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AN EVALUATION OF LIMIT AND TARGET REFERENCE POINTS AS PART OF A HARVEST CONTROL RULE: AN ATLANTIC SWORDFISH EXAMPLE

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SUMMARY

Management strategy evaluation has been proposed as an appropriate method to incorporate additional sources of uncertainty into the assessment process than is traditionally done. This addressing of additional uncertainty is more consistent with the precautionary approach to fisheries management. A simple harvest control rule incorporating both a target F and Biomass trigger was tested for the North Atlantic swordfish population using an MSE framework. The operating model was based on a past ADAPT-VPA assessment model. The MSE framework included four scenarios related to stock dynamics (OMs), two levels of data quality (OEMs) and two harvest control rules (MPs). Strong auto-correlation was found in the recruitment of the VPA, as seen in the autocorrelation coefficients. This autocorrelation had a significant effect on the simple projections. The outputs of the MSE process indicated that the influence of the auto-correlation and the inclusion of measurement error (in this case uncertainty in CPUE series), had a greater effect than changes in the type of recruitment relationship (assuming the dynamics of the VPA model). This clearly demonstrates that simple projections are less precautionary and do not take into account all the uncertainty inherent in the stock dynamics. In addition, the Btrigger had a greater effect on average annual variation (AAV) than on the actual estimated values with a lower value of Btrigger resulting in lower variability. Also, in reality catches, harvest (and hence fishing effort) and stock trends show great variability and do not follow the smooth trends implied by the median projections. Future HCR development should take this into account, possibly restricting inter-annual variability in TACs and fishing effort. Although this work is considered preliminary and much additional effort is needed, the benefit of the MSE process is clear.

RÉSUMÉ

L'évaluation de la stratégie de gestion a été proposée comme une méthode appropriée visant à incorporer des sources supplémentaires d'incertitude dans le processus d'évaluation par rapport à ce qui est fait traditionnellement. Le fait d'aborder l'incertitude additionnelle est plus cohérent avec l'approche de précaution vis-à-vis de la gestion des pêcheries. Une simple norme de contrôle de la ponction incorporant à la fois un F cible et un déclencheur de la biomasse a été testée pour la population d'espadon de l'Atlantique Nord à l'aide d'un cadre MSE. Le modèle opérationnel était basé sur le modèle d'évaluation antérieur ADAPT-VPA . Le cadre MSE incluait quatre scénarios portant sur la dynamique des stocks (OM), deux niveaux de qualité des données (OEM) et deux normes de contrôle de la ponction (MP). Une forte auto-corrélation est apparue dans le recrutement de la VPA, comme cela a été observé dans les coefficients d'auto-corrélation. Cette auto-corrélation a eu un effet important sur les projections simples. Les résultats du processus de MSE ont indiqué que l'influence de l'auto-corrélation et l'inclusion d'une erreur de mesure (dans ce cas, l'incertitude dans les séries de CPUE) ont eu un effet plus grand que les changements du type de relation de recrutement (en postulant la dynamique du modèle de VPA). Ceci démontre clairement que de simples projections sont moins prudentes et ne tiennent pas compte de toute l'incertitude inhérente à la dynamique des stocks. En outre, le Btrigger a eu un plus grand effet sur la variation annuelle moyenne (AAV) que sur les valeurs réelles estimées avec une valeur plus faible de Btrigger, ce qui a entraîné une plus faible variabilité. De surcroît, dans la réalité, les prises, la ponction (et par conséquent l'effort de pêche) et les tendances du stock font apparaître une grande variabilité et ne suivent pas les tendances lisses montrées par la médiane des projections. Le

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développement futur d'une norme de contrôle de la ponction devrait en tenir compte, en limitant éventuellement la variabilité interannuelle dans les TAC et l'effort de pêche. Même si ces travaux sont considérés comme préliminaires et que des efforts supplémentaires sont nécessaires, l'avantage du processus de l'évaluation des stratégies de gestion est indéniable.

RESUMEN

La evaluación de estrategias de ordenación se ha propuesto como un método apropiado para incorporar más fuentes de incertidumbre en el proceso de evaluación de las que se suelen incorporar tradicionalmente. Esta forma de abordar la incertidumbre adicional es más coherente con el enfoque precautorio para la ordenación de pesquerías. Se probó una norma sencilla de control de la captura que incorporaba tanto una F objetivo como un activador de biomasa para la población de pez espada del Atlántico norte, utilizando un marco MSE. El modelo operativo se basó en un modelo de evaluación ADAPT-VPA anterior. El marco MSE incluía cuatro escenarios relacionados con la dinámica del stock (OM), dos niveles de calidad de datos (OEM) y dos normas de control de la captura (MP). Se halló una fuerte autocorrelación en el reclutamiento del VPA, como se observa en los coeficientes de autocorrelación. Esta autocorrelación tenía un efecto importante en las proyecciones simples. Los resultados del proceso MSE indicaban que la influencia de la autocorrelación y la inclusión de errores de medición (en el caso de incertidumbre en las series de CPUE) tenían un mayor efecto que los cambios en el tipo de relación de reclutamiento (asumiendo la dinámica del modelo VPA). Esto demuestra claramente que las proyecciones simples son menos precautorias y no tienen en cuenta toda la incertidumbre inherente a la dinámica del stock. Además Btrigger tenía un efecto mayor en la variación media anual (AAV) que los valores reales estimados, ya que un valor inferior de Btrigger daba lugar a una variabilidad menor. Asimismo, en realidad, las capturas, extracción (y por tanto el esfuerzo pesquero) y las tendencias del stock dan muestras de una gran variabilidad y no siguen las tendencias suaves que muestran las proyecciones de la mediana. El desarrollo futuro de HCR debería tener esto en cuenta, posiblemente mediante la restricción de la variabilidad interanual en los TAC y en el esfuerzo pesquero. Aunque este trabajo se considera preliminar y se requieren muchos más esfuerzos en este sentido, sí han quedado claros los beneficios que implica el proceso MSE.

KEYWORDS

Yellowfin tuna, reference points

1. Introduction

The Commission [Rec. 10-02] has asked the SCRS to develop a Limit Reference Point (LRP) for North Atlantic swordfish that will trigger a rebuilding plan if biomass drops below it. The FAO Technical Consultation on the Precautionary Approach to Capture Fisheries (FAO, 1996) recommended the use of harvest control rule to specify in advance what actions should be taken when limits are reached. However, although harvest control rules may include several precautionary elements, it does not necessarily follow that they will be precautionary in practice (Kirkwood and Smith 1996). Since many harvest control rules are not evaluated formally to determine the extent to which they achieve the goals for which they were designed, given the uncertainty inherent in the system being managed (Punt 2008). Therefore Management Strategy Evaluation (MSE) based on simulation modeling has increasingly been used to evaluate the impact of the main sources of uncertainty inherent in the system being managed (Kirkwood and Smith 1996, Cooke 1999, McAllister et al. 1999, Kell et al.).

Under such an approach as well reference points and the specification of a HCR, the minimum data and knowledge requirements for types of assessment methods to be used for decision-making are evaluated.

MSE allows uncertainty, beyond just the assessment process, to be considered; since under active management uncertainties about management decisions, their effects and their implementation also affect management outcomes. However, Fisheries management advice has traditionally been based on a reductionist approach, where tasks are considered in a linear fashion e.g. collect the data, perform the assessment, compute reference points, then set the quota. However, just as in ecology where it is argued that inappropriate use of reductionism limits our understanding of complex systems, we need to understand how systems work and in particular how feedback loops influence those systems. Management Strategy Evaluation (MSE) has therefore become an important tool for evaluating management advice.

In this paper we show how Management Strategy Evaluation we evaluate the performance of candidate limit reference points as part of a HCR based on North Atlantic swordfish.

2. Management Strategy Evaluation framework

An important aspect of the MSE approach is that management outcomes from the HCR are fed back into the operating model so that their influence on the simulated stock and hence on the future simulated fisheries data is propagated through the stock dynamics **(Figure 1)**.

All terminology is based upon that of Rademeyer et al. (2007).

The main elements of the MSE approach are:

- Operating Model (OM); that represents alternative plausible hypotheses about stock and fishery dynamics, allowing integration of a higher level of complexity and knowledge than is generally used within stock assessment models;
- Management Procedure (MP); or management strategy which is the combination of the available pseudo-data, the stock assessment used to derive estimates of stock status and the management model or Harvest Control Rule (HCR) that generates the management outcomes, such as a target fishing mortality rate or Total Allowable Catch.
- Observation-error Model (OEM); that describes how simulated fisheries data, or pseudo-data, are sampled from the Operating Model; and
- The Management Procedure is linked to the operating model by the data and assumed level of knowledge, modelled by the Observation Error Model (OEM) and the dynamics assumed in the Stock Assessment Procedure (SAP). Depending upon the perceived stock status and reference points, the HCR then determines management action.

In the MSE approach complex models are used primarily to test the robustness of simpler assessment-management rules before implementation. This is done by conducting computer-based experiments that embody how the whole system reacts to a variety of possible management actions (Hilborn, 2003). Population and fleet dynamics are deduced from a range of plausible hypotheses and available data sets, rather than being based on a singular set of assumptions. This is because the objective is to develop strategies that are robust to our uncertainty about the true dynamics and, hence, to meet the requirements of the precautionary approach.

The challenge is no longer to build (and then justify) a single best model but to identify an appropriate of range of plausible models, parameterise and assigning weights to them (Punt, 2008). There is also a need to explore alternative model structures and ways of assigning weights or probabilities to them for example using Bayesian and meta-analytic techniques (Michielsens and McAllister, 2004).

All modeling was done using FLR (Kell et al. 2008) which was designed to be used to build simulation models representing alternative hypotheses about stock and fishery dynamics, hereby allowing a higher level of complexity and knowledge than used by stock assessment models and to explicitly include a greater range of uncertainty.

2.1 Uncertainty

A greater range of sources of uncertainty are considered than within traditional stock assessment. The latter mainly considers only uncertainty in observations and process (e.g. recruitment). However, uncertainty about the actual dynamics (i.e. model uncertainty) has a larger impact on achieving management objectives (Punt 2008). Therefore when providing management advice it is important to consider appropriate sources of uncertainty. Rosenberg and Restrepo (1994) catagorised uncertainties in fish stock assessment and management as:

- Process error; caused by disregarding variability, temporal and spatial, in dynamic population and fisheries processes;
- Observation error; sampling error and measurement error;
- Estimation error; arising when estimating parameters of the models used in the assessment procedure;
- Model error; related to the ability of the model structure to capture the core of the system dynamics;
- Implementation error; where the effects of management actions may differ from those intended.
- Sources of uncertainty related to Model Error include
- Structural uncertainty; due to inadequate models, incomplete or competing conceptual frameworks, or where significant processes or relationships are wrongly specified or not considered. Such situations tend to be underestimated by experts (Morganand Henrion, 1990).
- Value uncertainty; due to missing or inaccurate data or poorly known parameters.

2.2 Operating model

Setting up and conditioning Operating Models depends on the objectives of a particular study but if uncertainties in the resource assessment are large, the construction of a reference set of OMs is preferable to the use of a single reference case OM. However, in this study we constructed a single OM since we are mainly concerned in illustrating the utility of the approach rather than fully characterising uncertainty.

In the last assessment an aged based assessment using VPA-Adapt was considered (ref), which used catch-at-age data derived from catch-at-size. Only 5 age groups (age 1 to 5+) were used owing to the inability to reliably age older male fish. The results from the VPA were used to as the basis of an age based OM.

2.2.1 Conditioning

Future dynamics were based on the biological parameters used in the last ICCAT assessment **(Figure 3)**. However, these can easily be changed to consider uncertainty about life-history traits.

The assumed stock recruitment relationship is key to understanding stock dynamics. There was strong autocorrelation in the recruitment from the VPA assessment as shown by the autocorrelation coefficients in **Figure 5**. Where there is strong positive autocorrelation for low order lags and negative autocorrelation for higher order lags.

SSB and recruits from the VPA assessment are plotted in Figure 4 along with four alternative fits. The two Beverton and Holt fits (with and without autocorrelation) were very different and the results from a projection based upon either fit will be quite different.

The estimation of stock recruitment parameters are not always treated consistently in tuna stock assessments (ISSF). For example, many assessments either estimate or fix the value of steepness, a parameter that determines the degree to which average recruitment depends on parental stock biomass. This has a large effect on the assumed productivity of stocks and reference points. The ISSF workshop concluded that estimated steepness values from individual assessments should be treated with considerable caution. It was also recommended that scientists better characterise uncertainty in stock assessment. However, in this example, steepnesses below about 0.85 resulted in the SRR not passing through the data and so it was decided to use a hockey stick SRR instead. A main reason for doing so was not to predict future recruitment but to evaluate the robustness of the HCR to different assumptions, i.e. what if there is a level at which recruitment is impaired how important is the choice of Btrigger.

Combining the stock recruitment relationships with spawner and yield per recruit provides estimates of the equilibrium (i.e., the expected long-term dynamics). These are plotted for constant recruitment with the historical observations in **Figure 6**.

2.3 Management procedure

The SAP used was a Pella-Tomlinson surplus production or biomass dynamic model; In biological terms, a biomass dynamic model combines recruitment, body growth and natural mortality into three parameters the intrinsic rate of increase (r), carry capacity (K) and shape of the surplus production function (p, i.e. determines skewness). The maximum sustainable yield (MSY) is found at the maximum of the curve.

The Harvest Control Rule was based on that described in the Report of the 2010 ICCAT Working Group on Stock Assessment Methods (Anon. 2011). HCR incorporates limit and target reference points into a rule that dictates the action to be taken in terms of defining fishing mortality rates depending on the estimated biomass level (x-axis) **(Figure 2)**. The Btrigger causes F to be reduced if the stock falls below this level, otherwise fishing is at the target F level.

In this example, the target fishing mortality was 75% of FMSY and the Btrigger 75% of B_{MSY},

The historical values from the OM are contrasted with the estimates from the MP in **Figures 7, 8 and 9**. **Figure 7** shows time series of absolute values of stock, catch and harvest rate and **Figure 8** the same values relative to MSY benchmarks. **Figure 9** shows the relative values in the form of a Kobe phase plot.

For the same catch data the MP underestimates biomass and overestimates harvest rate. However; the opposite is true for the relative values as can be seen in the Kobe Phase plot where the trajectory for the MP is displaced towards the red quandrant (i.e. overfished and over fishing).

2.4 Scenarios

Four scenarios related to the stock dynamics (i.e. 4 OMs)) were considered:

1. No reduction in recruitment as SSB declines; i.e. Steepness=1.0
2. Hockey Stick stock recruitment relationship; i.e Steepness<1.0
3. Random recruitment around the expected value
4. Auto-correlated recruitment around the expected values Two levels of data quality (i.e., 2 OEMs)
    1. CV of CPUE = 30%.
    2. CV of CPUE = 30%, and two harvest control rules (i.e. 2 MPs) were evaluated,

    1. Btrigger=0.75*B_{MSY}.
    2. Btrigger=Perc 40 In addition for comparative purposes the OM was projected with an F of F_{MSY}.

2.5 Software

FLR (a fisheries library in R www.flr-project.org) developed as a generic MSE framework was used for the simulation modeling. The various FLR packages (including FLBioDym the biomass dynamic assessment model) can be downloaded from the FLR website.

3. Results

The results section is intended to illustrate the main features of an MSE rather than provide an exhaustive management advice.

Time-series in the form of medians and 95th and 5th percentiles of fishing mortality, Recruits, SSB and Yield are presented in **Fgure 10** for a traditional projection and from the OM of the MSE. In the projection only process error is considered (i.e., random recruitment around a stock recruitment relationship). In the case of the MSE process and estimation error and model mis-specification (i.e., assessment is biomass based although the OM is aged based). The main differences are that: (i) uncertainty in the MSE is much greater than in the traditional assessment; (ii) F is less in the MSE OM than in the projection; (iii) while SSB is greater; and (iv) initially the realised yield in the MSE OM is less eventually recovers to the same level as in the projection.

Figures 11, 12 and 13 shows the medians and 95th and 5th percentiles for the same quantities as in **Figure 10**, but also includes individual realisations from the Monte Carlo simulations (i.e, worm plots). These plots were recommended by the Working Group on Stock Assessment Methods (WG-SAM) as they show the variability that will be seen in the future. The median and quantiles are very misleading since the catches that managers and fishers see will not be the smooth trends implied, since HCRs with limits and targets will result in high variability in TACs between years.

Figure 11 is for random recruitment deviates and a Hockey Stick stock recruitment relationship, a CPUE CV of 30% and Btrigger of 75% of B_{MSY}. While recruitment is highly variable from year to year, F, SSB and Yield tends to over or underestimate the expected level. The harvest control rule with a Btrigger of 75% of B_{MSY} will tend to produce results that are much better or much worse than that predicted by the medians.

Figure 12 is for the same treatments as **Figure 11**, expect that recruitment is now auto-correlated, the main difference is that F and hence Yield is now show much more inter-annual variability. This will make it difficult for the industry to plan from one year to the next and also to undermine the scientific advice. Since advice between years will be contradictory.

Figure 13 is for the same treatments as in **Figure 12** (note recruitments are identical) but with a Btrigger of 40% of B_{MSY} ; in this case F and Yield still show high inter-annual variability, but variability is different in the same years; the overall levels of variability (given by their 5th and 95th percentiles) is similar.

These results show that time series of expected values and quantiles are misleading and so in the following figures summary statistics are presented instead.

Figure 14 shows the distribution of minimum values of SSB relative to B_{MSY} seen under the HCR for the two different stock recruitment relationships (Mean and Hockey Stick) and recruitment variability (random and auto-correlated). The box plots show the median and interquartiles. These show that in the MSE (green and blue) a higher level of minimum SSB is achieved than predicted with the traditional projection (red). The level of variability depends upon the quality of data used in the assessment (i.e. measurement error corresponding to a CPUE CV of either 30 or 50%) and to a lesser extent on the form of recruitment variability. The main factor of importance is that the bias in the assessment of the MP tends to underestimate the stock status relative to B_{MSY} and so sets a lower TAC than in the projection.

Figures 15 and **16** show the inter-annual average variation in fishing mortality and catch. In the traditional projection there is no variability, while in the MSE much greater variability is seen. The greatest variability is seen when autocorrelation in recruit occurs; the next important effect is measurement error followed by the Btrigger level.

4. Discussion

This study was intended to show how MSE can be used to evaluate reference points. Reference points make sense within a HCR, i.e. as targets or as limits or thresholds that trigger management action, such as a recovery plan.

The study is a worked example for North Atlantic swordfish and is a work in progress and is not intended to be used for advice, rather it demonstrates the importance of using MSE to evaluate reference points as part of a HCR and illustrates the limitations of evaluating reference points by traditional stock projections based upon a stock assessment.

Uncertainty. This MSE incorporates a greater range of uncertainty than is normally considered within stock assessment. The simulations conducted clearly demonstrate that considering more realistic sources of uncertainty is important when providing probablistic management advice. The main sources of uncertainty considered here were process error (i.e. recruitment variability), uncertainty about the true dynamics of the stock being evaluated (e.g., SRR and form of recruitment variability), measurement error (CPUE CV), model mis-specification (e.g., assessment was biomass based although the OM dynamics were aged based) and estimation error. As mentioned above, this is a considerable range of uncertainties when compared with most stock assessments. It was assumed that management, i.e. the TACs were implemented perfectly and that there was no misreporting of catch.

The main impact of the various sources of uncertainty was estimation error, in that the assessment within the MP, underestimated stock size relative to B_{MSY} resulting in the stock being fished at less than F_{MSY} and the stock being maintained at a level greater than B_{MSY}. However, despite this in the long-term catches were close to MSY due to the yield v F curve being fairly flat. The next most important source of uncertainty was the form of recruitment variability, i.e. random or autocorrelated. In the case of autocorrelated recruitment, several stock or week year classes would occur sequentially and this had a big effect on the TACs set by the HCR. In comparison the assumed SRR (mean or hockey stick) and measurement error had less effect. The hockey stick had less effect due to the assessment under estimating the true stock status.

Biomass Limits. Biomass limits have two main roles i.e., as in ICES to prevent the stock falling below a level where recruitment is impaired or to ensure that the stock does not fall below a level which can provide MSY. The latter is of greater priority for ICCAT in setting Btrigger. The values for Btrigger evaluated i.e. 40 and 75% of BMSY had little effect since the HCR (as noted above) set an F much below F_{MSY}.

AAV. The study showed that looking at trends either from the expected value or appropriate higher or lower percentiles is insufficient for providing management advice; since outcomes in practice would be very different. Showing great inter annual variation, where catches and fishing effort will vary wildly from year to year. This would make it difficult for the industry to plan and for managers to set limits to capacity. It will also undermine the credibility of the scientific advice which will appear to contradict itself on a annual basis.

Therefore HCRs should include elements that reduce inter-annual variability in TACs Kell et al. (2005a), Kell et al. (2005b).

Plausible Hypotheses for OM. An MSE that is to be used to provide management advice must include appropriate hypotheses to fully evaluate the proposed management strategy. In particular it is important to evaluate robustness to those hypotheses, i.e. is it true that the biomass limit of either 40 or 75% perform the same, or was this due to the SRR assumptions and should other SRR have been considered. Similarly is the bias in the assessment in the right direction, if the answer is only maybe then other biases need to be evaluated.

YFT-IOTC. A similar study was conducted for YFT-IOTC, the conclusions from that study which showed the importance of taking a case-specific perspective.

Management Objective and Summary Statistics, The next step is to come up with plausible hypotheses about stock dynamics and alternative candidates for Btrigger, then to evaluate these using MSE as part of a HCR, which, in turn, is considered as part of an MP. Evaluation will require the identification of management objectives and summary statistics that allow the risks (i.e. probability of not meeting those objectives) and trade-offs between them to be evaluated.

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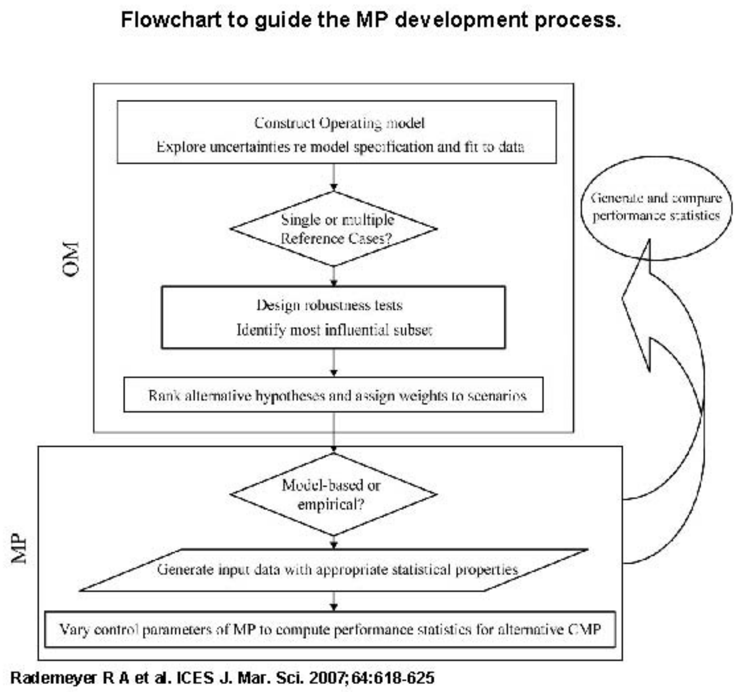

Figure 1. Conceptual framework for Management Strategy evaluation

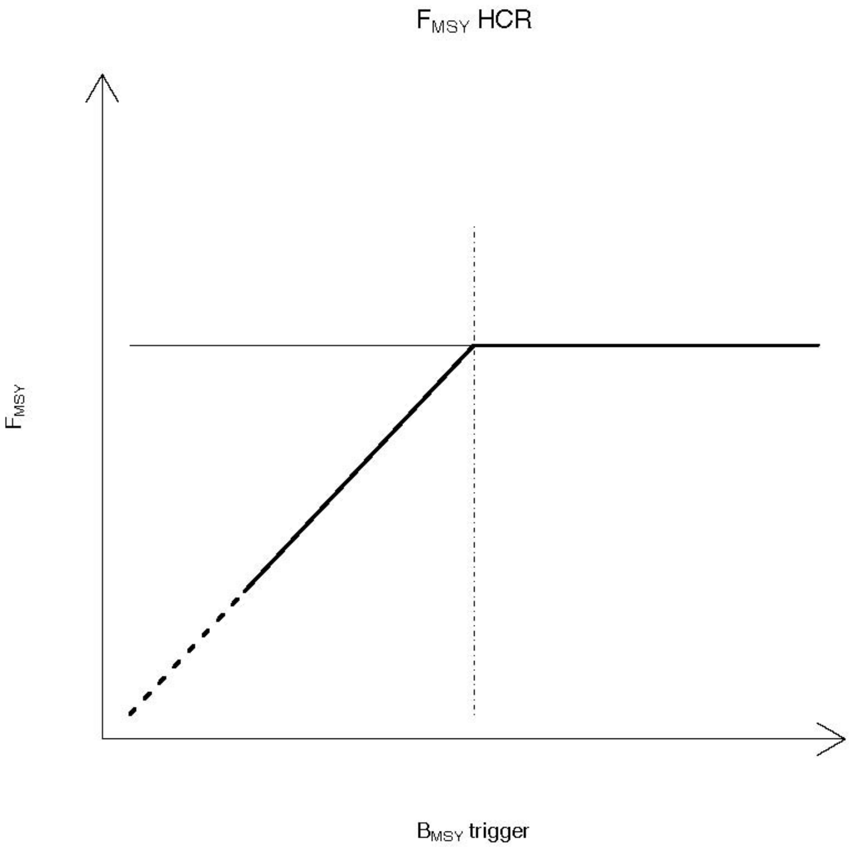

Figure 2. An example of a harvest control rule.

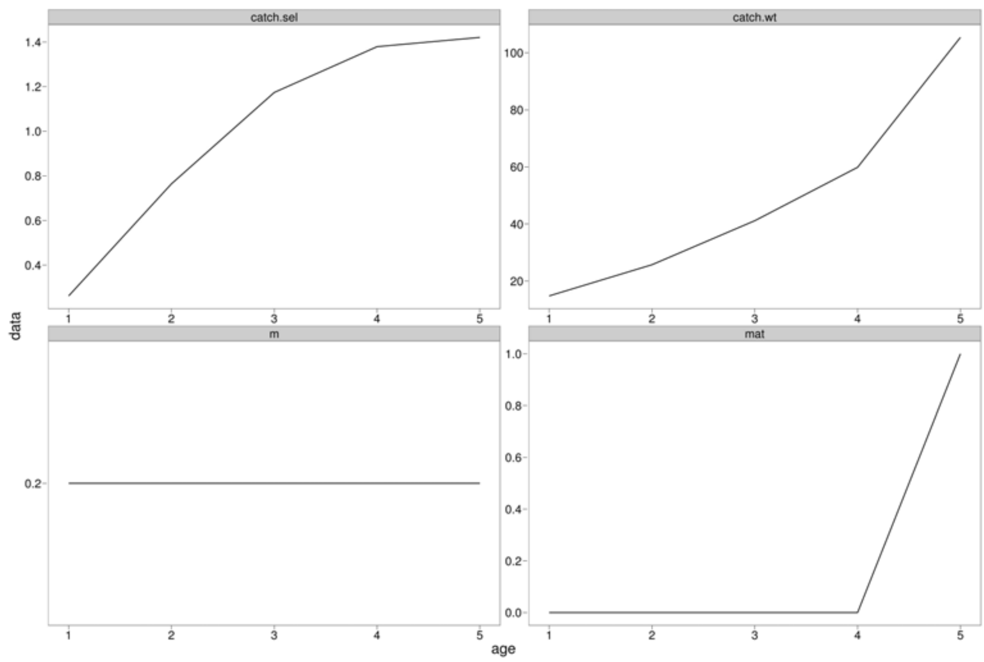

Figure 3. Plots of selectivity, mass, natural mortality and proportion mature-at-age as assumed for future dynamics.

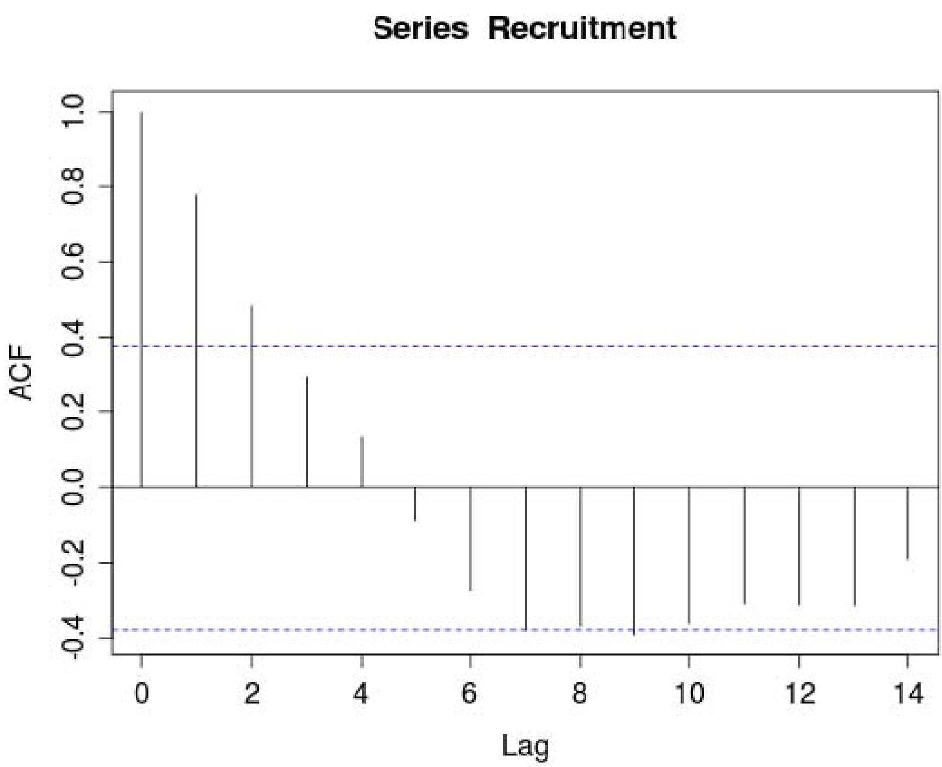

Figure 4: Plot of autocorrelations with lags 0 to 14 of recruitment residuals from Beverton and Holt t.

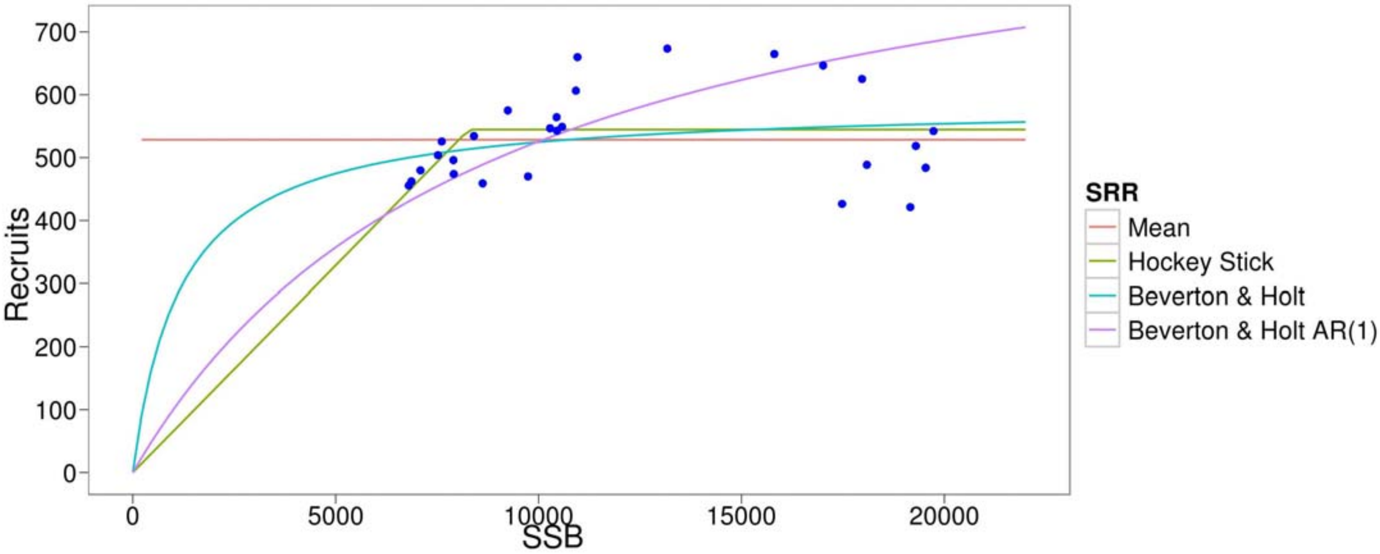

Figure 5. Stock Recruitment Relationships tted to Adapt-VPA estimates.

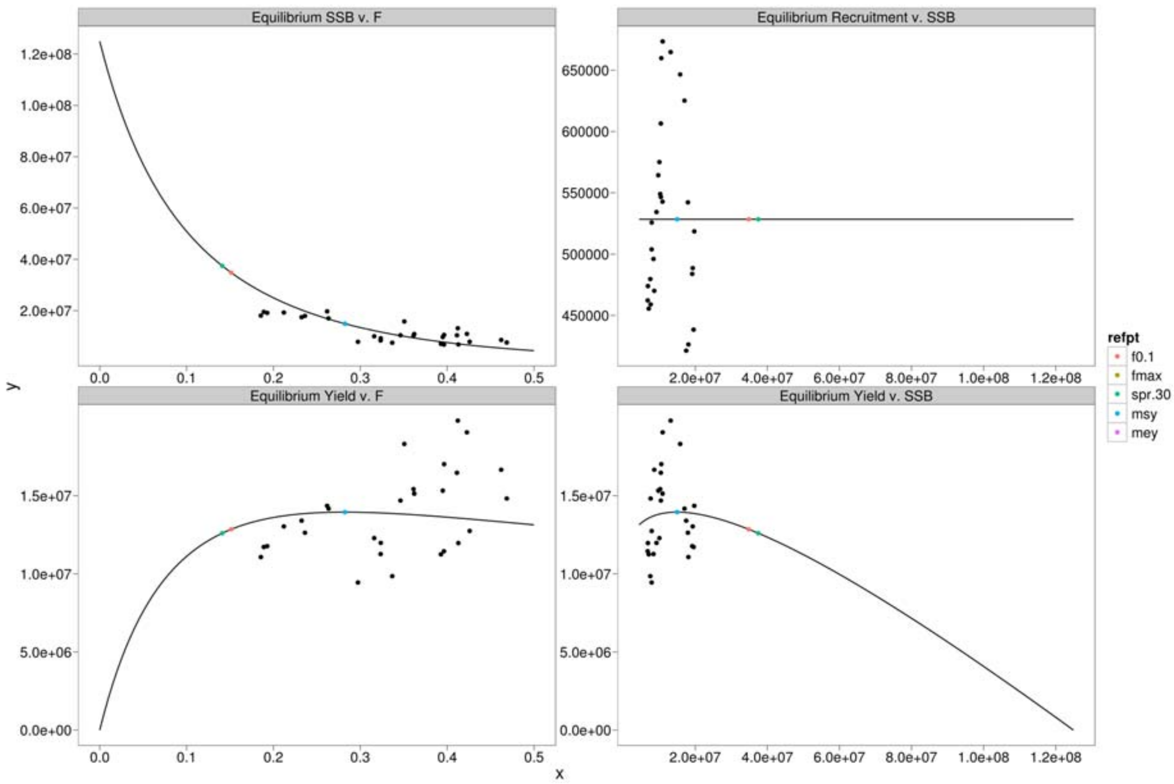

Figure 6. Plot of expected or equilibrium dynamics, with reference points and observations, assuming stationary dynamics and constant recruitment.

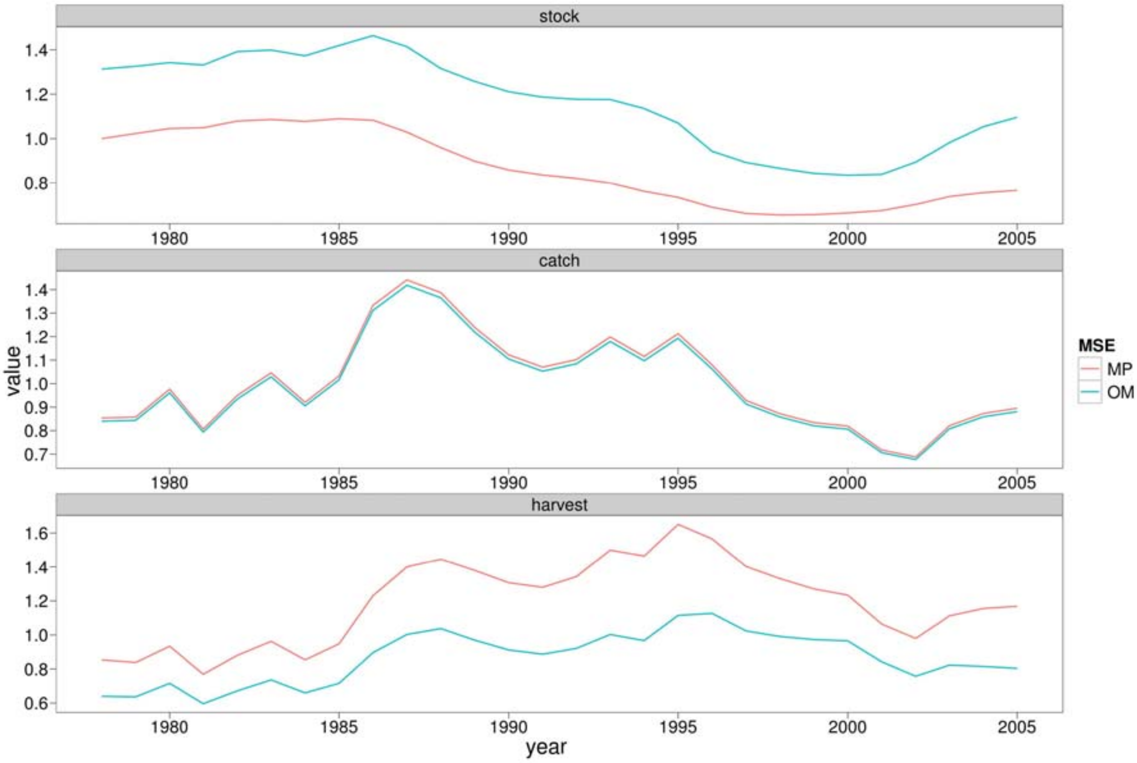

Figure 7. Time series of stock biomass, catch and harvest rate, as simulated in the operating model and estimated in the management procedure.

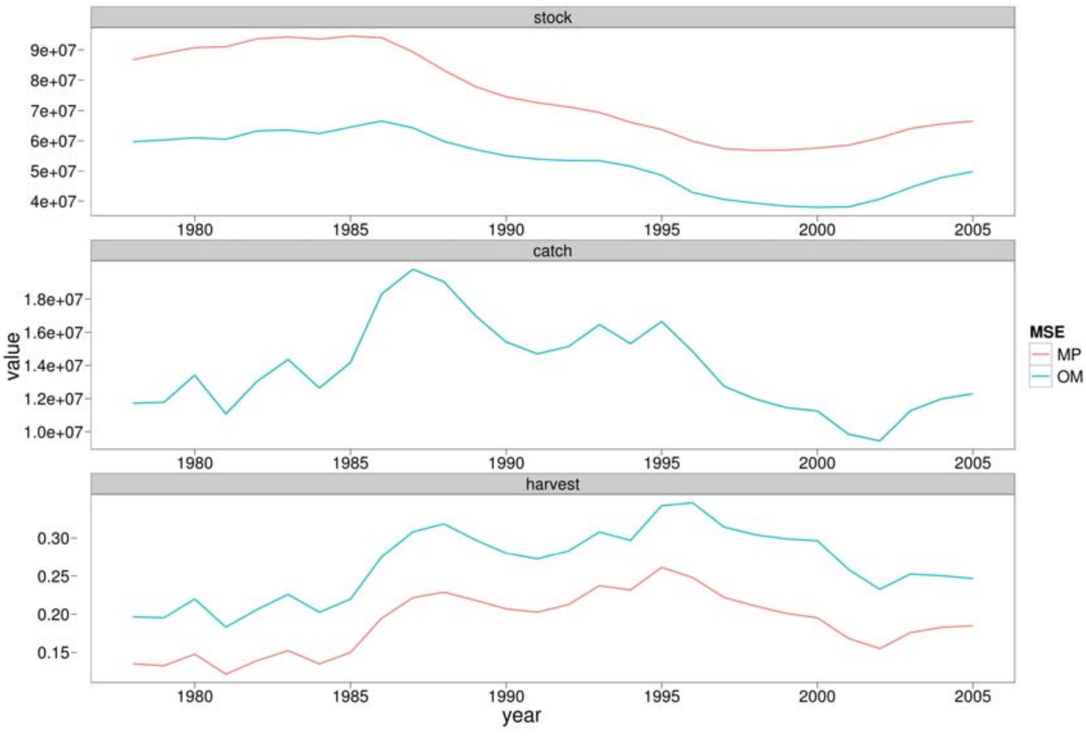

Figure 8. Time series of stock biomass, catch and harvest rate relative to MSY based benchmarks as simulated in the operating model and estimated in the management procedure.

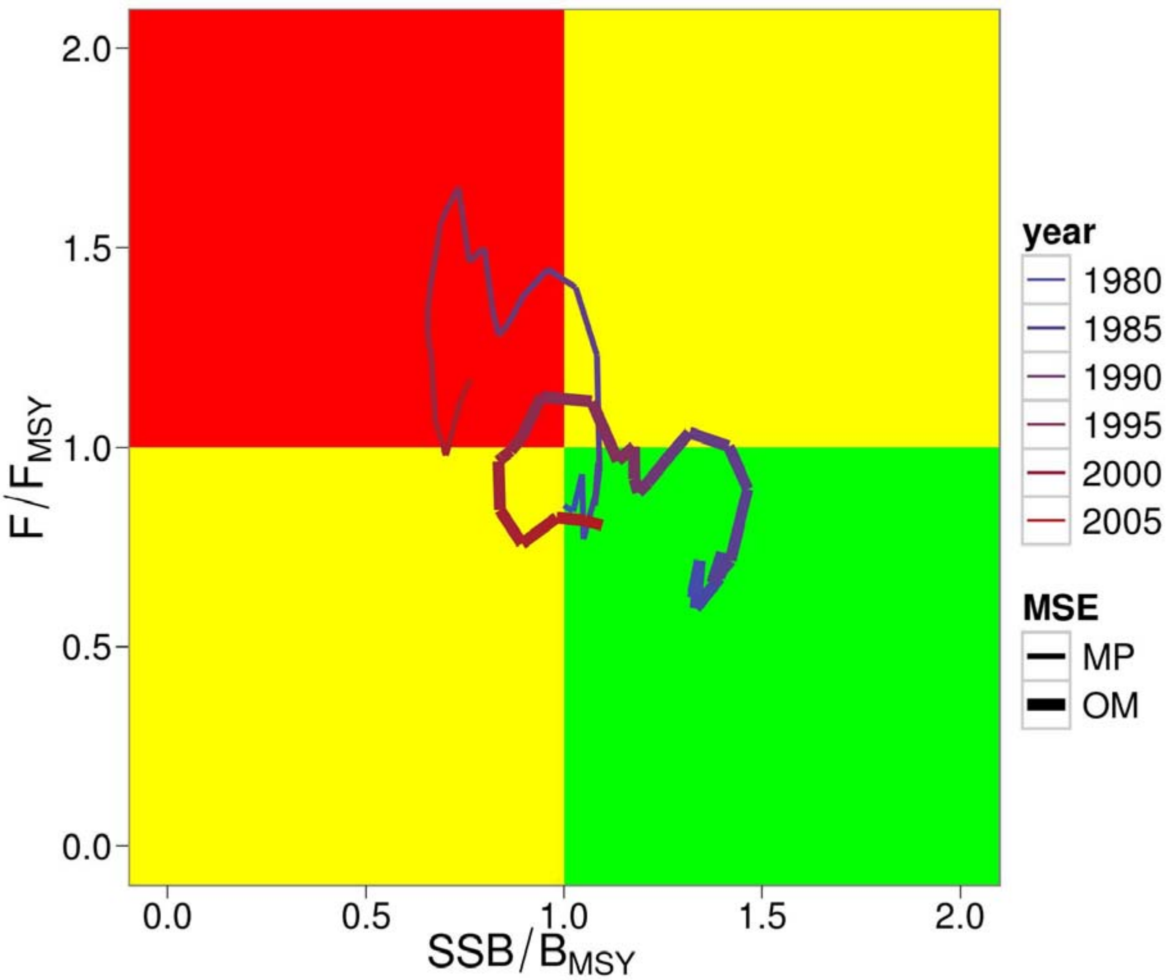

Figure 9. Kobe phase plot with OM & MP trajectories.

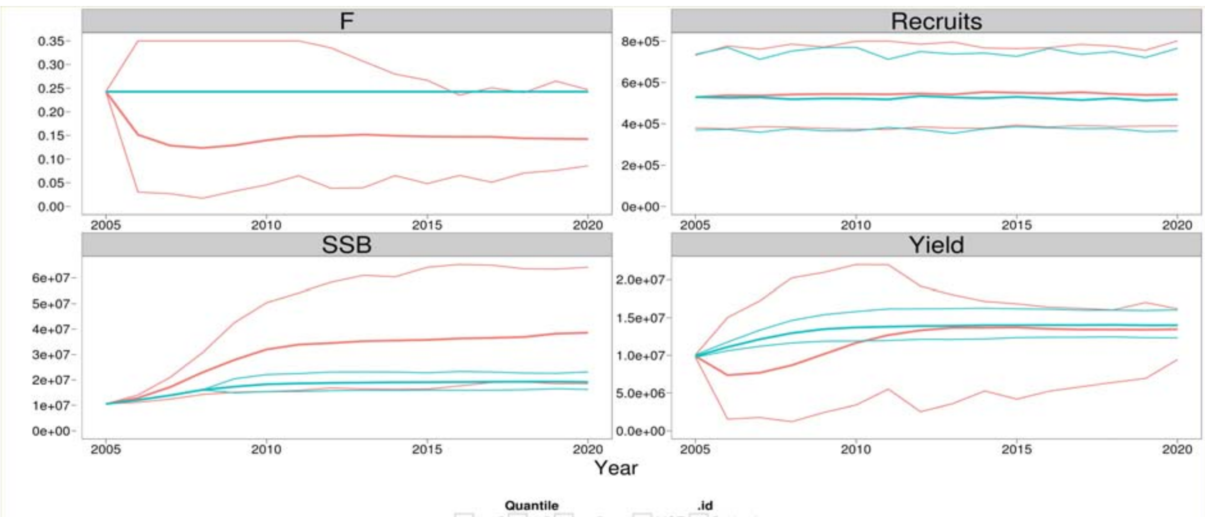

Figure 10. A comparison of time series, showing medians & interquantile ranges for MSE (pink) and projection (cyan).

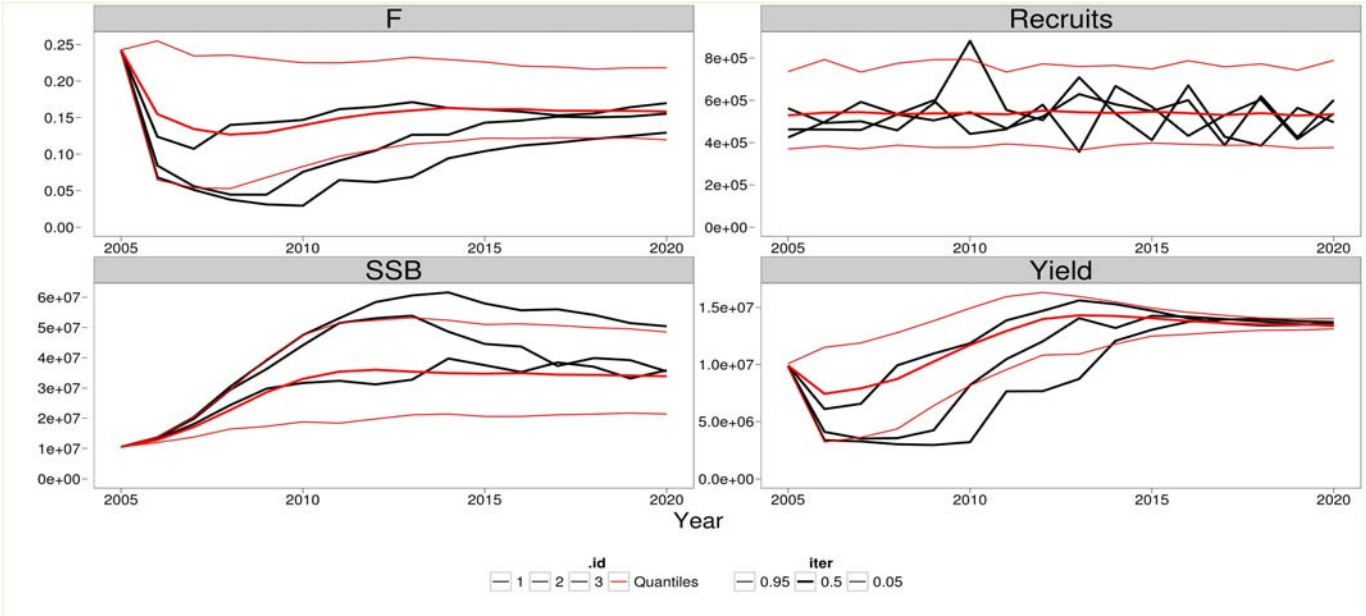

Figure 11. Worm plots; MSE with random recruitment deviates and Hockey Stick SRR, Btrigger=0.75 and CPUE CV=30%.

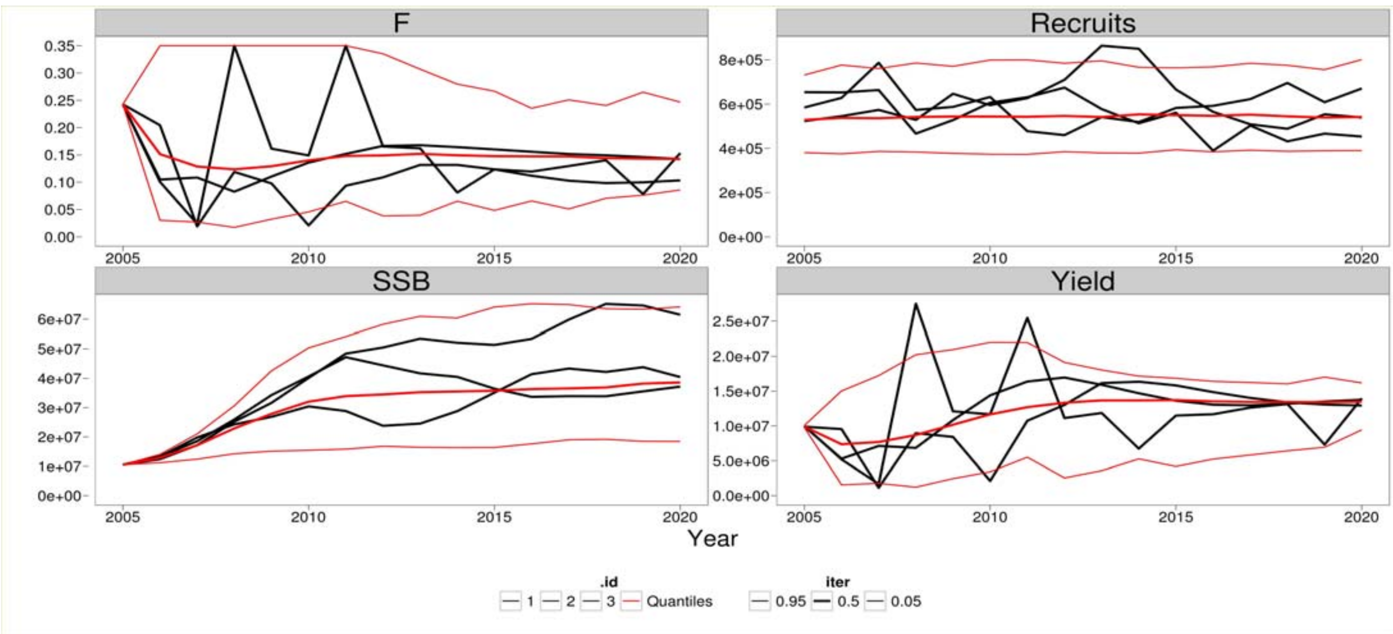

Figure 12. Worm plots; MSE with autocorrelated recruitment deviates and Hockey Stick SRR, Btrigger=0.75 and CPUE CV=30%.

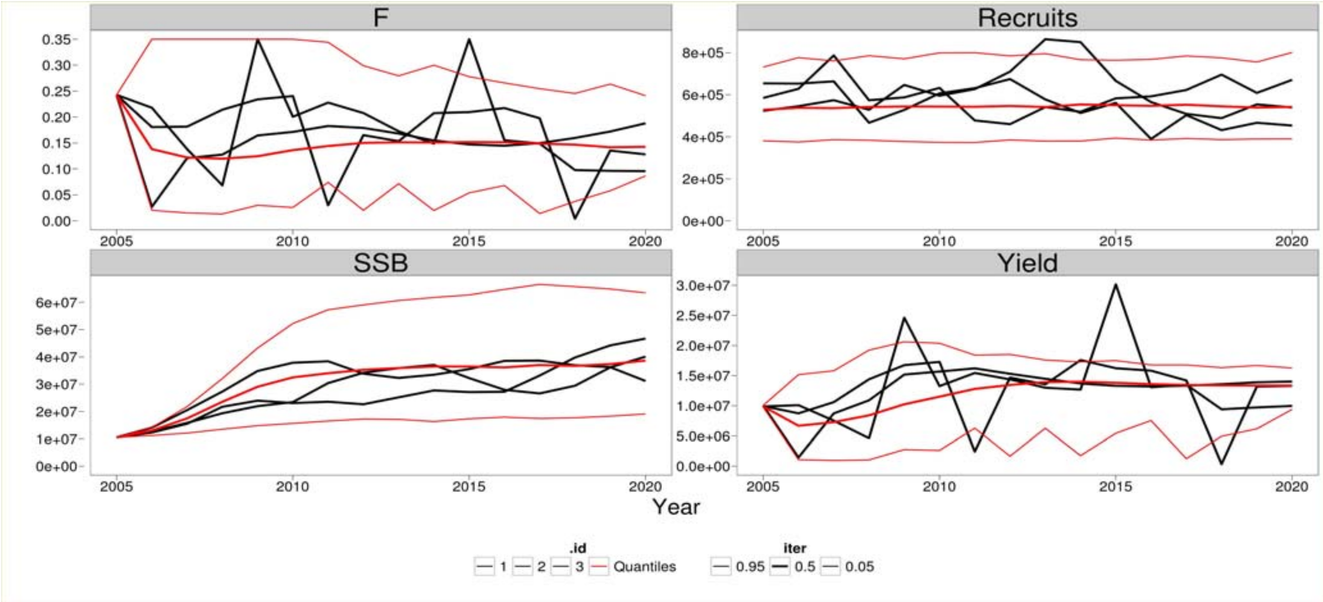

Figure 13. Worm plots; MSE with autocorrelated recruitment deviates and Hockey Stick SRR, Btrigger=0.40 and CPUE CV=30%.

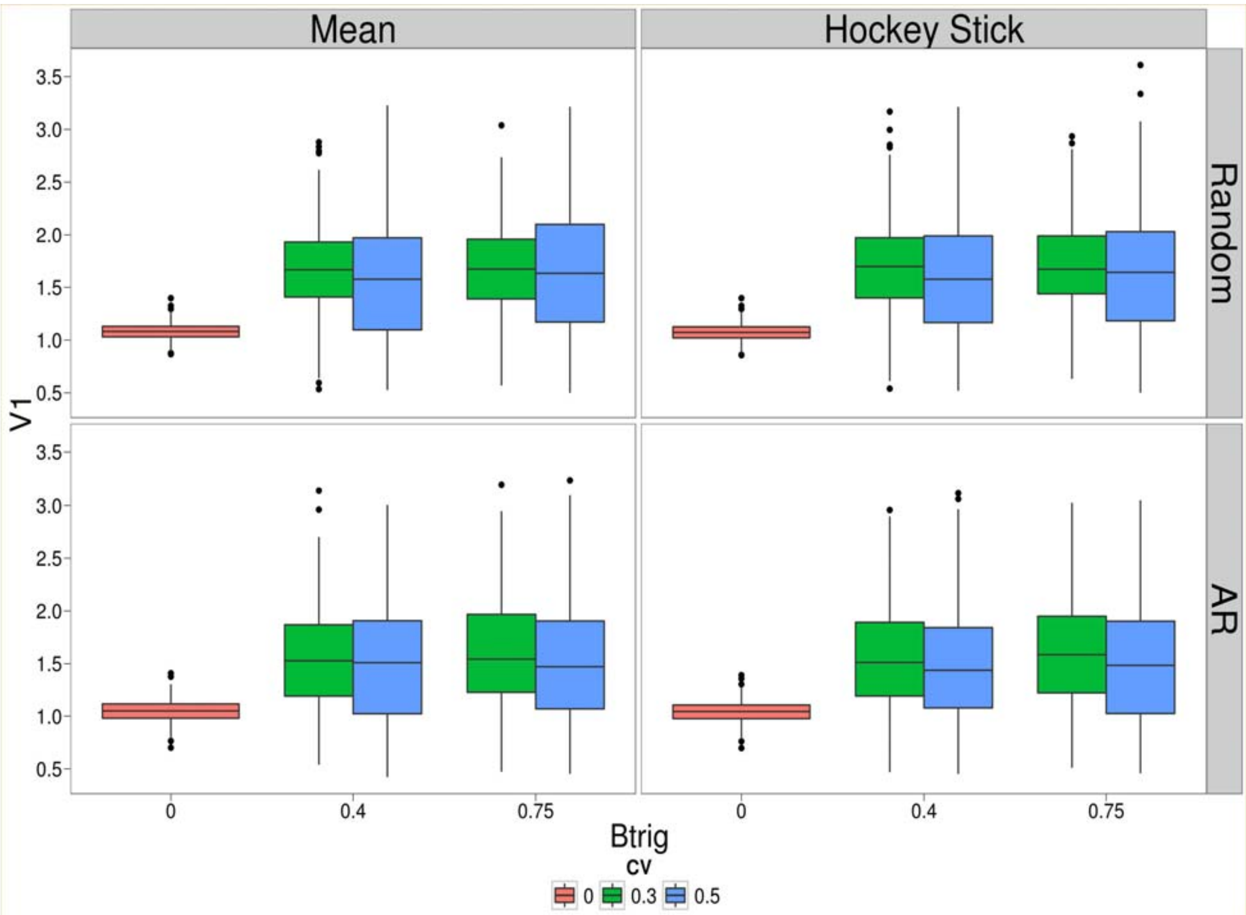

Figure 14. Minimum SSB relative to B_{MSY}.

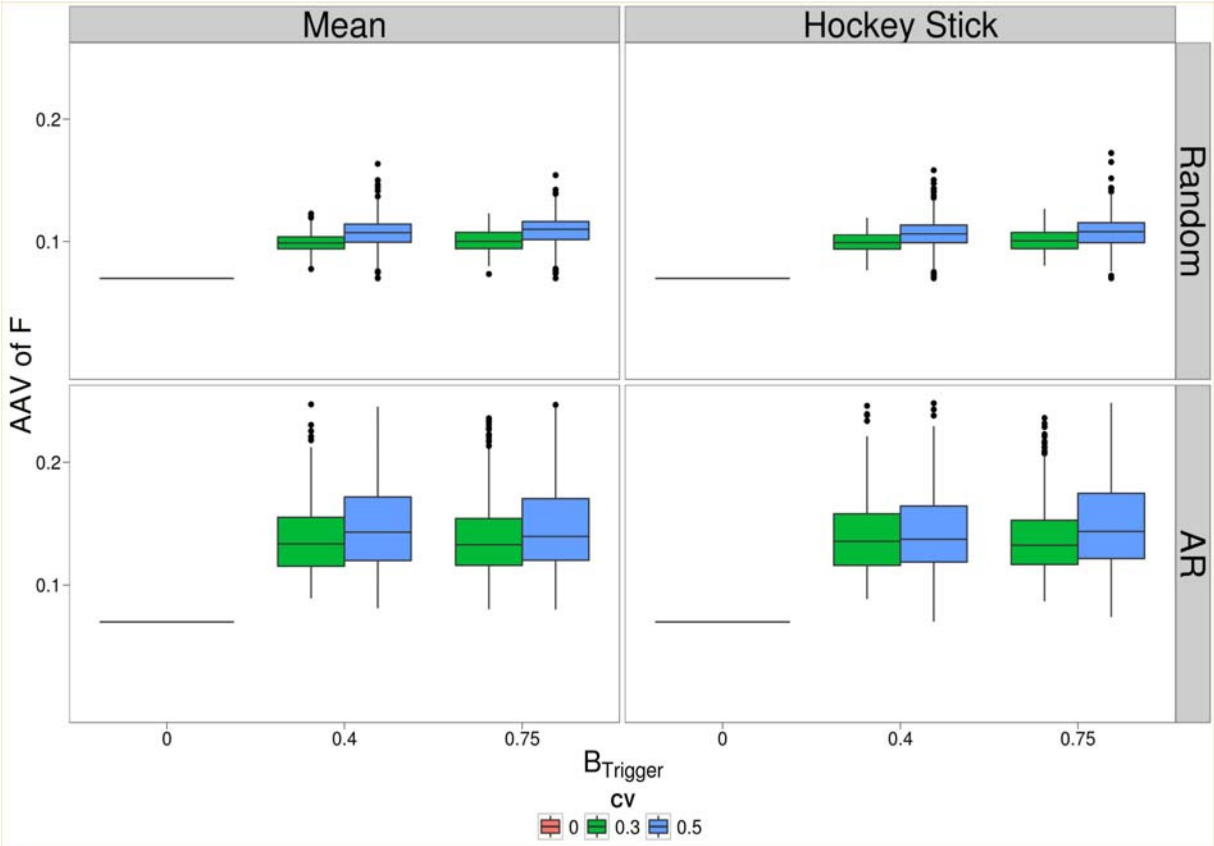

Figure 15. Plots of annual average variation in harvest rate.

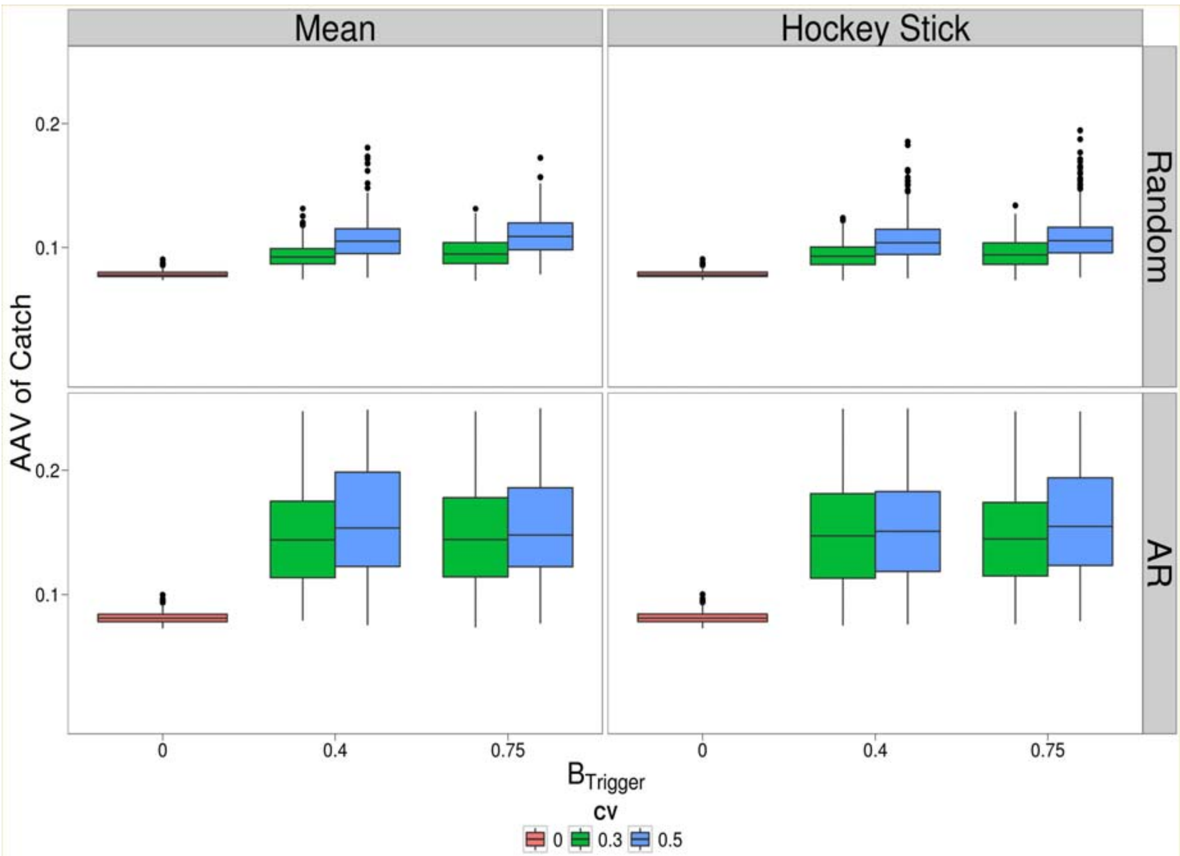

Figure 16. Plots of annual average variation in Catch.