

## Approximate estimate of the maximum sustainable yield from catch data without detailed effort information: application to tuna fisheries

Daniel Gaertner<sup>a\*</sup>, Alain Fonteneau<sup>b</sup>, Francis Laloë<sup>a</sup>

<sup>a</sup> Laboratoire halieutique et écosystèmes aquatiques (HEA), IRD, BP 5045, 34032 Montpellier, France

<sup>b</sup> IRD, BP 570, Victoria, Seychelles

Received 28 May 2000; accepted 18 December 2000

**Abstract** – Even when fishing effort data are not available in a developing fishery, it is often still possible to develop a simple fishery indicator to obtain information about the status of the stock. Using catch data only, Grainger and Garcia, (FAO Fish. Tech. Pap. 359, 1996) showed that the changes over time in the relative rate of catch increase (*RRCI*) can be used to detect when a stock reaches its over-fishing level, i.e., the year when *RRCI* falls to zero. The method presupposes that fishing effort increased steadily over the period concerned. We propose a generalization of this method that consists in obtaining a crude estimate of the maximum sustainable yield (*MSY*) by plotting the trend in catches against the smoothed *RRCI*. The yellowfin tuna (*Thunnus albacares*) fishery in the Eastern Atlantic was used to show the strong relationship between *MSY* estimates obtained from standard equilibrium production models and from this method. Given that it is very difficult to estimate effective fishing effort for skipjack tuna (*Katsuwonus pelamis*), we show how this simple fishery indicator can be used to obtain proxies of *MSY* for skipjack fisheries located in the Eastern Atlantic Ocean and in the Indian Ocean. © 2001 Ifremer/CNRS/Inra/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

stock assessment / precautionary approach / fishery indicator / tuna fishery / skipjack / yellowfin

**Résumé** – Estimation approchée de la prise maximale à l'équilibre, à partir de données de captures et en l'absence d'information précise sur l'effort de pêche : application aux pêcheries thonières. Lorsque les données sur l'effort de pêche dans une pêcherie en expansion ne sont pas disponibles, il reste possible de développer un simple indicateur des pêches afin d'avoir une indication sur l'état d'exploitation de ce stock. En utilisant uniquement des données de captures, Grainger et Garcia (FAO Fish. Tech. Pap. 359, 1996) ont montré que l'évolution au cours du temps du taux relatif d'accroissement des captures (TRAC) permet d'identifier l'année où le stock atteint sa pleine exploitation (implicitement, lorsque le TRAC s'annule). Cette méthode suppose un accroissement de l'effort de pêche au cours de la période analysée. Dans le but d'obtenir directement une valeur approchée de la prise maximale à l'équilibre (PME), nous proposons une généralisation de cette méthode qui consiste à représenter la tendance des captures par rapport aux valeurs lissées du TRAC. Les données de capture de l'albacore (*Thunnus albacares*) dans l'Atlantique ont été utilisées pour illustrer la forte similitude existant entre les estimations de la PME fournies par les modèles globaux traditionnels et par cette méthode. En raison de la difficulté posée par le calcul d'un effort de pêche effectif pour le listao (*Katsuwonus pelamis*), ce simple indicateur des pêches s'avère utile pour l'obtention d'une valeur approchée de la PME pour les stocks de cette espèce dans l'Atlantique Est et dans l'océan Indien. © 2001 Ifremer/CNRS/Inra/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

évaluation des stocks / approche de précaution / indicateur des pêches / pêche thonière / listao / albacore

### 1. INTRODUCTION

Surplus production models have been widely used in fisheries related applications because they require only simple information such as catch and effort data series. Despite recent criticisms of this type of model,

it appears to be a robust tool that is still valid for (1) tuna stock assessment diagnosis, and (2) decision-makers who can easily interpret it. However, in some circumstances a conventional production model cannot be used due to the lack of effort data. In such cases, and specifically when the available information is

\* Correspondence and reprints

E-mail address: gaertner@ird.fr (D. Gaertner).

limited to annual landings, it is possible to develop a simple fishery indicator to obtain information on the status of the fishery. Fishery indicators may be defined as simple variables that are useful in estimating trends in fishery systems and can be used in negotiations between the different fishing partners (e.g., fishermen, fishery managers, scientists, environmental groups, etc.). With the aim of obtaining an index that is easy to interpret, Grainger and Garcia (1996) showed that during the developing and mature phases of a fishery, the yearly relative rate of catch increase (*RRCI*) decreased over time. Consequently, they suggested performing a linear fit of the *RRCI* over time to detect when maximum potential production is reached (i.e., the year when this index falls to zero).

The purpose of the present paper is to generalize this relationship and to propose a new plot to directly evaluate a crude estimate of the maximum sustainable yield (*MSY*). To validate the method, *MSY* estimates obtained from standard equilibrium production models and from this new approach were compared in yellowfin tuna (*Thunnus albacares*) in the Atlantic Ocean. We propose to use the same method for skipjack (*Katsuwonus pelamis*) for which conventional methods have failed to perform stock assessment analyses. Skipjack catches have reached high levels in the Eastern Atlantic Ocean and in the Indian Ocean but considerable uncertainty remains about the level of exploitation of this species in the two oceans. Hence, in the context of precautionary approach developed by the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks (New York, 1992–1995), this new method may provide a way of overcoming the lack of adequate conventional assessment analyses.

## 2. METHODS

In the traditional surplus production approach, there is a steady decrease in the difference between catches in two consecutive years ( $\Delta C = C_{t+1} - C_t$ ) with an increase in fishing effort (figure 1). If we assume equilibrium conditions, the *MSY* is reached when this simple index equals zero. When fishing effort is not well quantified, but when there is sufficient belief about its continual increase over time (this is the case for most of the world's tuna fisheries), these observations remain implicitly correct.

In their review of the state of world fisheries, Grainger and Garcia (1996) showed the usefulness of performing a linear fit of the relative rate of catch increase (*RRCI*) over time. In order to eliminate non-suitable effects due to yearly fluctuations in catchability, and bearing in mind that the salient information is given by the trend of this fishery indicator, the *RRCI*

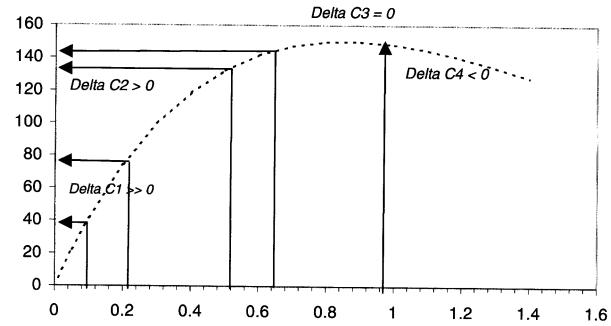


Figure 1. Changes in increase in catches ( $\Delta C$ ) during the developing phases of a hypothetical fishery.

was calculated with respect to the average catches observed in the recent years, for example:

$$RRCI_t = [C_t - [(C_{t-1} + C_{t-2} + C_{t-3})/3]/[(C_{t-1} + C_{t-2} + C_{t-3})/3]] = \beta_0 + \beta_1 t \quad (1)$$

with  $C_t$  = catch in year  $t$ .

However, in contrast to Grainger and Garcia's linear regression approach, in this paper we do not assume that this relationship is a priori linear. To reinforce this point, we simulated artificial increases in fishing effort from a fishery assumed to follow a generalized stock production model (Pella and Tomlinson, 1969):

$$C_t = f_t^{eq} [\beta_0 + (\beta_1 f_t^{eq})]^{(1/(1-m))} \quad (2)$$

with  $C_t$  = catch in year  $t$ ,  $f_t^{eq}$  = averaged fishing effort in year  $t$ , and  $\beta_0$ ,  $\beta_1$ , and  $m$  = the parameters of the production model.

Since equilibrium is rarely achieved, Gulland's equilibrium approximation was applied to the fishing effort. This approximation consists in averaging the efforts over a number of years,

$$f_t^{eq} = \left(\frac{1}{L}\right) \sum_{i=0}^{L-1} f_{t-i} \quad (3)$$

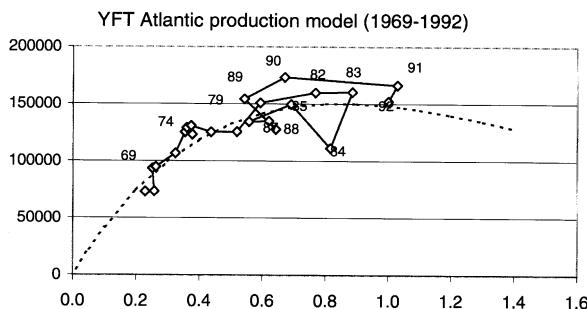
with  $L$  = mean life expectancy of an individual in the fishable population.

The first step in this simulation consisted in performing the parameters of a production model for Atlantic Ocean yellowfin tuna from 1971 to 1992 (figure 2). Next, simulated catches were inferred from the equilibrium production model for two hypothetical developing fisheries with different increasing rates of fishing effort:

$$f_{t+1} = f_t + [Af_t] \quad (4)$$

i.e. fishing effort in year  $t+1$  increases by a fixed percentage over the fishing effort observed in year  $t$ , and

$$f_{t+1} = f_t + A \quad (5)$$

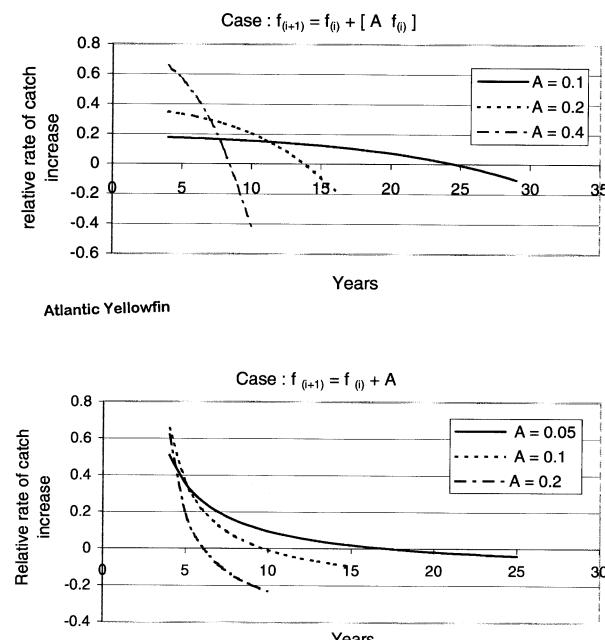


**Figure 2.** Equilibrium production model for yellowfin tuna in the Atlantic Ocean (1969–1992). Fishing effort was scaled with respect to the 1992 value.

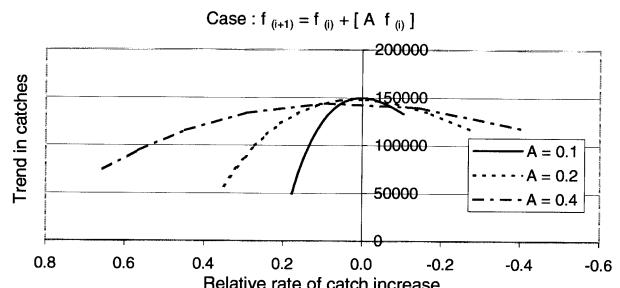
i.e. fishing effort increases regularly by a constant.

These two hypothetical fisheries are shown in *figure 3*. As can be seen, the shapes of the relationship between equilibrium *RRCI* and the years are not linear. The curve appears to be convex when the fishing effort increases by a fixed percentage of the last fishing effort and to be concave when the rate of increase in fishing effort is a constant. It can be implicitly assumed that a linear relationship between *RRCI'* and the years depicts a special case combining both fishing patterns (e.g.  $f_{t+1} = f_t + [Af_t + B]$ , or anything close).

To address this issue, we propose a generalization of Grainger and Garcia's linear regression approach



**Figure 3.** Changes in the relative rate of catch increase (*RRCI*) for a simulated Atlantic yellowfin tuna type fishery for different patterns of increase in fishing effort. In both cases, the decreasing trend of the *RRCI* is not linear.



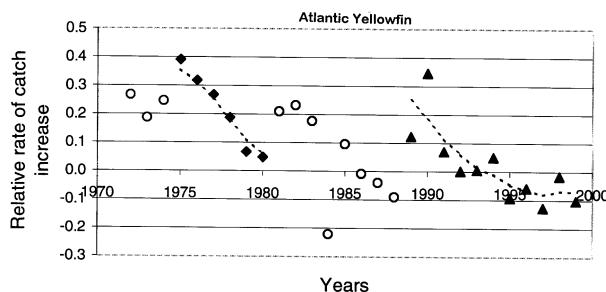
**Figure 4.** Changes in the trend of the catches versus the relative rate of catch increase (*RRCI*) for a simulated Atlantic yellowfin tuna type fishery with different patterns of increase in fishing effort. Under an equilibrium assumption, the maximum yield is assumed reached when the *RRCI* equals zero.

based on (1) a plot of the smoothed *RRCI'* over the period of increasing fishing effort, and (2) a plot of the averaged previous catches, *Cav* (i.e. an attempt to approximate equilibrium conditions) against the smoothed *RRCI'*,

$$RRCI'_t = \left(\frac{1}{3}\right) \sum_{t=1}^{t+1} RRCI_t \quad (6)$$

$$\text{and } Cav_t = \left(\frac{1}{L}\right) \sum_{i=0}^L C_{t-i} \quad (7)$$

In this approach, the data series easily can be fitted by a simple second-degree equation, and the approximate maximum yield directly estimated for  $Y = f(RRCI' = 0)$ . This new plot for the same two hypothetical developing fisheries is illustrated in *figure 4*. To take into account the developing phases of a fishery, the *RRCI'* axis (i.e. the X axis) was reversed with the negative values in the right part. Independently of the rate of increase in fishing effort, maximum yields converge to the same value. Catch data were provided by the International Commission of Atlantic Tuna (ICCAT) and by the Indian Ocean Tuna Commission (IOTC).



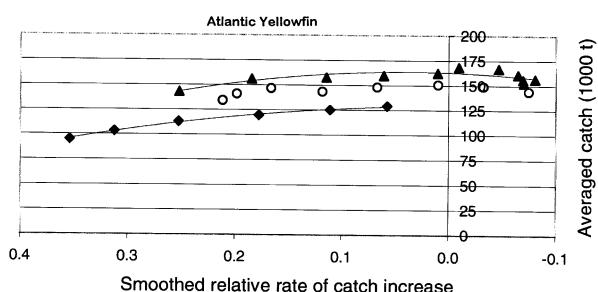
**Figure 5.** Changes over time in the relative rate of catch increase ( $RRCI$ ) for the yellowfin tuna in the Atlantic Ocean. Three periods with different fishing patterns were identified. It has been assumed that the year for which the smoothed  $RRCI$  drops to zero corresponds to the maximum yield. Due to the decrease in the purse seiner fishing effort between 1985 and 1989, the catches taken during the eighties were not used for estimating the proxy of the maximum yield and are represented by empty circles.

### 3. RESULTS

#### 3.1. Atlantic yellowfin fishery

Changes in the  $RRCI$  indicated three distinct periods, 1975–1980, 1981–1988, and 1989–1998 (figure 5). Because fishing effort decreased due to the partial relocation of E.U. purse seiners to the Indian Ocean in the second half of the eighties, the  $RRCI$  method was not applied to the catch data series during the 1980s. According to Grainger and Garcia's method, the lower level observed in 1979–1980 indicated that the fishery was approaching its maximum yield, whereas the negative values observed since 1994–1995 indicated signs of over-fishing. Nevertheless, this approach only allowed us to identify the year for which  $RRCI = 0$ . One of the limitations of this plot is the difficulty in estimating the resulting maximum yield, especially when there is considerable variability in observed catches in two consecutive years; for example observed catches varied between 170 100 t in 1994 and 152 200 t in 1995.

Faced with this uncertainty, we decided to plot the averaged catches (i.e. as an equilibrium approximation similar to Gulland's method used in the conventional production model) against the smoothed  $RRCI$  (i.e. the trend in  $RRCI$ ). Due to the duration of the yellowfin exploited life, the averaged catches were calculated from the observed catches taken in the six previous years. The intercepts with the  $Y$ -axis give the  $MSY$  proxies (hereafter  $MSY_{RRCI}$ ) for the two historical periods: 129 400 t (bearing in mind the danger implied in predicting a parameter outside the data range of the observed values), and 162 800 t (figure 6). It is quite clear that the high level of catches registered in the early nineties (with a maximum of 192 500 t in 1990) was not sustainable. These figures suggest that since 1994–1995 effort levels have exceeded  $MSY$  levels. Comparative analysis of the  $MSY$  estimates provided by this method and by equilibrium production models



**Figure 6.** Changes in the trend of catch ( $Cav$ ) for the Atlantic yellowfin tuna against changes in the relative rate of catch increase ( $RRCI$ ) for different periods. The corresponding maximum yields can be directly estimated when the  $RRCI$  drops to zero (approximately, 129 400 t for the period 1975–1980, and 162 800 t for the period 1989–1999).

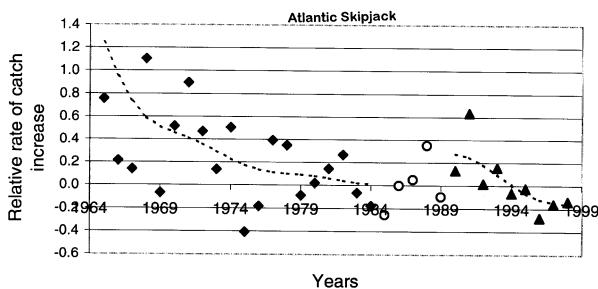
(hereafter  $MSY_{PM}$ ) showed a good correlation. For instance for three historical periods of the fishery: 1967, 1980 and 1997,  $MSY_{RRCI}$  estimates were 64 200 t, 129 400 t and 162 000 t, while  $MSY_{PM}$  were 50 000 t, 133 600 t and 151 700 t, respectively. In view of these results we applied the new method to Eastern Atlantic Ocean and to Indian Ocean skipjack fisheries for which the lack of suitable effort data prohibited the use of conventional surplus production models.

#### 3.2. Eastern Atlantic skipjack fishery

Figure 7 shows variations in  $RRCI$ . As skipjack landings generally vary considerably from year to year, changes in  $RRCI$  for this species exhibited a larger variability than for yellowfin. However, two periods can be distinguished: 1965–1984 and 1990–1998. These results are consistent with the changes in skipjack catches over the period considered. The total catch of skipjack in the Eastern Atlantic climbed from 48 000 t in 1971 to 100 000 t at the end of the seventies and remained stable until the end of the eighties. After reaching a maximum in 1991 with 174 000 t, catches have decreased to around 105 000 t during the three last years. As previously mentioned, the  $RRCI$  method was not applied during the late 1980s. According to Grainger and Garcia's approach, maximum yield was approached in 1983 and finally reached in 1994–1995. The new plot proposed in this paper (i.e. the average of the catches taken in the three previous years versus the smoothed  $RRCI$ ) appears to be a valid tool to provide approximate estimates of maximum yields for both historical periods: around 106 000 t during the first period, and around 151 000 t during the second (figure 8).

#### 3.3. Indian Ocean skipjack fishery

In the Indian Ocean fishery, the changes in  $RRCI$  indicated two distinct periods, 1966–1978 and 1984–1998, characterized by different fishing patterns



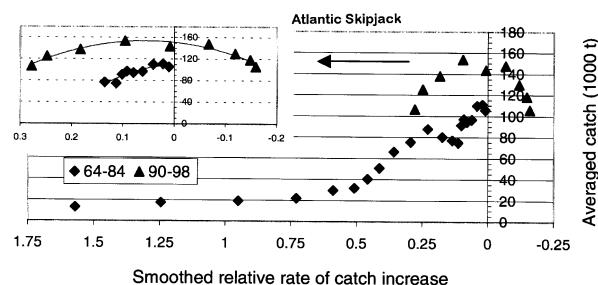
**Figure 7.** Changes over time in the relative rate of catch increase ( $RRCI$ ) for the Eastern Atlantic skipjack for two historical periods of this fishery. The last period began in the early 1990's with the massive use of FAD fishing operations. Years that correspond to major changes in the fishery were not used to estimate the proxy of the maximum yield and are represented by empty circles.

(figure 9). Skipjack catches remained stable at around 50 000 t from the mid-sixties to 1983. From 1984 catches rose continuously, reaching a peak of 313 000 t in 1994, followed by a slight decline (catches have been around 280 000 t in the last three years).

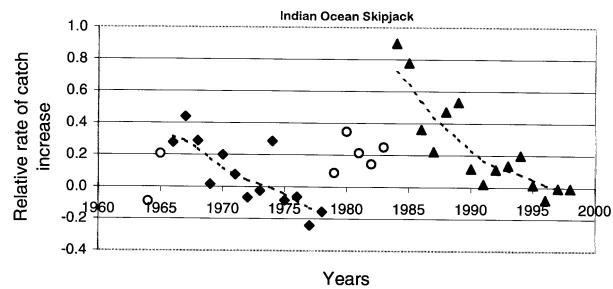
In the seventies, when the main components of the fishery were Sri Lankan and Maldivian bait boats,  $MSY_{RRCI}$  was estimated at close to 45 000 t and, as a result, the stock was showing signs of over-exploitation, or at least signs of local depletion (bearing in mind the regional fishing grounds of these fleets). During the last period, the low levels of RRIC recently observed revealed that  $MSY$  was being approached (figure 9), but now with an estimate around 288 000 t (figure 10).

#### 4. DISCUSSION

In the spirit of the FAO code of conduct for responsible fisheries, fisheries management authorities should be more cautious when information is poor. Absence of adequate scientific information (e.g., suit-



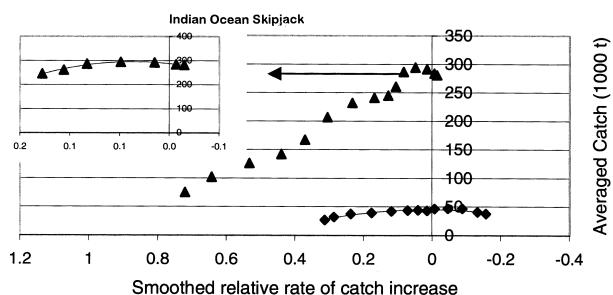
**Figure 8.** Changes in the trend of catch ( $Cav$ ) for the Eastern Atlantic skipjack tuna against changes in the relative rate of catch increase ( $RRCI$ ) for two historical periods of this fishery. The corresponding maximum yields can be directly estimated when the relative rate of catch increase drops to zero (approximately 109 800 t for the period 1964–1984 and 151 100 t for the period 1990–1999).



**Figure 9.** Changes over time in the relative rate of catch increase for the Indian Ocean skipjack for two historical periods of this fishery. Years that correspond to major changes in the fishery were not used to estimate the proxy of the maximum yield and are represented by empty circles.

able data on effective effort) should not justify putting off conservation measures. It must be emphasized for instance that despite the large catches of skipjack taken in the Atlantic and in the Indian Ocean (between 380 000 t and 480 000 t in the five last years), considerable uncertainty remains about the status of these stocks due to the difficulty in assessing the status of skipjack stocks using traditional assessment methods.

Analytical models have not generally been used on skipjack because of certain key aspects of its biology. Skipjack spawns in an opportunistic manner throughout the year and over large areas, so recruitment is continuous but heterogeneous in space and time (Cayré and Farrugio, 1986). This explains why the cohorts cannot easily be identified. Furthermore, skipjack growth parameters vary with latitude (Bard and Antoine, 1986). As a consequence catch-at-age matrix will not be consistent because fish of the same age will exhibit different sizes depending on their past movement patterns. Another difficulty concerns the fact that skipjack tuna is often a secondary species, depending on the price differential and on the catchability of other target species. Consequently, estimation of the effective effort exerted on skipjack (e.g. effort proportional



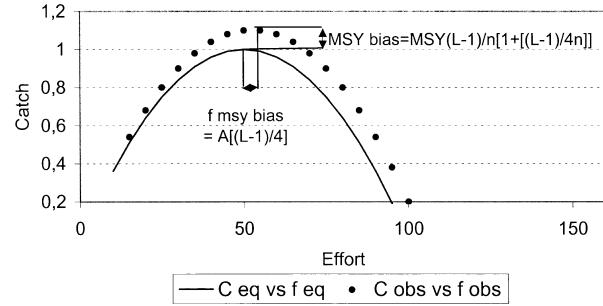
**Figure 10.** Changes in the trend of catch ( $Cav$ ) for the Indian Ocean skipjack tuna against changes in the relative rate of catch increase ( $RRCI$ ) for two historical periods of this fishery. The corresponding maximum yields can be directly estimated when the relative rate of catch increase falls to zero (approximately 45 000 t for the period 1966–1978 and 287 600 t for the period 1984–1998).

to fishing mortality) remains very problematic (Fonteneau, 1986; Forsbergh, 1989). Although promising new models that attempt to take into account these peculiarities have recently been proposed (Fournier et al., 1998) and used experimentally in skipjack fisheries (Maury, 1999), analysis of the trend in *RRCI* may offer a simple way of dealing with these difficulties.

It appears that the equilibrium *RRCI* plot provides, under certain assumptions (e.g., an increase in the exploitation rate), a way to detect over-fishing of stocks, especially for fisheries lacking effort data. In the Atlantic Ocean, the assumption concerning a continuous increase in the exploitation rate seems to be valid with the exception of the second half of the eighties, when fishing effort decreased due to the partial relocation of E.U. purse seiners to the Indian Ocean. The massive use of fish aggregating devices (FADs) in the early 1990's (Ariz, et al., 1992) and the introduction of multiple technical innovations on board purse seiners made it difficult to adequately estimate surface fishing effort, but there is no doubt about an increase in efficiency (Fonteneau et al., 1999). In the Indian Ocean, the increase in fishing power of mechanized vessels that were formerly sailing vessels, has been described by Anderson (1999) in connection with the Maldivian bait boat fishery. As far as purse seine fishery is concerned, there is evidence that changes in net dimensions, the increased use of electronic equipment, the use of FADs etc., have led also to an increase in the Indian Ocean purse seiners' efficiency (Hallier, 1994; Fonteneau et al., 1999).

In this context, the null rate of increase in catches (specifically, the threshold corresponding to *RRCI* = 0) may be used as a crude approximation of the conventional *MSY* estimate. The Eastern Atlantic stock of skipjack appears to have been fully exploited and possibly over-fished since 1994–1995. Like for yellowfin, the use of the FADs in surface fishing operations and the resulting expansion of the purse seine fishery towards the west has contributed to a new fishing pattern and has resulted in a new *MSY*. As in the conventional production model, the increase in the maximum yield over time was related to the geographical expansion of the fishery (Laloë, 1988). In the Indian Ocean the rapid development of E.U. purse seiners in the mid-eighties resulted in a dramatic expansion of the fishing area and of skipjack catchability. It must be stressed that the latter *MSY* proxy was obtained for a fishery pattern dominated by FAD-associated purse seine catches. However, taking into account the recent expansion of the fishery towards the Eastern Indian Ocean (Pianet, 1998), a larger estimate could be reached in the future.

It has been argued that this method may tend to over-estimate *MSY*, due to its underlying equilibrium assumption. However, we assumed that: (1) the equilibrium approximation provided by averaging the previous catches; (2) the application of this method for species with relative high intrinsic rate of population



**Figure 11.** Representation of the bias in the maximum sustainable yield (*MSY*) and in the fishing effort ( $f_{msy}$ ) estimates under an equilibrium Schaeffer model in a skipjack type fishery ( $L = 3, N = 20$ ) for which *MSY* has been fixed to 1 and assuming a constant increment  $A$  over time in fishing effort. Continuous line:  $C^{eq}$  vs  $f^{eq}$ ; dots:  $C^{obs}$  vs  $f^{obs}$ .

growth, such as skipjack, mitigate this risk. For instance, under a Schaeffer equilibrium model, when fishing effort increases regularly by a constant, it can be shown that when *RRIC* falls to zero,

$$\bar{f}_{(ACobs=0)} = f_{msy} + A\left(\frac{L-1}{4}\right) \quad (8)$$

and,

$$C^{obs}_{(ACobs=0)} \equiv \\ MSY\left[1 + \left(\frac{L-1}{n}\right)\left[1 + \left(\frac{L-1}{4n}\right)\right]\right] \quad (9)$$

(see annex and figure 11).

Considering that  $L = 3$  is commonly used for skipjack, the bias in the *MSY* estimate was estimated at close to 10% (annex). Because *MSY* values provided by conventional production models have very large confidence intervals, this level of bias appears reasonable. However, it would be interesting to evaluate the magnitude of this potential bias through simulation studies in other situations (including models under non-equilibrium assumption), specifically for stocks with low intrinsic rates of population growth.

The analysis of the changes in this simple fishery indicator is based on the same simple population dynamics rules used in the equilibrium production models. In this type of approach, assuming that fishing effort increases permanently over time, the equilibrium yield ( $Y_e$ ) climbs from moderate levels of fishing effort to a fully-fished level (i.e., the *MSY*). After this threshold,  $Y_e$  falls continuously, characterizing an over-fishing state of the fishery that is not considered desirable. However, the rate of decrease, and as a consequence the level of over-fishing, is closely related to the underlying production model used to describe the fishery. Hence, depending on the structure of the selected model, a fishery manager will perceive the risk of collapse differently for the same high level of fishing effort. Under a Schaeffer model ( $m = 2$ ), a rapid decrease in  $Y_e$  is expected when fishing effort

exceeds  $F_{MSY}$ . As a consequence, the probability that the fishery collapses will be estimated as likely. By contrast, under an exponential model ( $m = 1$ ), we will expect a slow decrease in  $Ye$  (and, similarly, the risk of collapse will be assumed to be lower than in the first model); the hyperbolic model ( $m = 0$ ), where  $Ye$  increases up to an asymptotic limit, can be considered as unrealistic. This means that even for stocks with valid fisheries statistics and monitored by simple production models, the uncertainty in the structure of the model (i.e. the way in which the links between the different components of the fishery are represented) can lead to different management measures. In practice, due to these uncertainties, the regulations proposed by fishery managers could generate undesirable consequences in that the measures may be unnecessary or alternatively, too weak to assure long-term sustainability of the resource (for a review of the different types of errors caused by uncertainties in stock assessments, see Garcia, 1996; Hilborn and Peterman, 1996). Hence, even in such ‘favourable’ situations, it would be appropriate to combine standard methods with auxiliary fishery indicators in stock-assessment related applications.

With this consideration in mind, the Bayesian approach may be of major interest because it permits the consideration of structurally different models as alternative hypotheses (Punt and Hilborn, 1997; McAllister and Kirkwood, 1998). Bayesian techniques also enable the construction of prior distribution for a quantity of interest derived from the model (Hoenig et al., 1994). An interesting application of Bayesian methods is when a developing fishery has been exploiting an increasing area over the years. This fishing pattern was commonly seen in the Eastern Pacific and Eastern Atlantic tropical tuna fisheries, and resulted in an increase in successive  $MSY$  estimates over the years (Laloë, 1988). In this type of situation and knowing the suitable habitat of each species, it appears reasonable to construct prior information with the aid of an index reflecting the productivity of the fishery per unit of surface area. The new potential maximum yield (that is, after the expansion of the fishery) could subsequently easily be estimated as the product of this productivity index and the new surface area explored.

## 5. CONCLUSION

The aim of this paper was to further develop Grainger and Garcia’s approach, which consisted in using a simple linear fit of the relative rate of catch increase ( $RRCI$ ) against the years, to assess the maximum yield of a fishery. One of the advantages of this new approach is that no detailed effort data are required, only general knowledge of its increasing trend. To improve the robustness of this fishery indicator, we proposed (1) to smooth the values of  $RRCI$  for the period of time during which the exploitation rate is assumed to have increased, and (2) to plot the averaged previous catches (i.e. as an equilibrium

approximation) against the smoothed  $RRCI$  in order to directly estimate the approximate  $MSY$ .

We suggest that this simple method may also be a valuable addition to conventional models when effort data are available but when there is no clear evidence that the fishing effort has been correctly standardized. Such a situation is well known in many tuna fisheries. Because new fish-finding devices and many technical innovations have been introduced on board purse seiners over the years, one of the major challenges faced by tuna scientists worldwide is to estimate the trend in increasing fishing power (Fonteneau et al., 1999). In addition, when fishermen use FADs equipped with radio beacons on a large scale, searching time is unsuitable to measure fishing effort (Hallier, 1994). Even when fishing effort is well standardized, these proxies of the maximum sustainable yield ( $MSY$ ) may offer a way to provide the information needed to select the most plausible production model among different choices.

**Acknowledgements.** We appreciate the comments given by the participants of the “First meeting of the ICCAT Working Group on Stock Assessment Methods”, celebrated in Madrid, Spain (April 8–11, 2000). We would like to thank S. Garcia (FAO, Rome) for his encouragement in this type of approach and the two anonymous referees, for their thoughtful comments on the earlier version of this manuscript.

## ANNEX

We consider a fishery with a constant increment  $A$  in fishing effort (i.e.,  $f_{t+1} = f_t + A$ ) and we suppose that the extinction mortality  $r$  is achieved after  $n$  steps, thus:  $nA = \frac{r}{q}$ . If we assume a Schaeffer type model with the Gulland’s equilibrium approximation, at  $t + 1$  the catch at equilibrium ( $C^{eq}$ ) is:

$$C_{t+1}^{eq} = qK \left[ 1 - \left( \frac{q}{r} \right) f_{t+1}^{eq} \right] f_{t+1}^{eq} \quad (10)$$

substituting  $f_{t+1}^{eq}$  by  $f_t^{eq} + A$ , leads to:

$$C_{t+1}^{eq} = qK \left[ 1 - \left( \frac{q}{r} \right) (f_t^{eq} + A) \right] (f_t^{eq} + A) \quad (11)$$

After some developments and bearing in mind that

$$C_t^{eq} = qK \left[ 1 - \left( \frac{q}{r} \right) f_t^{eq} \right] f_t^{eq} \quad (12)$$

we obtain:

$$\begin{aligned} C_{t+1}^{eq} &= C_t^{eq} + qK \left[ \left( 1 - \frac{q}{r} f_t^{eq} \right) A \right. \\ &\quad \left. - \frac{q}{r} f_t^{eq} \left( A - A^2 \frac{q}{r} \right) \right] \end{aligned} \quad (13)$$

As a result,  $\Delta C^{eq} = 0$  if:

$$qK \left[ \left( 1 - \frac{q}{r} f_t^{eq} \right) A - \frac{q}{r} f_t^{eq} \left( A - A^2 \frac{q}{r} \right) \right] = 0 \quad (14)$$

Consequently:

$$1 - \left( \frac{q}{r} f_t^{eq} \right) - \frac{q}{r} f_t^{eq} - A \frac{q}{r} = 0 \quad (15)$$

$$\text{thus } f_t^{eq} = \frac{r}{2q} - \frac{A}{2} \quad (16)$$

$$\text{As } f_{t+1}^{eq} = \frac{r}{2q} + \frac{A}{2} \quad (17)$$

averaging  $f_t^{eq}$  and  $f_{t+1}^{eq}$  leads to:

$$\bar{f}_{(\Delta Ceq=0)} = (f_t^{eq} + f_{t+1}^{eq})/2 = \frac{r}{2q} \quad (18)$$

By definition we know that

$$\frac{r}{2q} = f_{msy} \quad (19)$$

$$\text{so } \bar{f}_{(\Delta Ceq=0)} = f_{msy} \quad (20)$$

Considering now the observed CPUE at time  $t$ :

$$CPUE_t^{obs} = qK \left( 1 - \frac{q}{r} f_t^{eq} \right) \quad (21)$$

The observed catch ( $C_t^{obs}$ ) equals the observed CPUE multiplied by the observed fishing effort ( $f_t^{obs}$ ):

$$C_t^{obs} = qK \left[ 1 - \left( \frac{q}{r} \right) f_t^{eq} \right] f_t^{obs} \quad (22)$$

$$\text{and } C_{t+1}^{obs} = qK \left[ 1 - \left( \frac{q}{r} \right) f_{t+1}^{eq} \right] f_{t+1}^{obs} \quad (23)$$

With the same type of development mentioned above, when  $\Delta C^{obs} = 0$ , we obtain:

$$1 - \left( \frac{q}{r} f_t^{eq} \right) - \frac{q}{r} f_t^{obs} - A \frac{q}{r} = 0 \quad (24)$$

$$\text{thus } \frac{r}{q} = f_t^{eq} + f_t^{obs} + A \quad (25)$$

but keeping in mind the Gulland's equilibrium approximation,

$$f_t^{eq} = \frac{1}{L} \sum_{i=0}^{L-1} f_{t-i}^{obs} \quad (26)$$

we simplify to

$$f_t^{eq} = \frac{1}{L} \left[ L f_t^{obs} - A \left( \sum_{i=0}^{L-1} i \right) \right] = f_t^{obs} - A \left( \frac{L-1}{2} \right) \quad (27)$$

Substituting  $f_t^{eq}$  by this value in the previous equation leads to:

$$f_t^{obs} = \frac{r}{2q} - \left( \frac{A}{2} \right) + \left( \frac{A(L-1)}{4} \right) \quad (28)$$

In the same way, at  $t+1$  we have:

$$f_{t+1}^{obs} = \frac{r}{2q} + \left( \frac{A}{2} \right) + \left( \frac{A(L-1)}{4} \right) \quad (29)$$

As a result:

$$(f_t^{obs} + f_{t+1}^{obs})/2 = \bar{f}_{(\Delta Cobs=0)}^{obs} = \frac{r}{2q} + A \left( \frac{L-1}{4} \right) \quad (30)$$

which leads to:

$$f_{msy} = \bar{f}_{(\Delta Cobs=0)}^{obs} - A \left( \frac{L-1}{4} \right) \quad (31)$$

It thus appears that for species with relative high intrinsic rate of population growth (such as skipjack) and for a moderate increase in fishing effort, the bias is weak; i.e., if  $L = 3$ , we have:

$$f_{msy} = \bar{f}_{(\Delta Cobs=0)}^{obs} - \left( \frac{A}{2} \right) \quad (32)$$

Now, for performing MSY, we know that:

$$C_{t(\Delta Cobs=0)}^{obs} = qK \left[ 1 - \left( \frac{q}{r} \right) f_{t(\Delta Cobs=0)}^{eq} \right] f_{t(\Delta Cobs=0)}^{obs} \quad (33)$$

and

$$C_{t+1(\Delta Cobs=0)}^{obs} = qK \left[ 1 - \left( \frac{q}{r} \right) f_{t+1(\Delta Cobs=0)}^{eq} \right] f_{t+1(\Delta Cobs=0)}^{obs} \quad (34)$$

The maximum catch observed at the top of the yield curve between  $t$  and  $t+1$  is in fact slightly larger than the corresponding catches at  $t$  and  $t+1$  but this difference can be neglected. Accordingly,

$$C_{(\Delta Cobs=0)}^{obs} \approx qK \left[ 1 - \left( \frac{q}{r} \right) \bar{f}_{(\Delta Cobs=0)}^{eq} \right] \bar{f}_{(\Delta Cobs=0)}^{obs} \quad (35)$$

As mentioned above,

$$\bar{f}_{(\Delta Cobs=0)}^{obs} = f_{msy} + A \left( \frac{L-1}{4} \right) \quad (36)$$

$$\text{as } \bar{f}_{(\Delta Cobs=0)}^{eq} = \bar{f}_{(\Delta Cobs=0)}^{obs} - A \left( \frac{L-1}{2} \right) \quad (37)$$

$$\text{thus } \bar{f}_{(\Delta Cobs=0)}^{eq} = f_{msy} - A \left( \frac{L-1}{4} \right) \quad (38)$$

and

$$C_{(\Delta C_{obs}=0)}^{obs} \equiv qK \left[ 1 - \left( \frac{q}{r} \right) \left( f_{msy} - A \left( \frac{L-1}{4} \right) \right) \right] \\ \left( f_{msy} + A \left( \frac{L-1}{4} \right) \right) \quad (39)$$

$$C_{(\Delta C_{obs}=0)}^{obs} \equiv qK \left( 1 - \left( \frac{q}{r} \right) f_{msy} \right) f_{msy} + \\ qK \left[ A \left( \frac{L-1}{4} \right) + \left( \frac{q}{r} \right) \left( A \left( \frac{L-1}{4} \right) \right)^2 \right] \quad (40)$$

$$C_{(\Delta C_{obs}=0)}^{obs} \equiv MSY + \\ qK \left[ A \left( \frac{L-1}{4} \right) + \left( \frac{q}{r} \right) \left( A \left( \frac{L-1}{4} \right) \right)^2 \right] \quad (41)$$

Substituting  $A$  by  $\frac{r}{qn}$  in the previous equation gives:

$$C_{(\Delta C_{obs}=0)}^{obs} \equiv MSY + \\ \left( \frac{Kr}{n} \right) \left( \frac{L-1}{4} \right) \left[ 1 + \left( \frac{L-1}{4n} \right) \right] \quad (42)$$

$$\text{As } \frac{Kr}{4} = MSY \quad (43)$$

we obtain:

$$C_{(\Delta C_{obs}=0)}^{obs} \equiv MSY + \\ MSY \left( \frac{L-1}{n} \right) \left[ 1 + \left( \frac{L-1}{4n} \right) \right] \quad (44)$$

$$C_{(\Delta C_{obs}=0)}^{obs} \equiv \\ MSY \left[ 1 + \left( \frac{L-1}{n} \right) \left[ 1 + \left( \frac{L-1}{4n} \right) \right] \right] \quad (45)$$

For a species such as skipjack, assuming  $L = 3$  and  $n = 20$  (i.e., under a Schaeffer-model this means that the maximum sustainable yield can be reached after 10 years) the bias appears to be close to 10%. With this consideration in mind, averaging the previous catches can be seen as an attempt to reduce this potential bias.

## References

- Anderson, R.C., 1999. The Maldivian tuna fishery and Indo-Pacific Ocean variability. Doc. IOTC, WPTT/99/07, Mahé.
- Ariz, J., Delgado, A., Fonteneau, A., Gonzalez, F., Pallares, P., 1992. Logs and tunas in the Eastern tropical Atlantic. A review of present knowledge and uncertainties. ICCAT Coll. Vol. Sci. Pap. 40, 421–446.
- Bard, F.X., Antoine, L., 1986. Croissance du listao dans l'Atlantique Est. In: Symons, P.E.K., Miyake, P.M., Sakagawa, G.T. (Eds.), Proc. ICCAT conference on the international skipjack year program, Madrid, pp. 301–308.
- Cayré, P., Farrugio, H., 1986. Biologie de la reproduction du listao (*Katsuwonus pelamis*) de l'océan Atlantique. In: Symons, P.E.K., Miyake, P.M., Sakagawa, G.T. (Eds.), Proc. ICCAT conference on the international skipjack year program, Madrid, pp. 252–272.
- Fonteneau, A., 1986. Le modèle global et la dynamique du listao. In: Symons, P.E.K., Miyake, P.M., Sakagawa, G.T. (Eds.), Proc. ICCAT conference on the international skipjack year program, Madrid, pp. 198–207.
- Fonteneau, A., Gaertner, D., Nordstrom, V., 1999. An overview of problems in the catch per unit of effort and abundance relationship for the tropical purse seine fisheries. ICCAT Coll. Vol. Sci. Pap. 59, 258–278.
- Forsbergh, E.D., 1989. The influence of some environmental variables on the apparent abundance of Skipjack tuna, *Katsuwonus pelamis*, in the Eastern Pacific Ocean. Inter-Am. Tuna Trop. Comm. Bull. 19, 433–522.
- Fournier, D.A., Hampton, J., Sibert, J.R., 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. Can. J. Fish. Aquat. Sci. 55, 2105–2116.
- Garcia, S., 1996. The precautionary approach to fisheries and its implications for fishery research, technology and management: An updated review. In: Precautionary approach in fisheries. Part 2: Scientific papers. FAO Fish. Tech. Pap. 350, 1–75.
- Grainger, R.J.R., Garcia, S., 1996. Chronicles of marine fishery landings (1950–1994). Trend analysis and fisheries potential. FAO Fish. Tech. Pap. 359, 1–51.
- Hallier, J.P., 1994. Purse seine fishery on floating objects: what kind of fishing effort? What kind of abundance indices? In: Ardill, J.D. (Ed.), Proc. 5th Expert Consultation on Indian Ocean Tunas, Mahé Seychelles, pp. 192–198.
- Hilborn, R.M., Peterman, R.M., 1996. The development of scientific advice with incomplete information in the context of precautionary approach. Precautionary approach in fisheries, Part 2: Scientific papers. FAO Fish. Tech. Pap. 350, 77–101.
- Hoenig, J.M., Warren, W.G., Stocker, M., 1994. Bayesian and related approaches to fitting surplus production models. Can. J. Fish. Aquat. Sci. 51, 1823–1831.
- Laloë, F., 1988. Un modèle global avec quantité de biomasse inaccessible dépendant de la surface de pêche : application aux données de la pêche d'albacores (*Thunnus albacares*) de l'Atlantique Est. Aquat. Living Resour. 1, 231–239.
- Maury, O., 1999. Multi-fleet non-equilibrium production models including surface to assess tuna stocks dynamics. Doc. IOTC WPTT/99/05, Mahé.
- McAllister, M.K., Kirkwood, G.P., 1998. Bayesian stock assessment: A review and example application using logistic model. ICES J. Mar. Sci. 55, 1031–1060.
- Pella, J.J., Tomlinson, P.K., 1969. A generalized stock production model. Inter-Am. Tuna Comm. Bull. 13, 419–496.
- Pianet, R., 1998. The French purse seine tropical fishery in the Indian Ocean. Doc. IOTC TWS/98/2, Mahé.
- Punt, A.E., Hilborn, R., 1997. Fisheries stock assessment and decision analysis. The Bayesian approach. Rev. Fish Biol. Fish. 7, 35–63.