Uncertainty in National Marine Fisheries Service Stock Assessments

National Stock Assessment Program

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Introduction

The National Marine Fisheries Service (NMFS) is responsible for managing nearly 500 marine fish and shellfish stocks in United States waters. Management advice for these stocks comes in the form of roughly 200 stock assessments conducted annually by six NMFS regional Science Centers. A range of assessment types are employed depending on data availability, ranging from data limited or index based methods to full statistical catch at length or catch at age models. Scientific uncertainty, whether due to natural variability, measurement error, or statistical model complexity, is an integral component of these assessments and must be considered to the extent possible when making informed management decisions.

This report provides a regional overview of how NMFS currently captures and presents information related to uncertainty in stock assessments, and a description of how this information translates into management advice. Recommendations based on this information are also provided to improve the storage and presentation of uncertainty in the Species Information System (SIS), a central repository for stock assessment information across NMFS.

I: Summary of Stock Assessment Uncertainty by Science Center

The presentation of uncertainty in stock assessments varies regionally and by species according to data availability, model types used, and council needs. The following section provides a description of how each Science Center calculates and presents model uncertainty. The ways in which assessment uncertainty translates into management decisions is also outlined by region.

Northeast Fisheries Science Center

Model types vary by species, with ASAP (Age Structured Assessment Program; Legault and Restrepo 1998) used for most analytical assessments and VPA used for three stocks. Good estimates of uncertainty are typically not available for index-based assessments. Uncertainty in ASAP models comes from either the Hessian matrix or MCMC and uncertainty in VPA models is estimated by bootstrapping. Estimates of uncertainty are available for the full time series in ASAP modeled stocks, while in VPA modeled stocks uncertainty estimates are available for the terminal year but quickly drop to zero for prior years. Terminal estimates of biomass and fishing mortality are adjusted for retrospective patterns using Mohn's Rho with 7 peels (Mohn 1999). Sensitivity runs are performed for analytical assessments and jitter analysis is used in ASAP to increase the chances of finding the global minimum negative log likelihood. In some cases, multiple models are used for a stock, but in general, formal ensemble modeling is not yet implemented. A standard set of plots and tables displaying results of ASAP assessments, including uncertainty, are produced using the R package *ASAPplots* (https://github.com/cmlegault/ASAPplots). Assessment reports provide a section outlining the "key sources of uncertainty", which may not be directly quantifiable (e.g., limited range of survey data, unknown recruitment dynamics, etc.).

In a management context, assessment model estimates of uncertainty are generally not used by NEFMC, with the ABC typically set to 75% of MSY or MSY proxy. The council may be moving toward incorporating model based estimates of uncertainty for Herring. MAFMC uses a sigma/p* based approach, with uncertainty typically bumped up to a 100% PSE default value.

Southeast Fisheries Science Center

The SEFSC is responsible for conducting stock assessments for a wide range of species in support of three fishery management councils: Gulf of Mexico (GMFMC), South Atlantic (SAFMC), and Caribbean (CFMC), and the International Commission for the Conservation of Atlantic Tunas (ICCAT). Thus, there are a wide variety of methods used to convey uncertainty depending on the species, region, and management body.

- Gulf of Mexico

Coastal Species

Assessments are conducted using the Stock Synthesis modeling platform (Methot and Wetzel 2013), which calculates asymptotic estimates of uncertainty for modeled parameters based on the Hessian matrix. At the management level, uncertainty around the MSY is captured in the form of the sigma/p* approach (Ralston et al., 2004). In cases when the distribution of the MSY is directly modeled, the asymptotic uncertainty may be taken as sigma, while p*, the probability of overfishing, is selected by the SSC (not to exceed 0.5). In cases when an MSY proxy is used, the ABC is set by multiplying the OFL multipliers set according to a tiered control rule based on data availability and quality for a given species (lower multipliers for more data limited species, higher multipliers for more data rich species).

Highly Migratory Species

Uncertainty is conveyed to ICCAT in the form of tables with the probability of meeting a management goal under different catch levels a given number of years into the future. This may be the joint probability of keeping $F/F_{MSY} < 1$ (no overfishing) and $B/B_{MSY} < 1$ (stock not overfished). ICCAT is then responsible for setting the catch level corresponding to their desired probability of meeting the management goal (usually 50% after 10 years). Between model and within model uncertainty are both considered and presented as distributions of values on a Kobe plot rather than as single point estimates (e.g. the joint distribution of estimates from both a Bayesian surplus production model and an age-structured Stock Synthesis model may be displayed). Unlike assessments for other species, there is no data availability based tiered control rule in place for HMS. Assessment summaries with uncertainty clearly summarized in tabular and graphical form are available at https://www.iccat.int/en/assess.html.

Shrimp

Gulf of Mexico shrimp stocks are managed for effort at the fishery level and bycatch at the species level. The current target is 60% of the average effort between 2001 and 2003 while keeping red snapper bycatch below a set level. Sea turtle bycatch is also considered, however the red snapper bycatch limit is triggered before this would have an effect. Since 2005, three separate Stock Synthesis models have been used to conduct shrimp assessments. Prior to 2005, VPA based models were used. Models take into account catch, effort, CPUE (from SEAMAP data), indices of abundance, and growth constants. Parameters are based on a series of studies conducted in the 1970s. Standard errors are associated with catch inputs at the month level, while fishery CPUE is treated as a constant. Effort data is calculated from cellular electronic logbooks and applied without error. Only total estimated abundance is reported to the council (SSB/SSB_{MSY}), with no estimates of uncertainty.

- South Atlantic

Assessments are conducted using the Beaufort Assessment Model (BAM) (Williams and Shertzer 2015). Sensitivity analysis around a base run is conducted using a Monte-Carlo bootstrap ensemble approach. Key parameters in the base model (e.g., steepness, release mortality rate, etc.) are varied by drawing from assumed distributions, and this process is simulated many times to arrive at the final distribution of the parameter being estimated. Uncertainty in data inputs is also taken into account using CVs from data providers, and this uncertainty is carried forward throughout the estimation process as well as in forecasts (see Shertzer et al. 2008). Point estimates from the base run or median values from the final simulated distributions may be considered as management metrics by the SSC. Probabilities of overfishing (F/F_{MSY}), stock rebuilding (SSB/SSB_{MSY}), etc. are estimated using these simulated density functions.

- Caribbean

Carribean species are largely data limited. Past assessments have been conducted using a Management Strategy Evaluation (MSE) approach using the R *DLMtool* (see SEDAR 46, U.S. Caribbean Data Limited Species). This approach does not necessarily result in estimates of traditional key management metrics (e.g., MSY). A Stock Synthesis model was used for the 2020 Spiny Lobster assessment (SEDAR 57), incorporating landings and length data (with limited sample sizes). This marked the first Caribbean assessment for which the sigma/p* approach was used to set an ABC. Many key parameters (e.g., growth, mortality, sex ratio, steepness) are often fixed based on regional studies. Thus, uncertainty is known to be underestimated, and typically only point estimates are presented to the SSC. The SSC then selects a value for sigma (log-scale standard deviation of OFL distribution) ad-hoc. Typically, values between 0.4 and 0.45 are considered based on the Ralston et al. (2011) meta-analysis. This then passes through a tiered control rule to set the final OFL multiplier. p* (no greater than 0.5) is selected by CFMC. Various analogies are used to convey uncertainty to stakeholders, including bus arrival times and the hurricane cone of uncertainty.

Northwest Fisheries Science Center

Assessments conducted by the NWFSC use the Stock Synthesis modeling platform, with the exception of Pacific Hake which has used a Bayesian approach since 2011. Values of key parameters and associated uncertainty are therefore reported as means and asymptotic confidence intervals for Stock Synthesis based assessments and medians and quantiles of posterior distributions for Pacific Hake.

The sigma/p* approach is used to translate uncertainty into management, however, an assessment-based sigma is only used if it exceeds a predetermined threshold value (which was recently increased to 0.5 for Tier 1 stocks). These threshold values are necessary as oftentimes more data limited assessments result in underestimates of uncertainty since so many values must be held fixed due to lack of information.

Sigma for the first forecast year is calculated through the Stock Synthesis derived asymptotic standard deviation of the OFL. This estimate is converted to the log scale using the following equation, as the OFL is known to be better represented by a positive, right skewed distribution:

$$\text{sigma}_{OFL} = \text{sqrt}(\log((\text{std. dev./OFL})^2 + 1))$$

The uncertainty in the distribution of SSB may also be used to calculate sigma. It is possible for the derived uncertainty around SSB to be larger than that associated with the OFL. It is sometimes hard to tell the difference between stocks that are large but unproductive or small but productive, and SSB may better reflect this difference.

An alternative approach to calculate sigma involves the spread of uncertainty in comparing “states of nature”. A state of nature parameter is selected by the analyst as that which is believed to be highly influential or a large source of uncertainty. The base state of nature is delineated as the middle 50% density of the distribution of this parameter, low state of nature by the lower 25%, and high state of nature by the upper 25%. Sigma is then calculated as follows:

$$\text{sigma} = \log(\text{base state of nature / low state of nature}) / 1.15$$

where 1.15 is the normal quantile corresponding to a 75% two-sided confidence interval

The OFL is adjusted to obtain the ABC following Ralston et al. 2011 by using the assessment based sigma value and the PFMC determined p* ($\leq$ 0.5). The following equation shows this adjustment function in R syntax:

ABC = OFL * qlnorm(*p**, 0, *sigma*)

where the multiplier is the p* quantile of the log-normal distribution with log mean 0 and log standard deviation sigma

Beginning in 2019, sigma values increase with time post-assessment to account for increased scientific uncertainty as time passes (see Wetzel and Hamel 2019, Privitera-Johnson and Punt 2020). A function of the change in simga between the base and low state of nature across multiple species is used to determine the magnitude of this change in sigma over time. Methods are currently being developed to better account for scientific uncertainty in future projections.

Southwest Fisheries Science Center

Groundfish

Groundfish assessments conducted by the SWFSC use the same approach as that detailed above for the NWFSC. Decision tables based on data quality are used to decide exactly how the uncertainty buffer is applied.

Coastal Pelagic Species

All CPS assessment models are fit in Stock Synthesis, and asymptotic estimates of uncertainty are available for all derived parameters. The same sigma/p* approach that is used by the NWFSC is used to translate uncertainty into management, with the following minimum sigma thresholds:

Tier 1: 0.5
Tier 2: 1.0
Tier 3: 2.0

The uncertainty buffer is applied in a consistent manner for all CPS stocks (i.e., no decision tables are used as for groundfish). For Sardine and Mackerel, the ABC incorporates the estimated proportion of the stock in U.S. waters (i.e., ABC = B_{MSY} x uncertainty buffer x U.S. proportion).

Salmon

The salmon FMP contains roughly 60 stocks. Annual forecasts of abundance are based on estimated returns from the previous year. Assessments rely primarily on age structured VPA models. OFL to ABC buffers are constants codified in the FMP, based on a two tier system. For Tier 1 stocks (those with a known stock recruitment relationship), a 5% buffer is applied, and for Tier 2 stocks (those that are data poor), a 10% buffer is applied. Assessment model uncertainty is not currently factored into management. Confidence intervals around forecast point estimates were calculated in the past, but these were not used in any way by the council, so this effort was discontinued.

Highly Migratory Species

Most HMS stock assessments supported by scientists at the SWFSC are for temperate tuna species and sharks managed by ISC; the science and management for some of these stocks is cooperative with PIFSC/PIRO. For these assessments, NOAA staff often take the lead and conduct the assessments in Stock Synthesis. Results are provided using a base case with confidence intervals, as well as the probability of breaching reference points (when available). Sensitivity runs with alternative states of nature are conducted to show the range of probabilities. No attempt has yet been made to combine results from multiple models into a single probability distribution.

SWFSC scientists also participate in assessments for tropical tunas conducted by the Inter-American Tropical Tuna Commission (IATTC), although their role is on the Scientific Advisory Committee or occasionally on review panels; they do not perform the assessments. IATTC assessments have historically been conducted using a base case and sensitivity run approach (similar to tuna assessments produced for ISC, described above). However, in 2020 IATTC has introduced a 'risk assessment' approach based on a hierarchical model ensemble with model weightings dependent on a large suite of factors (e.g. expert opinion, model fit, model diagnostics). Uncertainty is transmitted to managers as a risk analysis with different probability distributions of breaching reference points under different harvest scenarios. However, this approach is still under development and has yet to be reviewed.

Alaska Fisheries Science Center

Groundfish

Objective uncertainty is currently only calculated for three Tier 1 stocks (those with well known recruitment dynamics): Walleye Pollock, Northern Rock Sole, and Yellowfin Sole. Estimates of uncertainty around SSB and recruitment are calculated either by Hessian approximation or MCMC. Analysts are not required to produce estimates of uncertainty for F. F_{OFL} is set to the point estimate of F_{MSY}. For Tier 1 stocks, the upper bound of the OFL multiplier to calculate the ABC is set as the ratio of the harmonic mean to the arithmetic mean of the probability density function of F_{MSY}. The ABC may be set substantially lower than the result of this calculation by

NPFMC. For higher tier stocks, adjustments for uncertainty do not explicitly map to a distribution, but F_{ABC} is always set lower than F_{OFL}.

Crab

Crab assessments comprise a range of model complexity, with inputs ranging from a simple time series of catch to full size based models. Age based models such as Stock Synthesis are not used since crabs cannot be aged reliably. Uncertainty around the OFL is calculated either as an asymptotic estimate using maximum likelihood or as quantiles of a posterior distribution when using a Bayesian approach. Models are custom-built by analysts for each assessment, although a “Stock Synthesis” like product for crab assessments is currently being developed. While the OFL is determined at the federal level, the final TAC is set by the state, and numerical assessment model uncertainty does not currently factor into that process. Rather, a tiered approach (1 through 5) is used based on the quality of information available. Most crab assessments fall into Tiers 3 to 5 (lower quality information), in which the OFL is adjusted using the following multipliers:

Tier 3: TAC = 0.85 x OFL
Tier 4: TAC = 0.80 x OFL
Tier 5: TAC = 0.75 x OFL

Pacific Islands Fisheries Science Center

Insular Species

Pacific Island domestic stock assessments use two primary modeling approaches: production models for more data-poor species (using Bayesian methods), and age structured models (using Stock Synthesis). Estimates of uncertainty are produced for all key parameters in each approach. In setting an ABC, the SSC employs a five-tiered system of control rules based on levels of available scientific information. Tiers 1 and 2 include data rich and data moderate stocks where the OFL and associated uncertainty can be estimated. Tiers 3 to 5 include data poor stocks for which the OFL is unknown. A sigma/p* approach is used for Tier 1 and 2 stocks, with p* set by the WPFMC to be no greater than 0.5. Stocks in Tiers 3 to 5 use an ABC control rule based on recent catch levels according to the following criteria:

$B > B_{MSY}$: ABC = 1 x recent catch
$B_{MSY} > B >$ MSST: ABC = 0.67 x recent catch
$B <$ MSST: ABC = 0.33 x recent catch

Highly Migratory Species

PIFSC scientists contribute to HMS stock assessments for the Western and Central Pacific Fisheries Commission (WCPFC) and International Scientific Committee for Tuna and Tuna-Like

Species in the North Pacific Ocean (ISC). Two approaches are used to describe uncertainty in model outputs:

1. Estimates of statistical uncertainty within a given assessment model (i.e. the 'base case') are provided by computing the approximate confidence intervals for parameters of interest (e.g., biomass and recruitment trajectories). This approach has been more commonly used in the past for ISC assessments, but recently ISC assessments are increasingly moving towards the second approach described below.
2. Structural uncertainty in the assessment is considered by focusing on the variation among a suite of models. A factorial grid of model runs (sometimes including hundreds of individual models) is developed, incorporating many of the options of uncertainty explored in one-off sensitivity analyses. This procedure attempts to describe the main sources of structural and data uncertainty in the assessment. Results of this grid analysis approach are summarized in several forms to provide to resource managers - time series plots of fisheries depletion for all models in the grid, time dynamic percentiles of depletion, boxplots of Frecent/FMSY and SBlatest/SBF=0 for the different levels of each of the three axes of uncertainty. This approach is used with increasing frequency, including for all assessments provided by the Ocean Fisheries Programme of the Pacific Community (SPC).

II: Recommendations for Displaying Uncertainty in SIS

The following list provides primary suggestions to improve the storage and display of assessment uncertainty information in SIS. Recommendations are based on a synthesis of the information in Part I in addition to direct comments from stock assessment analysts and SIS users:

1. Change the names of existing SIS uncertainty fields for B and F from "Min" and "Max" to "Lower" and "Upper". This will make it clearer that these fields should be populated with an uncertainty interval rather than the minimums and maximums of respective time series inputs.
2. Add optional uncertainty fields for B/B_{MSY}, F/F_{MSY}, and MSY in addition to B and F, as uncertainty around these parameters is often available for assessments conducted above the index-based level.
3. Add a numeric field associated with confidence bounds to specify the confidence level of a given interval. Allow values between 50 and 99 to be selected/entered and make this field mandatory whenever an interval is entered. This will make it clear exactly what the width of the interval corresponds to.
4. Add a drop down menu to specify an interval type (e.g., asymptotic, credible, bootstrapped), and make this field mandatory whenever an interval is entered. Likewise, allow the point estimate type to be selected from a drop down menu (e.g., mean, median, deterministic). This will add clarity to what these values represent and reduce the number of questions from management bodies.

5. Allow entry of a CV or PSE for each of the key parameter fields. This will make the magnitude of the uncertainty associated with each parameter estimate more readily interpretable. If possible, shade the value along a color gradient with green indicating lower values (lower uncertainty) and red indicating higher values (higher uncertainty).
6. Allow the selection of one or more values from a qualitative list of key sources of uncertainty (possibly five, no more than 10 choices) that commonly impact assessments (e.g., limited range of survey data, unknown recruitment dynamics, etc.). This would be useful for cases when a source of uncertainty cannot necessarily be captured numerically but still has a major impact on the assessment. These data could be queried to show a visual breakdown of the most common sources of uncertainty impacting assessments by region.
7. Allow data managers to check a box indicating if uncertainty from the current assessment model will directly impact management (required yes/no), and if so, optionally provide the associated parameter of which the distribution will be used (e.g., OFL, SSB). This would be especially useful for the simga/p* approach in which uncertainty from the assessment model is only used if it is greater than a prespecified threshold. It would also provide a means to summarize how model uncertainty is being used in decision making by region over time.

Discussion

A broad range of methods are used to calculate and convey uncertainty in stock assessments across NMFS. Mechanisms for incorporating this uncertainty into management decisions range from simple OFL multipliers to the more developed sigma/p* approach, in which numerical uncertainty from the assessment model can have a direct effect on regulations to achieve a given management goal. In order to ensure uncertainty information is presented in a meaningful way at the national level, it is critical that the SIS framework be made flexible enough to accommodate results from a range of approaches, especially as techniques for quantifying uncertainty continue to evolve.

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List of Acronyms

ABC	Acceptable Biological Catch
AFSC	Alaska Fisheries Science Center
ASAP	Age Structured Assessment Program
B	Biomass
BAM	Beaufort Assessment Model
CFMC	Caribbean Fishery Management Council
CPUE	Catch per Unit Effort
CV	Coefficient of Variation
F	Fishing Mortality
FMP	Fishery Management Plan
GMFMC	Gulf of Mexico Fishery Management Council
HMS	Highly Migratory Species
ICCAT	International Commission for the Conservation of Atlantic Tuna
MAFMC	Mid-Atlantic Fishery Management Council
MCMC	Markov Chain Monte Carlo
MSE	Management Strategy Evaluation
MSST	Minimum Stock Size Threshold

MSY Maximum Sustainable Yield

NEFMC Northeast Fishery Management Council

NEFSC Northeast Fisheries Science Center

NMFS National Marine Fisheries Service

NOAA National Oceanic and Atmospheric Administration

NPFMC North Pacific Fishery Management Council

NWFSC Northwest Fisheries Science Center

OFL Overfishing Limit

PFMC Pacific Fishery Management Council

PIFSC Pacific Island Fisheries Science Center

PSE Percent Standard Error

SAFMC South Atlantic Fishery Management Council

SEAMAP Southeast Area Monitoring and Assessment Program

SEDAR Southeast Data Assessment and Review

SEFSC Southeast Fisheries Science Center

SIS Species Information System

SSB Spawning Stock Biomass

SSC Scientific and Statistical Committee

SWFSC Southwest Fisheries Science Center

TAC Total Allowable Catch

VPA Virtual Population Analysis

WPFMC Western Pacific Fishery Management Council