**A State-Space Stock Assessment Model (SAM) for Gulf of Maine – Georges Bank Atlantic Herring**

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**Introduction**

Fish stock assessments rely on observations (e.g., survey indices, catch, age composition) to inform fishing, survival, and reproduction processes (e.g., fishing mortality, selectivity). The observations and the processes are both subject to error. Observations are collected through sampling procedures that are subject to measurement error, while some processes like selectivity and survival are not directly observed and so are subject to process errors not reflected in the observed data.

Stock assessment approaches vary in the degree to which observation and process errors are acknowledged. Virtual population analyses do not allow any observation or process errors because data are assumed perfectly known. Statistical catch-at-age (SCAA) models permit observation errors and limited process error in recruitment, but the extent of the errors are user specified and the models estimate relatively many parameters (e.g., a fishing mortality rate and recruitment for each year). State-space models can separate observation and process errors using relatively few parameters (Nielsen and Berg 2014). This efficiency is achieved by estimating the variances of the assumed distributions for the observation and process errors, and the fishing mortality and abundance states are predictions from the assumed distributions, as opposed to free parameters as in SCAA models.

The objective of this working document was to apply a SAM model to Gulf of Maine – Georges Bank Atlantic herring. I provide an overview of the model here, but details can be found in Nielsen and Berg (2014) and Berg and Nielsen (2016). Notation generally follows that of Nielsen and Berg (2014).

**Methods**

*Observations*

Catch and index observations are assumed to have lognormal errors, with separate variance parameters applied to different user selected age groups:

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Age groups were defined to share variance parameters based on AIC and residual patterns.

*Processes*

SAM allows for process errors in recruitment, survival between sequential ages, and age specific fishing mortality rates. The recruitment and survival processes are assumed to follow lognormal distributions:

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Recruitment in all model runs was assumed to follow a random walk. As with the observation variances, age groups were defined to share survival process variance parameters based on AIC and residual patterns.

Fishing mortality rates can be age-specific or groups of ages can be coupled to share fishing mortality rates, and these rates follow a random walk between years. The random walk fishing mortality rates can be correlated among the age couplings, for example, with a correlation of 0.0 producing independent random walks among age couplings and a correlation of 1.0 producing parallel time trajectories in fishing mortality rates among age couplings (i.e., time invariant selectivity). This results in age- and year-specific random walk increments following a multivariate normal distribution:

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The degree of correlation in the random walks can be fixed at 0.0 (i.e., independent) or estimated, and both were attempted. Age groups were defined to share fishing mortality states and process variances based on AIC and residual patterns.

*Input Data*

The input data were similar to that used in the ASAP base model, but SAM can only fit to age-based indices or indices of SSB. That is, SAM cannot fit to annual, aggregate index observations with user specified selectivity. Consequently, the SAM model only fit to NMFS spring, fall, and summer (shrimp) bottom trawl surveys for the years 1987-2017. In summary, input data were:

* Catches-at-age for ages 1-8+, with age 8 as a plus group, for the years 1965-2018.
* The NMFS spring and fall bottom trawl surveys for ages 2-8+ from years that used the vessel Albatross, 1987-2008.
* The NMFS spring and fall bottom trawl surveys for ages 2-8+ from years that used the vessel Bigelow, 2009-2017.
* The NMFS summer (shrimp) bottom trawl survey for ages 2-8+ from 1987-2017.
* Natural mortality equaled 0.35 for all ages and years.
* Age- and year-specific maturity was the same as the base ASAP model, as were weights at age.

**Results**

More than 20 models were run in the development of the SAM model. Presenting the AIC values and diagnostic plots that led to the final model structure would be voluminous. Consequently, only the final model structure is described. Supporting figures are at the end of this document.

*Observations*

Two separate observation variances were estimated for fishery catches, one that applied to ages 1-6 and another applied to ages 7-8+.

The spring NMFS survey for the Albatross years had separate catchabilities for age 2, 3, 4-6, and 7-8+, and different observation variances for age 2, 3-6, and 7-8+. The fall NMFS survey for the Albatross years had separate catchabilities for age 2, 3, 4, and 5-8+, and different observation variances for age 2-6 and 7-8+. The spring NMFS survey for the Bigelow years had separate catchabilities for age 2, 3, 4, and 5-8+, and different observation variances for age 2-3, 4-8+. The fall NMFS survey for the Bigelow years had separate catchabilities for age 2, 3, 4-6, and 7-8+, and a single observation variance that applied to all ages. The summer NMFS survey had separate catchabilities for age 2, 3, 4, 5, 6, and 7-8+, and different observation variances for age 2, 3-7, and 8+.

*Processes*

Unique fishing mortality rates were specified for age-1, age-2, age-3, age-4, age-5, age-6, and ages 7-8+. The fishing mortality rates were assumed to follow independent random walks. A model that estimated the degree of correlation among the fishing mortality rates improved the model fit based on log-likelihood, but did not resolve any residual patterns and so this parameter was not estimated.

Separate process variances were estimated for the fishing mortality rates at age 1, 2-4, 5-6, and 7-8+. Process variance in recruitment was estimated separately from a survival process variance shared among ages 2-8+.

*Summary of Final SAM Model Structure*

* Two fishery catch observation variances (2 parameters).
* Eleven observation variances among all the surveys (11 parameters).
* 22 catchability parameters among all the surveys (22 parameters).
* Four fishing mortality rate process variances (4 parameters).
* Process variance for recruitment and a survival process variance for ages 2-8+ (2 parameters).
* 41 total parameters.

*Overview of Final SAM Model Estimates and Results (“Run 13”)*

The time-varying fishing mortality rates suggested a generally flat-topped selectivity, with ages 7-8+ having the highest fishing mortality rates in most years and age 1 having the lowest selectivity in all years. The fishing mortality rates and subsequent selectivity at ages 2-6, however, were relatively variable. Age-2 had a relatively high selectivity in the 1970s due to higher catches from fixed gear sources during those years, but has since declined as mobile gears have become more dominant. Selectivity at other ages changes through time in a near parallel and cyclic manner.

Fishing mortality rates at age 1 had the largest of the process variances, followed by recruitment. Observation variances differed among ages and data sources.

The model did not exhibit a retrospective pattern. Fitting the model without each of the surveys resulted in time series that were withing the 95% confidence intervals of the base SAM model. Fits to the catch and survey observations varied by data source, with relatively few patterns visible for some inputs (e.g., spring Albatross years), but year effects evident for some surveys (e.g., summer survey). Process residuals did not have any obvious patterns.

Time series estimates of recruitment, fishing mortality rate, and biomass (abundance) were generally similar to the final ASAP run.

Maximum sustainable yield proxy reference points were calculated using similar methods as for the base ASAP model. More specifically, the 5-year average of life history traits from 2013-2017 (e.g., maturity, weights-at-age) were used to calculate F40% as an FMSY proxy. Given that selectivity varies through time in the SAM model, the selectivities at age from 2013-2017 were also averaged for purposes of reference point calculation. Consequently, the F40% value is not identical to that produced by the base ASAP model, nor is the corresponding BMSY proxy. The BMSY proxy was determined for the SAM model by conducting a 50 year projection at F40%, which was of sufficient length for the projection to reach equilibrium. Projected recruitments each year were resampled from the full time series of recruitment estimates from the SAM model. Various aspects about how process variance is carried forward in projections for the SAM model were not clear to the Working Group, and best practices for reference point calculation from a state-space model have not been developed. Consequently, the reference points and stock status from the SAM model should be used only for informational purposes and not considered for use in management. The F40% MSY proxy equaled 0.39 and the corresponding BMSY proxy equaled 197,000mt. Based on the SAM model, the stock is overfished and overfishing is occurring. Measures of uncertainty about stock status, however, were not readily available, but the uncertainty would likely be larger than that from the ASAP model due to the inclusion of process errors in SAM.

**References**

Berg, C.W., and Nielsen, A. 2016. Accounting for correlated observations in an age-based state-space stock assessment model. ICES Journal of Marine Science 73: 1788-1797.

Nielsen, A., and Berg, C.W. 2014. Estimation of time-varying selectivity in stock assessments using state-space models. Fisheries Research 158: 96-101.



