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MODELING RECRUITMENT IN THE EPO BIGEYE TUNA STOCK ASSESSMENT

CONTENTS

1. SUMMARY

The current EPO bigeye tuna assessment assumes recruitment is independent of stock size. Quarterly recruitment deviates are estimated using penalized likelihood based on a bias corrected lognormal distribution with a standard deviation of 0.6. It is unlikely that reliable estimates of steepness will be available for EPO bigeye tuna in the near future. The hockey stick stock model might be considered where recruitment declines only at abundance levels less than seen in the assessed history of the stock. The standard deviation of the recruitment penalty and the lognormal bias correction factor used for modelling recruitment variation need to be better handled to avoid biased estimates of average recruitment used for calculating management quantities.

2. INTRODUCTION

Recruitment is one of the main processes modelled in most contemporary fisheries stock assessments. It is typically separated into density dependent processes represented by the stock-recruitment relationship and density independent processes represented by the annual recruitment deviates. In general, it is difficult to estimate the stock recruitment relationship and results are either imprecise or biased, often towards recruitment being independent of stock size. Therefore, one or more parameters of the stock-recruitment relationship are fixed, often at somewhat arbitrary values. Typically, the stock-recruitment relationship does not have much of an influence on the estimates of historic recruitment, particularly if there are ample composition data, but it has a large influence on some management reference points and on projections. Kolody et al. (2019) review recruitment in tuna stock assessments and Maunder et al. (2012) review recruitment specific to EPO yellowfin tuna.

The current EPO bigeye tuna assessment assumes recruitment is independent of stock size. Quarterly recruitment deviates are estimated using penalized likelihood based on a bias corrected lognormal distribution with a standard deviation of 0.6.

Much of the information presented here is taken directly from other IATTC documents.

3. THE STOCK-RECRUITMENT RELATIONSHIP

The stock-recruitment relationship is the main, if not the only, density dependent process modelled in most stock assessments. Typically, the stock-recruitment relationship does not have much of an influence on the estimates of historic recruitment, particularly if there is ample composition data, but it has a large influence on some management reference points and on projections. Attempts to estimate the parameters of the stock-recruitment relationship inside the stock assessment model have shown that the parameter estimates are imprecise or are biased towards recruitment being independent of stock size (Magnusson and Hilborn 2007, Conn et al. 2010; Lee et al. 2012).

The base case EPO bigeye tuna stock assessment assumes that recruitment is independent of stock size (the steepness of the Beverton-Holt stock-recruitment relationship, the recruitment realized when the population is at 20% of its unexploited level as a ratio of the recruitment from an unexploited level, is fixed equal to one). Sensitivity analyses are conducted by fixing steepness at 0.75. When steepness is estimated in the bigeye tuna assessment, the estimate hits the upper bound of 1.0, the value used in the base case. This is an intuitive result since the base case estimates a regime shift in recruitment from a low level before the expansion of the floating object fishery in the mid 1990's to a higher level afterwards (Figure 1). This occurs as the population is declining (Figures 2 and 3). The regime shift in recruitment is thought to be an artifact of model misspecification and may be biasing the estimate of steepness.

One issue to keep in mind is that the model estimates quarterly recruitment and, if there is any seasonal pattern in recruitment, this should be removed before fitting a stock-recruitment relationship, otherwise the relationship may be hidden by the seasonal variation (Figure 3).

4. OTHER INFORMATION ABOUT THE STOCK-RECRUITMENT RELATIONSHIP

He et al. (2006) and Mangel et al. (2010) developed priors for steepness based on the evolutionary principle of persistence and life history parameters, respectively. Unfortunately, the priors from their methods, when considered in the context of the data used and assumptions made, are very broad and/or provide no advice over that which is already assumed when considering plausible values for steepness. In addition, some of the assumptions underlying these methods are questionable.

Meta-analyses have been conducted in an attempt to improve estimates of the parameters of the stock-recruitment relationship (Myers et al. 1999; Dorn 2002), but these studies are questionable because the authors lack knowledge of the individual data sets that have been used (e.g. they ignore the influence of regime-shifts), are fellable to the same issues mentioned in the previous section, or make biased assumptions (Maunder 2012).

Myers et al. (1999) estimated steepness for 8 stocks of Scombridae, including 5 tuna species. The median value of steepness was relatively low (0.52) and the median for the two bigeye stocks was also low (0.57). ISSF (2011) applied meta-analysis of steepness to stock size and recruitment time series for a variety of tuna species from three oceans. However, these estimates are suspect because they do not account for factors such as regime shifts (e.g. the EPO data is included and contains the regime shift for yellowfin tuna resulting in a h =0.69) or other bias (e.g. the increase in recruitment for EPO bigeye tuna as the floating object fishery expanded, which is thought to be an artifact of the assessment model). The mean from the available assessments (15 populations) was approximately h=0.8. Simulation analysis for EPO yellowfin tuna to test the estimability of steepness of the Beverton-Holt stock recruitment relationship were problematic with convergence problems, but did confirm that regime shifts could cause substantial negative bias in the estimates of steepness (Maunder et al. 2012).

Inherent correlation among life history characteristics has often been used to provide estimates of unknown parameters, particularly for estimating natural mortality (e.g. Jensen 1996). Myers et al. (1999) found a positive relationship between reproductive longevity (the expected number of years that an individual reproduces) and steepness, which Myers et al. (2002) used to develop a prior for use with stocks that have insufficient information to estimate steepness. Shertzer and Conn (2012) found no statistically significant relationships between steepness and natural mortality and age at maturity. ISSF (2011) found no relationship between steepness and life history parameters. Given the poor performance of these methods for natural mortality, it is unlikely that they will be useful for steepness.

Maunder and Deriso (2013) developed a stock–recruitment model for highly fecund species based on the contraction of the spatial and temporal extent of spawning when a population is reduced in size. The stock-recruitment curve may not be that useful itself, but it does highlight the point that the commonly used stock-recruitment relationships do not necessarily model the right type of dynamics and the spatial and temporal extent of spawning should be given more consideration.

5. DEFINITION OF SPAWNING BIOMASS

Development of a stock-recruitment relationship requires a definition of the effective spawning biomass. If the spawning biomass is defined incorrectly, then the relationship will be biased and may be difficult to estimate from the available data. It is common to assume that effective spawning biomass is proportional to the weight of mature individuals. However, egg production is generally not a linear function of body weight and the viability of eggs may differ with age. Generally, only female spawning biomass is used and imbalances in the ratio of males and females and its effect of fertilization are ignored. Minte-Vera et al. (2019) found that the definition of spawning biomass impacted both the stock assessment results and the evaluation of reference points for yellowfin tuna in the EPO. The spawning potential of EPO yellowfin tuna is estimated from the numbers of mature females adjusted for batch fecundity and spawning frequency. The EPO bigeye tuna assessment uses weight-at-age and a logistic length-at-maturity schedule to define spawning biomass based on females. Use of female abundance for bigeye tuna is significant because the sex ratio changes with age, which is assumed to be caused by differences in female and male natural mortality.

6. TEMPORAL VARIATION

Bigeye tuna recruitment may occur continuously throughout the year, because individual fish can spawn almost every day if the water temperatures are in the appropriate range (Kume 1967; Schaefer et al. 2005). Therefore, recruitment in the EPO bigeye tuna assessment is modeled to occur quarterly with deviates around the stock-recruitment relationship. The quarterly recruitment is assumed to be lognormally distributed with a standard deviation of 0.6 (note that this is quarterly not annual). A seasonal (quarterly) model (a parameter for each season in addition to the temporal deviates) has been applied in past assessments, but it was found that phase shifts in the seasonal pattern occur invalidating a seasonal model.

The standard approach assumes that recruitment is lognormally distributed around the Beverton–Holt stock–recruitment relationship. The lognormal distribution is commonly implemented by estimating parameters representing annual deviates constrained by a penalty added to the objective function based on the lognormal distribution assumption and application of a bias correction factor, the size of which depends on the amount of information about recruitment in the data (Methot and Taylor 2011). This is an approximation to a random effect or state-space modeling approach which appropriately integrates out the random variable (Maunder and Deriso 2003), but is too computationally intensive for many stock assessment applications. The standard deviation of the log normal distribution should be estimated, but this generally requires integrating out the random variable (Maunder and Deriso 2003), and is often pre-specified.

The base case assessment uses the number of wells sampled (this is for the purse seine, the longline sample size is scaled to be the same for the fishery with the highest sample size) to weight the length composition data and is then further down weighted by a factor of 0.05. This means that the quarterly estimates of recruitment are imprecise and have less temporal variation than might be expected.

As mentioned earlier, there is a regime shift in recruitment and this is thought to be an artifact of model misspecification rather than true temporal patterns in recruitment. However, the yellowfin tuna assessment shows several potential regime shifts in recruitment and is not subject to the same model misspecification (Minte-Vera et al. 2018).

Auto-correlation can also be modeled in the process variation, which may impact the steepness estimates (Ianelli 2002).

Minte-Vera et al. (2017) showed using the Age-Structured Production Model diagnostic that recruitment variation must be taken into account to interpret the absolute abundance and trend information contained in indices of relative abundance. Therefore, getting estimates of temporal variation in recruitment are important.

6.1. Sigma R

The ISSF (2011) preliminary meta-analysis (based on time series of spawning biomass and recruitment point estimates) mostly indicated $0.2 \leq \sigma_R \leq 0.5$ (Although, it is no clear if these estimates are for an annual or quarterly time step). The EPO bigeye tuna assessment assumes a standard deviation of 0.6. If these are independent, this corresponds to a standard deviation of 1.2 on an annual basis. However, the four quarterly recruitments within a year are not independent and those for the same quarter among years are not independent. An alternative approach is to make σ_R large so that the penalty does not have much influence on the recruitment estimates, but then not use R0 in any calculations of management quantities or reference points due to the inappropriateness of the bias correction factor (see below).

6.2. Bias correction

Full bias correction (-0.5*0.6*0.6) is applied to the quarterly recruitment deviate except for the time period described by the Stock Synthesis ramp. No bias correction ends in the third quarter of 1970 (before the start of the model and used to create the initial age-structure) and full bias correction starts in the second quarter of 1977. The full bias correction ends in the first quarter of 2015 and no bias correction starts in the fourth quarter of 2017 (the last year of data in the model). The Sock Synthesis bias correction ramp suggests that the full bias correction should be less only about 50% (See Figure 4). Keep in mind that the length composition data is highly down weighted and the value of the standard deviation is probably wrong. Therefore, the bias correction ramp is probably biased.

7. ENVIRONMENTAL RELATIONSHIPS

The environment can have a large influence on population processes including recruitment. The environment is often auto-correlated and can show substantial long term shifts that may produce similar patterns in recruitment. It is likely that bigeye tuna recruitment is influenced by the environment. However, the model misspecification that causes the regime shift in recruitment needs to be fixed and the full weighting of the length composition data applied before any reliable correlations with environmental covariates are conducted.

8. SENSITIVITY OF MANAGEMENT QUANTITIES TO THE STOCK-RECRUITMENT RELATIONSHIP AND TEMPORAL VARIATION

Standard management reference points such as F_{MSY}, MSY and S_{MSY}/S_0 are dependent on the stock-recruitment relationship. The equilibrium yield curve that is used to calculate MSY is the product of YPR and the stock-recruitment relationship. The target reference points for EPO bigeye tuna are S_{MSY} and F_{MSY}. The limit reference points are the spawning biomass and fishing mortality rate corresponding to stock size that produces 50% of the recruitment of an unfished population when the steepness of the Beverton-Holt stock-recruitment relationship is 0.75.

Currently, assessments of bigeye tuna in the EPO are always accompanied by a sensitivity analysis that uses steepness = 0.75 to provide managers with information about the consequences of a relationship between recruitment and spawning stock size. However, probability statements about this state of nature being true are not provided. The management advice is sensitive to the steepness parameter, except MSY (Table 1).

The regime shift in recruitment has implications for calculation of reference points and forward projections. Reference points for EPO bigeye tuna are calculated using the R0 recruitment over the whole stock assessment time period, which may include multiple regime shifts. The impact of regime shifts on reference points can be calculated for EPO bigeye tuna by simply multiplying MSY, S_{MSY}, and S_0 by the ratio of the average recruitment in the regime to the average recruitment in the whole time series. These can then be used to calculate the other reference points and management quantities. The recruitment from 1975-1993 is 22% less than the average and the recruitment from 1994-2017 is 17% greater than average. Regime shifts in recruitment do not impact F_{MSY}, which is used for managing EPO bigeye tuna. However, temporal changes in the steepness of the stock-recruitment relationship will. When there are trends or regime shifts in recruitment, it may be more appropriate to calculate dynamic reference points such as dynamic B0 (dB0) (Maunder and Watters 2003).

A commonly overlooked bias is caused by mispecifying the standard deviation of the recruitment distribution and is use in the lognormal bias correction factor (Crone et al. 2019). If σ_R is misspecified, then average recruitment estimated in the model over the appropriate time period will not equal R0 (or adjusted appropriately for the stock-recruitment relationship). Therefore, management quantities calculated using R0 will not be based on average recruitment. The average recruitment from 1975 to 2017 estimated in the bigeye tuna assessment is 10% less than R0.

9. PROXIES AND ROBUST MANAGEMENT STRATEGIES

Many common reference points are dependent on the stock-recruitment relationship as well as other parameters such as natural mortality, growth, and selectivity. Proxy reference points have been developed to be robust to uncertainty in the stock assessment parameters, particularly the stock-recruitment relationship, or to be precautionary (e.g. Clark 1991, 1993, 2002). Given that the appropriateness of some proxy reference points are dependent the true stock-recruitment relationship, proxy reference points have been discouraged by some researchers (Maunder 2012). Williams and

Shertzer (2003) suggest using proxy or precautionary values for the stock-recruitment parameters (e.g. steepness). No proxy reference points are used for bigeye tuna in the EPO.

Management quantities that are used for managing EPO bigeye tuna (e.g. Fmultiplyer and Scurrent/SMSY) are highly sensitive to the assumed value of steepness. Zhu et al. (2012) suggest that it is less risky in terms of lost equilibrium yield to under-estimate rather than over-estimate steepness. These analyses suggest that a lower, more conservative, value for steepness might be appropriate. However, if fishing mortality has to be reduced from current levels based on the new pre-specified value of steepness, there will be short term loss in yield.

10. PROJECTIONS

Both parameter uncertainty and future process variation should be included in projections. However, including both for fisheries stock assessment models is computationally intensive. Maunder et al. (2006) discuss this issue and recommend an approximation based on treating the projections like the historic estimation period, which is used in the bigeye tuna assessment. This approach does not adequately address the effects of the stock-recruitment relationship. The projections for bigeye tuna also do not consider regime shifts in recruitment or other non-random patterns in recruitment.

11. DISCUSSION

The current EPO bigeye tuna assessment assumes recruitment is independent of stock size. Quarterly recruitment deviates are estimated using penalized likelihood based on a bias corrected lognormal distribution with a standard deviation of 0.6. Biologically this is unrealistic because recruitment should reduce as the spawning biomass gets very low. However, this assumption only has to be valid for the stock sizes experienced during the assessment period and valid in any projections. It is unlikely that reliable estimates of steepness will be available for EPO bigeye tuna in the near future. The hockey stick stock model might be considered where recruitment declines only at abundance levels less than seen in the assessed history of the stock.

The standard deviation of the recruitment penalty and the lognormal bias correction factor used for modelling recruitment variation need to be better handled to avoid biased estimates of average recruitment used for calculating management quantities.

Kolody et al. (2019) suggest that effort spent expressing uncertainty in the stock-recruitment relationship and developing harvest strategies that are robust to this uncertainty is likely to be more productive than attempting to identify and defend a specific functional form or steepness value.

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TABLE 1. Estimates of the MSY and its associated quantities for bigeye tuna for different assumptions on steepness (h). All analyses are based on average fishing mortality during 2015-2017. Brecent and BMSY are defined as the biomass of fish 3+ quarters old (in metric tons) at the beginning of 2018 and at MSY, respectively. Srecent and SMSY are in metric tons. Crecent is the estimated total catch in 2017. The F multiplier indicates how many times effort would have to be effectively increased to achieve the MSY in relation to the average fishing mortality during 2015-2017. From Xu et al. (2018).

	Base case-Caso base	***h* = 0.75**
MSY-RMS	95,491	97,766
B_{MSY}- B_{RMS}	371,078	718,860
S_{MSY}- S_{RMS}	93,329	200,723
B_{MSY}/B_0- B_{RMS}/B_0	0.26	0.33
S_{MSY}/S_0- S_{RMS}/S_0	0.21	0.30
C_{recent}/MSY- C_{recent}/RMS	1.15	1.13
B_{recent}/B_{MSY}- B_{recent}/B_{RMS}	0.91	0.85
S_{recent}/S_{MSY}-S_{recent}/S_{RMS}	1.02	0.92
F multiplier-Multiplicador de *F*	0.87	0.80

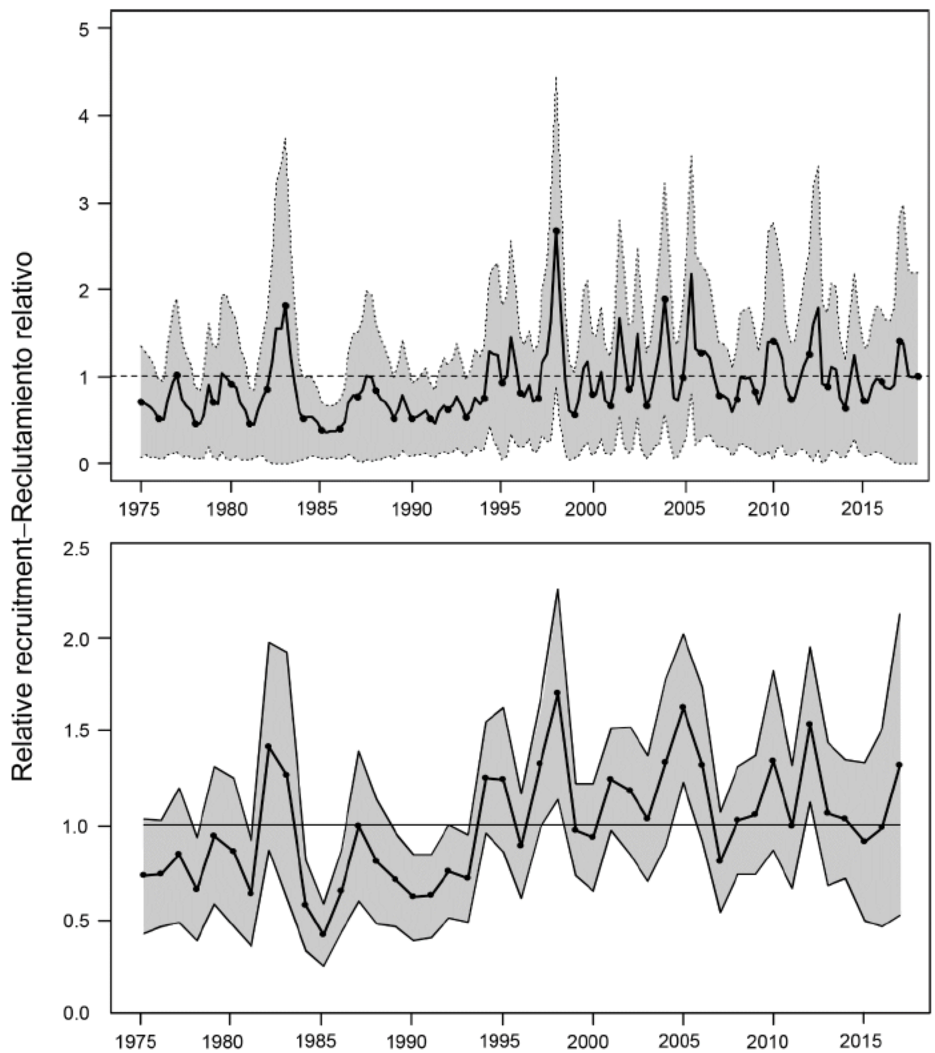

FIGURE 1. Estimated quarterly (top panel) and annual (bottom panel) recruitment of bigeye tuna to the fisheries of the EPO. The estimates are scaled so that the estimate of virgin recruitment is equal to 1.0 (dashed horizontal line). The solid line shows the maximum likelihood estimates (MLE) of recruitment, and the shaded area indicates the approximate 95% intervals around those estimates. From Xu et al. (2018).

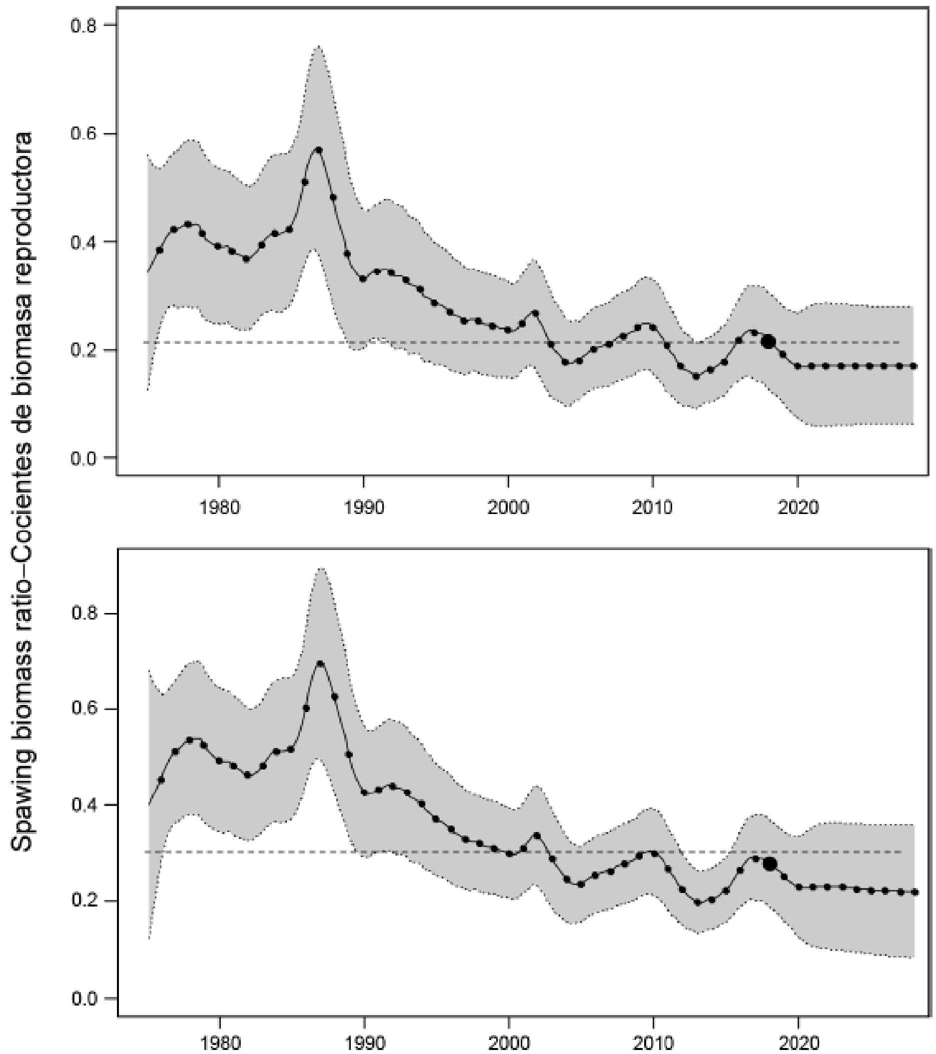

FIGURE 2. Estimated spawning biomass ratios (SBRs) of bigeye tuna in the EPO, including projections for 2018-2028 based on average fishing mortality rates during 2015-2017, from the base case (top panel) and the sensitivity analysis that assumes a stock-recruitment relationship (h = 0.75, bottom panel). The dashed horizontal line (at 0.21 and 0.30, respectively) identifies the SBR at MSY. The solid line illustrates the maximum likelihood estimates, and the estimates after 2018 (the large dot) indicate the SBR predicted to occur if fishing mortality rates continue at the average of that observed during 2015-2017, and recruitment is average during the next 10 years. The shaded area indicates the approximate 95-percent confidence intervals around those estimates. From Xu et al. (2018).

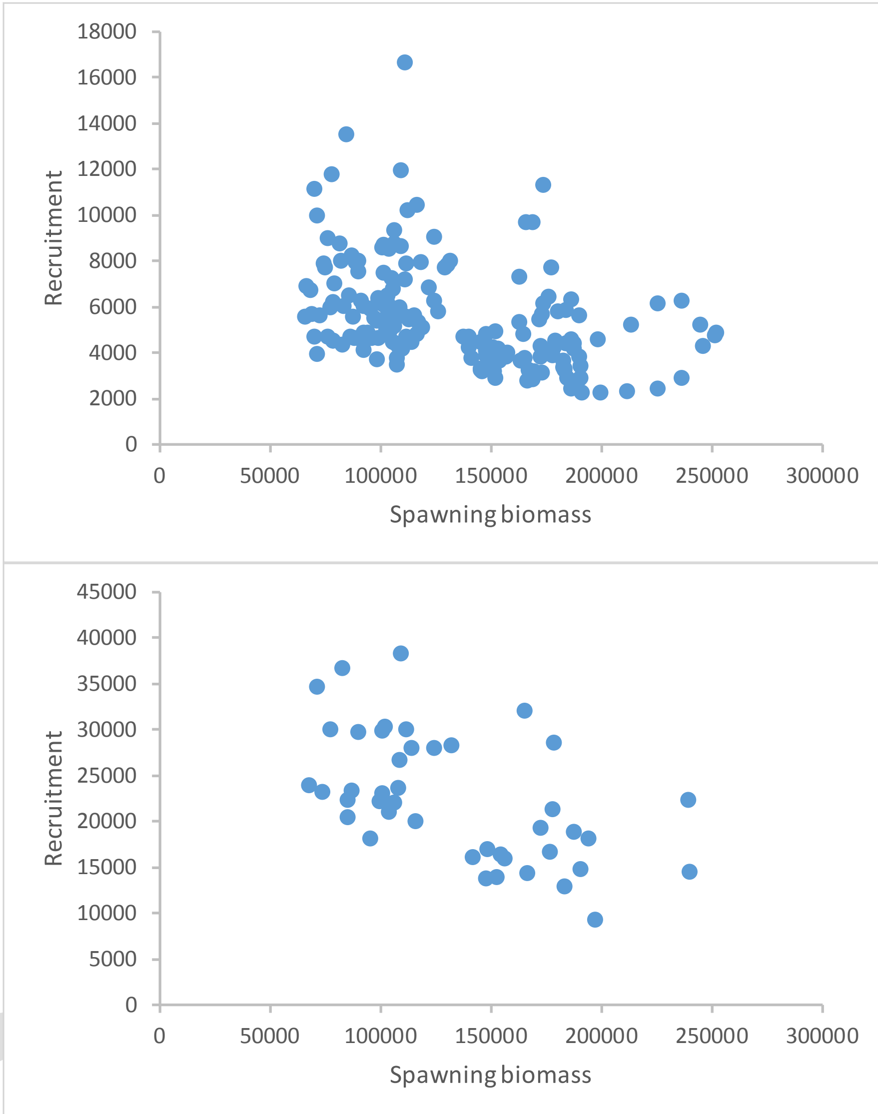

FIGURE 3. Recruitment plotted against spawning biomass on a quarterly time step (top) and aggregated by year (bottom).

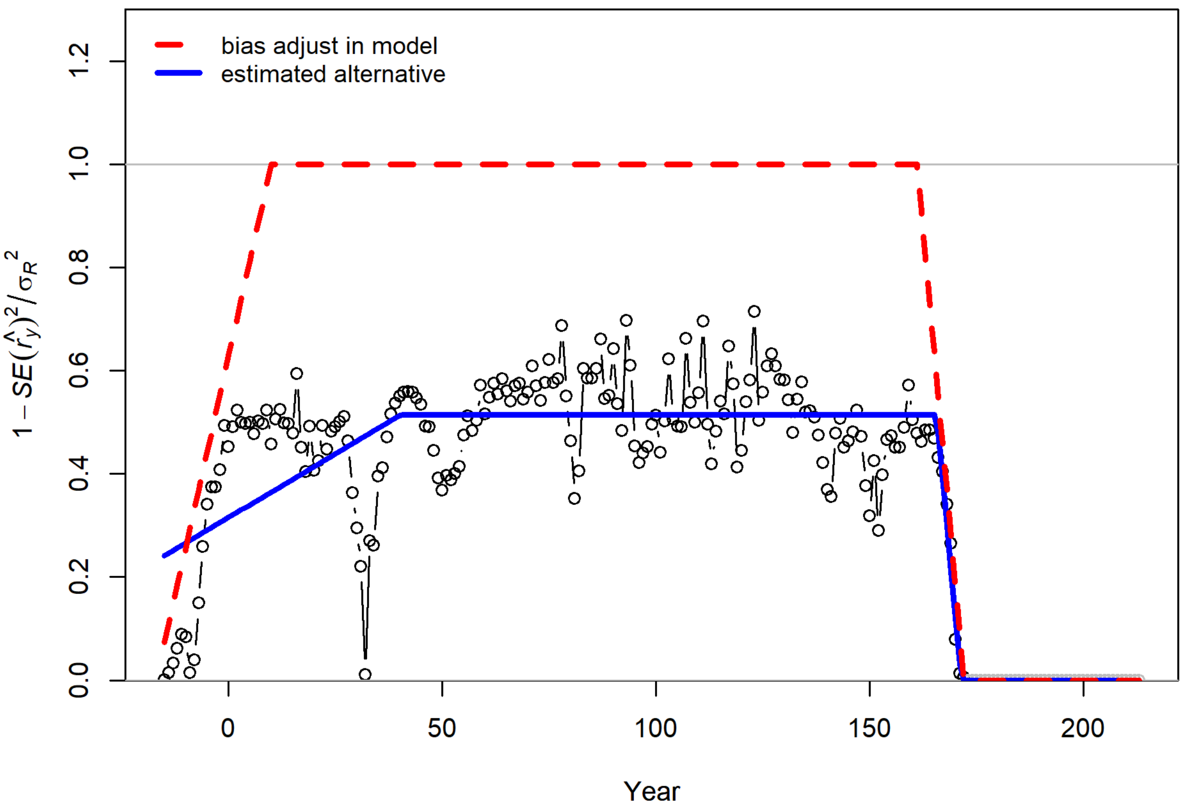

FIGURE 4. The recruitment bias correction ramp from Stock Synthesis.