Using the probabilistic MCB runs to set management parameters and determine stock status

The existence of uncertainty is a well-accepted and thoroughly documented part of the stock assessment process in fisheries science (Quinn and Deriso, 1999). This uncertainty stems from our inability to precisely and accurately measure the marine system due to a lack of knowledge of all the factors influencing fish population dynamics, natural stochasticity, and an all too often problem of insufficient sampling efforts due to lack of resources. However, these assessments are used to make important management decisions affecting the livelihood many people involved in the fishing and tourism industries. Therefore, it becomes very important to develop a good understanding of what the uncertainty is in the assessment model and a way to take that uncertainty into consideration when making important management decisions.

There have been many techniques developed to characterize uncertainty in assessment models, from simpler sensitivity runs to more complex Bayesian techniques and Monte Carlo Bootstrapping analyses (MCB; Quinn and Deriso, 1999). In the South Atlantic, assessment scientists routinely use sensitivity runs and MCB analyses to characterize uncertainty in stock assessment models (SEDAR, 2010). Sensitivity runs explore model sensitivity to changes in certain parameters, data sets, and model assumptions by changing one parameter or omitting one dataset at a time in order to determine how the model deals with the change and to see if there is any change in the estimated status of the stock (Cooper, 2006). The MCB analysis is used to characterize uncertainty in the model estimates by producing distributions for all the estimates based on the estimated uncertainty of the input parameters and input data. This uncertainty is estimated by resampling the input data and parameters from a distribution using bootstrapping techniques (Cooper, 2006; SEDAR, 2010).

Under the Magnuson Act, The South Atlantic Fishery Management Council's (Council) Science and Statistical Committee (SSC) is directed to consider uncertainty when making its fishing level recommendations, such as the Overfishing Level (OFL) and Acceptable Biological Catch (ABC). Guidance is provided by the ABC Control Rule, a set of criteria approved by the Council that relates the separation between OFL and ABC to uncertainty and risk tolerance. While the ABC control rule addresses the full range of available data and analyses use to support fishing level recommendations, the discussion and recommendations in this paper address the provisions for evaluating the uncertainty estimated in quantitative stock assessments.

Most assessments conducted of South Atlantic resources include uncertainty estimates based on a "P-Star" analysis (P*; Shertzer et al., 2008). The P* value is the probability that a stock is undergoing overfishing at a certain level of landings. The OFL is determined by a P* value of 50%, meaning that by fishing at the OFL, there is a 50% probability that overfishing is occurring. The P* value for ABC is determined by evaluating several factors related to the susceptibility of a particular species to overfishing and how well we understand the uncertainty in the model structure and input data (fish biology, population dynamics, model complexity, and the characterization of uncertainty). Then the P* value I adjusted down from 50% based on those factors. The amount of the reduction from 50% is dependent on how susceptible the stock is to overfishing and how well we understand the uncertainty in the estimated population dynamics.

Uncertainty characterization from the stock assessment impacts fishing level recommendations in several ways when the SSC applies the ABC Control Rule and considers ABC recommendations. First, the SSC considers the extent to which uncertainty is characterized by the assessment analyses when deciding the overfishing probability (also called the P*) that is acceptable. In addition, the uncertainty characterization provides inputs that are included in the analyses, through the P* and MCB approaches described above, that provide the actual yield associated with the chosen probability level. In the first part of this process, the ABC is reduced from the OFL by an amount dependent on the process described in the earlier paragraph concerning how much the P* is reduced from 50%. For example, the better the characterization of uncertainty (i.e. the more types of uncertainty and the higher the amount of uncertainty that is estimated), the lower the penalty that is given, and the closer the resulting P* value will be to 50%. Since an MCB analysis is considered a desirable and effective method of quantifying uncertainty, its use in an assessment to characterize uncertainty will result in a lower "penalty", or reduction in the P* value than would occur if a less robust uncertainty evaluation were provided. The second way the characterization of uncertainty is used is that the MCB analysis itself provides yield based on the chosen probability (P*).

As mentioned above, the characterization of uncertainty is used is when the SSC decides on a P* value, and in the estimation of the ABC itself. This is best illustrated through an example, using South Atlantic black sea bass. A revised updated assessment added an MCB analysis. When the SSC recognized the improvement in uncertainty characterization and incorporated it into the calculation used to derive P*, the P* value increased from P*=37.5% to P*=40%. This means that the SSC recommended an ABC that allows a slightly higher probability of overfishing occurring, based on an improved method of characterizing uncertainty reducing the overall level of assessment uncertainty. In terms of yield, the higher P* value will result in a higher catch level, with that catch level based on the uncertainty evaluation applied at the 40 probability of overfishing occurring. So the better uncertainty is characterized in a model, the less of a penalty is incurred when the P* is calculated, and the higher the level of allowable yield.

Under the current approach used to determine ABC, the P* analysis is the only place the MCB characterization of uncertainty is used when making management decisions, setting benchmarks, and determining stock status, despite the fact that the MCB analysis provides a statistical evaluation of uncertainty in the model parameters. At their April 2013 meeting, the SSC considered using the probabilistic MCB analysis, which is how uncertainty in the model is characterized, to set benchmarks and determine stock status. This was in response to the P* results from the black sea bass update, which estimated an ABC value that was above the deterministic MSY value, which the Council has traditionally used to set the OFL. This was not an unexpected outcome, as short-term yields such as ABC respond to recent abundance and recruitment, and can exceed long-term measures of average productivity when recruitment is particularly good. However, in this case an additional concern noted was that the fishing mortality rate that was allowed under the P* analysis for the chosen probability of overfishing occurring exceeded the base estimate of Fmsy, which is commonly recommended as the maximum fishing mortality threshold (MFMT). The SSC recognized that the underlying problem was tied to mixing a probabilistic analysis with a deterministic result. Specifically, using the MCB and P* analyses to set the level of yield, while using the base run point estimate of F_{MSY} to set a benchmark reference point. In the case of the black sea bass recommendations, the SSC decided to include both the deterministic and the probabilistic estimates of benchmarks and status indicators when evaluating the status of the stock. The SSC also requested an opportunity to reconsider the basis of fishing level recommendations, including how the MCB results can be used in setting management benchmarks related to stock status. The advantage is that using the probabilistic MCB runs for stock status determination will incorporate more of the uncertainty in the parameter estimates when estimating benchmarks and determining status. A major drawback, and issue that has prevented this approach in the past, is that the suite of management benchmarks (e.g., MFMT, MSST, MSY) will not be based on a single iteration or 'run' of the assessment model. Instead, they will come from a distribution that is provided by the MCB analysis.

In order to use the probabilistic MCB analysis to estimate benchmarks and determine status, however, there are several decisions that must be made and several matters to consider. The MCB analysis generates distributions for benchmark parameters and stock status. So how can these be translated into an MSY level or a determination of whether the stock is overfished or not? The first step is to decide on a statistic that describes the central tendency of these distributions. This statistic could be used to estimate the benchmark parameters.

The next step is to decide on a methodology for estimating stock status. This step could be a simple one, where the statistic decided on in step one is used to determine status. Or it can use estimates of the uncertainty to make the determination of stock status. These estimates of uncertainty (such as standard deviation of the MCB distribution, or percentage of MCB runs with a particular outcome) can allow the decision of status to be more liberal (where there is less uncertainty) or more conservative (when there is a very high degree of uncertainty). These steps are described below in greater detail with some options to consider and some examples to help illustrate how they might work in a real stock assessment setting.

Management Parameters

In order to use the MCB distributions to estimate all of the management parameters, a statistic must be chosen to describe the central tendency of the MCB distribution. There are 3 main options for this statistic, each with its pros and cons.

1. Mean – Most commonly used to describe the central tendency of continuous data and is very easy to calculate, but is highly susceptible to outliers and skewed data. Here, Mean refers to the arithmetic mean, which is calculated by summing all the values in the dataset and dividing by the number of data points. The geometric mean is not an appropriate statistic to use here because the assumption when using the geometric mean is that the data points are no independent of each other. However, in an MCB analysis with replacement, each run is independent of every other run.
2. Median – Most robust statistic to outliers and skewed data, but is more difficult to calculate since there is no easy mathematical formula for calculating the median. To find the Median of a dataset, the data need to be put in an ordered list and the Median is simply the middle value.
3. Mode –Most commonly used for categorical data, can miss the true central tendency if a distribution is heavily skewed or if it is bimodal. Finding the Mode of an MCB analysis equates to identifying the maximum point on the curve, which is the simplest statistic to calculate of the three mentioned here. However, simply using the maximum value ignores the structure of the distribution and can potentially miss important trends and values that will; be accounted for in both the Mean and Median values.

MCB distribution examples:

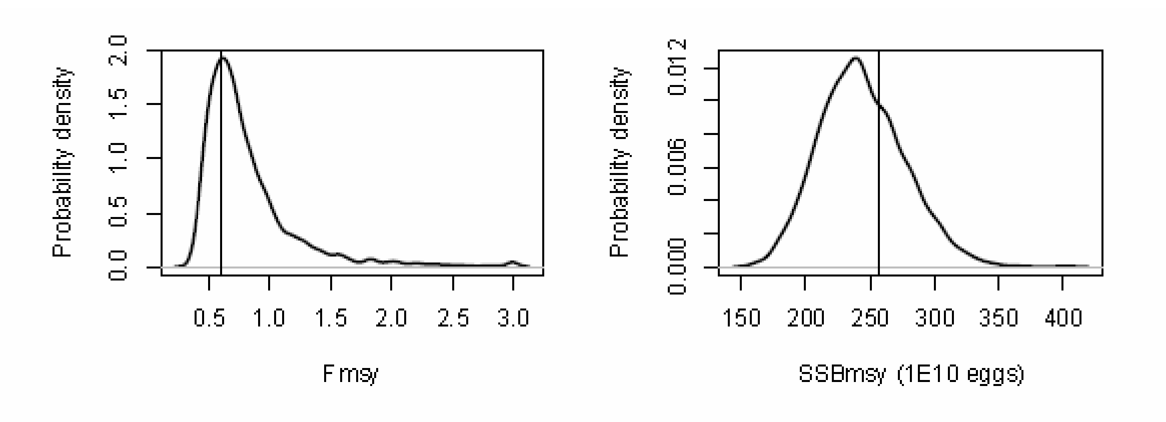

Figure 1. Probability densities from MCB runs of F_{MSY} and SSB_{MSY} for black sea bass from the 2012 black sea bass assessment update.

These are the MCB probability densities from the most recent black sea bass update for F_{MSY} and SSB_{MSY}. The probability density for SSB_{MSY} approaches a Normal statistical distribution or bell curve (although this is not always true), but the probability density for F_{MSY} has a heavy right tail, meaning the right side of the distribution stretches out a long way from the Mode as opposed to the left side of the distribution (which is actually fairly common for this parameter).

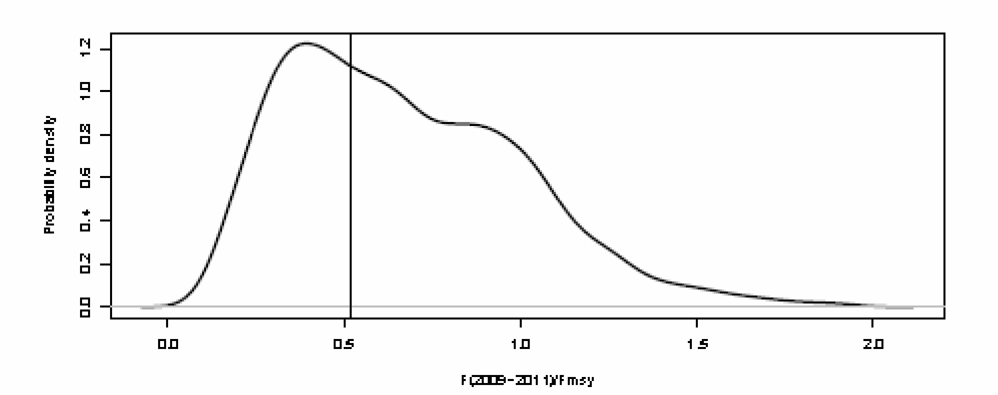

Figure 2. Probability density from MCB runs of F/F_{MSY} for Spanish mackerel from SEDAR 28.

This is the MCB distribution of F/F_{MSY} for Spanish mackerel. It is a good example of a situation where the mode would not be a good estimate of the central tendency. This is due to the fact that the distribution approaches a multi-modal distribution, meaning there is more than one peak in the distribution. There is an obvious maximum, but that point ignores the significant number of runs with values to the right of that maximum value.

The SSC discussed using the median value of the MCB distributions for the management parameters of Spanish mackerel and cobia from SEDAR 28 at their April 2013 meeting. Due to this discussion, the median will be used in the next section for all examples.

Stock Status Determination

Once a statistic is chosen to provide values for the management benchmarks, the next step is to compare conditions to that benchmark. In order to use the MCB runs to make a status determination, a statistic or methodology must be used to determine where the current F and SSB are in relation to the MSY management parameters. There are several methods that could be used to make this determination.

1. Use the median of the stock status criteria from the MCB runs to determine the status relative to the benchmarks.
   - A probability density is calculated from the MCB analysis for each of the status criteria (ex. F/F_{MSY}, SSB/SSB_{MSY}, SSB/MSST).
   - Simply use the median of this distribution to determine stock status.
     a. A stock is undergoing overfishing if the median value of the MCB distribution of $F/F_{MSY} > 1$.
     b. A stock is considered overfished if the median value of the MCB distribution of SSB/MSST < 1.
     c. A stock is considered rebuilt if the median value of the MCB distribution of $SSB/SSB_{MSY} > 1$.
2. Use the standard error (SE) of the MCB distribution to determine stock status
   - This approach takes the uncertainty of the model into account when making a status determination.
   - There are two ways of using the standard error to make a status determination, depending on how conservative one wishes to be.
     a. Overfishing is occurring when the median value of F/F_{MSY} is above 1 + SE, the stock is overfished when the median value of SSB/MSST is below 1 – SE, the stock is rebuilt when the median value of SSB/SSB_{MSY} is above 1 – SE.
     b. Overfishing is occurring when the median value of F/F_{MSY} is above 1 – SE, the stock is overfished when the median value of SSB/MSST is below 1 + SE, the stock is rebuilt when the median value of SSB/SSB_{MSY} is above 1 + SE.
3. Use the P* analysis to inform a status determination based upon the percentage of MCB runs that result in a particular status determination.
   - This method uses the P* approach, which takes into consideration the uncertainty of the model and the susceptibility of a particular species to overfishing.
   - The P* analysis not only estimates the ABC, but also determines the appropriate buffer between ABC and OFL based on several criteria, including the level of information provided by the assessment, the characterization of uncertainty, the stock status, and the level of risk of overexploitation determined from life history characteristics and population dynamics.
   - The degree to which the P* value is penalized based on the criteria above would translate into a buffer when determining stock status as described below.
   - Using a stock which has a P* value of 40%, status determination would proceed as follows:
     a. A stock is undergoing overfishing if at least 40% of the MCB runs show that $F>F_{MSY}$.

b. A stock is considered overfished if at least 40% of the MCB runs show that $SSB<MSST$.
c. A stock is considered rebuilt when at least 60% of the MCB runs show that $SSB>SSB_{MSY}$.

Example: Black Sea Bass

Here, black sea bass is used to illustrate how the above methods would work in assigning stock status. Table 1 shows the statistics used to calculate stock status based on the methodologies above. The median and standard deviations are from the MCB distributions of F/F_{MSY}, SSB/MSST, and SSB/SSB_{MSY}. There is also the percent of MCB runs that came out above or below the MSY values. Most of these statistics are not the actual model estimates, but simply derived from the base run in order to be used for this example.

Table 2 shows the actual outcome, using the statistics from Table 1, under each of the methodologies outlined above. Method 1 simply compares the median of the distribution to 1 (parameter = MSY value). Method 2a is the more liberal version of the methodology utilizing the standard error (SE). For overfishing, you add the SE to 1 and compare with the median value. For overfished and rebuilt, you subtract the SE from 1 and compare to the median value. Method 2b is the more conservative SE methodology. For overfishing, you subtract the SE from 1 and compare with the median value. For overfished and rebuilt, you add the SE to 1 and compare to the median value.

Finally, Method 3 uses the P* value for the particular species. For overfishing, the percent of MCB runs is compared to the P*. If the percent of MCB runs below the MSY level is greater than 1 - P*, then overfishing is not occurring. For overfished and rebuilt, if the percent of MCB runs above the MSY level is greater than 1 – P*, then the stock is not overfished or is rebuilt. Basically, overfishing is occurring even if up to 60% of the MCB runs show $F < F_{MSY}$, a stock is overfished if more than 40% of the runs show $SSB < MSST$, and a stock is not rebuilt until at least 60% of the MCB runs show $SSB > SSB_{MSY}$ for a stock with a P* of 40%.

In this case, most of the methods come up with similar recommendations for stock status. The obvious outlier is Method 2b, which uses the standard deviation from the MCB analysis. This is the most conservative of the methods, penalizing the status determination based on the magnitude of the standard deviation. Basically, this method says there is X amount of variation in the data and we really want to be conservative about the status of this stock, so we are going to increase our buffer by the magnitude of the variation. Method 2a says the exact opposite of Method 2b and is the most liberal of the methods described. It says that since we aren't sure what the status is, let's allow some extra exploitation based on the magnitude of the variation.

Method 1 is neither conservative, nor liberal. Although the uncertainty is incorporated into the estimate of status, Method 1 does not build in any buffer based on the level of uncertainty. Method 3 does build in a buffer, but it is not as conservative as Method 2b and it takes into consideration other factors besides the uncertainty in the model. Also, Method 3 does not use the magnitude of the variation to set the buffer, but rather sets a threshold by which the MCB distribution is compared to make a status determination.

Summary

The use of the MCB analysis to set management parameters has several important advantages. The MCB analysis examines uncertainty in the input data as well as assumptions on certain input parameters, such as natural mortality and steepness. This uncertainty is incorporated into the estimate of management parameters when the MCB analysis is used to determine these parameters. This is an important advantage of this method, especially in areas such as the South Atlantic, where data often is insufficient to estimate parameters such as natural mortality and steepness, resulting in fixing these parameters at values determined via ad hoc methods. Also there tends to be a high degree of uncertainty in landings data in areas such as the South Atlantic because of the high proportion of recreational landings, which are measured via survey rather than census and has no ground-truthing, as is the case in commercial data.

The major disadvantage to using the MCB analysis stems from the use of a distribution to determine the management parameters as opposed to a single model iteration. When a single base run is used, F_{MSY} is estimated and then MSY and SSB_{MSY} are derived from that estimate of F_{MSY} using the spawner-recruit relationship from the base run. The MCB analysis creates distributions for each parameter by running multiple iterations of the model, each with its own set of parameter estimates, and then plotting the probability density function of each parameter. Therefore, if the F_{MSY} estimate derived from the MCB analysis is used to derive MSY and SSB_{MSY} from a spawner-recruit relationship (for example, from the base run), the resulting parameter estimates will not be the same as the MCB derived estimates of those same parameters. Also, if you take the MCB derived terminal F value and divide it by the MCB derived F_{MSY} value for fishing status, you will not get the exact value of the MCB derived F/F_{MSY}.

The use of the MCB analysis, and each of the different methods described above, for estimating stock status also has its own advantages and disadvantages. Method 1, which uses the central tendency of the MCB, is easily calculated and easily understood by managers and decision makers. Although the median of the MCB tends to be more conservative than the base run, this is not always the case. Whether the median is conservative or liberal, and the degree to which this is true, is dependent on the shape of the MCB distribution and not the amount of variation in the outputs. The shape of the MCB distribution is affected by the distribution of the input parameters (such as steepness and M) and the input data, as well as nonlinearities in the model itself. Also, this method does not consider the variation in the estimate itself.

Methods 2a and 2b both use the SE of the MCB analysis directly in the determination of stock status. Method 2a allows more fishing to take place and allows for lower levels of biomass before requiring action. This method is the opposite of the precautionary approach, allowing higher levels of harvest and lower biomass based on the amount of uncertainty in the model outputs. This method would be reasonable for species which are resilient to high levels of fishing pressure and low stock sizes, but has the potential to allow overfishing to occur in stocks that are particularly susceptible to overfishing and take a long time to recover from an overfished condition.

Method 2b is a more precautionary approach to stock status. It does this by creating a buffer that is directly proportional to the amount of variation in the model outputs, as estimated by the MCB analysis. This method resolves the problem of Method 2a of potentially allowing overfishing to occur in susceptible stocks. However, Method 2b may be overly restrictive when applied to resilient stocks. The model outputs of a resilient stock may contain high degrees of variation, causing the buffer to be large. However these same stocks may be able to sustain higher levels of fishing pressure without any large adverse effects to stock status.

Method 3 also sets a precautionary buffer, but this buffer is not proportional to the amount of variation in the model outputs, as in Method 2b. Instead, it uses the P* analysis to set the buffer, which is based on four major factors, including assessment information, uncertainty characterization, stock status, and risk analysis. To use the risk analysis tier as an example (risk of overfishing), those species that are susceptible to overfishing would have a wider buffer than those that are resilient to overfishing. Method 2 uses the SE to either inflate or deflate the benchmark, then compares the appropriate statistic through the use of a central tendency estimator, such as the median. Therefore, the variation in the outputs is directly used in the determination of stock status. Method 3 sets a buffer in the benchmark based on outside factors describing the biology of the species and the methodology in the assessment. The variation in the model outputs is incorporated by using the distribution itself to determine stock status (i.e. the percentage of runs above or below a particular benchmark). The biggest drawback to this method is that it is the most complicated and difficult to understand of all the methods presented.

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Table 1. Status indicators for black sea bass, along with the median and standard deviation (St. Dev.) from the MCB distribution, and % of the MCB runs above or below the MSY value from the 2012 black sea bass assessment update. *These numbers are not the actual values, but were calculated from the base run and used for example purposes only. However, the St. Err. column contains the actual MCB SE from the model.

Status Indicator	**Median**	**St. Err.**	**% MCB Runs**
F/F_{MSY}	0.66*	0.24	93% below F_{MSY}
SSB/MSST	1.66*	0.51	98% above MSST*
SSB/SSB_{MSY}	1.03*	0.23	68% above SSB_{MSY}

Table 2. The status of black sea bass using the methods described above and the statistics from Table 1.

Status	**1. Median**	**2a. St Err**	**2b. St Err**	**3. P* (40%)**
Overfishing	0.66 < 1 No	0.66 < 1.24 No	0.66 > 0.76 Yes	93% below F_{MSY} > 60% No
Overfished	1.66 > 1 No	1.66 > 0.49 No	1.66 > 1.51 No	98% above MSST > 60% No
Rebuilt	1.03 > 1 Yes	1.03 > 0.77 Yes	1.03 < 1.23 No	68% above SSB_{MSY} > 60% Yes

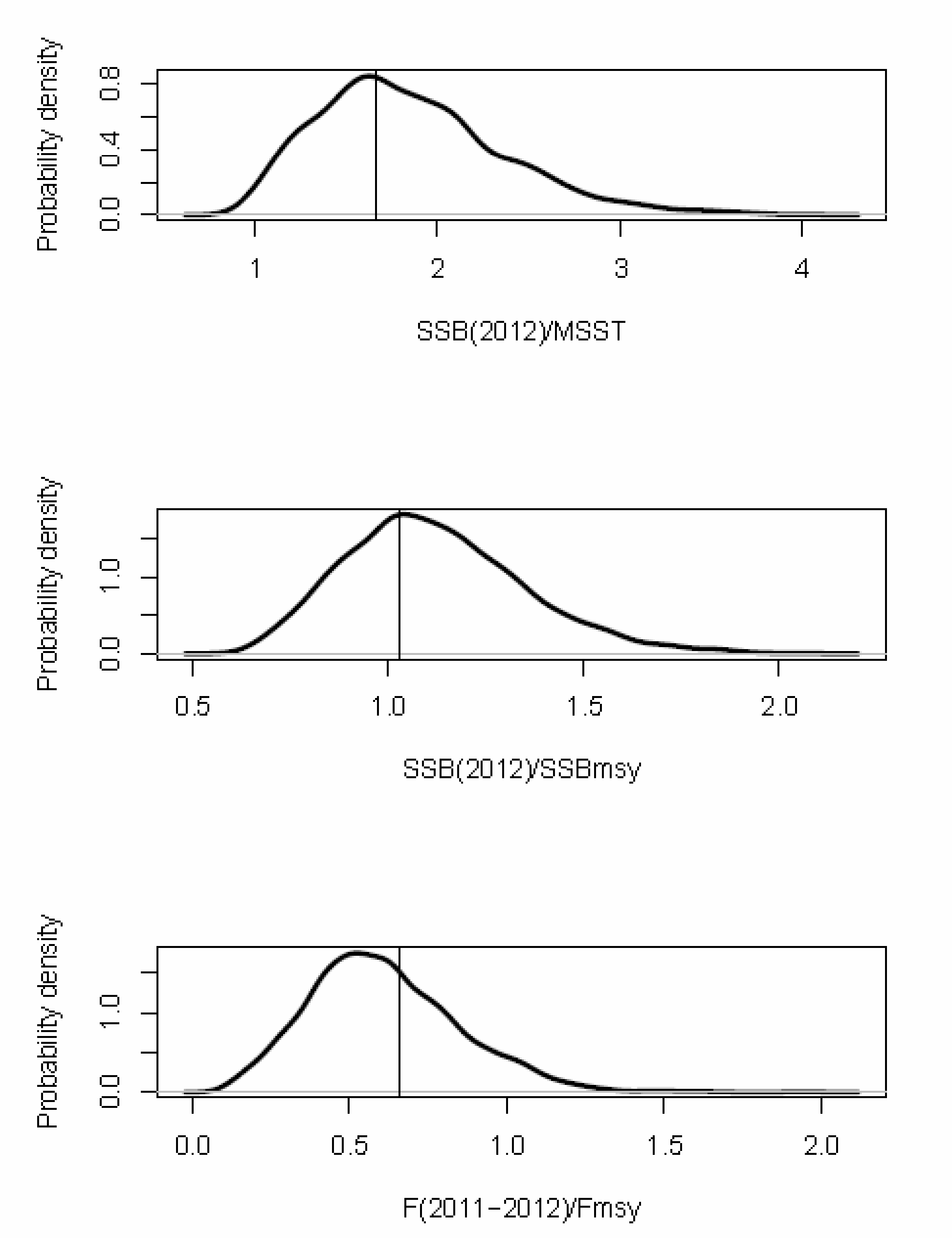

Figure 3. Probability densities of the MCB runs for the black sea bass status indicators from the 2012 black sea bass assessment update.