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AN EVALUATION OF THE IMPLICATIONS OF POPULATION STRUCTURE ON THE CURRENT BLUEFIN TUNA ADVICE FRAMEWORK

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SUMMARY

The objectives of the comprehensive ICCAT Atlantic-Wide Research Programme on Bluefin Tuna (GBYP) are to improve data collection, knowledge of key biological and ecological processes, assessment models and management. An important element of which is to develop a robust advice framework consistent with the Precautionary Approach. The current advice framework, which is based upon Virtual Population Analysis, demonstrates how a Management Strategy Evaluation (MSE) framework can be used to evaluate the robustness of management advice to uncertainty about stock structure.

RÉSUMÉ

Les objectifs du Programme exhaustif de recherche de l'ICCAT sur le thon rouge englobant tout l'Atlantique (GBYP) visent à améliorer la collecte des données, la compréhension des processus biologiques et écologiques fondamentaux, les modèles d'évaluation et la gestion. Un élément important du Programme est de mettre sur pied un cadre d'avis solides conforme à l'approche de précaution. Le cadre d'avis actuel, reposant sur l'analyse virtuelle de population, est la preuve qu'un cadre d'évaluation des stratégies de gestion peut être utilisé pour évaluer la solidité de l'avis de gestion concernant l'incertitude de la structure du stock.

RESUMEN

Los objetivos del Programa de investigación sobre atún rojo para todo el Atlántico (GBYP) son mejorar la recopilación de datos, los conocimientos de procesos ecológicos y biológicos clave, los modelos de evaluación y la ordenación. Un importante elemento del programa es desarrollar un marco de asesoramiento robusto coherente con el enfoque precautorio. El actual marco de asesoramiento se basa en el análisis de población virtual, y demostramos cómo puede usarse un marco de evaluación de estrategias de ordenación para evaluar la robustez del asesoramiento de ordenación ante la incertidumbre acerca de la estructura del stock.

KEYWORDS

Bluefin, Management Strategy Evaluation, robustness, stock structure, VPA

1. Introduction

The main objectives of the ICCAT Bluefin Research Programme (GBYP) are to improve knowledge about key biological processes and develop new methods for stock assessment and advice. The knowledge gained under the GBYP will allow the development of biologically based simulation or operating models to evaluate the robustness of alternative advice frameworks. In this study we show how Management Strategy Evaluation (MSE) can be used as part of that modelling process based upon an example that considers uncertainty about population structure.

A key concept in fishery science and management is the unit stock, defined as a population aggregate that can be managed as a discrete unit (Quinn and Deriso, 1999). The definition implies that stocks of the same species are largely isolated from each other and are self-sustaining, that fisheries do not take mixed catches from different stocks, and that management regulations can be enforced by stock. However, Waples and Gaggiotti (2006), in their review entitled "What is a population?" conclude that no consensus has yet emerged regarding a quantitative definition of a stock or a population. Instead, one has to rely on qualitative descriptions, such as "a group of organisms of the same species occupying a particular space at a particular time" (Krebs, 1994). If fisheries catch fish from aggregations of mixed origins and these catches are assigned to a specific stock, the results of assessments using classical methods are confounded for all stocks involved. Furthermore, management advice in terms of total allowable catches (TACs) from a stock that is defined operationally (e.g. by the area within which a fishery operates), rather than in terms of biological understanding of population structure (Reiss *et al*., 2009), may have unforeseen ecological and evolutionary impacts. To avoid confusion, the term "population" will be used here to refer to more-or-less reproductively isolated spawning components within a metapopulation (Levins, 1969), and "stock" to the management unit as defined by catches from the fisheries.

Current advice for bluefin tuna is based upon Virtual Population Analysis (VPA), which assumes that the 2 stocks Eastern and Western considered since 1981 are homogeneous and that there is no sub stock structure within them. Here we address the consequences for stock assessment of defining stocks based on fisheries, rather than on reproductive isolation (i.e. real populations), through a generic operating model (or simulation framework) that may be applied to all exploited fish stocks. To do so, we developed a simulation framework that can be used to investigate the consequences of taking into account/ignoring the structure of a given stock into two populations. Specifically, we tested our ability to provide robust advice on spawning stock biomass (*S)* and fishing mortality (F*)* where two populations are caught within a single fishery.

2. Material and methods

The "Fisheries Library in R" (FLR) framework (Kell *et al*., 2007; www.flr-project.org) for management strategy evaluation was used to build an Operating Model (OM) to represent alternative hypotheses about stock and fishery dynamics, allowing a higher level of complexity and assumptions than used by standard stock-assessment models. An Observation-Error Model is used to sample pseudo-data from the OM, and then a Management Procedure (MP); 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,) is used to derive estimates of stock status from the pseudo-data and to provide management advice.

According to the hypothesis that the current East Atlantic and Mediterranean bluefin tuna stock could actually include at least two populations (Carlsson et al. 2004, Fromentin 2009), we constructed a simple operating model for a stock that includes two allopatric populations (i.e. displaying distinct spatial distributions) with no mixing. Exploitation occurs on both populations but the intensity may change through time on each population. These fisheries define the fish as belonging to a single stock. Biological parameters were taken from the literature and the most recent ICCAT assessment of bluefin tuna; average-at-age vectors for weight, proportion mature, natural mortality and selectivity derived from the Adapt-VPA stock assessment output are presented in **Figure 1**. These values can easily be changed to consider values based on the work of GBYP.

Life-history traits for both sub-populations are identical and are:

- annual spawning (1 cohort per year),
- 50% maturity at age 4, 100% maturity at ages 5+,
- fecundity is linearly proportional to weight,
- growth following the von-Bertalanffy equation used in the ICCAT working group (with the following parameters: $L\infty$ = 318.85, k=0.093, t_O=-0.97),
- length-weight relationship used in the ICCAT working group ($W=2.95.10^{-5}*L^{2.899}$),
- lifespan of 40 years.
- age-specific, but time-invariant, natural mortality based on tagging experiments on the southern bluefin tuna and used in the ICCAT working group (i.e., M=0.49 for age 1, M=0.24 for ages 2 to 5, M=0.2 for age 6, M=0.175 for age 7, M=0.15 for age 8, M=0.125 for age 9 and M=0.1 for ages 10 to 20).

Given the selection pattern (*s*) of a fishery, and the catchability (*q*) of a population for a given effort (*E*), the fishing mortality rate ($F_{a,y,j}$) for age *a*, year *y*, and population *j* is given by:

$$F_{a,y,j} = E_y*q_j*s_{a,j} \qquad (1)$$

Through time, E is assumed to be constant over the first 10 years to lead to F = 0.5 F_{MSY}, then to increase over the following 25 years to lead to F = 1.5 F_{MSY} and finally to decrease to lead to F=0.5F_{MSY} over the last 24 years. The effort can vary between the two sub-populations.

Catchability, *q*, is assumed to be constant among sub-population, age and time.

The selectivity pattern (s_a) is assumed to vary by age and corresponds to the long-term average seen in the Bluefin tuna fisheries (Fromentin and Bonhommeau 2011).

The abundance (N_j) at age $a+1$, at the start of year $y+1$, in sub-population j, is:

$$N_{a+1,y+1,j} = N_{a,y,j} * exp(-F_{a,y,j} - M_{a,y,j}) \quad (2)$$

The virgin biomass of a population can be of any relative size and differences in productivity can be modelled through the stock recruitment relationship. Two stock recruitment relationships were considered (i) recruitment is assumed to be independent of spawning stock biomass (S), i.e.is environmentally driven so that $R = R_{MAX}$ or (ii) the recruitment is assumed to be dependent on S and follows a Beverton and Holt (1957) stock–recruitment relationship with fixed parameters.

The expected or equilibrium dynamics, conditioned on average-at-age vectors and the stock recruitment relationships are shown in **Figure 2**. F_{MSY} is shown for the Beverton and Holt based curve and $F_{0.1}$ for the one based on constant recruitment.

2.1 Stock assessment procedure

The Stock-Assessment Procedure (SAP) combines a particular sampling regime and stock-assessment technique. The sampling regime is simulated by the Observation-Error Model (OEM), which generates catch-at-age array and indices of abundance from the fisheries on the two populations. The indices of abundance were derived from the adults during the spawning season and thus represent an estimate of the spawning populations.

Using the indices of abundance for calibration, a statistical virtual population analysis (ADAPT-VPA; Porch 1997) is performed to estimate F and N-at-age in the stock, conditional on the assumed values of M and reported catch-at-age. In estimating the terminal Fs, the relationship between number-at-age and the index of abundance is assumed to include measurement and process error, whereas the catch-at-age is assumed to be exact. This means that the estimation errors are largest for the older age groups and smallest for the recruiting age class.

2.2 Scenarios

Two sets of scenarios representing population status and stock-assessment assumptions were considered.

Four scenarios were considered for the 2 populations that correspond to two different developments of effort (and fishing mortality) and two stock recruitment relationship, i.e.:

Population 1cr: Fishing mortality increasing linearly with constant recruitment (i.e. environmentally driven recruitment);

Population 1 bh: Fishing mortality increasing linearly and Beverton and Holt stock recruitment relationship (i.e., depensatory stock recruitment dynamics);

Population 2 cr: Fishing mortality constant at F_{MSY} with constant recruitment; and

Population 2 bh: Fishing mortality constant at F_{MSY} and Beverton and Holt stock recruitment dynamics.

Figure 3 shows the times series F, catch, recruits, SSB, number in plus group and mean size for the four scenarios.

Pairs of these populations were then combined to represent a meta-population where one population was exploited with an increasing fishing mortality and the other with a constant fishing mortality; i.e., options I & III for constant recruitment and II & IV for the Beverton and Holt stock-recruitment relationship.

Four stock assessment scenarios (based on population and age range) were then considered related to the source of the indices of abundance used to calibrate the VPA i.e.:

A: Indices of abundance available for both juveniles and adults based on both populations
B: Index of abundance available for only adults based on both populations
C: Index of abundance available for only adults based on population 1
D: Index of abundance available for only adults based on population 2.

Catch-at-age in all cases was summed across the catches from two populations.

In total, this gives eight scenarios, two for the population assumptions by four for the assessment scenarios. The only uncertainty considered was structural uncertainty, i.e. the assessment assumed one population while the data actually came from two populations. The reason for excluding uncertainty such as stochastic variation due to process and measurement error was because this made it easier to see the consequences of violation of the VPA assumptions.

3. Results

Figure 4 shows the Catch, F and SSB for the meta-population scenario where recruitment dynamics are modeled by a Beverton and Holt stock recruitment relationship and one population is exploited at F_{MSY} and in the other F is constant. Red corresponds to the sum of the catches and SSB across the two populations. There is no corresponding value for F as this does not make sense for the meta-population. As expected for a constant F the population is in equilibrium, while for an increasing F catch initially increases until F_{MSY} & B_{MSY} are exceeded after which catch declines. The two columns are identical as no results from the stock assessment are presented.

Figure 5 presents the same quantities as in **Figure 4** but this time also included the estimates from VPA. Estimates were derived from VPA including year 30, 40, 50, 60 or 70. Therefore for the assessment or management procedure (MP, black line) there are retrospective patterns; i.e. where the end of the time series do not coincide with estimates made subsequently.

It can be seen that the actual catch and that used in the VPA are the same (top row). This time F for the meta-population (i.e., 2 stocks combined) is plotted. It can be seen that the estimate of F is biased and there is a strong retrospective pattern; the magnitude of the bias and whether the retrospective pattern is due to an over or underestimation of F depends upon the index used in the VPA (column). F is essentially the log ratio of catches less M along a cohort. If catches come from two stocks with one stock at MSY then F will be biased towards F_{MSY} since by definition more catch will come from the stock being exploited at MSY. The index chosen also has an effect since VPA requires an estimate of current stock size or F; if this is derived from the overexploited stock then F will be higher than if derived from the stock at F_{MSY}. This explains the differences in the retrospective patterns among the two populations.

The estimates of SSB are similar to those seen in F but the retrospective patterns are in the opposite directions. Estimates of SSB are greatly overestimated and estimates of F underestimated if the survey comes from the population exploited at MSY.

Figure 6 presents the same scenarios along with two additional scenarios where either a combined index is available for both juveniles and adults or only a combined adult index is available. Those results further stress the importance to get indices of abundance for both populations; if not, the biases and the retrospective patterns from the VPA increase substantially. **Figure 7** presents the results for constant recruitment and similar patterns are seen.

In the case of the dynamics assuming a Beverton and Holt stock recruitment relationship an important phenomenon can be seen. In this case a population may go extinct while F appears to decline. However there is no subsequent stock recovery.

The index of mean size also shows a bias in that as a population becomes extinct mean size increases.

4. Discussion and conclusions

The relatively simple simulations conducted here showed that if there are two sub-populations within a stock defined for stock assessment that overexploitation/extinction of a sub population may be undetected when assessed by VPA. The exact bias also depends on the indices of abundance used. A simple metric such as mean size was less affected but again still tends to underestimate overfishing.

A particular important phenomenon is when a sub-population becomes extinction F appears to decrease although there is no subsequent stock recovery.

This work shows the potential bias when using VPA to assess meta-populations and the importance of considering stock sub-structure. Therefore it is proposed to build simulation model to allow alternative hypotheses about stock dynamics to be modeled and then to evaluate alternative data collection regimes, stock assessment methods and management measures to be evaluated.

Such measures may be based on stock assessment models or empirical indices of directly measurable quantities, e.g., catch rate, size composition, tag recovery rate or survey estimates of abundance.

5. Acknowledgements

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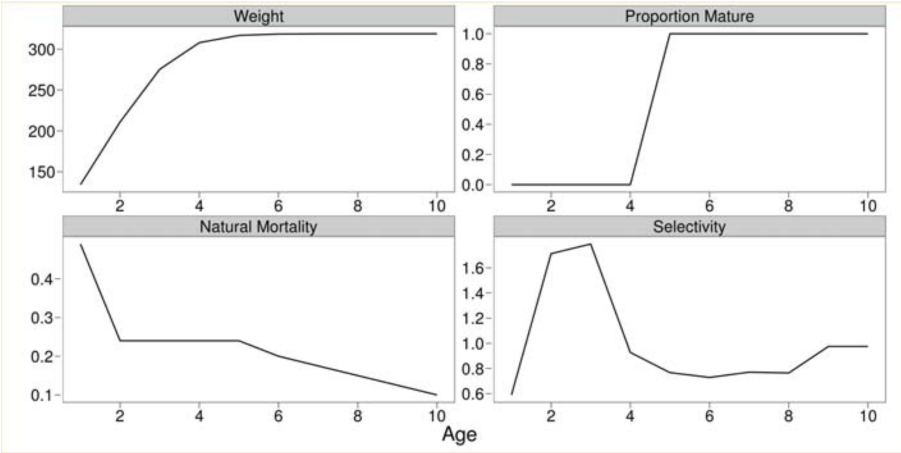

Figure 1. Weight, proportion mature, natural mortality and selectivity-at-age vectors, derived from Adapt-VPA stock assessment estimates for the period 1950 to 1990.

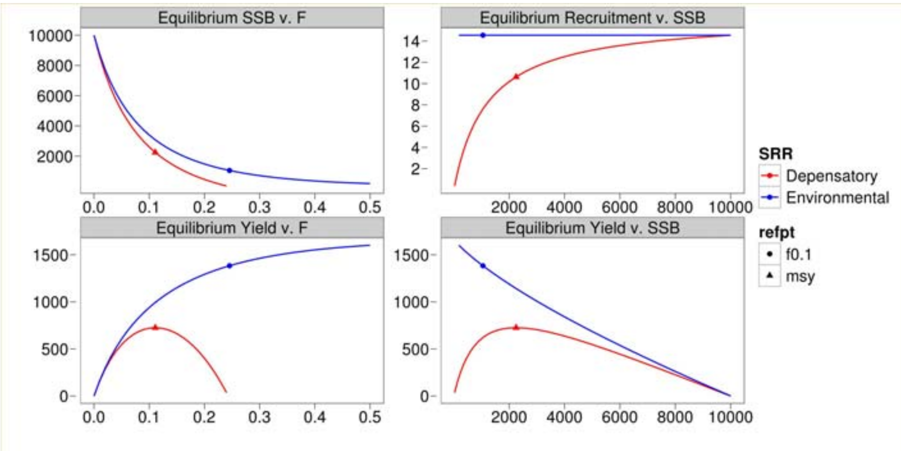

Figure 2. Expected or equilibrium dynamics contrasted for a Beverton and Holt stock recruitment relationship and constant recruitment; reference points F0.1 and FMSY are indicated.

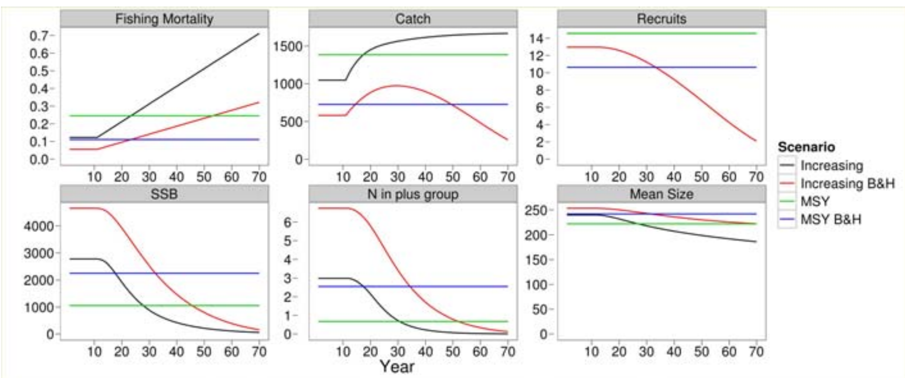

Figure 3. Simulated times series, of F, catch, recruits, SSB, number in plus group and mean size for the four scenarios for the Operating Model.

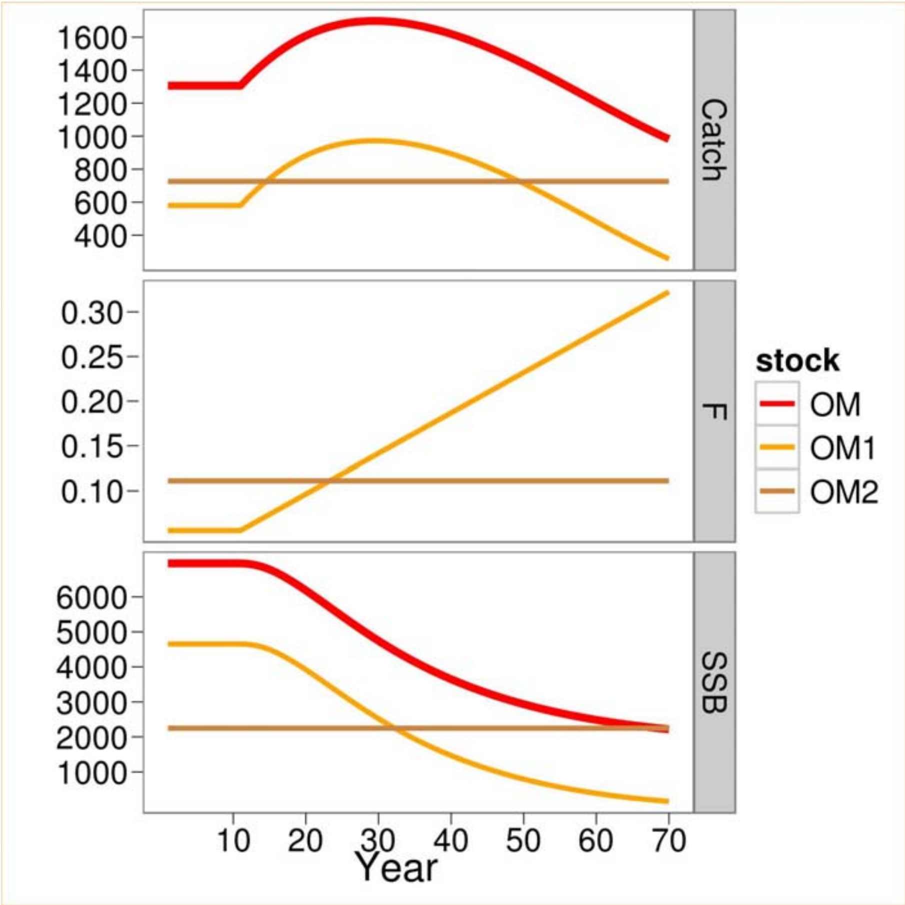

Figure 4. Assessed times series (black) for catch, F and SSB compared with simulated values, assuming constant recruitment; lines corresponding to simulated populations are for increasing F (orange) or constant F (brown) and conbined (red).

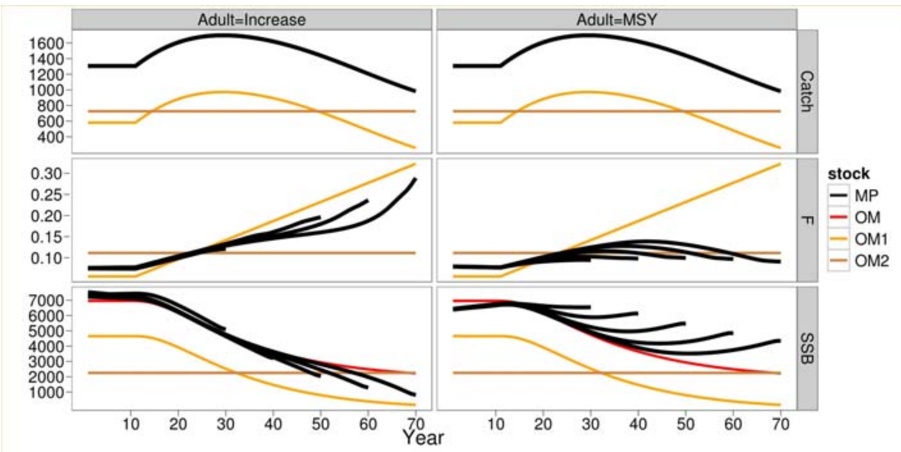

Figure 5. Times series, of catch, F and SSB, from the simulated populations with constant recruitment, as in figure 3 but including estimated values from VPA, in the 1st column the CPUE index is from the population with increasing F and in the 2nd constant F.

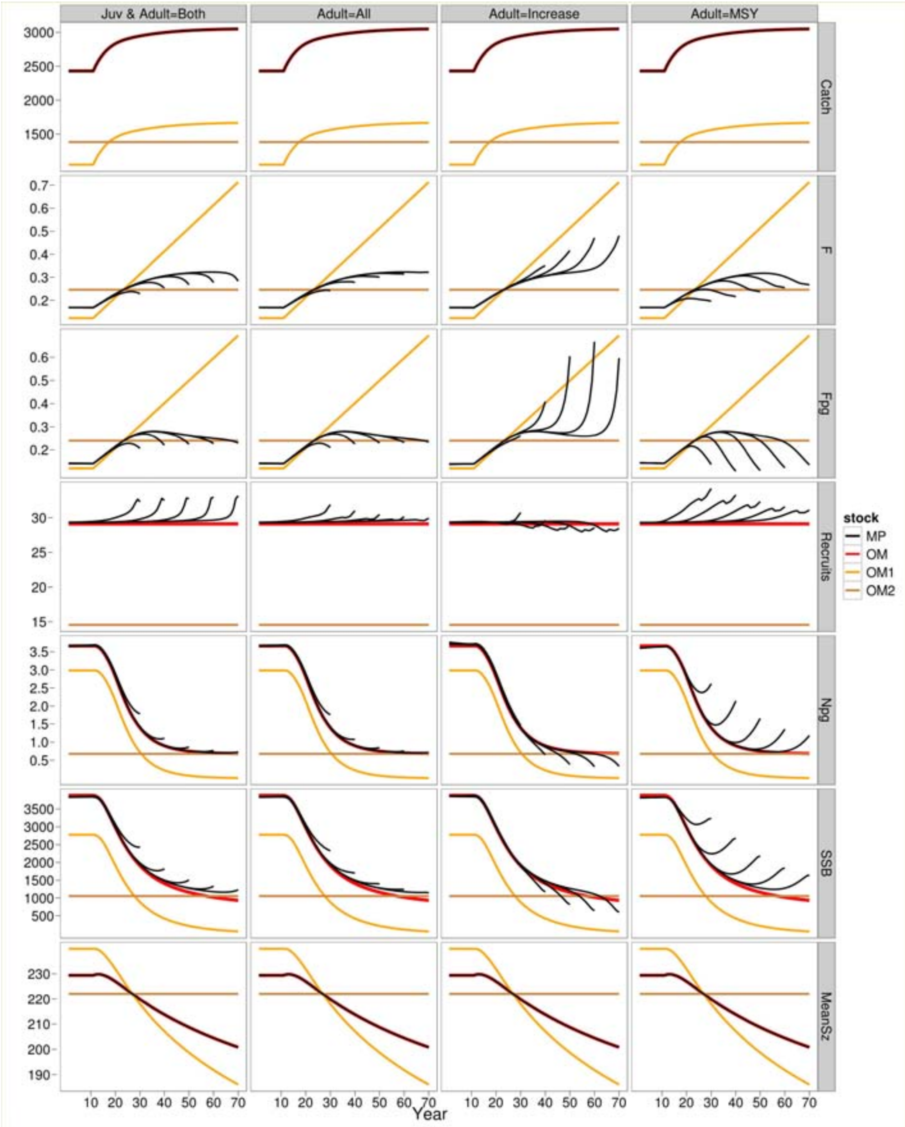

Figure 6. Times series, of catch, F, plus group F, recruits, number in the plusgroup, SSB and mean size, from the simulated populations with constant recruitment. Columns contrast the index of abundance used to calibrate the VPA.

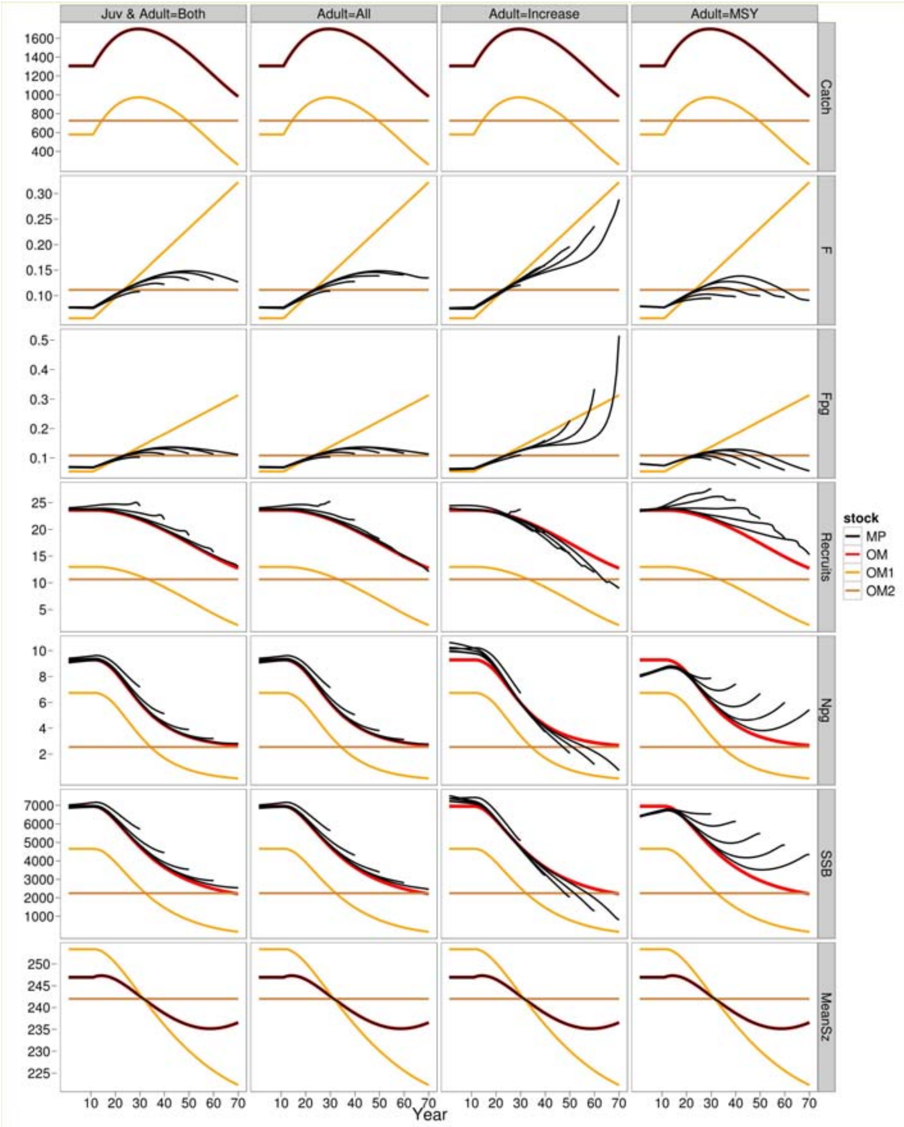

Figure 7. Times series, of catch, F, plus group F, recruits, number in the plusgroup, SSB and mean size, from the simulated populations with a Beverton and Holt stock recruitment relationship. Columns contrast the index of abundance used to calibrate the VPA.