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ARTICLE

# Using Harvest Slot Limits to Promote Stock Recovery and Broaden Age Structure in Marine Recreational Fisheries: A Case Study

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***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 with a 40-cm minimum size limit (MSL), is a candidate species for slots because it is relatively long-lived and 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 cm (small–wide), 38–42 cm (small–narrow), 40–50 cm (large–wide), and 43–47 cm (large–narrow), inclusive of lower and upper length limits. Angler behavioral responses were evaluated at 0, 10, and 20% noncompliance with the upper slot limit. The biomass and number of fish removed were reduced with harvest slot limit management relative to the MSL, but because the harvest was redirected to smaller fish the reduction in numbers removed was 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 (3–6 years to reach SSB associated with a fishing mortality that yields 30% spawners per recruit as compared to 9 years with MSL management). We concluded that harvest slot limits can**

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**broaden age structure and restore biomass in overfished fisheries, but they should be evaluated when managing coastal fisheries as a reduction in biomass removed is required.**

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, such as 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 (i.e., 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 may 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 (MSLs; 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; GMFMC 2020; WDFW 2019). In some marine recreational fisheries, harvest slots have been implemented and apparently not evaluated, whereas in others, 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* (Berkeley 2006) and simulated species (Gwinn et al. 2015). In these examples, harvest slot limits were 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 and 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 that is regionally popular among marine recreational anglers, Tautog *Tautoga onitis*. Tautog is cooperatively managed through the Atlantic States Marine Fisheries Commission (ASMFC); individual states (North Carolina to Massachusetts) 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 are overfished and experiencing overfishing in the terminal year (ASMFC 2016). The recreational sector accounts for 90% of the harvest (ASMFC 2016), and Tautog have 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 $2 \times 2$ 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; SSB is more widely employed in stock assessments because it can be more readily quantified. To estimate these changes appropriately, we reparameterized 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.

## 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 (Connecticut and north shore of Long Island, New York) are assessed and managed as a subunit of the coastwide stock. Connecticut, New York, the U.S. 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 (number per tow) was developed using the Connecticut Long Island Sound Trawl Survey, a stratified-random survey (CT DEEP 2016), using a negative binomial generalized linear model 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 (number 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 generalized linear models. The Peconic survey formula used abundance ~ year; the Western Long Island Sound survey formula used abundance ~ year + temperature (ASMFC 2016). Fish from these three surveys were aged (opercular bones), measured for TL (mm), and in the case of the Connecticut 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 provided the fishing effort index, estimated the numbers of fish caught and harvested, and contributed to the harvest- and discards-at-length observations (National Marine Fisheries Service, Fisheries Statistics Division, personal communication). The New York party (head) boat survey, the Connecticut Marine Volunteer Angler Survey Program, and the American Littoral Society tagging program contributed length-at-age (New York survey) and additional harvest- and discards-at-length observations (see Table 1 for details; ASMFC 2016). Detailed descriptions of the data preparation are provided (Appendix 1).

*Stock characteristics and assessment.*— The Connecticut survey was used to evaluate changes in female age structure in Long Island Sound (Figure 1). A one-way ANOVA was used to test for changes over time in female catch at age. We aggregated years into four selectivity blocks (periods of relatively consistent regulations) for this test; the

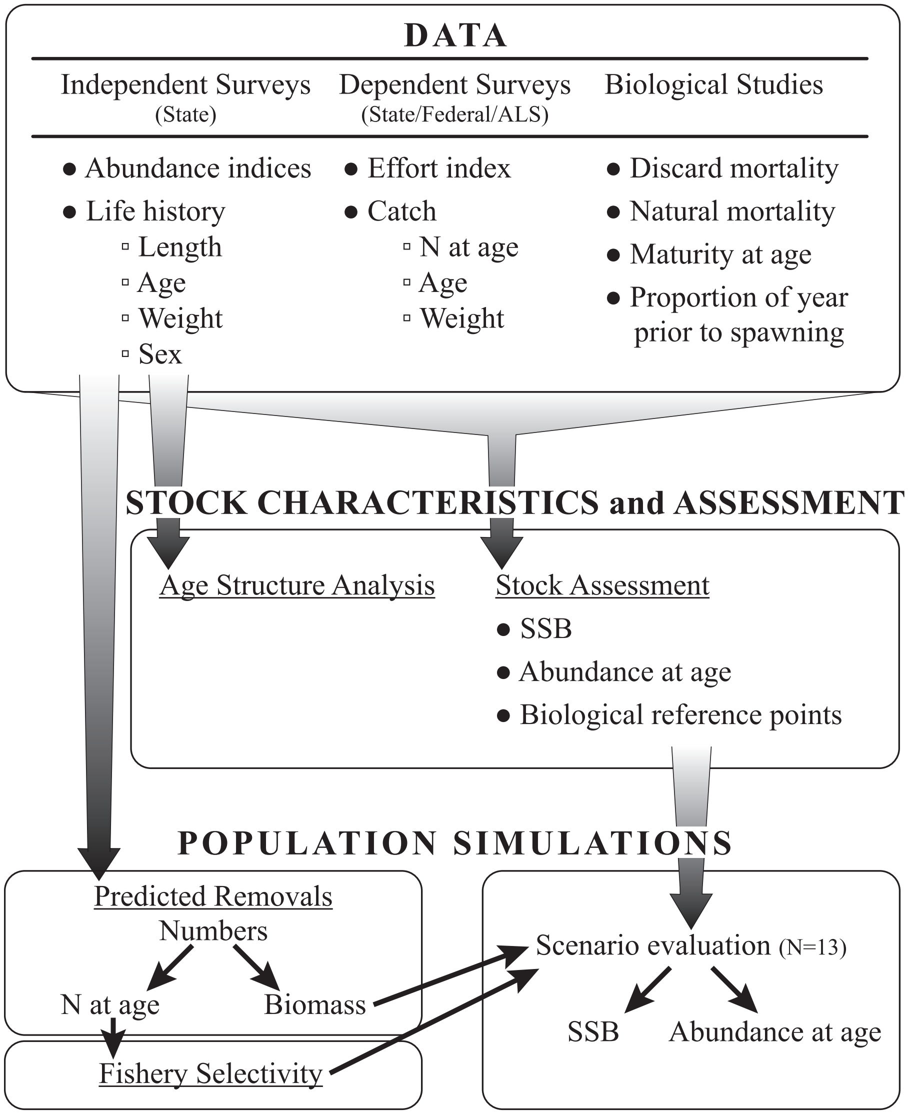


FIGURE 1. Schematic representation of the data flow and modeling. Data collected by state and federal agencies and the American Littoral Society (ALS) include stratified random fishery-independent surveys, fishery-dependent angler surveys of catch and harvest, and biological studies. Independent survey data were 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 scenario evaluation. 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 were estimated in the population simulation model.

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 a post hoc Tukey's test.

The stock assessment developed for this analysis covers the same years (1984–2015) and applies the same data sets 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 Age Structured Assessment Program (ASAP) version 3.0.17 (NOAA Fisheries Toolbox 2014). The 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 ($PM_a$; Chenoweth 1963), the weight at age ($W_a$), and

TABLE 1. Data sources and their contribution to the Tautog stock assessment model for Connecticut 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, and 2008.
[b]Except years 1985, 1994, and 2009.
[c]Except years 2000–2007.

survivorship, which is the product of the proportion of fish that survive to the spawning period ($P_{\mathrm{SSB}}$; Cooper 1967) and total mortality at age ($Z_a$):

$$\mathrm{SSB}_t = \sum_a N_{t,a} \cdot PM_a \cdot W_{t,a} \cdot e^{-P_{\mathrm{SSB}} \cdot Z_{t,a}}. \tag{1}$$

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*):

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

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 SSB ($\mathrm{SSB}_0$) and unexploited spawners per recruit ($\mathrm{SPR}_0$):

$$R_t = \frac{\mathrm{SSB}_0}{\mathrm{SPR}_0}. \tag{3}$$

Abundance for age 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:

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

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 ($\alpha_b$) and the slope ($\beta_b$) 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 Markov chain–-Monte Carlo with 1,000 iterations and a thinning factor of 200 (200,000 Markov chain–Monte Carlo calculations) to characterize uncertainty in parameter estimates. Fishing mortality reference points were based on spawners per

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 |
| $M$ | Natural mortality | 0.15 |
| $PM_a$ | Proportion mature 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 | |
| $PH_L$ | 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 | |
| $\alpha_z$ | Ascending ($z = 1$) and descending ($z = 2$) of the midpoint of the double logistic | |
| $\beta_z$ | 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 | |

recruit estimated in ASAP: $F_{\text{Target}} = F_{40\%\text{SPR}}$ and $F_{\text{Threshold}} = F_{30\%\text{SPR}}$. Further, $SSB_{\text{Target}}$ and $SSB_{\text{Threshold}}$ were the median of terminal SSB values when the stock was managed with $F_{\text{Target}}$ or $F_{\text{Threshold}}$ for 55 years in the forward population simulation (detailed below).

*Population simulations.*— Spawning stock biomass 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 (AgePro) version 4.3.2 (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 Markov chain–Monte Carlo model (detailed above); thus, each projection consisted of 50,000 simulated population trajectories (Brodziak 2009). These trajectories were used to calculate median and 5th and 95th percentile values (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 ($PM_a$, $W_a$, $P_{\mathrm{SSB}}$, 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 2–15 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 and 11 cm, inclusive of lower and upper length limits) each of which was centered on 40- or 45-cm lengths. The narrow breadth of 5 cm was selected because a slot narrower than 5 cm (2 in) seemed unlikely to be implemented. The wide breadth of 11 cm was employed after preliminary analysis indicated that broader slots resulted 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 cm [small–wide], 38–42 cm [small–narrow], 40–50 cm [large–wide], and 43–47 cm [large–narrow], 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 that 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. Total removals ($R_N$) was the product of the catch at length ($C_L$) and the proportion harvested at length ($PH_L$). Discard mortality was the product of $C_L$, the discard mortality rate ($F_D$), and the proportion discarded (1 – $PH_L$):

$$R_N = \sum_{L=11}^{76} C_L \cdot PH_L + C_L \cdot F_D \cdot (1 - PH_L). \qquad (9)$$

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

$$R_B = \sum_{L=11}^{76} C_L \cdot PH_L \cdot W_L + C_L \cdot F_D \cdot W_L \cdot (1 - PH_L). \qquad (10)$$

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 (compliant harvest), 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 4 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 22–39 cm in length. We assumed that below-slot noncompliance behavior would be the same as noncompliance with the MSL. The proportion of noncompliant harvest ($PH_L$) for these 13 length increments (Appendix Table A.3.1) 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 harvest removal was 20.3% ($PH_L = 0.797$), as justified above. For fish larger than the slot, proportion harvested ($PH_L$), in this case noncompliance, was 0, 10, or 20%.

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

$$R_L = C_L \cdot PH_L + C_L \cdot F_D \cdot (1 - PH_L). \qquad (11)$$

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 (Venables and Ripley 2002) in R (R Core Team 2020). 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 Connecticut and New York trawl survey as well as the New York head (party) boat survey were used to fit the multinomial model. The resulting coefficients (Table A.1.1) 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:

$$P_a = \frac{R_a}{R_N}. \quad (12)$$

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

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

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 1.0. 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 across all scenarios and (2) to account for the change in selectivity due to the previously mentioned 2018 regulatory changes.

## RESULTS

### 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 reparameterized stock assessment characterized the SSB and fishing effort in the region in a similar manner as the

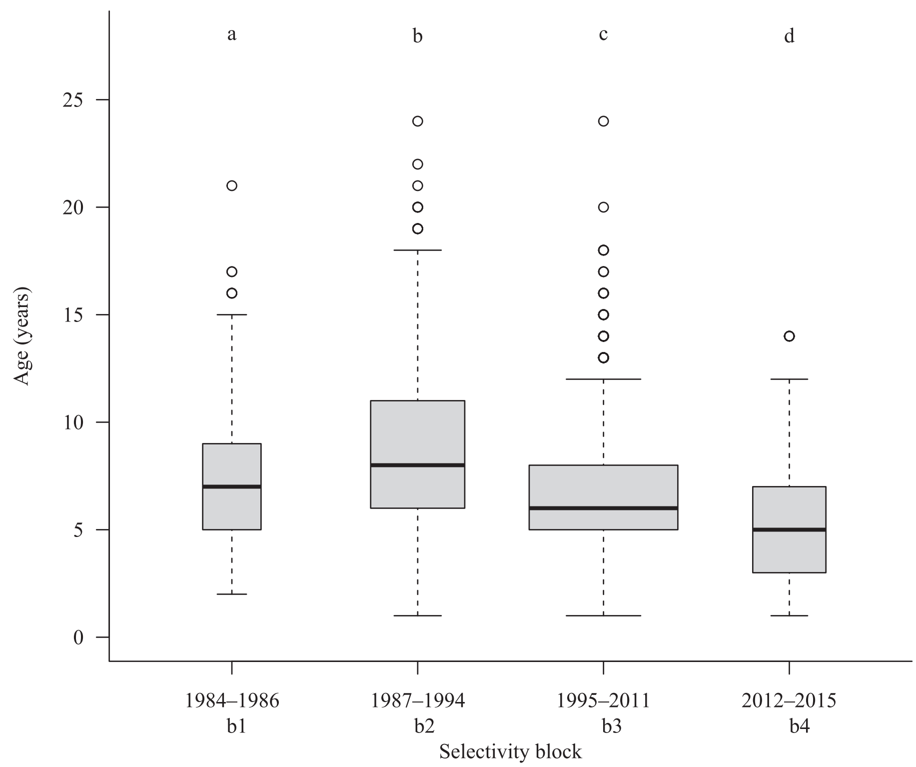


FIGURE 2. Change in age structure of female Tautog caught in the Connecticut Long Island Sound Trawl Survey by fishery selectivity block (*b*). The size distribution of females is shown. In each box, the center line represents the median, the lower and upper boundaries represent the 25th and 75th percentiles,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

ASMFC assessment, despite differences in the approach. Tautog were overfished in the terminal year; $SSB_{Terminal}$ (1,937 metric tons) was lower than $SSB_{Target}$ (3,397 metric tons) and $SSB_{Threshold}$ (2,549 metric tons). 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.3.2).

## Population Simulations

*Harvest slot limit yield.*— Changes in slot breadth, slot location, and noncompliant harvest modified removals. Removals decreased relative to the MSL regulation 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 slots. The small–narrow and large–wide slots generated the smallest change in the number of fish removed compared to the 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 the 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 the 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 (number 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 the MSL. The median relative abundance for age 5 to about age 10 (depending on scenario and noncompliance) were depressed with harvest slot management due to the redirected fisheries selectivity. This reduction was 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.

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*), removals in thousands of fish (*N*), and the percent change compared to minimum size limit (MSL) management are shown. Removals were constant in the forward population simulations and based on past fishery performance.

| Scenario | *B* (metric tons) | *N* (thousands) | 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 |

## DISCUSSION

Managing with harvest slot limits broadens age structure and rebuilds SSB more quickly and to larger magnitudes than managing with MSLs (Table 3; Figure 4). Slot limits reduce removal biomass relative to management with the 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

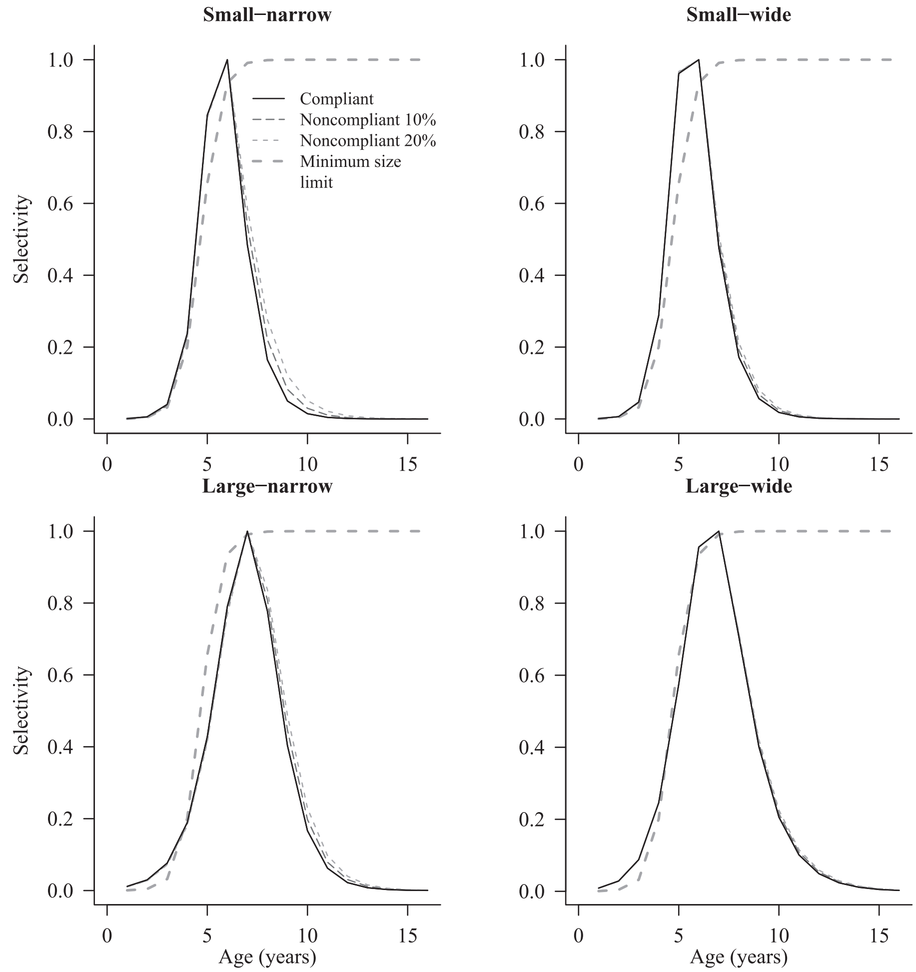


FIGURE 3. Selectivity at age used in Tautog population projections. Full compliance and 10% and 20% noncompliance with the upper size of the harvest slot limit were evaluated. Selectivity at age with the current minimum size limit of 40 cm is included in each panel.

age structure than the MSL. Finally, biological reference points are reached more quickly with slots than with 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 $SSB_{Target}$ was 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 $SSB_{Target}$ 5 and 15 years faster, respectively, while simultaneously broadening age structure. While Tautog is not managed by the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006, we considered the stock rebuilding requirements therein. Under federal management, overfished stocks must be rebuilt within 10 years. Had this stock been managed by the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006, a larger removal 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 (Appendix Figure A.3.1) but was less effective at broadening age structure (Figure A.3.2). 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 increased relative to MSL management. In the current study, the predicted rapid increase in the relative abundance of older

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 was largest relative to SSB with MSL management (maximum [max] relative change) and the year in which SSB reached equilibrium are also included. Median and 5th and 95th percentile values (confidence limits) are provided in parentheses. Scenarios in which SSB crashed are indicated (–).

| Scenario | Year SSB ≥ $SSB_{Target}$ | 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) |

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 it is resolved by implementing reference points based on spawners per recruit. 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. If reproductive capacity had been measured in total egg production, we would have expected the reproductive capacity of the narrow slots to be even larger relative to MSL management than reported.

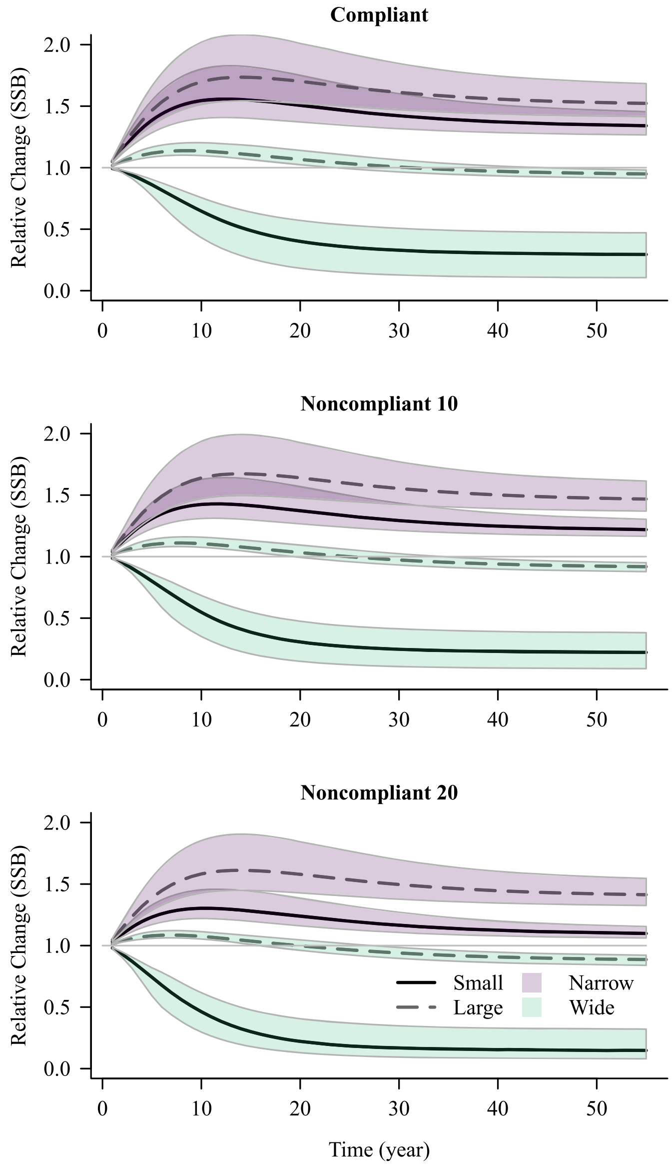


FIGURE 4. Median change in Tautog spawning stock biomass (SSB) when managed with harvest slots limits relative to management with the minimum size limit. Full compliance (top panel), 10% noncompliance (middle panel), and 20% noncompliance (bottom panel) with the upper slot limit were evaluated. Shaded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

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 are associated with decreased resilience (Rouyer et al. 2011; Stewart 2011). However, 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 slot permits the harvest of fewer larger fish (52% reduction in number harvested) and the small–narrow slot (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? While the large–wide scenario allowed 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 management. Despite the reduction in $SSB_{Terminal}$, biomass rebuilt to $SSB_{Target}$ and $SSB_{Threshold}$ more quickly than with MSL management, and age structure broadened. 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, modifications to length limits are more effective. Angler behavior responds unpredictably to changes in bag limits and season length. For example, angler effort did not respond linearly to changes in bag limits in an Atlantic Salmon *Salmo salar* fishery (Veinott et al. 2018) but did exhibit such a response 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 northwest Atlantic demonstrate angler support for slot limits in Tautog (Schultz et al. 2020) and Striped Bass *Morone saxatilis* (Murphy et al. 2015) fisheries.

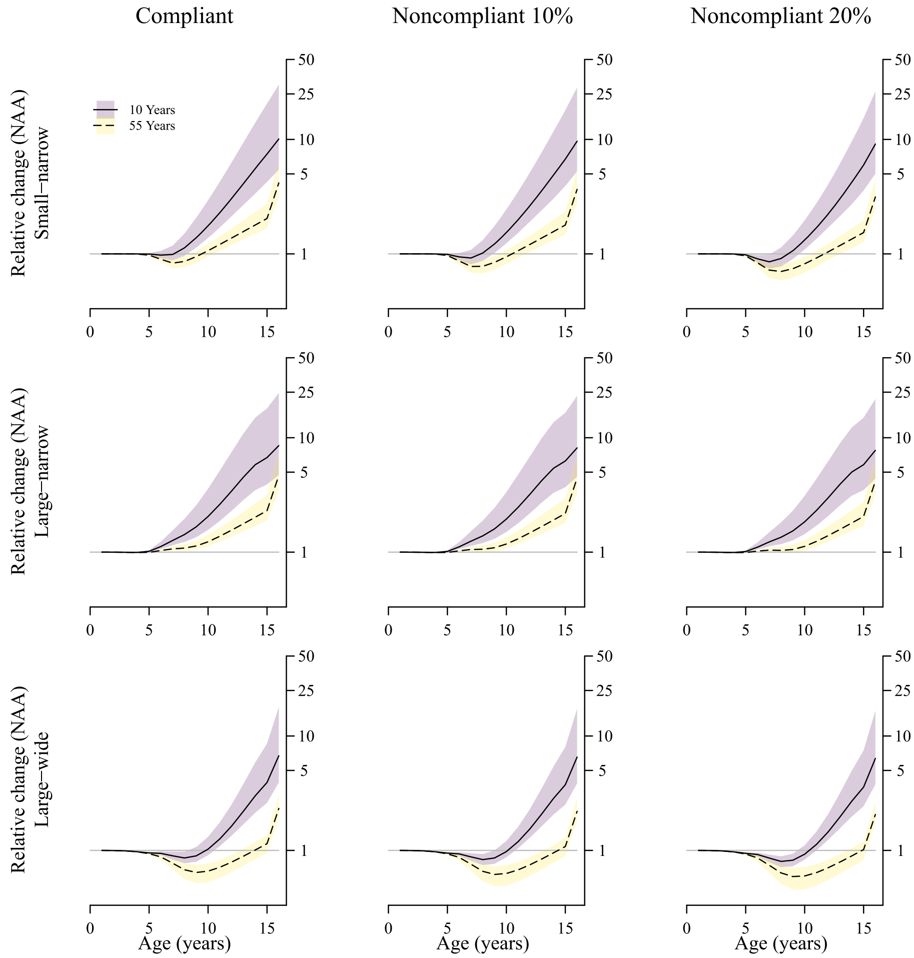


FIGURE 5. Median change in Tautog abundance at age for three harvest slot limit scenarios relative to management with the current minimum size limit. Changes in abundance at age after 10 and 55 years of management for the fully compliant models and 10% and 20% noncompliance with the upper slot limit 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 spawning stock biomass crashed. [Color figure can viewed at afsjournals.org.]

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 recovered and age structure broadened in two of our scenarios. However, 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 are 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., Black Sea Bass *Centropristis striata* and other serranids), 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 in many cases seemingly 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 that define the selectivity curve. As the stock recovers, fishing mortality will decrease if removals are constant. 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 is constant, the biomass of removals will increase, particularly in the scenarios for which the strongest recoveries are predicted. The increase in removals would ultimately dampen the $SSB_{Terminal}$ estimates and may reduce the broadening of the age structure. Either of these approaches (constant removals or constant fishing mortality) is an approximation of a future scenario. In practice, stock assessments are updated every 5 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 SSB 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's 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 are 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 they deserve more real-world evaluation and experimentation with actively managed fish stocks.

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# 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 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.1.1) 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.1.2). Weight at length was calculated by fitting a linear model to log-transformed observations from the Connecticut 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.1.2) 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.

TABLE A.1.1. 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.1.2. 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** | | |
| $L_\infty$ | Asymptotic length (cm) | | 58.7 |
| $K$ | Growth coefficient | | 0.171 |
| $t_0$ | Time at zero length (year) | | −0.08 |
| | **Weight–length relationship** | | |
| $\alpha_1$ | Length–weight coefficient | 1 | $1.80 \times 10^{-5}$ |
| $\beta_1$ | Length–weight exponent (cm to kg) | 1 | 3.07 |
| $\epsilon_1$ | Bias correction factor | 1 | 1.007 |
| $\alpha_2$ | Length–weight coefficient | 2 | $1.40 \times 10^{-5}$ |
| $\beta_2$ | Length–weight exponent (cm to kg) | 2 | 3.13 |
| $\epsilon_2$ | Bias correction factor | 2 | 1.009 |
| $\alpha_3$ | Length–weight coefficient | 3 | $2.00 \times 10^{-5}$ |
| $\beta_3$ | Length–weight exponent (cm to kg) | 3 | 3.02 |
| $\epsilon_3$ | Bias correction factor | 3 | 1.011 |
| $\alpha_4$ | Length–weight coefficient | 4 | $2.10 \times 10^{-5}$ |
| $\beta_4$ | Length–weight exponent (cm to kg) | 4 | 2.99 |
| $\epsilon_4$ | Bias correction factor | 4 | 1.016 |

### 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, and 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, $F_{40\%\text{SPR}}$ is the $F_{\text{Target}}$ and $F_{30\%\text{SPR}}$ is the $F_{\text{Threshold}}$.

## Appendix 3: Magnuson–Stevens Act Recovery

### 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 (Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006). The removal value

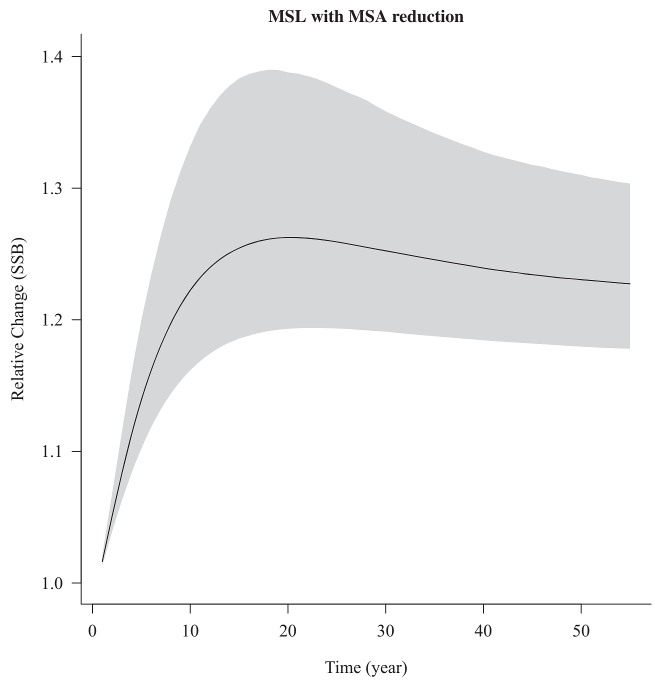


FIGURE A.3.1. Median changes in spawning stock biomass (SSB) when managed with the minimum size limit and the harvest reduction in compliance with the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act (MSA) of 2006, relative to the current Atlantic States Marine Fisheries Management Commission strategy. Shaded regions indicate 90% confidence limits estimated from forward population simulations.

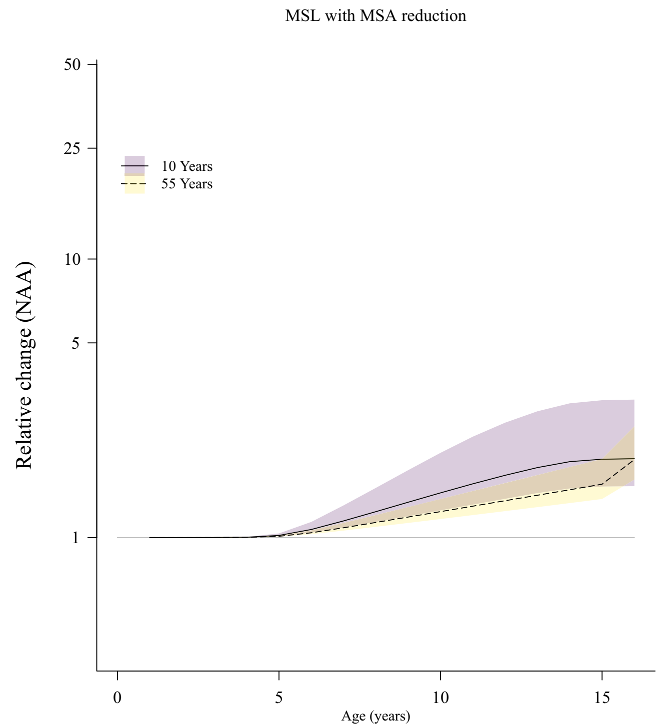


FIGURE A.3.2. Median change in abundance at age (NAA), when managed with the minimum size limit and the harvest reduction in compliance with the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act (MSA) of 2006, relative to the current Atlantic States Marine Fisheries Management 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. [Color figure can viewed at afsjournals.org.]

TABLE A.3.1. 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.3.2. Comparison of biological reference points estimated in the ASMFC (2016) 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 metric tons | 1,937 metric tons |
| $SSB_{Target}$ | 2,980 metric tons | 3,397 metric tons |
| $SSB_{Threshold}$ | 2,238 metric tons | 2,549 metric tons |
| $F_{Terminal}$ | 0.51 | 0.75 |
| $F_{Target}$ | 0.28 | 0.29 |
| $F_{Threshold}$ | 0.49 | 0.54 |

estimated by the reiterative process was then utilized in the forward population simulation model.

## 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 Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006 required reduction, SSB recovers relative to the current management approach (Figure A.3.1) and age structure broadens (Figure A.3.2). But this management approach is not as effective at broadening age structure as harvest slot limits.