	1,603 mt	1,937 mt
SSB_{Target}	2,980 mt	3,397 mt
$SSB_{Threshold}$	2,238 mt	2,549 mt
$F_{Terminal}$	0.51	0.75
F_{target}	0.28	0.29
$F_{Threshold}$	0.49	0.54

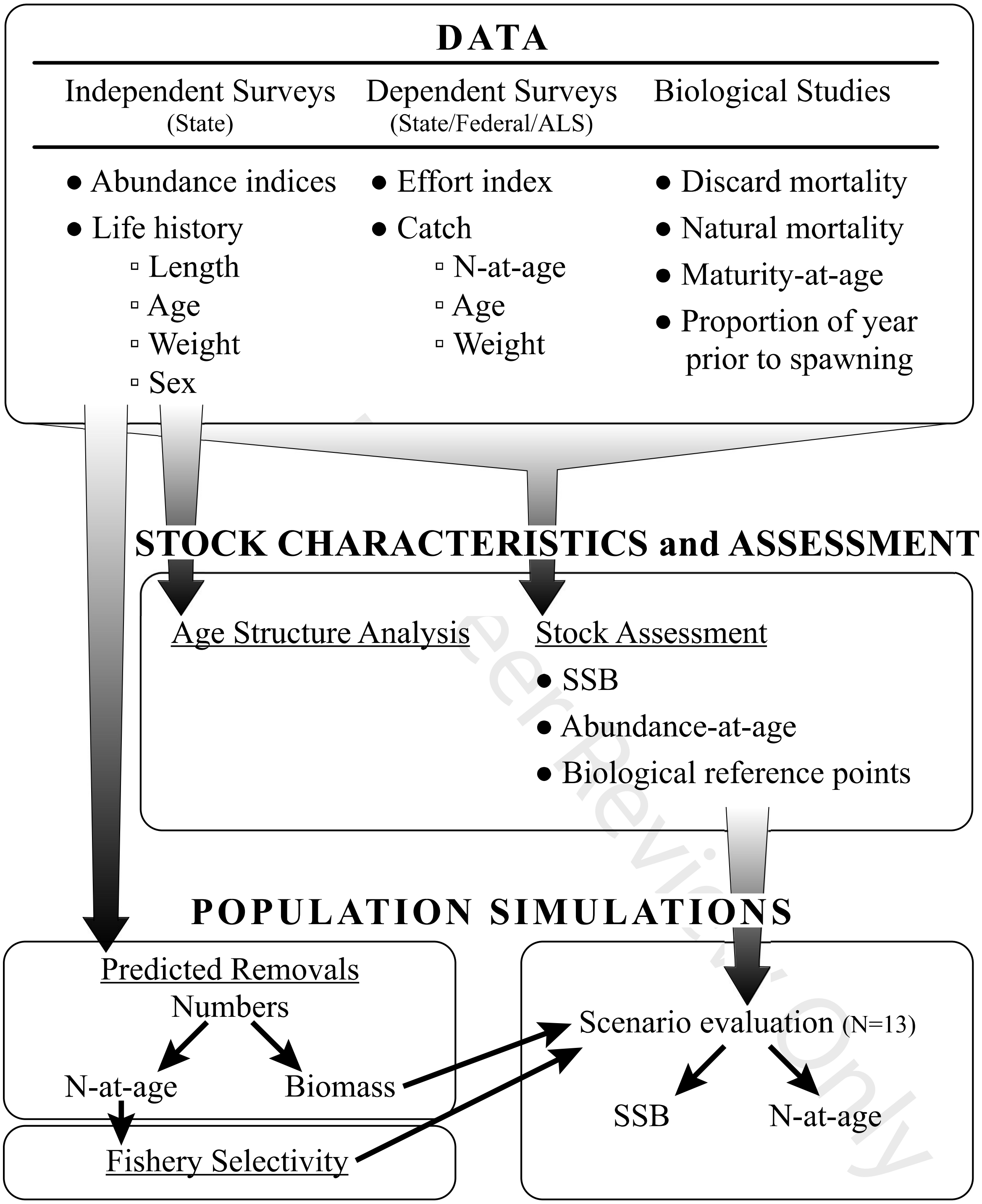

FIGURE 1. Schematic representation of the data flow and modeling. Data are collected by state and federal agencies and the American Littoral Society (ALS) include stratified random fishery-independent surveys, fishery-dependent angler surveys of catch and harvest, and biological studies. Independent survey data was used to analyze age structure. All available surveys and biological data were used in the statistical catch-at-age stock assessment model. Dependent surveys informed the removal (sum of harvest and dead discards) for the harvest slot limits and both dependent and independent surveys informed fishery selectivity for the harvest slot limits. Fishery selectivity and the assessment model parameterized the forward population simulations for each of the 13 scenarios evaluated. Spawning stock biomass (SSB) and numbers-at-age (N-at-age) were estimated in the population simulation model.

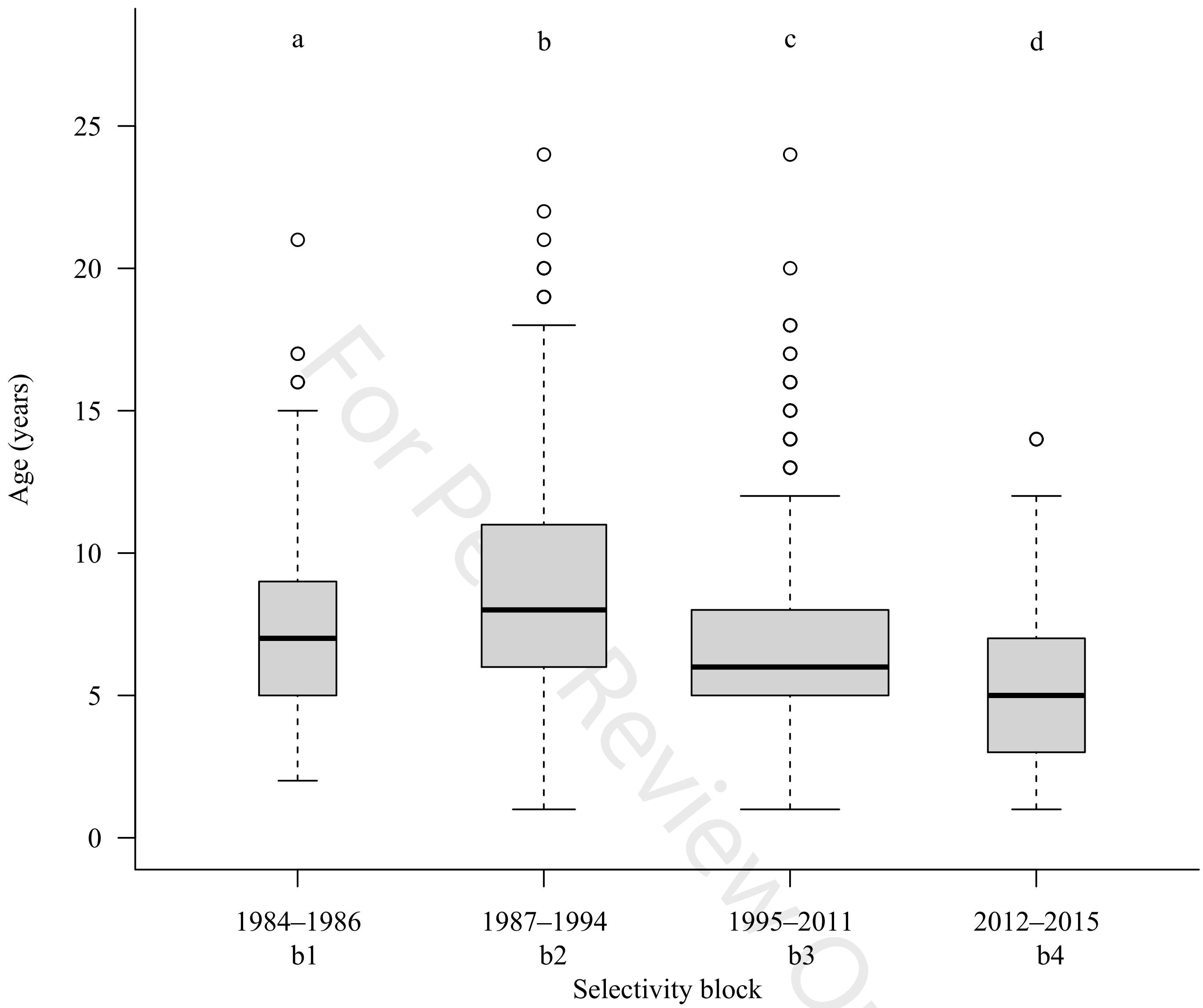

FIGURE 2. Change in age structure of female Tautog caught in the Connecticut Long Island Sound Trawl Survey by fishery selectivity block (b). The size distribution of females is shown (in each box the center line represents the median, the lower and upper boundaries represent the 25th and 75th percentiles, whiskers extend to 1.5 times the interquartile range, single point outliers (which also indicates maximum age observed in each selectivity block) are indicated with circles, and box width varies with sample size. The survey targeted 200 stations per annum in the spring and fall (the average annual number of station per selectivity varied: b1 = 218, b2 = 243, b3 = 182, b4 = 200). The mean age in each selectivity block was significantly different from each other (all p-values < 0.0001) as analyzed by Tukey's honest significant difference (indicated by the letters above the boxes).

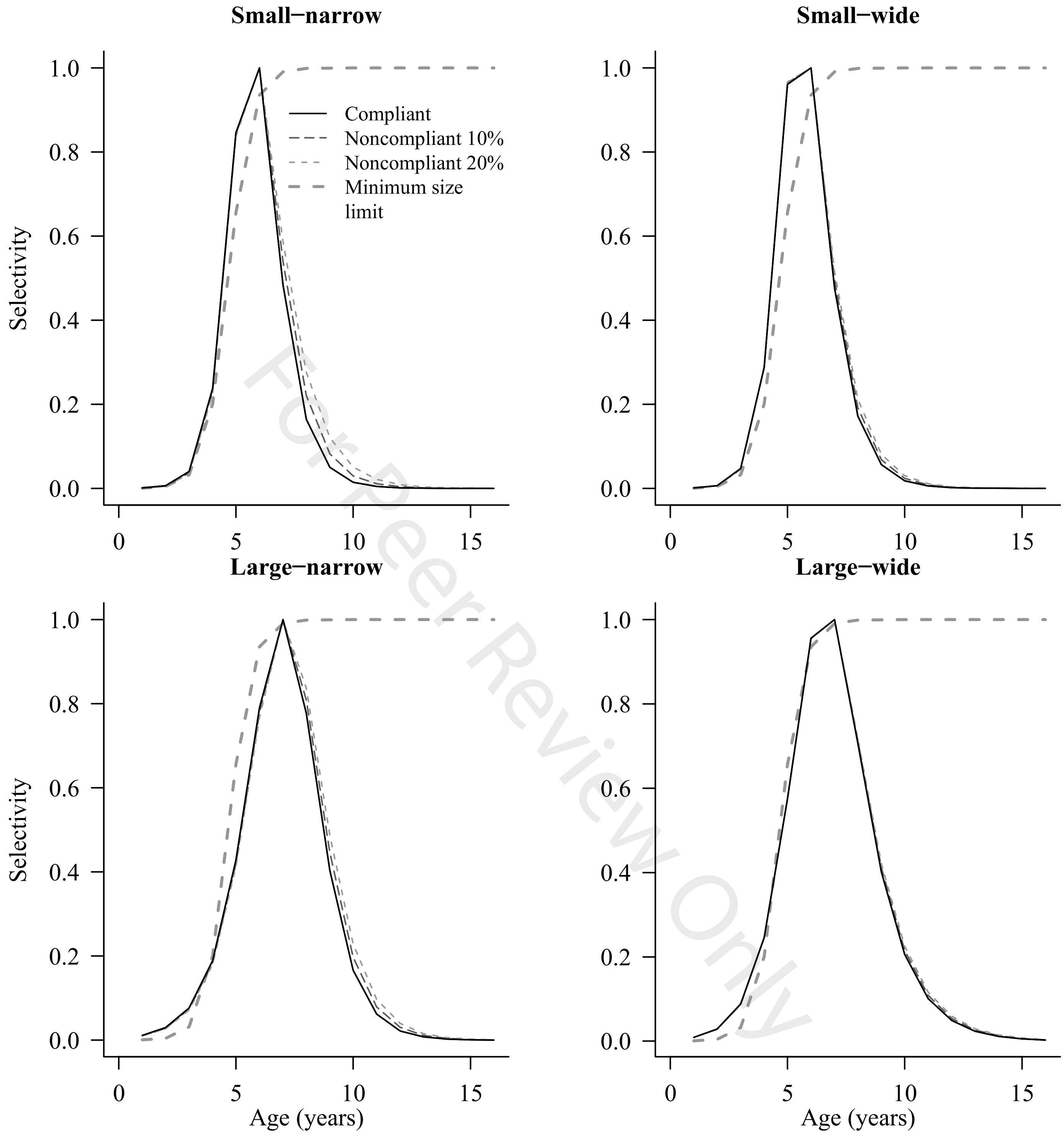

FIGURE 3. Selectivity-at-age used in population projections. Full compliance and noncompliance with the upper size of the harvest slot limit were evaluated at 10% and 20%. Selectivity-at-age with the current minimum size limit (MSL) of 16" is included in each panel.

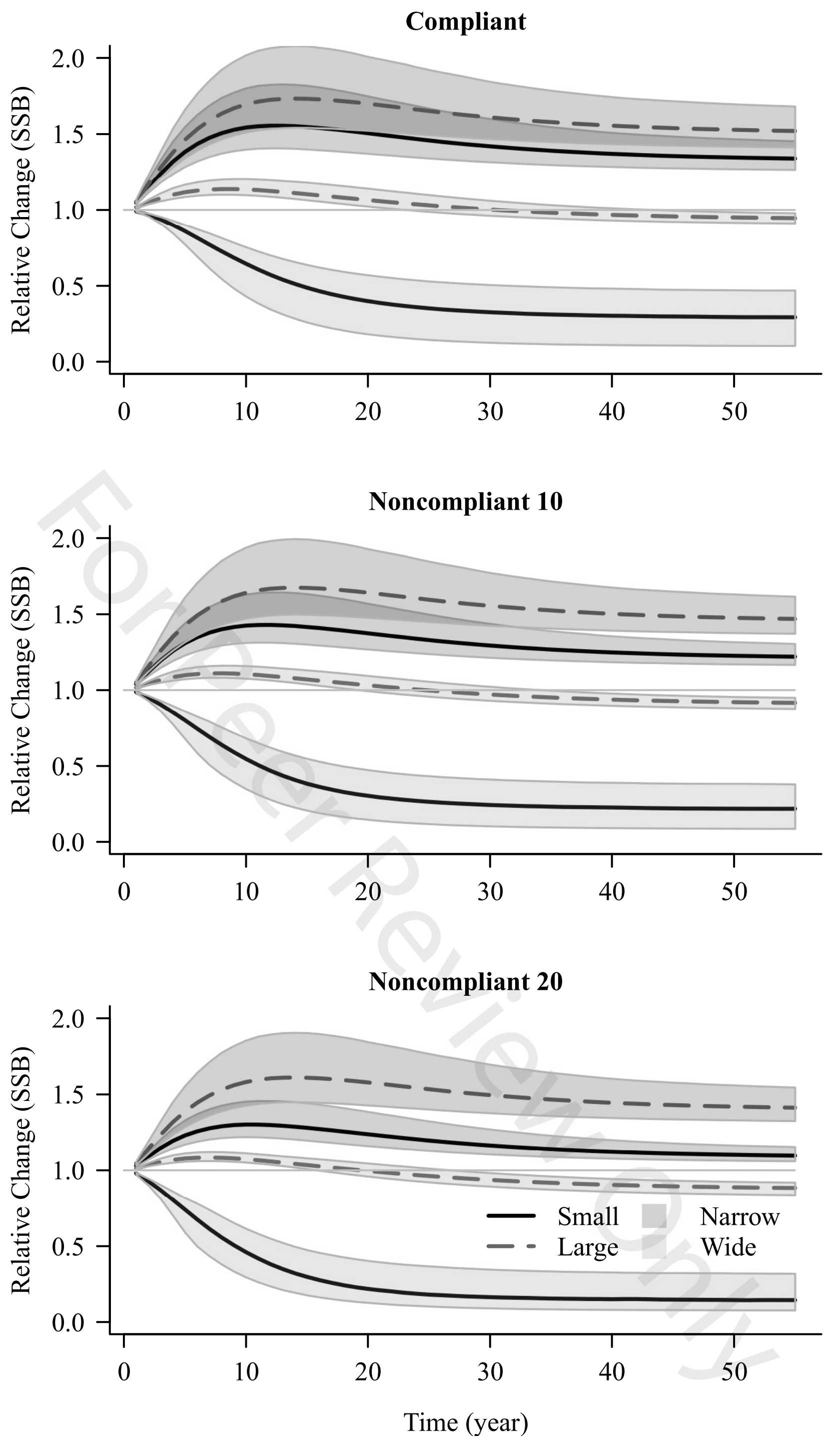

FIGURE 4. Median change in SSB when managed with harvest slots limits, relative to management with minimum size limits. Full compliance (top panel), and noncompliance with upper slot limit were evaluated at 10% (middle panel), and 20% (bottom panel). Shaded regions indicate 90% confidence limits of the forward population simulations. Darker colors that do not appear in the legend indicate overlap.

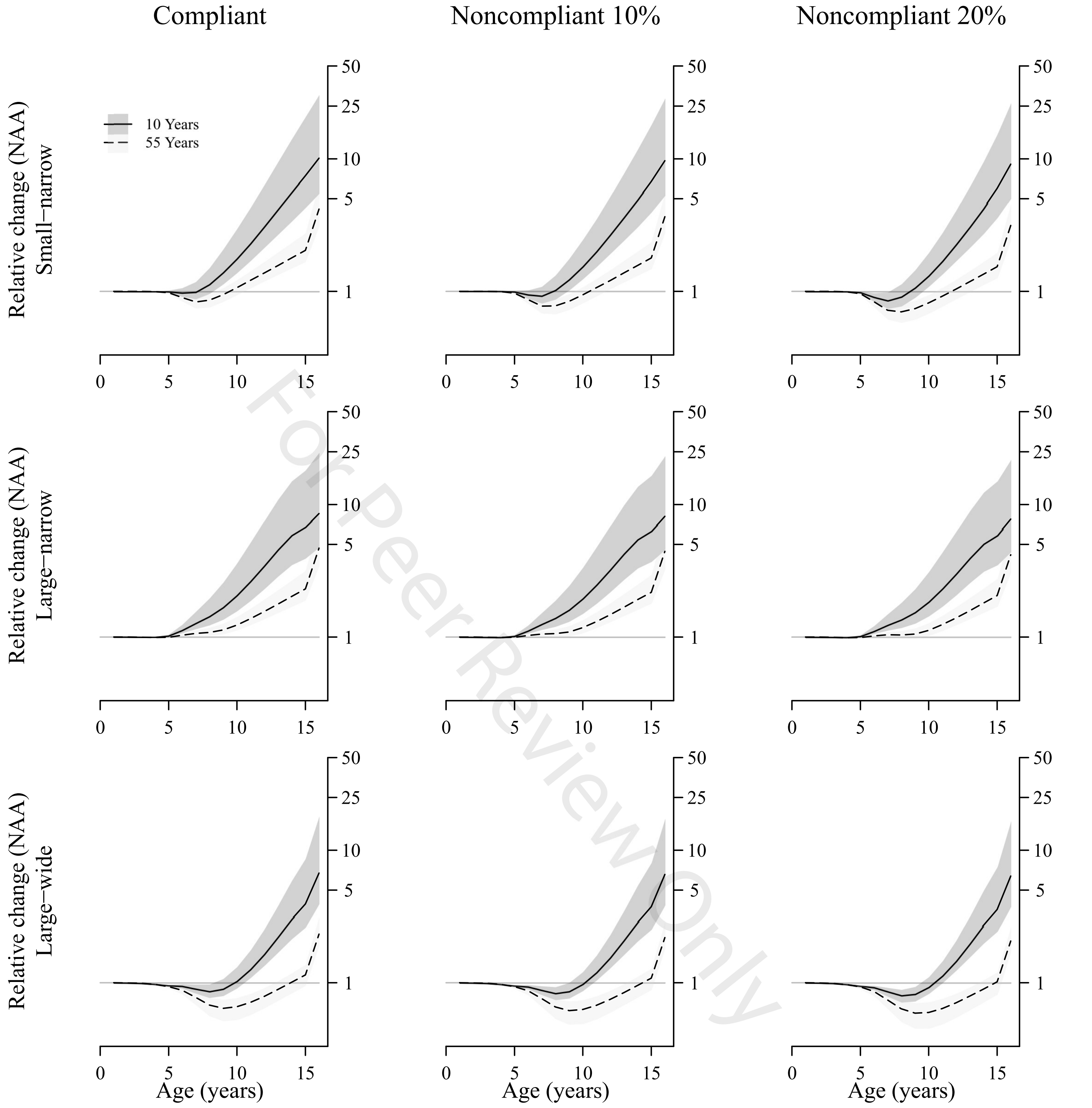

FIGURE 5. Median change in abundance-at-age, for three harvest slot limit scenarios relative to management with minimum size limits (MSL). Changes in abundance-at-age after 10 and 55 years of management for the fully compliant models and 10% and 20% noncompliance with the upper slot limit are shown. Shaded regions indicate 90% confidence limits estimated from forward population simulations. Darker colors that do not appear in the legend indicate overlap. Changes in abundance-at-age are not shown for the small-wide slot, where SSB crashed.

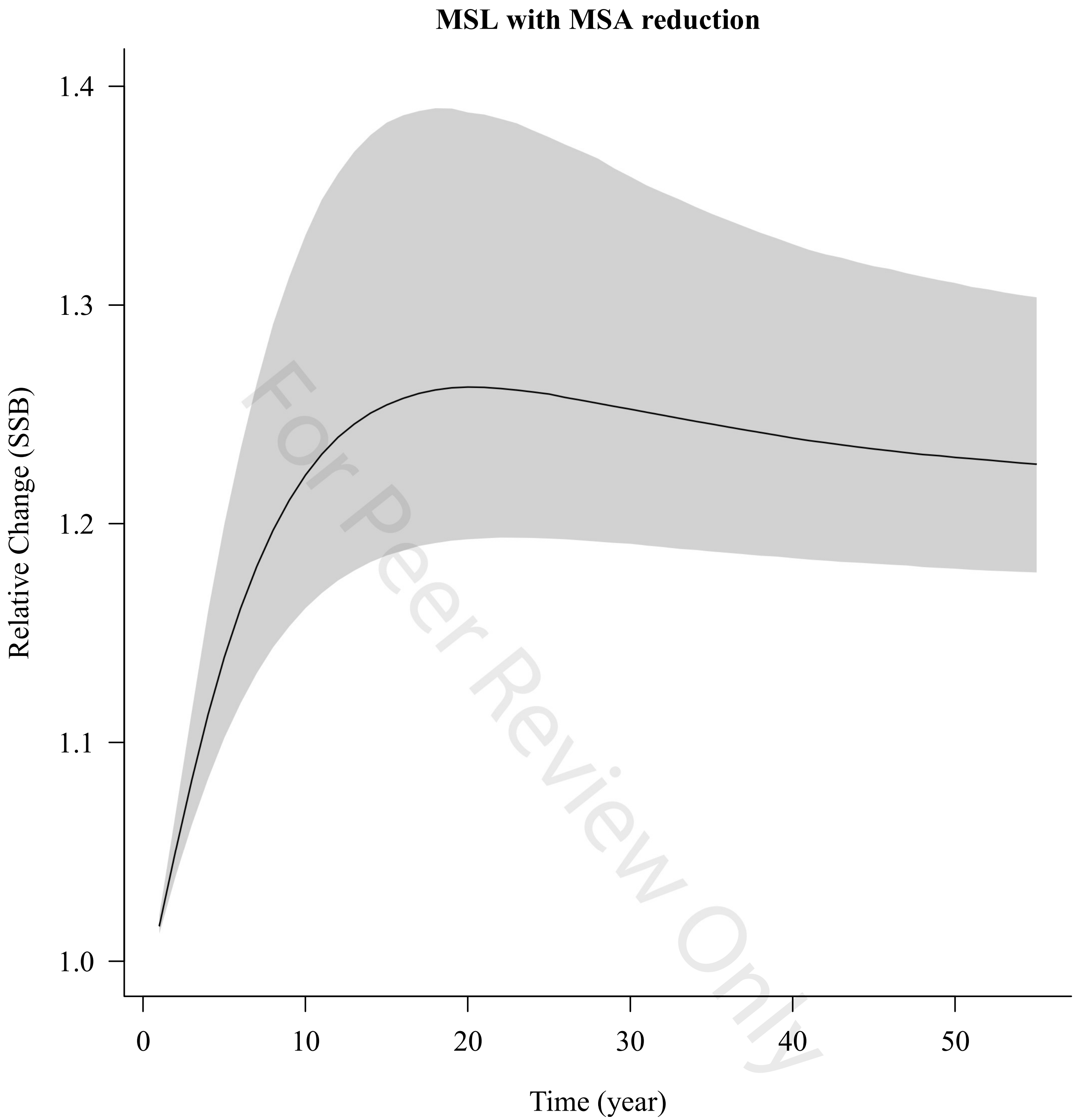

FIGURE A1. Median changes in spawning stock biomass (SSB) when managed with the minimum size limit and the harvest reduction in compliance with the Sustainable Fisheries Act of the Magnuson-Stevens Fishery Conservation and Management Act, relative to the current Atlantic States Marine Fisheries Management Commission strategy. Shaded regions indicate 90% confidence limits estimated from forward population simulations.

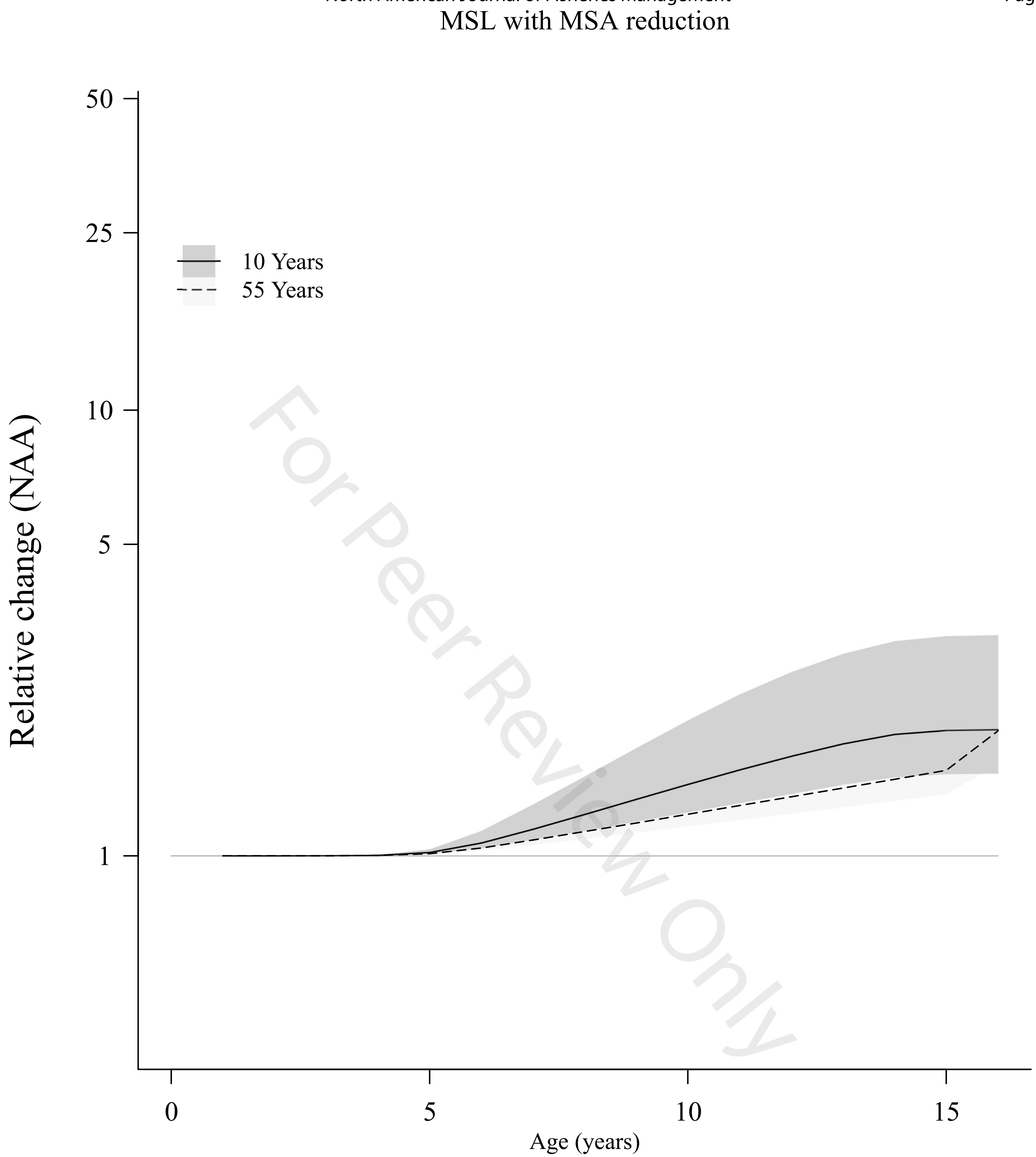

FIGURE A2. Median change in abundance-at-age (NAA), when managed with the minimum size limit and the harvest reduction in compliance with the Sustainable Fisheries Act of the Magnuson-Stevens Fishery Conservation and Management Act, relative to the current Atlantic States Marine Fisheries Management Commission strategy. Changes in abundance-at-age after 10 and 55 years of management is shown. Shaded regions indicate 90% confidence limits estimated from forward population simulations.