Abstract:

Résumé :

Empirical Management Procedure for Mediterranean Bluefin Tuna

Laurence T. Kell and Jean-Marc Fromentin

Introduction

When managing fisheries decisions have to be made with incomplete knowledge, therefore a number of international instruments have requested the adoption and implementation of the Precautionary Approach (PA, **?**). The PA requires that undesirable outcomes be anticipated and measures taken to reduce the probability of them occurring. This requires determining how well management measures achieve their objectives given uncertainty, intrinsic variability and the occurrence of environmental events inherent to the system (**?**).

However, uncertainty sometimes causes management action to be delayed (**?**). Reframing uncertainty as risk requires a proactive approach, since most risk standards define risk as *an uncertainty that, if it occurs, will have an effect on objectives* (**?**). This requires managing the causes of uncertainty rather than the consequences.

The adoption of the PA means that stocks are assessed regularly with respect to limit reference points (LRPs) which indicate the state of a fishery or a stock considered undesirable and when fishing effort should be reduced so that are not reached. Ideally LPRs are used as part of a harvest control rule (HCR) in combination with target reference points (TRPs) to specify in advance what actions to take.

However, traditional stock assessment and advice based upon it, mainly considers measurement and process error when uncertainty about the actual dynamics has a larger impact on achieving management objectives (**?**). For this reason, Management Strategy Evaluation (MSE) and simulation modelling is increasingly been used to evaluate the robustness of advice frameworks to the main sources of uncertainty. In engineering a robust control (or management) system is one that still functions correctly in the presence of uncertainty or stressful environmental conditions (**?**). When running an MSE control actions from the HCR are fed back into an Operating Model (OM) that represents the system being managed so that its influence on the simulated stock and hence on future fisheries data is propagated through the stock and fishery dynamics. In engineering this is known as closed loop feedback control (**?**). Feedback relaxes the requirement of having to have an exact model of the system being managed since the effect of the control actions on the system are monitored and adjusted accordingly.

There are various definitions of stock assessment, we define stock assessment based on the definition of Holt (pers comm.) as *The description of the characteristics of a 'stock' so that its biological reaction to being exploited can be rationally predicted and the predictions tested*. Under this definition MSE is an important tool to test predictive and management capability. The 'characteristics' of a stock

Received . Revision received . Accepted . Revision accepted .

Laurence T. Kell. ICCAT Secretariat, C/Corazón de María, 8. 28002 Madrid, Spain; Laurie.Kell@iccat.int; Phone: +34 914 165 600 Fax: +34 914 152 612.
Jean-Marc Fromentin. IFREMER - UMR EME 212, Av. Jean Monnet, 34200 Sète, France.

are represented by the OM, which is then used to evaluate what combinations of data, knowledge and algorithms to estimate stock status and set control measures, i.e. a Management Procedure (MP) will best meet management objectives. Algorithms to estimate stock status in the MPs are generally simpler than traditional stock assessments and (**?**) showed that simple MPs can perform as least as well as conventional stock assessments. The specification of the OM then becomes a key task, there are various ways to do this (**?**) but all require consideration of a range of hypotheses about resource dynamics.

MSE can help to provide stability and reduce risk if management objectives and how to evaluate how well alternative management strategies meet them are agreed through a dialogue between scientists and stakeholders. It can also guide the institutional process by identifying where the reduction of uncertainty will reduce risk and thereby help to ensure that expenditure is prioritised to provide the best research, monitoring and enforcement (**?**).

We therefore use MSE to determine under what conditions simple stock assessment methods, based on biomass, can be used to manage stocks. Biomass dynamic models have been criticised (e.g. **?**) as being too simplistic to capture the actual population dynamics. However, if a simple model can provide advice on stock status relative to reference points and predict the response of a stock to management why use anything more complicated (**?**)? For example the Pella-Tomlinson model is used to set catch limits for baleen whales by the IWC. Neither the form of the model nor its parameters are meant to provide an accurate representation of the dynamics of the population. Rather, it has been demonstrated by MSE that when used as an integral part of a management strategy with a HCRs it allows the robust calculation and setting of catches limits (**?**).

Material and Methods

Case Study

Stock assessment methods are often classified on their information and data requirements (e.g. **??**). The highest information/data-rich tier uses catch-at-age and research surveys and the lowest tier is when only life history and limited fishery data are available. Advice for the majority of stocks assessed by the International Commission for the Conservation of Atlantic Tunas (ICCAT), the Regional Fisheries Management Organisation (RFMO) responsible for the management of tuna and tuna like species in the Atlantic and adjacent seas, is based on fisheries dependent data and catch biomass using biomass dynamic stock assessment models (e.g. **??**).

Although age based models are used by ICCAT assessment working groups, a lack of confidence in the quality of size and age data (**?**) means that in most cases these models are not used to provide advice. However age based models could be used to develop hypotheses about stock dynamics.

Eight out of the ten commercial stocks that the SCRS provides ICCAT management advice on are assessed using biomass dynamic models. Even if MPs are not developed for these stocks MSE can be used to ensure that this advice is robust and that risks are managed.

A stock may be defined on an ecological, evolutionary, or operational basis (**?**). In this study we assume the later and that there is no immigration or emigration and that a stock is homogeneous.

Management Strategy Evaluation

Conducting an MSE involves a number of steps, (i.e. after **?**)

1. Identification of management objectives and mapping these to performance measures in order to quantify how well they have been achieved;

2. Selection of hypotheses for the OMs;

3. Conditioning of the OMs using data and knowledge and possible rejection and weighting of hypotheses;

4. Identifying candidate management strategies and coding these as MPs, i.e.the combination of pre-defined data, together with an algorithm to which such data are input to set control measures;

5. Projecting the OMs forward using the MPs as a feedback controller, i.e.where information about the gap between the actual and reference levels is used to alter the gap in some way (**?**); and

6. Agreeing the MP that best meets management objectives.

Management Objectives

The original management objective of ICCAT is to provide the maximum continuing catch (**?**), interpreted as using maximum sustainable yield (MSY) as a target. However, the United Nations Conference On Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA **?**) now defines F_{MSY} (fishing mortality associated with MSY) as an upper limit. ICCAT has recently asked the Standing Committee on Research and Statistics (SCRS) to define biomass limit reference points for some stocks and work has started on evaluating HCRs (**?**).

To help provide consistency of advice across the Tuna RFMOs a common management advice framework (i.e. the Kobe Framework **?**) has been developed with a main objective of keeping stocks above B_{MSY} and fishing below F_{MSY}. This requires management strategies to be reported with respect to the probabilities of maintaining the stock above B_{MSY} and fishing mortality below F_{MSY}. Advice on stock status is normally given in the form of a phase plot (Figure with a green quadrant corresponding to the target region (i.e. where the stock is neither overfished ($B \geq B_{MSY}$) nor subject to overfishing ($F \leq F_{MSY}$). Management advice is determined upon which quadrant a stock falls into. If the stock is in the green quadrant the objective is to maintain the stock in this state with high probability. While if the stock is in the red quadrant then management measures should be adopted immediately taking into account the biology of the stock and scientific advice to result in a high probability of ending overfishing in as short a period as possible (REC-11-13).

Although often not explicitly specified social and economic objectives need to be considered (**?**). These may include minimising variability in catch and/or effort since wide annual fluctuations in catch and effort limit the ability of the fishing industry to plan for the future (**??**). There will also be trade-offs between objectives, e.g. reducing variability in catches may require effort to be low. While some objectives may take precedence over others since without sustainability there will be no catch.

Quantifying how well management objectives are achieved is done using performance statistics, which are used to report on probabilities, risk levels, time scales and the power of the scientific advice framework to estimate stock status and to predict management performance. We consider five objectives (Table 1) and performance measures (Table 2) i.e. i) probability of being in the green quadrant; ii) average catch:MSY; iii) average Effort:(Effort at F_{MSY}); iv) average inter-annual variation (AAV) in catches expressed relative to MSY; and v) average inter-annual variation in Effort relative to Effort at F_{MSY}.

0.1. Observation Error Model

An Observation Error Model (OEM) was constructed to generate two unbiased abundance indices corresponding to the adult biomass and numbers of recruits. A log normal random error of 30% was added to these time series.

All modelling was conducted in R **?**

Scenarios

When providing traditional stock assessment advice important sources of uncertainty are often underestimated by experts (**?**), i.e. model error which includes structural uncertainty due to inadequate models, incomplete or competing conceptual frameworks, or where significant processes or relationships are wrongly specified or not considered. Even if the form of a process is known, the parameters may not be (i.e. value uncertainty) due to missing or inaccurate data or poorly known parameters. In ICCAT stock assessments there is uncertainty about biological parameters such as growth, maturity and natural mortality while the lack of age data means that stock recruitment relationships can not be fitted reliably (**?**). Therefore to evaluate the risk due to uncertainty about stock dynamics we conditioned the OM on hypotheses from a literature review of North Atlantic albacore (*Thunnus alalunga*) (**??**) and life history theory (**?**).

Life history parameters have been described for many taxonomic groups and biological parameters are often strongly correlated (e.g. **??**). This allows us to draw general conclusions about the impact of uncertainty about processes on the performance of the MP and associated risks.

For conditioning the OMs a factorial design was used with factors with 2 levels (Table 3); where the factors represent alternative hypotheses about biological processes, i.e. growth, maturity, natural mortality and recruitment and targeting of age classes (i.e. relative fishing mortality-at-age). The different factors and levels could have been weighted based on how well they are supported by the available data or following discussion with stakeholders (**?**). However as in this study we are mainly concerned with identifying the factors that affect the performance of the MP the results and analyses are presented without weighting.

For growth and maturity two hypotheses are considered based on (**??**) and life history theory (**?**). While for natural mortality (M), a process about which there is considerable uncertainty (**?**), two hypotheses concerning the mortality of older ages were considered related to the functional form (i.e. (**?**) and (**?**)).

The main form of density dependence assumed in most fishery models is based on the stock recruitment relationship, although other processes (e.g. M, **?**) could have been considered, where at high stock levels survival of recruits declines. However, it is difficult to actually estimate stock recruitment relationships for most stocks. **?** showed that the environment may more strongly influence recruitment than spawning biomass over the observed stock sizes for many stocks. We therefore included hypothesis that recruitment exhibits long term fluctuations (i.e. red noise **?**) nas well as those based on a S-R, i.e. Beverton and Holt or Cushing.

The Beverton and Holt stock recruitment relationship (**?**) is derived from a simple density dependent mortality model where the more survivors there are the higher the mortality. It is assumed that the number of recruits (R) increases towards an asymptotic level (R_{max}) as egg production increases. In contrast (**?**) proposed a power-law SRR for stocks where resources are not locally limiting and recruitment continues to increase with increasing stock size, but at a decreasing rate. Stock recruitment relationships were reformulated in terms of steepness (h) and virgin biomass (v) where steepness is the proportion of the expected recruitment produced at 20% of virgin biomass relative to virgin recruitment (R_0). However, there is often insufficient information to allow its estimation from stock assessment(**?**) and so two values of steepness were assumed i.e. 0.7 and 0.9. Virgin biomass was set at 1000 Mt to allow comparisons to be made across scenarios.

Uncertainty about the ages targeted by the fishery was modelled by changing the selection pattern, i.e. i) mature or juvenile, by assuming the selection pattern is the same as the maturity ogive or the maturity ogive offset by 2 ages to the left; ii) flat topped or dome shaped selection.

The OM was conditioned so that the stock was originally in the green quadrant of the Kobe Phase plot and then effort (and fishing mortality) increased annually until it ended up in the Red quadrant (Figure **??**). Shortly after entering the red quadrant a recovery plan was implemented to reduce F linearly to the target. The MP then started in year 55 after the 5 year recovery period. This follows the general pattern of exploitation seen in ICCAT stocks.

Equations

Growth was modelled by the **?** growth equation i.e.

$$L_t = L_\infty(1 - e^{-kt-t_0}) \tag{1}$$

where L_∞ is the asymptotic length attainable, k the rate at which the rate of growth in length declines as length approaches L_∞, and t_0 is the time at which an individual is of zero length.

Mass-at-age is then derived from length using a scaling exponent (a) and the condition factor (b)

$$W_t = a \times W_t^b \tag{2}$$

Maturity (Q) was either based on **?** or derived as in **?** from the theoretical relationship between M, K, and age at maturity (a_Q) based on the dimensionless ratio of length at maturity to asymptotic length (**?**). It was then modelled by the logistic equation with 2 parameters: age at 50% (a_{50}) and 95% (a_{95}) mature.

$$f(x) = \begin{cases} 0 & \text{if } (a_{50} - x)/a_{95} > 5 \\ a_\infty & \text{if } (a_{50} - x)/a_{95} < -5 \\ \frac{m_\infty}{1.0+19.0^{(a50-x)/a95)}} & \text{otherwise} \end{cases} \tag{3}$$

Natural mortality (M) at-age was derived from **?** and **?**, i.e.
for Lorenzen

$$M_t = 3.00 * W_t - 0.288 \tag{4}$$

and Chen-Watanabe

$$M_t = \begin{cases} \frac{k}{1-e^{-k(t-t_0}} & \text{for } t < t_m \\ \frac{k}{a_0} + a_1(t - t_m) + a_2(t - t_m)^2 & \text{for } t < t_m \end{cases} \tag{5}$$

where
$a_0 = 1 - e^{-k(t-t_0)}$

$a_1 = ke^{-k(t-t_0)}$

$a_2 = -0.5k^{2e^{(-k(t-t_0))}}$

$t_m = \frac{1}{k}log(1 - e^{-kt_0}) + t_0$

Selectivity was modelled using a double normal (see **?**) with three parameters that describe the age at maximum selection ($a1$), the rate at which the left hand limb increases (sl) and the right hand limb decreases (sr) which allows flat topped or domed shaped selection patterns to be chosen.

$$f(x) = \begin{cases} 2^{-[(x-a_1)/s_L]^2} & \text{if } x < a_1 \\ 2^{-[(x-a_1)/s_R]^2} & \text{otherwise} \end{cases} \tag{7}$$

Stock recruitment relationships were either (**?**)

$$R = aS^b \tag{8}$$

or Beverton and Holt (**?**)

$$R = \frac{S}{a + bS} \tag{9}$$

0.1.1. Scenarios

The scenarios are given in **Table ??**.

0.2. Management Procedure

The MPs are based on the model free HCR developed by CCSBT. The TAC is an average of candidate TACs obtained from two harvest control rules. Here we run the two HCRs separately in order to compare their performance (**?**).

0.2.1. Harvest Control Rule I

The first HCR is based on a single index i.e.

$$TAC^1_{y+1} = TAC_y \times \begin{cases} 1 - k_1 |\lambda|^\gamma & \text{for} \quad \lambda < 0 \\ 1 + k_2 \lambda & \text{for} \quad \lambda \geq 0 \end{cases} \tag{10}$$

where λ is the slope in the regression of $\ln B_y$ against year for the most recent n years, k_1 and k_2 are *gain* parameters.

giving 4 tunable parameters (**Table ??**)

0.2.2. Harvest Control Rule II

The second HCR uses both a biomass and a juvenile index i.e.

$$TAC_{y+1} = 0.5 \times \left(TAC_y + C^{\text{targ}}_y \Delta^R_y\right), \tag{11}$$

and

$$\begin{aligned} TAC^2_{y+1} &= 0.5 \times \left(TAC_y + C^{\text{targ}}_y \Delta^R_y\right), \\ C^{\text{targ}}_y &= \begin{cases} \delta \left[\dfrac{B_y}{B^*}\right]^{1-\varepsilon_b} & \text{for} \quad B_y \geq B^* \\ \delta \left[\dfrac{B_y}{B^*}\right]^{1+\varepsilon_b} & \text{for} \quad B_y < B^* \end{cases}, \\ \Delta^R_y &= \begin{cases} \left[\dfrac{\bar{R}}{\mathcal{R}}\right]^{1-\varepsilon_r} & \text{for} \quad \bar{R} \geq \mathcal{R} \\ \left[\dfrac{\bar{R}}{\mathcal{R}}\right]^{1+\varepsilon_r} & \text{for} \quad \bar{R} < \mathcal{R} \end{cases} \end{aligned} \tag{12}$$

where δ is the *target* catch; B^* the *target* CPUE (i.e. the mean observed CPUE corresponding to some multiple of a biomass reference point such as B_0 or M_{MSY}) and $\bar{R}$ is the average recent juvenile biomass i.e.

$$\bar{R} = \frac{1}{\tau_R} \sum_{i=y-\tau_R+1}^{y} R_i, \tag{13}$$

$\mathcal{R}$ is a “limit” level derived from the mean recruitment over a reference period;
while $\varepsilon_\bullet \in [0, 1]$ actions asymmetry so that increases in TAC do not occur at the same level as decreases.

There are therefore 5 tunable parameters, **Table ??**

In our example we use reference periods to set δ as well as $\mathcal{R}$.

The MP operates every three years, i.e.

1. In year t historical data up to and including $t-1$ are sampled from the OM by the oem
2. These data are then used by the MP to set a quota for 3 years starting in years $t+1$.
3. repeat step 1 for year $t+4$

Simulation

Results

Discussion

Conclusions

1. Acknowledgement

This study does not necessarily reflect the views of ICCAT and in no way anticipates the Commission's future policy in this area.

Tables

	Levels (N)	$\prod$ N	Values
SRR	2	2	**Beverton and Holt**; Cushing
Steepness	2	4	**.9**; .75
M	2	8	**Lorezen**; Chen & Watanabe
$Growth$	2	16	**N. Atl. Life History**; Slower growth
$Maturity$	2	32	**N. Atl.**; Life History
Selectivity I	2	64	**as Mat**, domed
Selectivity II	2	128	**as Mat**, juvenile
Autocorrelation	2	256	**0**; 0.3

Table 1. Operating Model Scenarios; Base Case values in bold.

Rule	Definition
O1	Maintain the stock in the *green kobe quadrant*
O2	Achieve the maximum continuing catch
O3	Maintain high employment
O4	Stability of yield
O5	Stability of effort

Table 2. Management Objectives

Statistic	Definition
P1	Probability of SSB $\geq B_{MSY}$ and F $\leq F_{MSY}$
P2	Catch
P3	Effort
P4	AAV Catch
P5	AAV Effort

Table 3. Performance Statistics

Figures