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Preliminary examination of steepness in tunas based on stock assessment results

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Summary

In this paper I describe a preliminary meta-analysis of steepness values across several age-structured tuna assessments conducted under the world's RFMOs. The key findings are that:

- A range of values of steepness are estimated across the world's tuna stocks
- For some stocks steepness estimates from the Beverton-Holt curve were very close to the maximum of 1 and were associated with very tight [and presumably unrealistic] estimates of statistical uncertainty. This made it difficult to conduct a reasonable meta-analysis from the Beverton-Holt based estimates.
- The mode of the random effects distribution for steepness from the Ricker curve was 0.80. This value was used in the reference case models for the 2011 WCPFC assessments of bigeye, yellowfin, and skipjack tuna.

Further work is required towards meta-analysis of model outputs and the alternative approach to examining steepness through life history parameters may also yield useful results. In the interim I note the two key recommendations from the ISSF-funded workshop on steepness held in Rome, Italy earlier this year:

- The Workshop recommended that estimated values of steepness from individual assessments be treated with considerable caution. Analysts should evaluate the extent to which the stock--recruitment estimation or assumptions influence the estimates of recruitment; and
- The Workshop recommended that stock status advice incorporate stock assessment structural and parameter uncertainty including a range of plausible steepness values.

Introduction

The steepness of a spawner-recruitment (SR) curve is one of the most influential parameters in any stock assessment that relies on MSY-based reference points as benchmarks for stock status. At the same time it is notoriously difficult to estimate reliably in a stock assessment (Harley et al. 2009). Of particular interest to the WCPFC is the very high estimates obtained from the bigeye tuna assessment compared to the low-to-moderate levels estimated for yellowfin tuna.

Different approaches have been used to determine likely values of steepness for a given stock. The most common approach has been through the analysis of SR data from multiple stocks to look for evidence of common patterns or values across species / species groups. This analysis of data for multiple stocks is typically referred to as a 'meta-analysis' as it is an analysis of analyses. The most well known of these meta-analyses is from Myers et al. (1999) which examined over 700 SR time series. Later Myers et al. (2002) investigated whether it was possible to derive priors for steepness for a stock given knowledge of some of the stock's key life history characters.

An alternative approach involves deriving the value of steepness from 'first principles' of biological characteristics and early life history parameters (Mangel et al. 2009). This approach requires knowledge of the egg and larval life stages of the species under consideration and unfortunately this is generally poorly known for most tuna populations.

In this paper I apply the basic methodology of Myers et al (1999) to SR data from ten tuna stocks around the world. The goals of this work were to examine the variability in estimates of steepness across stocks, and determine if there are any common patterns or relationships with known life history parameters.

Methods

At the ISSF stock assessment workshop held in Rome 14-17 March, 2011 (ISSF, 2011), estimated SR time series and other key biological parameters were collated for most of the age-structured stock assessments that currently exist for tunas. At this meeting we were not able to resolve some problems with all the data sets, so only a subset was used for the current analysis. A list of the stocks for which data were used is provided in Table 1.

Table 1: Species and stocks included in this preliminary analysis. A reference code is provided and is used in the figures.

Species	Stock	Code
Albacore tuna	North Atlantic Ocean	ALB_AT
	North Pacific Ocean	ALB_NP
	South Pacific Ocean	ALB_SP
Bigeye tuna	Atlantic Ocean	BET_AT
	Indian Ocean	BET_IO
	Western and Central Pacific Ocean	BET_WC
Bluefin tuna	Eastern Atlantic	BFT_EA
Skipjack tuna	Western and Central Pacific Ocean	SKJ_WC
Yellowfin tuna	Indian Ocean	YFT_IO
	Western and Central Pacific Ocean	YFT_WC

Myers et al. (1999) only considered the Ricker functional form of the spawner recruitment curve, but in this analysis I consider both Ricker and Beverton Holt forms. Further, I investigate the likelihood profile for the parameter of interest using the raindrop plot (Barrowman and Myers 2003) which is a useful for way for displaying both the likelihood-based confidence limits, but also exploring any complexity in the likelihood surface. The horizontal extent of the ellipse represents the 95% confidence interval while the vertical width of the ellipse is proportional to the support for that value of steepness. It is important to note that often the likelihood surface can be far from smooth. In this preliminary analysis I did not attempt to fine-tune the likelihood profiles to ensure that the best fits were being made at each point.

Considering a time series of spawner abundance (S_t) and recruitment (R_t), the Ricker and Beverton Holt functional forms are:

Ricker $R_t = \alpha \mathrm{e}^{-\beta S_t}$

Beverton Holt $R_t = \frac{\alpha S_t}{(S_t / K+1)}$

where α represents the slope at the origin of the SR. In order for α to be comparable across stocks some further standardization is required. It is necessary to convert the estimated recruits into replacement spawners and this is done by user the spawning biomass per recruit in the absence of fishing – this calculation incorporates information on growth, natural mortality, and maturity. So we can replace R_t with $\widehat{R_t}$ where the latter represents the replacement spawners at low population size. The slope at the origin α now becomes $\hat{\alpha}$ and represents *the number of spawners produced each spawner over its lifetime and very low spawner abundance (i.e., assuming absolutely no density-dependence)*.

Finally we can now get estimates of steepness (h) and these are obtained from the estimated $\hat{\alpha}$ based on the following transformation

$h = \frac{\hat{\alpha}}{\hat{\alpha}+4}$ where $0.2 < h < 1$.

In the analyses that follow, $\hat{\alpha}$ is the primary parameter of interest to be measured and is then transformed to steepness based on the above transformation.

After conducting individual model fits and likelihood profiles with each curve I fitted a mixed effects model for each SR curve whereby all stocks were modeled simultaneously. In these analyses, the assumption is made that there is a true distribution for $\hat{\alpha}$ and that the values for the stocks are drawn from this distribution. This does not assume that there is a single value for steepness in tunas, but rather it allows steepness to vary between species and stocks.

If $\widehat{\alpha_i}$ represents the true value of steepness for stock i, then the assumption being made is $\log \widehat{\alpha_i} \sim N(\mu_{\hat{\alpha}}, \sigma_{\hat{\alpha}})$. It is this distribution which is commonly proposed for use as a prior distribution in stock assessments that use Bayesian approaches.

All analyses were undertaken using the R statistical software[2] with the individual model fits obtained using nlminb and the non-linear mixed models implemented using nlme[3].

[2] http://www.r-project.org/
[3] http://cran.r-project.org/web/packages/nlme/nlme.pdf

Results

The SR data for each stock with maximum likelihood based fits for the Beverton Holt and Ricker SR curve are presented in Figure 1. This figure also includes the raindrop plots which provide the likelihood-based confidence intervals for steepness from each SR curve. A summary of the point estimates of steepness are provided in The mixed effects models provide two outputs of interest: 1) the random effects distribution thought to describe the true distribution of steepness; and 2) new estimates of steepness for each stock where the SR curve is fit to the data while assuming that the true value of steepness comes from a common distribution. This latter output is the best linear unbiased prediction (BLUP – Searle et al. 1992) and are commonly referred to as the random effects estimates (Figure 2).

Table 2.

While there was a strong correlation between estimates of steepness from each curve, the estimate from the Ricker curve was always lower than that from the Beverton Holt curve. Three of the stocks had estimates of 1.0 from the Beverton Holt curve (ALB_NP, BET_WC, and BFT_EA) with the latter two stocks being associated with an estimated increase in recruitment as spawning stock declined. A further three stocks (ALB_AT, BET_OI, and SKJ_WP) had Beverton Holt estimates of steepness greater than 0.94. Conversely ALB_SP had a very low estimate of steepness (0.37 and 0.45) and from the spawner recruitment curve you can see that SR estimates are only just above the replacement line (Figure 1).

For many of the likelihood profiles for the Beverton Holt model we see “ramped” likelihoods where the model has information on the lower bound for steepness (i.e. if steepness was any lower than this we really would have detected a reduction in recruitment given the observed reduction in spawning biomass), but cannot determine an upper bound. Also apparent in the likelihood profiles are some very strange shapes that represent either complexity in the likelihood surface (i.e. that surface is not uni-modal), or a failure to completely converge (note that in this preliminary analysis I did not attempt to address this).

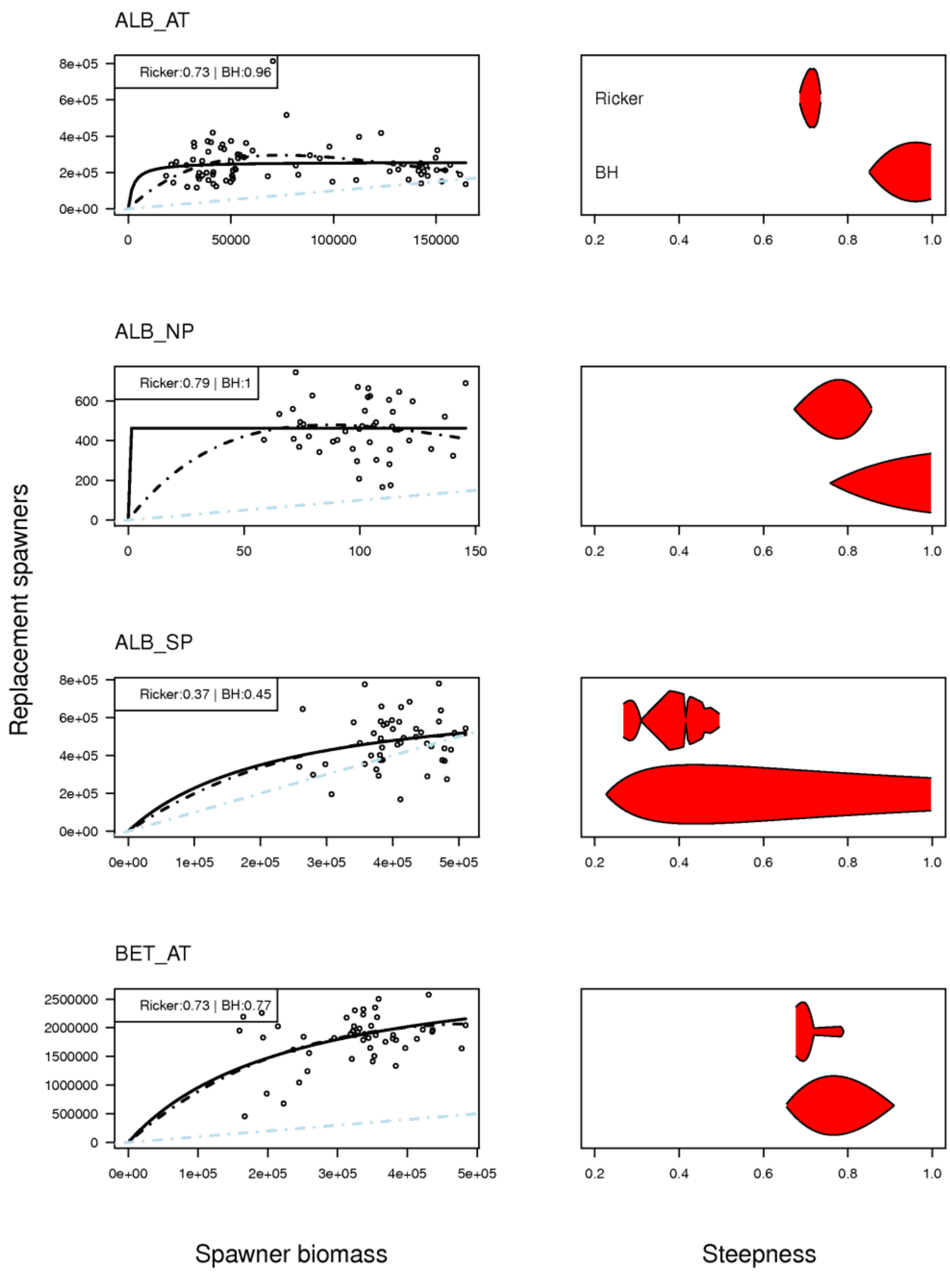

Figure 1: Individual SR time series and maximum likelihood fits for the Beverton Holt (solid) and Ricker (dashed) SR curves are provided on the left. For reference the point estimate of steepness for each curve is provided and the blue dashed line represents the replacement line for the SR curve. The right hand plots show the "raindrop" representation of the likelihood profile plot for steepness based on the slope at the origin estimated for each curve. Note the common pattern of complexity in the likelihood profile surface. Stocks plotted are: ALB_AT – albacore (Atlantic), ALB_NP – albacore (North Pacific), ALB_SP – albacore (South Pacific), and BET_AT – bigeye (Atlantic).

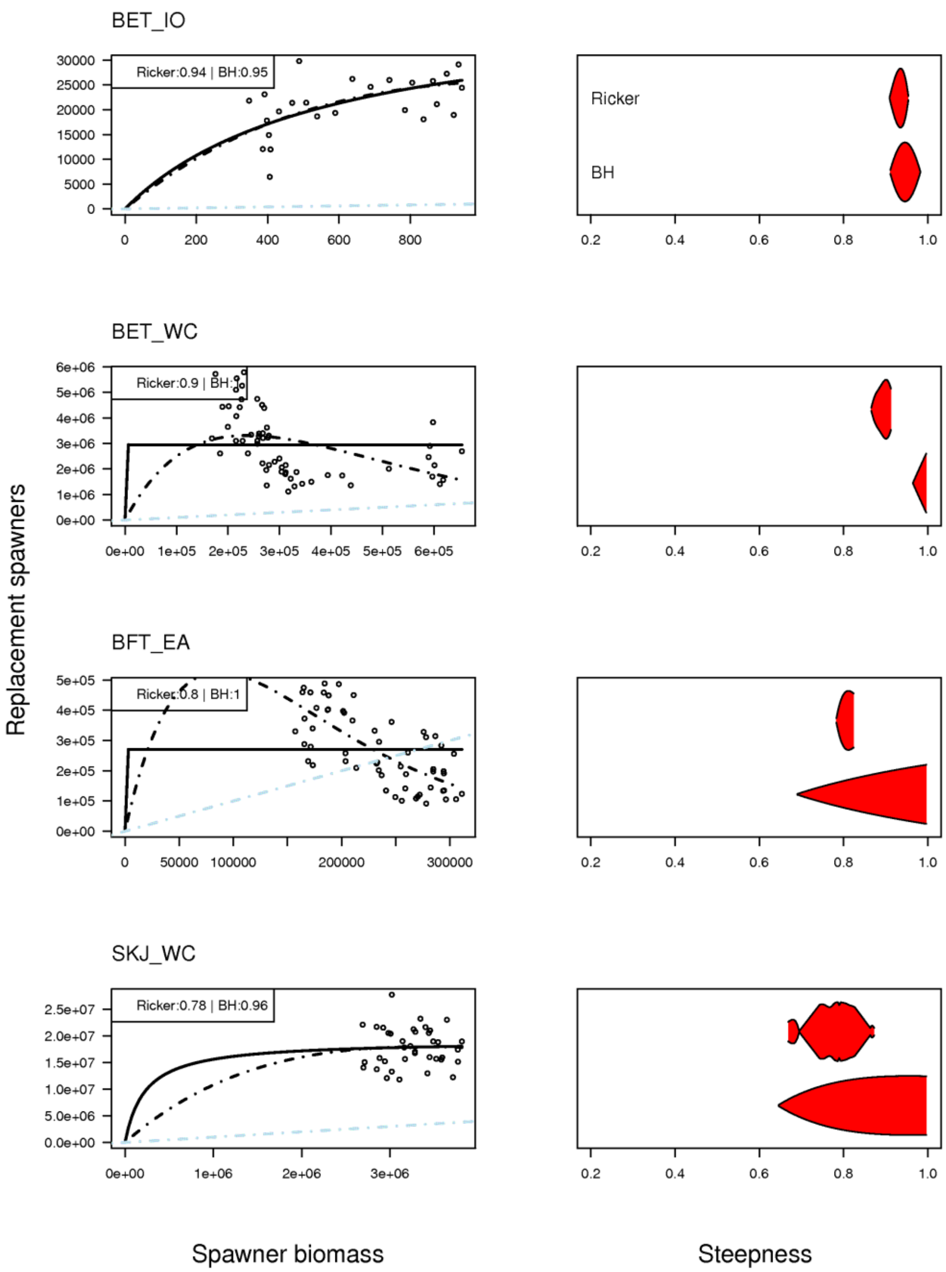

Figure 1 continued: Stocks plotted are: BET_IO – bigeye (Indian), BET_WC – bigeye (WCPO), BFT_EA – bluefin (East Atlantic), and SKJ_WC – skipjack (WCPO).

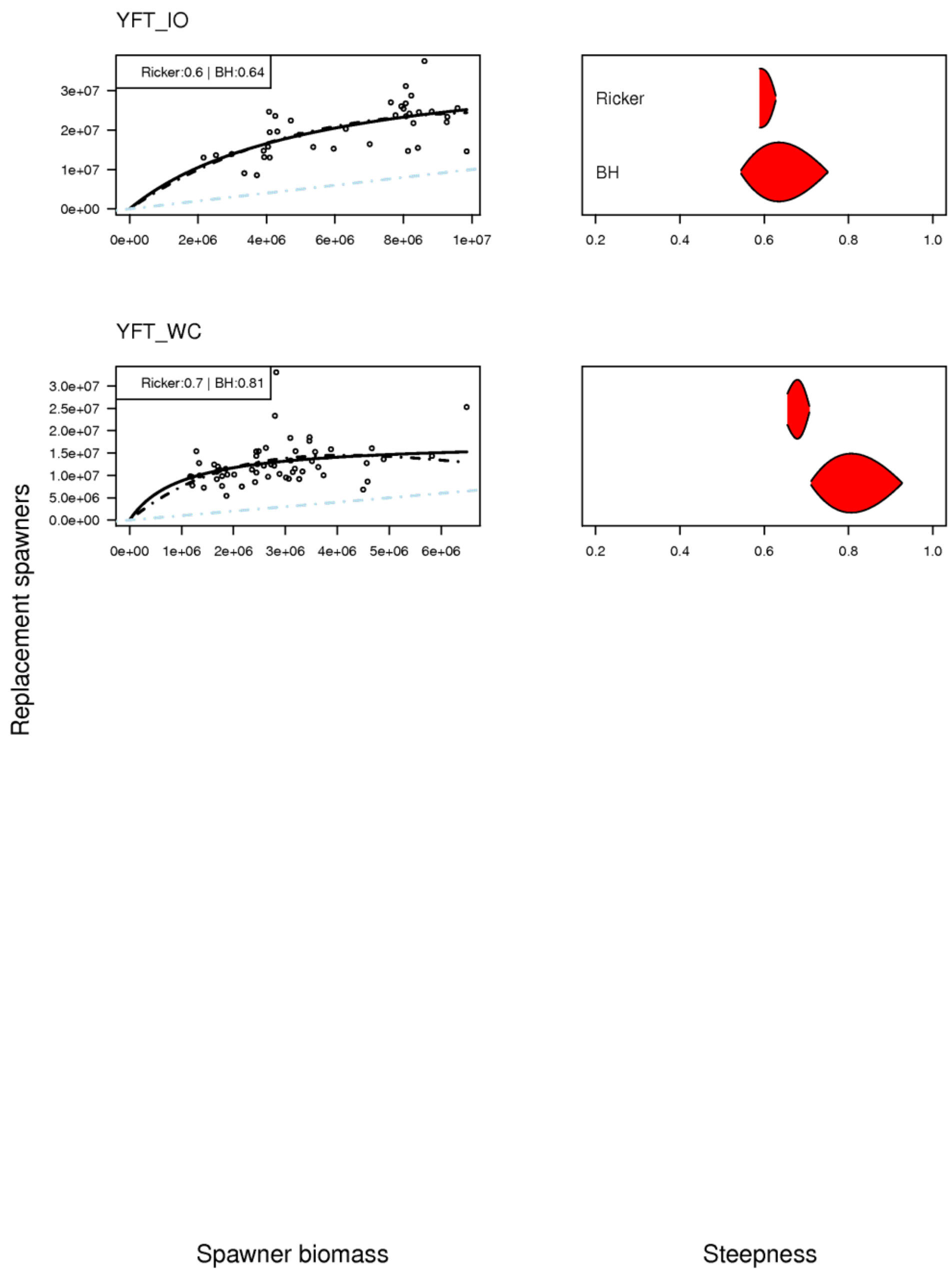

Figure 1 continued: Stocks plotted are: YFT_IO – yellowfin (Indian) and YFT_WC – yellowfin (WCPO).

The mixed effects models provide two outputs of interest: 1) the random effects distribution thought to describe the true distribution of steepness; and 2) new estimates of steepness for each stock where the SR curve is fit to the data while assuming that the true value of steepness comes from a common distribution. This latter output is the best linear unbiased prediction (BLUP – Searle et al. 1992) and are commonly referred to as the random effects estimates (Figure 2).

Table 2: Point estimates of steepness for each stock from fitting the Ricker and Beverton Holt SR curves.

Species	Stock	Ricker	Beverton Holt
Albacore tuna	North Atlantic Ocean	0.73	0.96
	North Pacific Ocean	0.79	1.00
	South Pacific Ocean	0.37	0.45
Bigeye tuna	Atlantic Ocean	0.73	0.77
	Indian Ocean	0.94	0.95
	Western and Central Pacific Ocean	0.90	1.00
Bluefin tuna	Eastern Atlantic	0.80	1.00
Skipjack tuna	Western and Central Pacific Ocean	0.78	0.96
Yellowfin tuna	Indian Ocean	0.60	0.64
	Western and Central Pacific Ocean	0.70	0.81

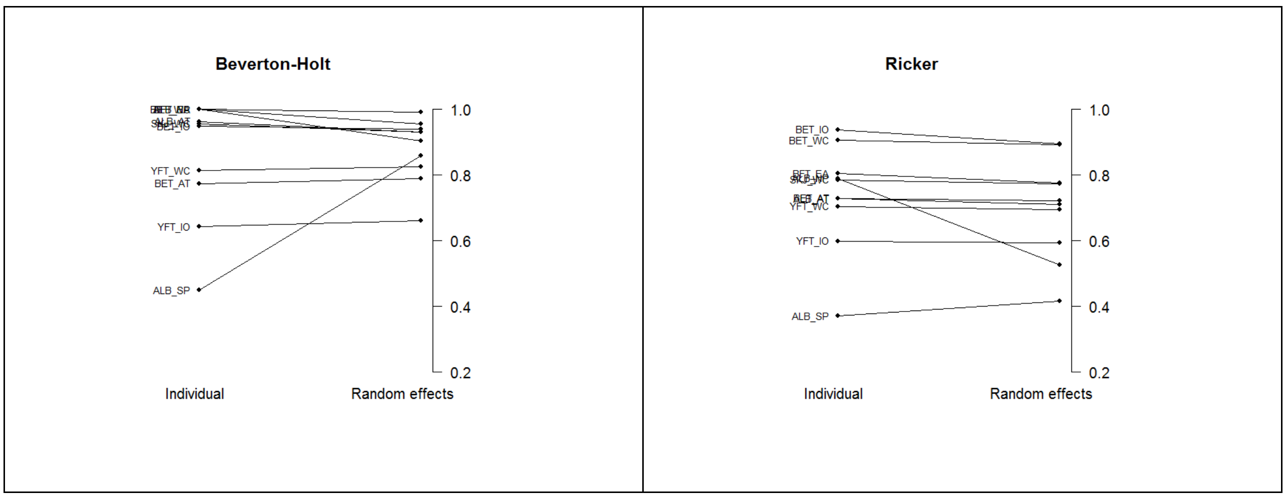

Figure 2: Estimates of steepness from the individual and random effects analyses for the two SR curves.

For each model we see that the individual estimates are "shrunk" (i.e. the spread is much less) when they are treated as random effects. For the Beverton-Holt estimates for ALB_SP, which had a particularly wide likelihood profile, the shrinkage to the mean of the distribution is quite large. For the Ricker the range of both the individual and random effects estimates are much wider and there is less shrinkage suggesting evidence for wide variation in the true distribution for steepness. There is one anomalous random effects estimate for ALB_NP where the random effects estimate is actually further from the mode of the random effects distribution than the individual estimate – this clearly requires further examination.

Finally we can get to the random effects distributions for the true values of steepness (Figure 3). The distribution from the Beverton Holt curve has most of its mass near one – which is not surprising as six of the ten individual estimates were greater than 0.94. The distribution from the Ricker fits is much broader with a mode around 0.8.

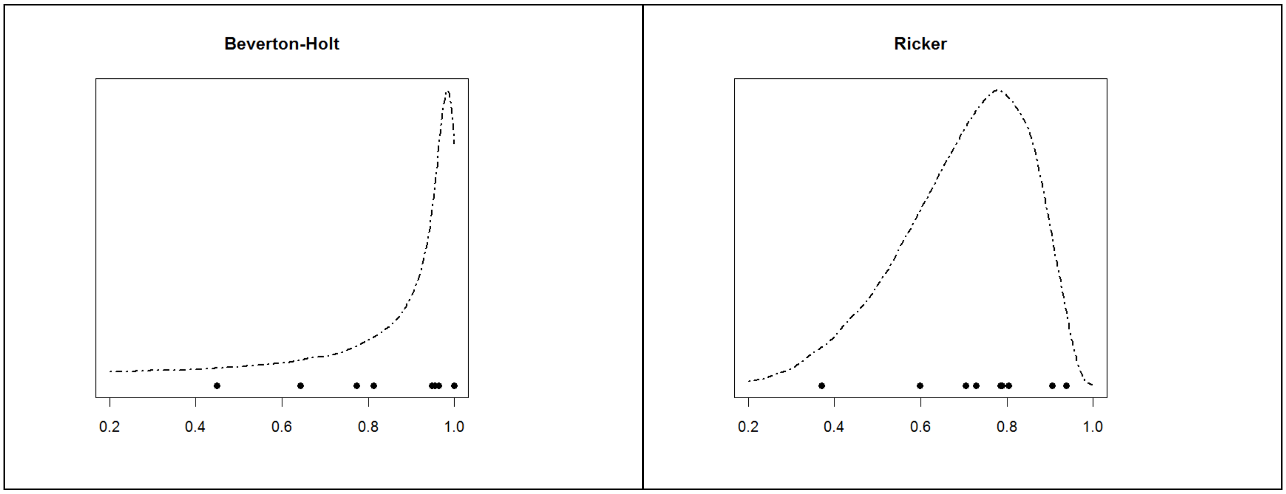

Figure 3: Individual estimated value of steepness (solid dots) and the estimated random effects distribution for steepness (dashed line) for the two SR curves.

Discussion

There remains considerable uncertainty about plausible values of steepness. This is a problem which plagues many assessments and complicates the use of MSY-based reference points.

Meta-analysis is one useful approach for reducing this uncertainty; however, it is not the only approach currently being considered. I note with interest that work of Mangel and colleagues in using biological information – in particular early life history characteristics to attempt to estimate steepness from first principles. This approach seems to be very well suited to shark species where the level of uncertainty in survival at the youngest ages is relatively small e.g. Brooks et al. (2010), but it is yet unclear if sufficient information exist to estimate steepness this way for other highly migratory fish stocks.

Of immediate interest from such life history approaches would be determination of the relative values of steepness for bigeye and yellowfin tuna. While yellowfin is a faster growing and shorter lived species, the estimated values for steepness are lower than those estimated for bigeye tuna. This is without being able to include the estimates from the EPO assessments, the results of which only reinforce this pattern. There may be characteristics of the species' biology that leads to yellowfin tuna being less resilient to overfishing. Alternatively, the pattern may simply be a model artifact for one (or maybe both) species.

One obvious question about the use of meta-analysis is "if we do not necessarily believe the estimates of steepness that come from individual stock assessment models – why would we believe the result of combining them all together?" This is a very fair question – can we say that many wrongs can approximate a right?

If we view a stock assessment as an 'estimator' of steepness, this conclusion could hold best if it was an 'unbiased estimator' – the estimates could be quite variable, but provided that they were not biased then the approach to combine them (incorporating uncertainty in the individual estimates) does not seem unreasonable. However, recent simulation studies have shown that steepness estimates can tend towards the upper bound or 1 irrespective of the true productivity of the stock (Conn et al. 2010).

Therefore estimates that tend to 1 could be more biased, yet the statistical estimates of uncertainty are usually smaller. It is for these reasons that I favour the results from the Ricker curve implementation rather than that of the Beverton Holt where problems with the upper bound frequently occur.

This was a preliminary analysis, yet represents arguably the best available information on plausible levels of steepness in tunas. The next steps for this analysis include increasing the number of stocks included in the analysis including updating with the results from the 2011 assessments for WCPO bigeye, yellowfin, and skipjack tunas, and the South Pacific assessment for albacore tuna, incorporation of the estimation errors is the SR time series, and potentially incorporating any structural uncertainty in the individual stock assessments by incorporating SR series from multiple model runs. A final part of the additional work will involve simulation studies to compare the biases inherent in using the Ricker and Beverton Holt models – particularly for the purpose of deriving potential priors for use in stock assessments.

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