An Introduction to a Management Strategy Evaluation for Atlantic Herring Harvest Control Rules

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Introduction

Attention has been given to applying a harvest control rule to Atlantic herring *Clupea harengus* that considers a fishery objective related to their role as a forage fish. The fishery also has other competing objectives, however, such as attaining relatively high and stable yields. The information available to evaluate the relative performance of control rules at meeting these competing fishery objectives is limited to analyses that are not specific to the system (Pikitch et al., 2012; Deroba and Bence 2008). While "borrowing" control rules from other systems or species might be a valid last resort, it is not the ideal method (Deroba and Bence 2008). Applying generic control rules may have unintended consequences, may not achieve fishery objectives, and may not adequately consider uncertainty in the way in which the control rules were derived (Deroba and Bence 2008). Control rules and the parameters that define them are best chosen based on stochastic simulations that consider key uncertainties for the specific system (e.g., management strategy evaluation; MSE; Deroba and Bence 2008).

Methods

Basics.—An MSE was developed specific to Gulf of Maine – Georges Bank Atlantic herring. The MSE was a modified version of that used in Deroba (2014), and symbols are largely consistent with Deroba (2014; Table 1). The MSE was based on an age-structured simulation that considered fish from age-1 through age-8+ (age-8 and older). The abundances at age in year one of all simulations equaled the equilibrium abundances produced by the fishing mortality rate that would reduce the population to 40% of $SSB_{F=0}$, where $SSB_{F=0}$ equaled 600,000mt for all simulations. Abundance in each subsequent age and year was calculated assuming that fish died exponentially according to an age and year specific total instantaneous mortality rate:

$$N_{a+1,y+1} = N_{a,y}e^{-Z_{a,y}};$$

$$Z_{a,y} = F_{a,y} + M.$$

Natural moratlity was invariant and equaled 0.5.

Recruitment followed Beverton-Holt dynamics, with steepness as a simulation (s) specific uniform random variable limited by 0.5 and 0.9, which was a similar range to the 80th percentiles for steepness reported for *Clupeidae* by Myers et al. (1999):

$$R_{1,y+1} = \frac{\left(\frac{SSB_{F=0}}{R_{F=0,s}}\frac{1-h_s}{4h_s}\right)SSB_y}{1+\left(\frac{5h_s-1}{4h_sR_{F=0,s}}\right)SSB_y}e^{\varepsilon_{Ry}-\frac{\sigma_R^2}{2}};$$

$$\varepsilon_R \sim N(0,\sigma_R^2);$$

$$SSB_y = \sum_{a=1}^{8+} N_{a,y}m_aW_a;$$

(Francis 1992). The level of variance $\left(\sigma_R^2\right)$ defining the lognormal errors for recruitment equaled 0.36 and was consistent with variation in recruitment estimates from a recent Atlantic herring stock assessment (NEFSC 2012). Other life history characteristics (e.g., weights at age, maturity) were simulation and time invariant, and equaled the average values at age from 2007-2011 reported in NEFSC (2012; Table 2). These stock-recruitment characteristics and other life history traits produced SSB_{MSY} that on average among simulations was approximately 0.25 $SSB_{F=0}$.

Assessment Error.—A stock assessment was approximated (i.e., assessment errors) similar to Punt et al. (2008) and Deroba and Bence (2012):

$$\widehat{N}_{a,y} = N_{a,y} e^{\varepsilon_{\varphi y} - \frac{\sigma_\varphi^2}{2}};$$

where:

$$\varepsilon_{\varphi y} = \vartheta \varepsilon_{\varphi y-1} + \sqrt{1-\vartheta^2}\tau_y;\ \tau_y \sim N(0, \sigma_\varphi^2).$$

The variance of assessment errors $\left(\sigma_\varphi^2\right)$ equaled 0.05 and autocorrelation (ϑ) equaled 0.7. Assessed spawning stock biomass $\left(\widehat{SSB}_y\right)$ was calculated similarly to SSB_y except with $N_{a,y}$ replaced with $\widehat{N}_{a,y}$, and assessed total biomass $\left(\widehat{B}_y\right)$ was calculated as the sum across ages of the product of $\widehat{N}_{a,y}$ and W_a.

Harvest Control Rules.—Five variants of a biomass based control rule (Katsukawa 2004) and one variant of a proportional threshold control rule (Engen et al., 1997) were evaluated (Figure1; Table 3). The biomass based control rule was defined by three parameters: the proportion (ψ) of $F_{msy,s}$ that dictates the maximum desired fishing mortality rate $\left(\tilde{F}\right)$, an upper *SSB* threshold (SSB_{up}), and a lower *SSB* threshold (SSB_{low}). The $\tilde{F}$ equaled the maximum when $\widehat{SSB}$ was above the upper threshold, declined linearly between the upper and lower thresholds, and equaled zero below the lower threshold:

$$\tilde{F}_y \begin{cases} F_{msy,s}\psi & \text{if } \widehat{SSB}_y \geq SSB_{\mathrm{up}} \\ \left(F_{msy,s}\psi\right)\dfrac{\widehat{SSB}_y - SSB_{\mathrm{low}}}{SSB_{\mathrm{up}} - SSB_{\mathrm{low}}} & \text{if } SSB_{low} < \widehat{SSB}_y < SSB_{up} \\ 0 & \text{if } \widehat{SSB}_y \leq SSB_{low} \end{cases}$$

The $\tilde{F}_y$ was then used to set a quota in year y + 1:

$$Q_{y+1} = \sum_{a=1}^{8+} \frac{\tilde{F}_{a,y}}{\tilde{F}_{a,y}+M} \hat{B}_{a,y}\left(1 - e^{-\left(\tilde{F}_{a,y}+M\right)}\right); \quad (11)$$

where $\tilde{F}_{a,y}$ equaled $\tilde{F}_y$ times S_a, and S_a was time invariant selectivity at age equal to the values for the mobile gear fishery reported in NEFSC (2012; Table 1). $\tilde{F}_y$ was used to set a quota in the following year to approximate the common practice of using projections based on an assessment using data through year y, or sometimes y – 1, to set quotas in the following several years. Furthermore, although $\tilde{F}_y$ was set using $\widehat{SSB}_y$, the quota was based on $\hat{B}_y$ because most fisheries likely select some immature ages. The fully selected fishing mortality rate that would remove the quota from the true population $\left(\bar{F}_y\right)$ was found using Newton-Raphson iterations.

The proportional threshold control rule was defined by two parameters: an *SSB* threshold (SSB_{pt}), and the fraction (μ) of the difference between $\hat{B}_y$ and the total biomass of the stock at SSB_{pt} (B_{pt}) to be harvested (Figure 1; Table 3; Engen et al., 1997). The μ parameter was defined as a proportion of $F_{msy,s}$, similar to the biomass based control rule:

$$\mu_a = \frac{F_{msy,s}\psi S_a}{F_{msy,s}\psi S_a + M}\left(1 - \exp^{-\left(F_{msy,s}\psi S_a + M\right)}\right).$$

This equation for μ_a also converts from an instantaneous rate to an annual rate (Ricker 1975). The quota in year y + 1 using the proportional threshold control rule equaled:

$$Q_{y+1} \begin{cases} \displaystyle\sum_{a=1}^{8+} \mu_a\left(\hat{B}_y - B_{pt}\right) & if\ \hat{B}_y > B_{pt} \\ 0 & otherwise. \end{cases}$$

$\hat{B}_y$ was used to set a quota in the following year to approximate the common practice of using projections based on an assessment using data through year y or $y-1$, similar to the lag induced for the biomass based control rule. $\bar{F}_y$ was found using Newton-Raphson iterations.

Implementation Error.—Implementation errors were also included in a similar way as in Punt et al. (2008) and Deroba and Bence (2012):

$$F_{a,y} = \bar{F}_y S_a e^{\varepsilon_{\theta y} - \frac{\sigma_\theta^2}{2}}; \varepsilon_\theta \sim N(0, \sigma_\theta^2).$$

The variance of implementation errors $\left(\sigma_\theta^2\right)$ equaled 0.001.

Performance metrics.—For each control rule, 100 simulations were conducted, each for 100 years. The mean $\frac{SSB}{SSB_{F=0}}$, $\frac{SSB}{SSB_{MSY,S}}$, $\frac{\text{yield}}{MSY_S}$, and interannual variation in yield (IAV) were calculated over the last 50 years of each simulation. The proportion of the last 50 years with *SSB* less than 0.4 $SSB_{F=0}$, and the proportion of years with fishery closures were also recorded for each simulation. Each metric was multiplied by 100 to convert to percentages. The median, 25th, and 75th percentiles among simulations were presented as barplots for each metric and control rule.

Results

Median $\frac{SSB}{SSB_{F=0}}$ and $\frac{SSB}{SSB_{MSY,S}}$ was highest for the Lenfest control rule. The BioBasedB and BioBasedC control rules had the second highest *SSB* levels, and these were followed in performance by the PropThreshA, 75%F_{MSY}, and the BioBasedA control rules (Figure 2). The interquartile range for the Lenfest rule exceeded 50% of $SSB_{F=0}$, the BioBasedA control rule overlapped 25% of $SSB_{F=0}$, and the other control rules were intermediate. All of the control rules produced *SSB* at or above SSB_{MSY} (i.e., $\frac{SSB}{SSB_{MSY,S}}$ ≈100%).

The relative performance of the control rules for the frequency of *SSB* being less than 0.4 $SSB_{F=0}$ was in the opposite order as for $\frac{SSB}{SSB_{F=0}}$ and $\frac{SSB}{SSB_{MSY,S}}$. The Lenfest rule produced *SSB* less than 0.4 $SSB_{F=0}$ the least frequently and the interquartile range was below 25%. The BioBasedA control rule produced *SSB* less than 0.4 $SSB_{F=0}$ the most frequently, with the interquartile range exceeding 75%. Other control rules were intermediate.

Median $\frac{\text{yield}}{MSY_S}$ was greater than 75% for all control rules, except for the Lenfest rule (Figure 2). The 75%F_{MSY} and BioBasedA control rules provided the highest yield, with interquartile ranges overlapping 100%. The Lenfest rule provided the least yield, and other control rules were intermediate. All of the interquartile ranges overlapped to some extent, except for the Lenfest rule.

Median IAV was highest for the Lenfest rule, with an interquartile range extending approximately from 75% to 125%. Median IAV was second highest for the PropThreshA and BioBasedC control rules, with interquartile ranges overlapping 50%. The 75%F_{MSY} control rule had the lowest IAV and the BioBasedA and BioBasedB control rules were intermediate.

Median percent of years with fishery closures was 0% for the BioBasedA, BioBasedB, and 75%F_{MSY} control rule. The Lenfest control rule had the most fishery closures with a median of 16% of years, which was followed in performance by the BioBasedC control rule with a median of 4% of years, and the PropThreshA control rule with a median of 2% of years.

Discussion

The only source of uncertainty in life history parameters considered in this MSE was the steepness of the stock-recruit relationship. Uncertainty in life history parameters can affect relative control rule performance (Deroba and Bence 2008), and further developments of this MSE should consider other uncertainties in life history parameters. Developments to MSEs are best done through facilitated discussions with stakeholders (Irwin et al., 2008; Irwin et al., 2011). Until such refinements are made to this MSE, the results should be considered preliminary and used only for demonstration purposes. Results should not be used for providing management advice.

The parameters defining the control rules in this MSE were not chosen to optimize any fishery objective or set of objectives. Such optimization could be accomplished by evaluating relative control rule performance over a range of parameter values for each control rule. Consequently, the results and conclusions about relative control rule performance from this MSE may not be general.

This MSE also assumed that the reference points used to define the harvest control rules (i.e., $F_{msy}$and $\mathrm{SSB}_{F=0}$) were known without error. The bias and precision of such reference points, however, can depend on life history characteristics, exploitation history, and autocorrelation in recruitment (Brodziak et al., 2008; Haltuch et al., 2008; Haltuch et al., 2009). Incorporation of errors in these reference points into an MSE is not a trivial task (see discussion in Deroba and Bence 2012), but should be a topic of future research.

No single control rule variant provided the best performance for all metrics. Generally, those control rules that provided relatively higher *SSB* also provided lower yields and higher IAV. These results are generally consistent with previous research comparing relative control rule performance (Irwin et al., 2008; Punt et al., 2008; Deroba and Bence 2012). Generally, biomass based control rules that decrease desired fishing mortality rates as biomass declines maintain higher levels of biomass than alternative control rules that maintain fishing pressure as biomass declines, such as constant fishing mortality rate rules (e.g., 75%F_{MSY}). The higher levels of biomass achieved by biomass based control rules, however, come at the cost of high variability in yield. Properly chosen parameters for biomass based control rules can also simultaneously attain high yield and biomass relative to constant fishing mortality rate alternatives (Deroba and Bence 2008), but that was not realized in this MSE likely because of the limited number of variants tested. Minimum biomass thresholds that trigger fishery closures can also produce less yield than some constant fishing mortality rate alternatives and exacerbate interannual variability in yield, but at the benefit of increased biomass. Choosing a control rule will require managers to specify relative preferences for these competing fishery objectives (e.g., Is the benefit of higher biomass worth the costs of possibly lower yield and higher variability in yield?).

The variant of the proportional threshold control rule evaluated here performed at an intermediate level for maintaining relatively high *SSB* and yield, but performed second worst for IAV. The poor performance for IAV was likely caused by desired fishing morality for the proportional threshold control rule being non-constant for all *SSB*, which may be destabilizing. This result is also in contrast to previous research on proportional threshold control rules (Engen et al., 1997; Milner-Gulland et al., 2001; Lillegard et al., 2005), but again, the results of this MSE may not be general.

The current application of this MSE assumed unbiased assessment errors. An uncertainty in the stock assessment for Atlantic herring is *M* (NEFSC 2012), and incorrect assumptions about time varying *M* can cause biased stock assessment estimates (Deroba and Schueller 2013), and using biased stock assessment estimates can affect control rule performance (Deroba 2014). Thus, a reevaluation of control rule performance in the presence of biased stock assessment estimates may be warranted here. Similarly, assessment errors in this MSE were induced by applying multiplicative error to the underlying true abundance, but incorporation of a full stock assessment model (e.g., statistical catch-at-age) into MSEs can affect control rule performance (Cox and Kronlund 2008). Incorporation of the assessment models intended for use in making management recommendations should be the goal of this MSE.

The motivation for this MSE was born out of a concern for maintaining Atlantic herring as a source of forage for predators in the region. Aside from specifying a level of *M* and evaluating the consequences of biased stock assessment estimates possibly caused by incorrect assumptions about *M*, this MSE is a single species framework. Adding multi-species interactions to the MSE may be considered in the future. Currently, concerns about maintaining enough Atlantic herring for forage could be evaluated by specifying a minimum biomass threshold, and control rules compared for the frequency with which they cause biomass to decline below this level. Predatory consumption estimates like those used in the 2012 Atlantic herring assessment (NEFSC 2012) could inform selection of this minimum biomass. The utility of the predatory consumption estimates has been questioned, however, because they are imprecise and likely biased in an unknown direction and to an unknown degree (Brooks and Deroba in press).

Discussion Topics

- What dynamic life history traits are important to include (e.g., time varying weight at age, selectivity)?
- Similarly, what uncertainties should we consider in the MSE? For example, $\mathrm{SSB}_{F=0}$, steepness, assessment and implementation errors (add full assessment?), spatial considerations (long-term).
- What fishery objectives are we interested in and what metrics from the MSE do we use to evaluate relative control rule performance?
- What control rules should we evaluate?
- If this MSE is to be applied for decision making, we should discuss how and when (how frequently) the MSE will be maintained and reevaluated.

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Figure 1.—Control rules evaluated in this MSE. Dashed lines are for reference only.

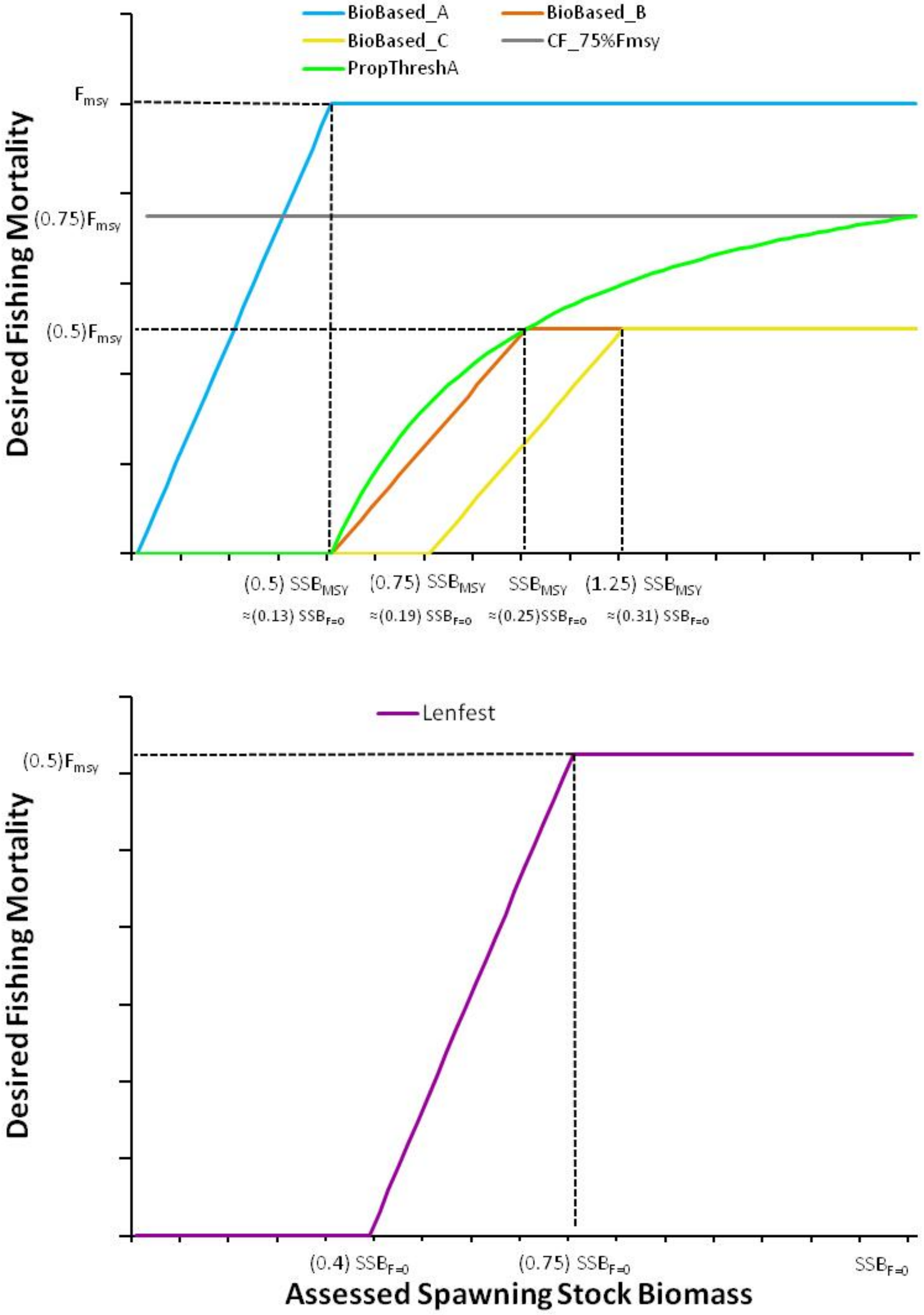

Figure 2.—Median (bars) and interquartile ranges (lines) for performance metrics for harvest control rules evaluated in this MSE.

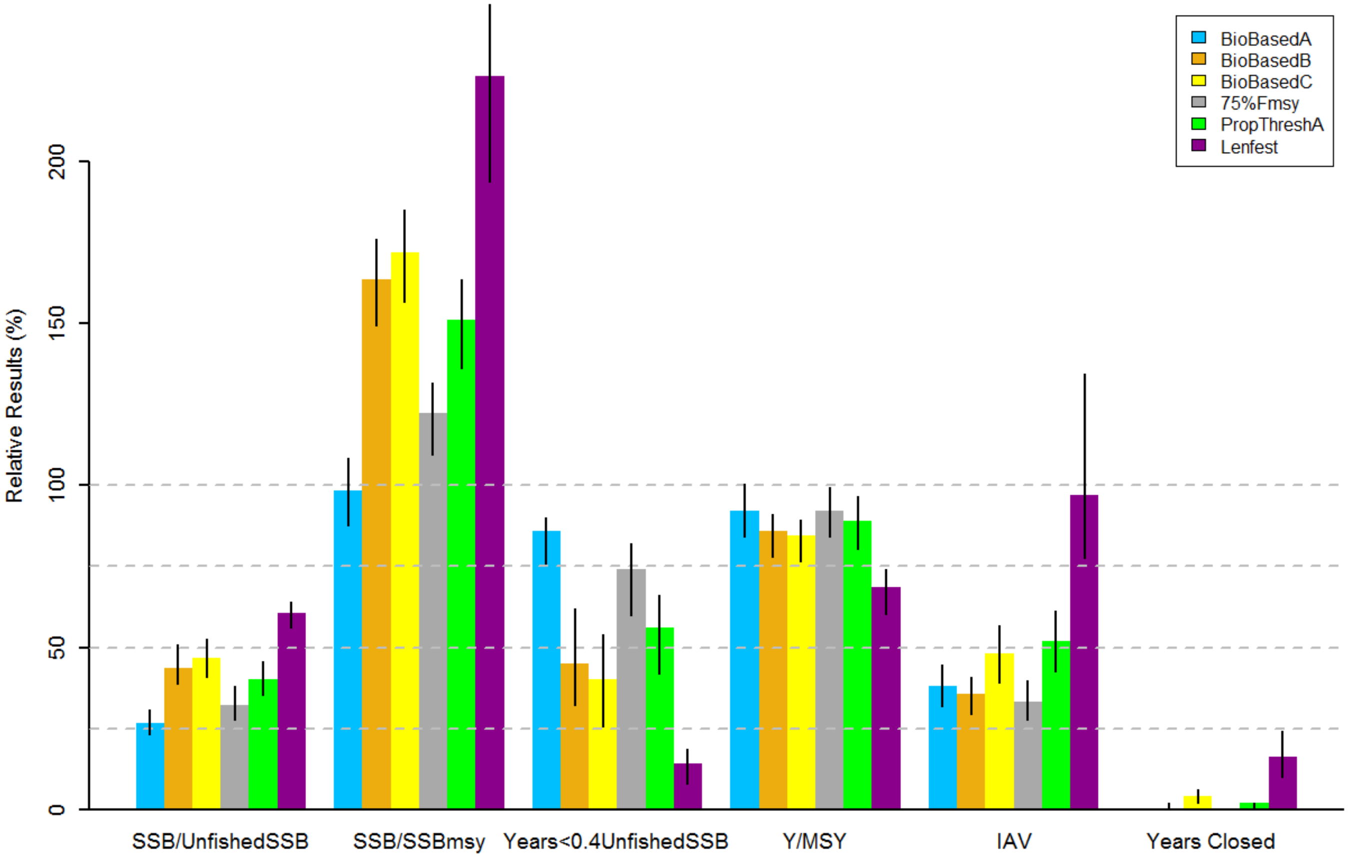

Table 1.
Symbols and descriptions of parameters or variables used in the simulation model

Symbol	Description
y	Year
a	Age
N	True abundance
F	Actual fishing mortality rate applied to the population
M	Natural mortality
Z	Total mortality
R	Recruitment
h	Steepness of the stock-recruitment relationship
SSB	Spawning stock biomass
ε_R	Process error for the stock-recruitment relationship
σ_R^2	Variance of the stock-recruitment process errors
$SSB_{F=0}$	Unfished spawning stock biomass
$R_{F=0}$	Unfished recruitment
$\widehat{N}$	Assessed abundance
ε_φ	Assessment errors
σ_φ^2	Stationary variance of assessment errors
τ	Errors for ε_φ
ϑ	Autocorrelation coefficient for assessment errors
$\widehat{SSB}$	Assessed spawning stock biomass
m	Maturity
W	Weight
$\hat{B}$	Assessed total biomass
SSB_{MSY}	Spawning stock biomass at maximum sustainable yield
$\tilde{F}$	Desired fishing mortality rate
S	Selectivity
Q	Desired quota
$\bar{F}$	Fishing mortality rate that would produce the desired quota when applied to the true population
ε_θ	Implementation errors
σ_θ^2	Variance of implementation errors
s	Simulation
IAV	Interannual variation in yield

Table 2.—Values of Atlantic herring life history characteristics used in the MSE.

Age	Maturity	Weight(kg)	Selectivity	Natural Mortality
1	0.00	0.027	0.0011	0.5
2	0.03	0.052	0.1455	0.5
3	0.60	0.088	0.5170	0.5
4	0.98	0.120	0.6710	0.5
5	1.00	0.140	1.0000	0.5
6	1.00	0.160	1.0000	0.5
7	1.00	0.180	1.0000	0.5
8	1.00	0.220	1.0000	0.5

Table 3.—Parameters defining the control rules evaluated in this MSE. ψ is a proportion of F_{msy}. Values for the *SSB* parameters are reported as proportions of SSB_{MSY} (i.e., would be multiplied by SSB_{MSY} for application of the control rules), except for the Lenfest control rule, which are proportions of $\mathrm{SSB}_{F=0}$.

	Control Rule Parameter			
Control Rule	ψ	SSB_{up}	SSB_{low}	SSB_{pt}
75%F_{MSY}	0.75	0.00	0.00	NA
BioBasedA	1.00	0.50	0.00	NA
BioBasedB	0.50	1.00	0.50	NA
BioBasedC	0.50	1.25	0.75	NA
PropThreshA	1.00	NA	NA	0.50
Lenfest	0.50	0.75	0.4	NA