MULTI-FLEET NON-EQUILIBRIUM PRODUCTION MODELS INCLUDING SURFACE TO ASSESS TUNA STOCKS DYNAMICS.

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SUMMARY

Production models have proven for long to be very useful assessment tools. But two main problems make difficult their use for investigating the status of tropical tuna stocks. The first problem is the calculation of the effective fishing effort. Indeed, many different fleets with heterogeneous and changing catchabilities are often exploiting the same population. Consequently, scientists in charge of tropical tunas stock assessment are seldom in a position to estimate accurately a standardized effective fishing effort (e.g. an effort proportional to the fishing mortality) which is targeting the considered stock. The other important problem concerning the use of production models for tropical tunas stock assessment is the fluctuation of the overall size of the exploited area. Indeed, for tuna fisheries, the estimated production curve and its associated MSY are closely linked to the exploited surface and the stock biomass located in the fished area interacts more or less strongly with a "cryptic" part of the population located outside the fishing area.

In this paper, our goal is to address both categories of problems by formulating different multi-fleet non equilibrium production models incorporating or not the fished surface. A maximum likelihood approach is provided to estimate the models parameters in a bayesian context. Once parameters have been estimated, the model can be used to estimate the overall effective effort and the stock status. The comparison of different formulations of the model may help to better understand the fishery dynamics.

INTRODUCTION

Production models have long proven to be very useful assessment tools because of their flexibility and low data requirements, but two main problems make their use difficult for investigating the status of tropical tuna stocks:

- The first is the calculation of the effective fishing effort. Often, many different fleets (mainly baitboats, longliners and purse seiners) with heterogeneous and changing catching power (in general showing an increasing efficiency) are exploiting the same population. For many of these fisheries, the tuna stock considered is a secondary or by-catch species whose targeting depends on the relative prices and on the availability of other targeted species. Consequently, scientists in charge of tropical tuna stock assessment are seldom in a position to estimate accurately a standardized effective fishing effort (e.g. an effort proportional to the fishing mortality) targeting the considered stock.
- The other is the fluctuation of the overall size of the exploited area. It is well known in tuna fisheries that the estimated production curve and its associated MSY are closely linked to the exploited area (Fonteneau, 1988). Tuna populations are not homogeneous and there is probably not total mixing between different regions (Hilborn and Sibert, 1988). The stock biomass located in the fished area therefore interacts more or less strongly with a "cryptic" part of the population located outside the fishing area. To override this problem, different production models incorporating the exploited surface have been proposed (Laloë, 1989, Die *et al*., 1990). Such models, which incorporate the fishery area must be used and adapted to fisheries where it is clear that the evolution of total catches is highly correlated with the evolution of the surface fished (Figure 1).

In this paper, our goal is to address both categories of problems by formulating different multi-fleet non equilibrium production models that incorporate or not the area fished. A maximum likelihood approach is used to estimate the models parameters in a Bayesian context. Once parameters have been estimated, the model can be used to estimate the overall effective effort and the stock status. The comparison of different formulations of the model may help to better understand the fishery dynamics.

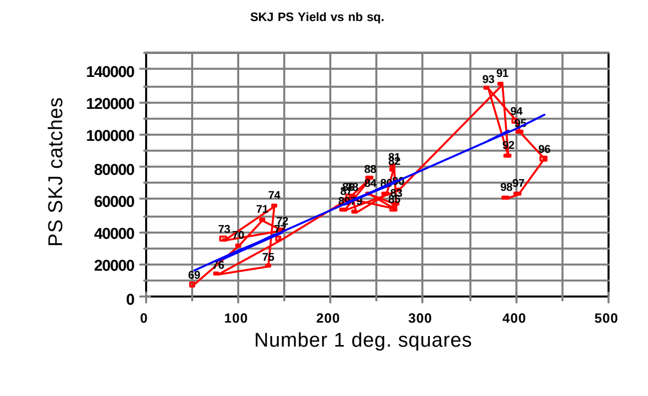

Figure 1 : Skipjack catches versus area fished in the Atlantic Ocean (Fonteneau pers. com.).

MATERIAL AND METHODS

Data requirements

The model presented here requires catches and nominal fishing efforts for each fleet present in the fishery considered. It is not necessary to standardise effort as the standardization is fully integrated in the model formulation. Also needed is the overall area fished by the fishery which will be used to define the stock frontiers.

The "reference model"

All the models used here are based on the classic Pella and Tomlinson (1969) generalized production model which links the stock biomass B with the fishing mortality F by the mean of an ordinary differential equation continuous in time:

$$\frac{dB_t}{dt} = r.B_t.\left(1-\left(\frac{B_t}{K}\right)^{m-1}\right) - F_t.B_t \qquad with \quad m>1 \qquad (1)$$

Where B_t is the biomass at time t; F_t, the instantaneous fishing mortality rate; K, the carrying capacity of the stock; r, the *per capita* intrinsic growth rate of the population and m, the shape parameter (the model becomes a simple Schaffer model when m=2).

To introduce catches and effort for multiple fleets into the model, the fishing mortality F_t is expressed as the sum of each fleet's instantaneous fishing mortality:

$$\frac{dB_t}{dt} = r.B_t.\left(1-\left(\frac{B_t}{K}\right)^{m-1}\right) - \sum_{i=1}^{n} q_{i,t}.f_{i,t}.B_t \qquad (2)$$

Where n, is the total number of fleets; q_i, the catchability coefficient for fleet i at time t and $f_{i,t}$, is the measured fishing effort for fleet i at time t.

The model incorporating the area fished

Equation (2) corresponds to our "reference model" which does not take into account the variation of exploited area. To include it into the model, different assumptions can be made concerning its effects (see for instance Laloë, 1989 and Die *et al*., 1990). In the following paragraph, an original approach is retained for comparison with the reference model. It assumes a partial mixing of the stock/population system but it only deals with the dynamics of a single stock[1] compared with Laloë's model (1989) which consider the whole population dynamics or Die *et al*. (1990) model which explicitly considers the dynamics of the two fractions (available and non available to fishing) of the population.

How to represent fluctuations of stock size related with fluctuations of the area fished

In this model, the exploited stock is considered as being isolated from the rest of the population but related to the size of the exploited area. Hence, we suppose that the *per capita* growth rate of the population r is independent of the exploited area but that the carrying capacity K and the biomass accessible to the fishery depend on it. The catchability q is considered to be inversely proportional to the area fished (Paloheimo and Dickie, 1964)[2]. Given these hypotheses, two extreme cases can be distinguished:

- If there is absolutely no mixing of fish between the exploited stock and the rest of the population at the time scale relevant for its dynamics (according to MacCall (1990) terminology, the population is very viscous): the stock is only a fraction of the population determined by the ratio of the fished surface to the population. Then, we can write the stock carrying capacity as a function of the whole population carrying capacity:

$$K_{f,t} = \frac{S_{f,t}}{S}.K \qquad (3)$$

Where $S_{f,t}$, is the area fished; S, the area of the whole population; $K_{f,t}$, the carrying capacity of the fished stock and K, the carrying capacity of the whole population.

- Conversely, if the population mixing is total at the time scale considered (according with MacCall (1990) terminology, the population is very fluid): the stock and

[1] According with Laurec and Le Guen (1981), we define the stock as the exploited fraction of the population.

[2] Catchability is generally considered to be linked to the fished surface: $q = \frac{q'}{S_t}$ with $S_{f,t}$, the fished surface and q', the local catchability which is a constant linked to the fish density: $U_t = q.N_t = q'.D_t = q'.\frac{N_t}{S_t}$.

the population can be combined. Then, the relations (3) becomes:

$$K_{f,t} = K \qquad (4)$$

As reality is necessarily somewhere in the range defined by these two extreme cases, we use the following formulation where ? is a parameter characterizing the level of mixing of the stock/population system:

$$K_t = \left(\frac{S_t}{S}\right)^{b}.K \qquad 0 \le b \le 1 \qquad (5)$$

Then, rewriting the equation (2) considering that an increase of the area fished corresponds with an increase Y of the stock biomass proportional to the virgin population biomass density (this is equivalent to saying that the unfished population is always in an equilibrium state), and assuming that, due to partial mixing between the stock and the population, a quantity U from the virgin part of the population plays a role in the stock dynamics but remains unavailable for fishing (Figure 2)[3], we obtain model (6).

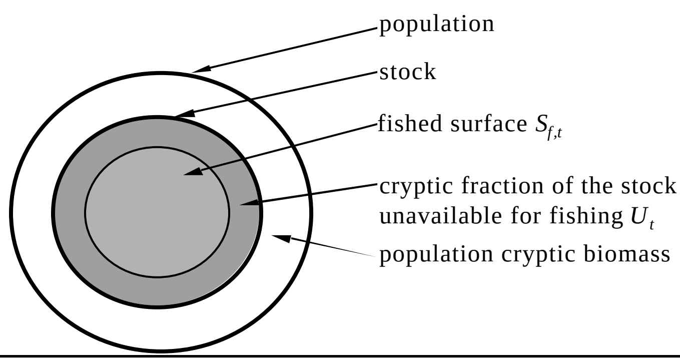

Figure 1 : conceptual structure of the model showing the differences between the stock, the population and the fraction U.

$$\begin{cases} \dfrac{dB_t}{dt} = y_{B,t} + \dfrac{dU_t}{dt} + r.\left(B_t + y_{B,t} + \dfrac{dU_t}{dt}\right).\left(1 - \left(\dfrac{\left(B_t + y_{B,t} + \dfrac{dU_t}{dt}\right)}{\left(S_{f,t}/S\right)^{b}.K}\right)^{m-1}\right) - \sum_{i=1}^{n} q_i^{'}.\left(S_{f,t}/S\right)^{-1}.f_{i,t}.\left(B_t + y_{B,t} - U_t\right) \\ \dfrac{dC_t}{dt} = \sum_{i=1}^{n} q_i^{'}.\left(S_{f,t}/S\right)^{-1}.f_{i,t}.\left(B_t + y_{B,t} - U_t\right) \\ y_{B,t} = K.\dfrac{dS_{f,t}}{S.dt} \qquad if \quad \dfrac{dS_{f,t}}{dt} \ge 0 \\ y_{B,t} = B_t.\dfrac{dS_{f,t}}{S_{f,t}.dt} \qquad if \quad \dfrac{dS_{f,t}}{dt} < 0 \\ U_t = K.\left(\left(S_{f,t}/S\right)^{b} - \left(S_{f,t}/S\right)\right) \\ \dfrac{dU_t}{dt} = K.\dfrac{d\left(\left(S_{f,t}/S\right)^{b} - \left(S_{f,t}/S\right)\right)}{dt} = \dfrac{K}{S}\left[b.\left(\dfrac{S_{f,t}}{S}\right)^{b-1} - 1\right].\dfrac{dS_{f,t}}{dt} \\ 0 \le b \le 1, \quad m > 1 \end{cases}$$

(6)

[3] It is equivalent to state that there is two different characteristic time scales for the processes related to fishing and for the processes related to the stock dynamics: processes related to fishing are assumed to occur much faster than the mixing which influence the stock dynamics.

Where Bt, is the stock biomass at time t; Ct, the instantaneous catches at time t; S, the total surface of the population; Sf,t, the surface fished at time t; ? a parameter characterizing the population mixing at the time scale relevant for population dynamics; Y, the stock biomass variation due to the variation of the fished area and U, the fraction of the population unavailable for fishing but involved in the sock dynamics because of mixing.

When there is no mixing between the stock and the population (b=1), the quantity U is null. On the contrary, where there is a total mixing (b=0), the stock and population are confounded at the level of the dynamics. When there is no variations of the fished area, $Y_{B,t}$=0 and dU_t/dt=0. Then, model (6) reduces to a modified version of equation (3) where the carrying capacity K and the catchability q depend on the area fished and a fraction of the stock potentially remains unavailable for fishing:

$$\begin{cases} \dfrac{dB}{dt} = r.B.\left(1 - \left(\dfrac{B_t}{\left(S_{f,t}/S\right)^{b}.K}\right)^{m-1}\right) - \sum_{i=1}^{n} q_i^{'}.\left(S_{f,t}/S\right)^{-1}.f_{i,t}.\left(B - U_t\right) \\ \dfrac{dC_t}{dt} = \sum_{i=1}^{n} q_i^{'}.\left(S_{f,t}/S\right)^{-1}.f_{i,t}.\left(B - U_t\right) \\ U_t = K.\left(\left(S_{f,t}/S\right)^{b} - \left(S_{f,t}/S\right)\right) \\ 0 \le b \le 1, \quad m > 1 \end{cases} \qquad (7)$$

For their visual interest, the equilibrium curves $\left(\dfrac{dB_t}{dt} = \dfrac{dS_{f,t}}{dt} = 0\right)$ are presented in Figure 1 for different values of the area fished in the case where there is no mixing (b=1).

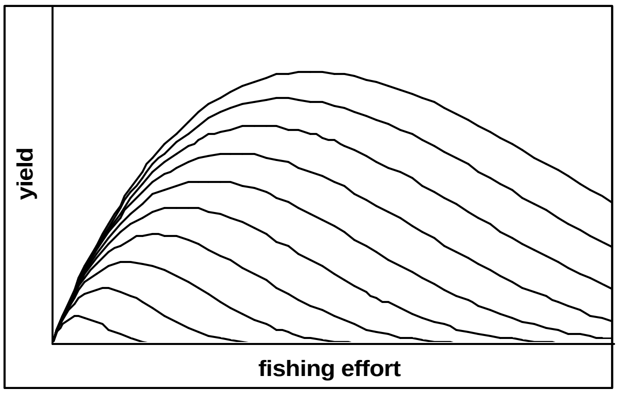

Figure 1 : Equilibrium model for m=1,3 and b=1. Ten different values of the surface ratio $S_{f,t}/S$ *ranging from 0.1 to 1 are presented.*

Fitting and comparing the different models in a Bayesian context

To take into account potential fluctuations of the carrying capacity due to environmental fluctuations or to modifications of the fishery configuration, the parameter K is assumed to be dependent on time and to vary according to external factors. At the same time, the local catchability by the fleet is supposed to vary each year. In this case, the production models as formulated previously are clearly overparameterized and need to be statistically structured (*i.e.* their total number of degrees of freedom must be reduced) with prior hypothesis on parameter distribution identifiable.

- Concerning the carrying capacity, we assumed that the parameters $\log(K_t)$ have the structure of a random walk which is the simplest type of time series to allow a parameter to vary slowly over time (Fournier, 1996). For that purpose, we assume that :

$$K_{j+1} = K_j.e^{J_j} \qquad J \sim N(0, s_J) \qquad (7)$$

- Concerning the catchability coefficient, the fishing mortality error structure is assumed to be lognormal. Then, the fishing mortality of fleet i in year j is written $F_{i,j} = \frac{q'_{i,j}}{S_{f,j}}.f_{i,j}.e^{h_i}$ where the h_i are robustified normally distributed random variables with mean 0. To take into account potential fluctuations of fishing power for each fleet, two different methods are used and compared. The first one follows the same principle as that used for the carrying capacity and gives a random walk structure to the catchability time series for each fleet: $q'_{i,j+1} = q'_{i,j}.e^{e_{i,j}}$ with $e \in N(0, s_{e_i})$ (Fournier *et al.*, 1998). The second mean assumes a deterministic structure of the catchability time series with a constant rate of increase (or decrease) g_i for each fleet i in year j: $q'_{i,j} = Q'_i.e^{g_i \cdot j}$.

To estimate the parameters in a Bayesian context, we used the method of the maximum of posterior distribution (Bard, 1974) by maximizing the sum of the log-likelihood of the data plus the log of the prior density function. Then, given the data, the Bayesian posterior distribution for the model parameters has 6 components (one for the log-likelihood of the catch by fleet estimates, one for the log-likelihood of the total catch estimates, one for the log of the prior distribution for the carrying capacity variability, one the log of the prior distribution for the effort-fishing mortality relationship, one for the catchability variability and one for prior assumption on the parameter m and b values) and is proportional to the quantity L:

$$L = -\frac{(k+4).n-1}{2}.\log\left[\frac{1}{k}.\sum_{i=1}^{k}\sum_{i=1}^{n}\left(\log\left(\hat{C}_{i,j}\right)-\log\left(C_{i,j}\right)\right)^2 + \sum_{j=1}^{n}\left(\log\left(\hat{C}_j^{tot}\right)-\log\left(C_j^{tot}\right)\right)^2 + p_J.\sum_{j=1}^{n}J_j^2 + \sum_{j=1}^{n}\log\left(e^{p_h.h_j^2}+0.01\right) + p_e.\sum_{j=1}^{n}e_j^2\right] - p_m.\log(m)^2 - p_b.\log(b)^2 \qquad (8)$$

Where k, is the fleet number; n, the total number of time period; $\hat{C}$, the observed catches; C, the predicted catches; i and j, the subscripts for fleets and years and p_q, p_h, p_e, p_b, p_m, weights.

This function assumes that the log of the predicted catches are the expected values of a random variable with a normal distribution. The prior distribution for the h_i is assumed to be a robustified normal distribution which increases the probability of unlikely events relative to a standard normal distribution (Fournier *et al.*, 1998)[4]. Important additional information is provided through the use of the weight p which fix the strength of the Bayesian constraints. The parameters of the model are estimated by finding the values of the parameters which minimize the opposite of the equation (8). This minimization was performed with a quasi-Newton numerical function minimizer using exact derivatives with respect to the model parameters with the AD model builder software (ADMB © 1993-1996 by Otter Research Ltd). ADMB calculates the exact derivatives with a technique named automatic differentiation (Griewank and Corliss, 1991) and also provides the variance of the parameter estimates by computing the Hessian matrix, ***H***, the elements of which are:

$$H_{i,j} = \frac{\partial^2(-\log L)}{\partial q_i . \partial q_j} \quad (9)$$

Where q_i and q_j are any two model parameters.

The covariance matrix of the model parameters is estimated by computing the inverse of the Hessian (9) at the minimum.

Following Fournier *et al*. (1998), it is possible to use Posterior Bayes Factors (PBF) to compare the different models used from a statistical point of view. The asymptotic form of PBF is a weighted version of likelihood ratio.

CONCLUSION

Facing the problematic lack of data to assess tuna stocks in the Indian Ocean, there is a need for developing new statistical approaches explicitly dealing with uncertainties. Two alternative and complementary ways must be explored. The first, which is developed here, concerns the use of global production models and their adaptation to particularities of tropical tunas. The second, more complex but potentially more powerful, concerns the development of new analytical spatialized models sufficiently structured to represent correctly the very complex dynamics of the tuna populations and to allow their quantitative assessment. This latest solution will be the object of future research to be operational in the near future.

"The addition of 0.01 improves the robustness of the estimator by reducing the influence of observations that are more than about three standard deviations from the mean" (Fournier *et al*., 1990).

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