An evaluation of management strategies for Atlantic tuna stocks*†

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SUMMARY: International agreements for the International Commission for the Conservation of Atlantic Tunas (ICCAT) convention area imply that Atlantic tuna stocks should be managed by strategies based on maximum sustainable yield (MSY); however, there is concern whether this will actually ensure sustainability with sufficiently high probability consistent with the principals of the precautionary approach. Therefore, the performance of MSY management strategies based on current assessment procedures was evaluated using a computer simulation framework. The framework includes the data collection, assessment, prediction, and management processes, as well as the implementation of management regulations. It therefore provides an integrated way to evaluate the relative importance of and the interactions between each component of the system with regard to the overall success of the management strategy. The study elucidates guidelines about assessment and management that are general enough to be applied to all tunas in the Atlantic Ocean. It does so by comparing different hypotheses about management and assessment for three stocks (North Atlantic albacore, Atlantic bigeye and East Atlantic skipjack), which are representative of the variety encountered (i.e. from data rich to poor and tropical to temperate waters) in ICCAT stocks. Management performance was especially sensitive to the carrying capacity of the stock. The type of proxy used for MSY was more important to the success of the procedure than the frequency of assessment or the number of indices used in the assessment. Whilst the procedure was successful at achieving the management objectives for albacore, it was only partially successful for bigeye and was too conservative for skipjack.

Key words: albacore, bigeye, skipjack, management, strategy, evaluation, simulation, ICCAT.

INTRODUCTION

This study uses a simulation framework to develop management strategies, consistent with the International Commission for the Conservation of Atlantic Tunas (ICCAT) Convention. The robustness of these strategies is tested for different manage-

ment/assessment options and hypotheses about the dynamics of three contrasting tuna stocks. The study stocks were North Atlantic albacore, Atlantic bigeye and East Atlantic skipjack, chosen since they represent a variety of stocks from data rich to poor and from those inhabiting tropical to temperate waters.

Management strategies for Atlantic tunas should be consistent with the precautionary approach (FAO 1996), as embodied in the Code of Conduct for Responsible Fisheries (FAO, 1995) and the Agree-

ment for the Implementation of the Provisions of the United Nations Convention of the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (Doulman, 1995). In addition, management strategies that can be considered by ICCAT are restricted by Article VIII of the Basic Texts which states that "*The Commission may, on the basis of scientific evidence, make recommendations designed to maintain the populations of tuna and tuna-like fishes that may be taken in the Convention area at levels which will permit the maximum sustainable catch.*" Here maximum sustainable catch is interpreted as the Maximum Sustainable Yield (MSY).

However, it has been pointed out (Rosenberg and Restrepo, 1995) that stocks managed to provide MSY may not lead to sustainable and/or optimal management because of:

i) Uncertainties associated with the data

ii) Simplifying assumptions made in modelling biological processes

The Standing Committee on Research and Statistics of ICCAT (ICCAT, 1999a) therefore recommended that current assessment and management systems be evaluated through computer simulations using the type of framework developed by Kell *et al.* (1999a, b). This allows the reliability of decisions under a variety of plausible hypotheses about the system to be measured directly by comparing the actual realisation of objectives with anticipated results.

Management strategies can be expressed as harvest control rules (HCR), which are pre-agreed actions taken conditionally on quantitative comparisons between indicators of the status of the stock and some sustainability or optimality indicators. These HCR are a form of adaptive management (Walters, 1986). For Atlantic Tuna stocks, a HCR consistent with the Basic Texts is to reduce fishing mortality whenever the biomass of a stock falls substantially below the biomass that would on average produce MSY (B_{MSY}) and/or when fishing mortality substantially exceeds the fishing mortality that on average would produce MSY (F_{MSY}) for a stock. Such a control rule would also have to specify how effort or catch is to be reduced, by imposing quotas or by reducing fishing effort.

Once a proposed management strategy has been coded as an HCR, simulation can be used to conduct experiments that evaluate the response of the fishery system to the strategy. The framework includes mathematical representations of both the 'true' and the observed systems (data collected, assessment model used and reference points used to guide HCRs and their implementation) and so is able to investigate the robustness of management strategies to both the intrinsic properties of the natural system and to our ability to understand, monitor and control them.

Examples of factors that can be investigated are long-term fluctuations in productivity (Fromentin *et al.*, 1999), errors in estimating fishing effort, choices of assessment models, biological reference points and data collection strategies. Importantly, such a framework has the advantage of considering the interactions between all these components and provides an integrated way to evaluate the relative importance of system components for the overall success of management (Wilimovsky, 1985; De la Mare 1998; Holt 1998).

METHODS

The simulation model framework is illustrated in Figure 1. The "true" stock and fishery dynamics are represented as the operating model, from which pseudo-data are sampled. These data are then used within an assessment procedure to determine the status of the stock and, depending on the perception gained, management controls are applied to the fishery.

The approach is able to model the uncertainties discussed by Rosenberg and Restrepo (1995). These include: process error due to natural variation in dynamic processes (e.g. recruitment, somatic growth, natural mortality); measurement error generated in collecting observations from a population; estimation error that arises from trying to model the dynamic process (i.e. during the assessment process); and implementation error since management actions are never implemented perfectly. These uncertainties can be modelled as random variables for which values are obtained using Monte Carlo simulation. Performance statistics in the form of probability distributions are then collected and used to evaluate the performance of management strategies. Such statistics are related to the management objectives and typically include biological constraints (the probability of the stock being above some minimum biological threshold) and economic measures (value of the fishery catch over time).

The model was written in Visual Basic, calling routines from the FishLab library. This allows for modular programming and helps to ensure the integrity of component algorithms.
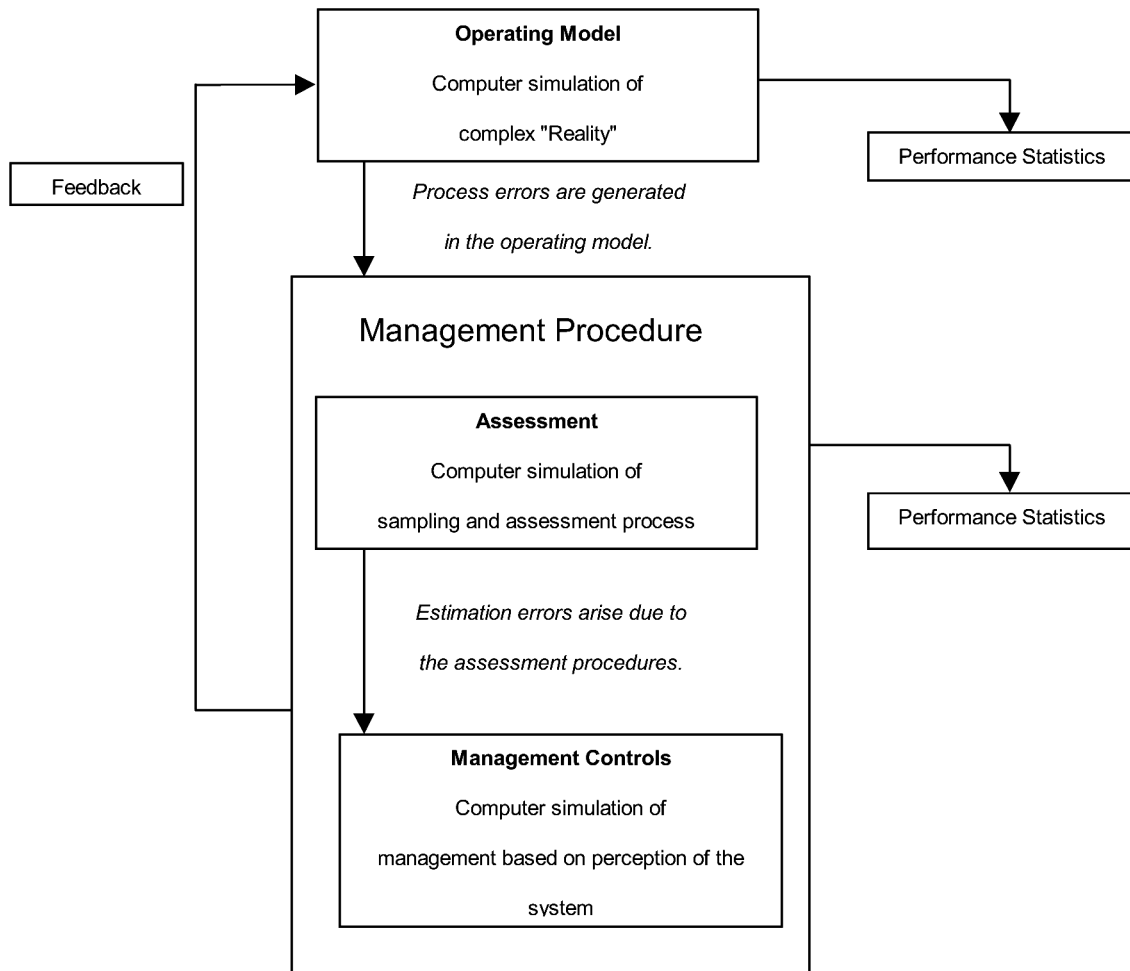
FIG. 1. – Simulation model structure (after ICES, 1994).

The operating model

The operating model (i.e. the true system) is an age-structured forward projection population model in which recruitment, exploitation pattern, growth, maturity, and natural mortality are modelled as random variables. A greater variety of historic stock status can be modeled using such forward projection models than using virtual population analysis (VPA), the usual assessment method for the study stocks. VPA reconstructs a stock's historic status using total catch-at-age data and the main source of variation is only in the stock status in the current year.

Future stock status is determined by catches, which are set by the management procedure that combines the perception of the stock and the implementation of management. The historical stock is conditioned on both the observed catch and catch per unit effort (CPUE) so that current status is consistent with the observations from the fishery.

Assumptions on selectivity, growth, maturity and natural mortality are consistent with those made by the SCRS ICCAT stock assessment group (ICCAT, 1999b, 2000a, b).

Abundance and fishing mortality at age are obtained using a forward population model constrained for different ratios of current to virgin biomass. The model is then fitted to explain the trends in indices of abundance, given the observed yields and biological characteristics of the stock. The stock recruitment relationship was parameterised in terms of steepness and virgin biomass steepness (Francis, 1992), where steepness was assumed to be less for temperate than for tropical tunas: i.e. 0.6 for albacore and 0.9 for bigeye and skipjack.

Aged structured population model

$$N_{age,year+1} = R_{year+1}$$

$$N_{age+1,year+1} = N_{age,year} e^{-\left(M_{age,year}+\sum_{fleet} S_{fleet,age,year} FMult_{fleet,year}\right)}$$

$$N_{PlusGroup,year+1} =$$

$$= N_{PlusGroup,year} e^{-\left(M_{PlusGroup,year}+\sum_{fleet} S_{fleet,PlusGroup,year} FMult_{fleet,year}\right)} +$$

$$+ N_{PlusGroup-1,year} e^{-\left(M_{PlusGroup-1,year}+\sum_{fleet} S_{fleet,PlusGroup-1,year} FMult_{fleet,year}\right)}$$

Recruitment

Recruitment is modelled as a Beverton and Holt stock recruitment relationship

$$R_t = \frac{aSSB_{t-RecruitAge}}{b + SSB_{t-RecruitAge}} e^{\varepsilon} e^{-\frac{\sigma^2}{2}}$$

where

$$\varepsilon \sim N\left(0, \sigma^2\right)$$

A CV for recruitment of 40% was assumed for all stocks.

Selectivity

Selectivity is decomposed into age and year effects, which are both modelled as log normal random variables. i.e.

$$\log\left(Selectivity_{age,Year}\right) \sim \left(Selectivity_{age}, \sigma^2_{age}\right) -$$

$$- \frac{\sigma^2_{age}}{2} + N\left(0, \sigma^2_{age}\right) - \frac{\sigma^2_{age}}{2}$$

Fishing mortality

Fishing mortality is modelled as the sum of the partial Fs of the fishing fleets.

$$F_{age,year,stock} = \sum_{fleet}^{NFleets} \sum_{area}^{NAreas} \times Selectivity_{age,year,fleet.area,stock} \times$$

$$\times q_{fleet,year} \times Effort_{year,fleet,area}$$

Catch-at-age

Catch-at-age is modelled by the catch equation

$$Catch_{fleet.age,year} = N_{age,year} \frac{F_{fleet,age,year}}{F_{age,year} + M_{age,year}} \times$$

$$\times \left(1 - \exp\left(-F_{age,year} - M_{age,year}\right)\right)$$

Natural mortality

The expected values of natural mortality are given by an age specific vector and are equal to the values assumed in the current assessment. Uncertainty is then modelled assuming that M at age is multivariate-normal distributed. On ecological grounds, it is expected that similar life history stages will experience similar levels and variations in natural mortality. Therefore, where adjacent age classes had the same expected value a correlation of 1.0 between M-at-age was assumed.

Growth

Growth was assumed to follow a Von Bertalanffy growth model

$$Length_{age} = L_{\infty}\left\{1.0 - e^{-K(age-t_0)}\right\}$$

and weight at age was determined by the length weight relationship

$$Weigth_{age} = \alpha Length_{age}^{\beta}$$

Uncertainty in the expected length at age was modelled by making K a random variable within a year i.e.

$$K \sim N(0, \sigma^2_K)$$

Maturity

The proportion of individuals mature is considered as an age specific vector; no uncertainty was modelled.

Estimation of effort by fleet

Effort was estimated for each fleet by solving the catch equation for each fleet. Catch per unit effort was then derived as the ratio of catch to effort.

Calculation of Maximum Sustainable Yield

If the functional form of the stock recruitment relationship is known, then equilibrium spawning stock can be derived as the product of spawner per recruit (SPR) and recruitment i.e.

$$SSB(F) = SPR(F) \times R(F)$$

For the Beverton and Holt stock recruitment model, rearranging SSB and R gives SSB as a function of spawner per recruit:

$$SSB = a\frac{SSB}{R} - b$$

This allows both spawner per recruit and recruitment to be derived as functions of fishing mortality:

$$SSB(F) = SPR(F) \times R(SPR(F))$$

Likewise, equilibrium yield can also be derived as a function of fishing mortality:

$$Yield(F) = YPR(F) \times R(SPR(F))$$

The maximum value of yield calculated from this relationship corresponds to the maximum sustainable yield (MSY) and the fishing mortality and spawning stock biomass to F_{MSY} and B_{MSY} respectively.

Conditioning the operating model

Because of uncertainties associated with the data and model assumptions, current stock status was made a factor in the experimental design. This was possible since the operating model is based upon a forward projection that allows a variety of historic and future responses to exploitation to be modelled. Spawning stock biomass in the operating model at the start of the management period corresponded to one of three states within an experiment:

   i) Overfished
   ii) Close to B_{MSY}
   iii) Underfished

This was achieved by constraining the spawning stock biomass at the start of the management period to be a ratio of the virgin spawning stock biomass (depletion level). The effect of this was to model stocks with different carrying capacities and correspondingly different initial depletion levels (i.e. at the start of the management period). This constraint results in vastly different historical trends for the different biological reference points and stock indicators (Fig. 2).

The forward projection was validated by comparison to the most recent assessment made by ICCAT. In all cases when current stock status in the operating model was similar to that in the assessment, historic time series were also similar.

The ICCAT management procedure

Although no formal management procedure exists within ICCAT, the assessment approach used for all stocks tends to be very similar (Fig. 3). Assessment process tasks are performed by individual countries, by the secretariat or by assessment working groups. Data on landings (L) are collected by member states; catches are sampled so that the total length frequency distributions of the catches of the various fleets (LF) can be estimated. In addition, indices of abundance (U) are prepared wherever possible by national scientists using effort data. Total catches and the length frequency samples and fishing effort are sent to the ICCAT secretariat for collation and preparation of catch-at-age data.

Total landings and length frequency distributions are then combined by the ICCAT secretariat with a growth model to generate landings by age class (C). The catch-at-age data are then typically analysed using virtual population analysis to derive estimates of numbers (N) and fishing mortality (F) at age. Natural mortality (M) is generally unknown and has to be assumed. Once the current stock status is estimated, projections are made to determine future status of the stock under various catch or effort regimes.

For the purposes of the current study, the above process has been simplified. The operating model generates catch-at-age and effort data that are used to provide estimates of current stock status and productivity. It was assumed that all catches were reported and that there was no discarding. The assessment method used is FADAPT Version 4 (Restrepo, pers. comm.), and the target reference points chosen for use in management were all proxies for F_{MSY} i.e. $F_{0.1}$, $F_{30\%SPR}$ and $F_{40\%SPR}$, where $F_{30\%SPR}$ and $F_{40\%SPR}$ are the fishing mortalities that correspond to values of spawner per recruit that are 30 and 40% respectively of the virgin values (i.e. fishing mortality is zero).

Proxies for MSY and B_{MSY} were calculated from the yield and spawner per recruit curves times mean recruitment. A stock projection (where future recruitment is equal to the geometric mean recruitment of the last five years) is then made to estimate catches.

The implied management objective of ICCAT is to maintain the stock at a level that will support the maximum sustainable yield; if the stock is below this level (i.e. overfished), then it has to be rebuilt to or above this level within an appropriate time. If fishing mortal-
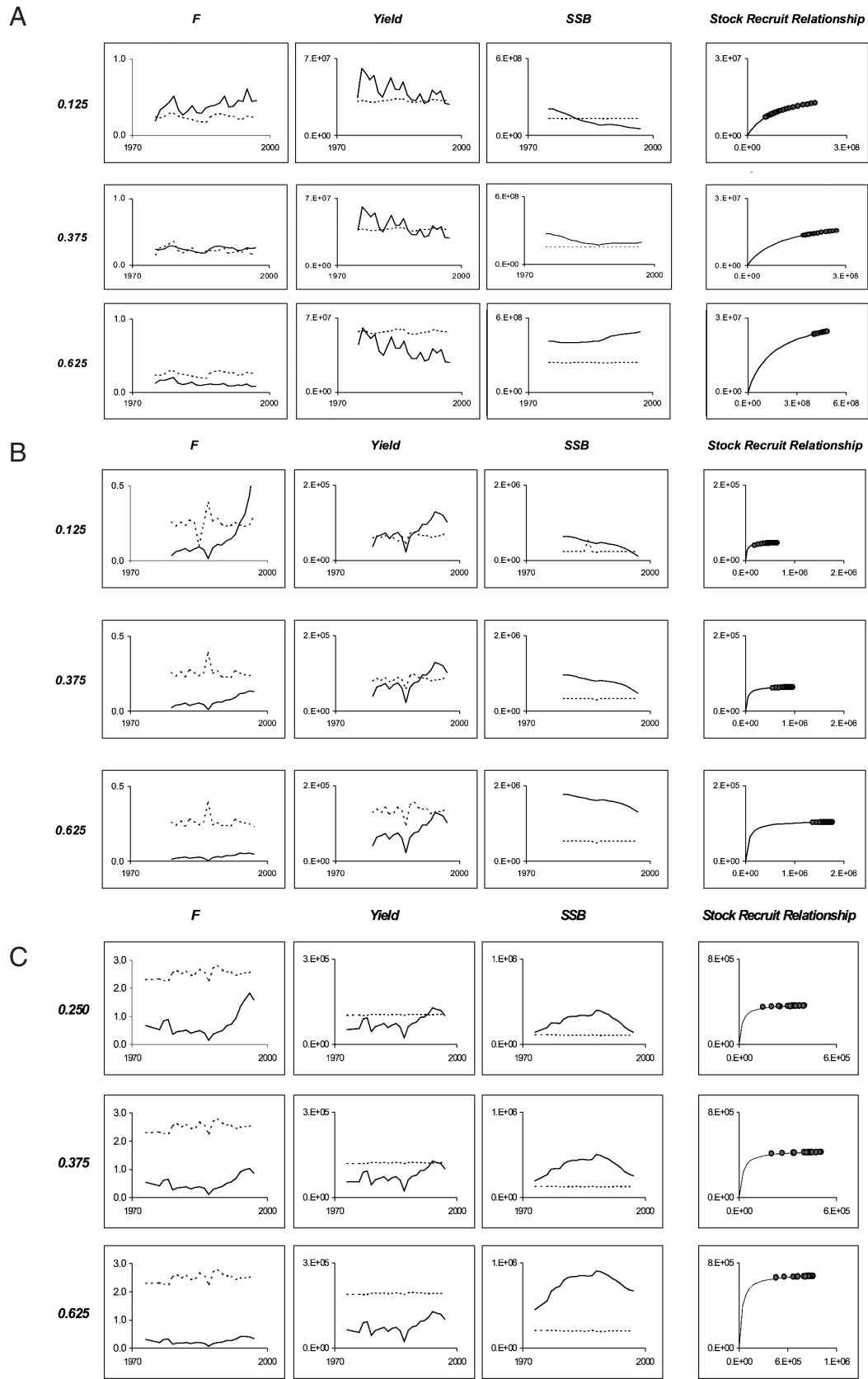
FIG. 2. – Historical stock status (solid lines): Fishing mortality (F), yield and spawning stock biomass (SSB) and spawning stock-recruitment relationships at three carrying capacity levels for a) albacore, b) bigeye and c) skipjack. Dotted lines represent reference points, F_{msy}, MSY and SSB_{msy}. Circles are the expected recruitments for the expected historical biomasses.
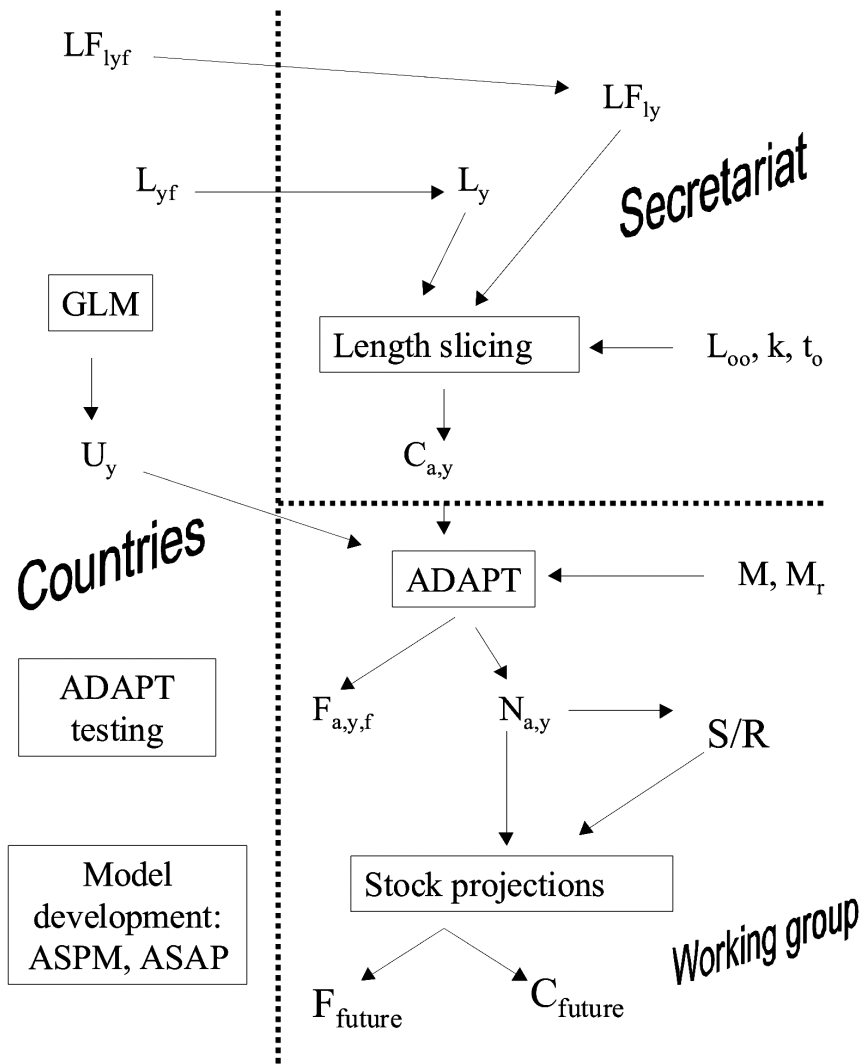
FIG. 3. – Idealised ICCAT assessment process. L = landings, LF = length frequency samples, U = index of abundance, C = landings by age class, M = Natural mortality, L_{oo}, k and t_o = growth parameters, S = selectivity, N = Abundance, F = Fishing mortality, S/R = Stock- ecruitment relationship, C_{future} = Constant catch strategy, F_{future} = Constant mortality strategy. Subscripts are: l = length, a = age, y = year, f = fleet. Dotted lines separates work done by ICCAT countries from that done by the ICCAT secretariat and the ICCAT working groups.

ity is greater than F_{msy} (i.e. overfishing is occurring), then F must be reduced. This objective can be represented in the form of a harvest control rule, although these have yet to be strictly defined by ICCAT for a given stock. Lately, however, some regulations have been imposed to rebuild stocks of species like bluefin and swordfish. In this study we therefore consider a harvest control rule that attempts to rebuild the stock when it is estimated to be overfished:

1. If the spawning stock biomass is below 90% of that at MSY (B_{msy}), then a rebuilding plan is implemented, i.e. the total allowable catch (TAC) is set to the maximum catch that allows the stock to recover to B_{msy} within a period of one lifespan.

2. Every time an assessment is conducted, stock status is re-assessed and the TAC is adjusted so that the stock is still projected to reach B_{msy} (as estimated at the start of the period) by the original rebuilding date. If the stock does not actually rebuild by the target date, another rebuilding plan is implemented. If the stock is between B_{msy} and 1.1 times B_{msy} the TAC is not adjusted.

3. If the stock is above 1.1 B_{msy}, then a development plan is implemented, i.e. the total allowable catch (TAC) is set to the maximum catch that allows the stock to be reduced to B_{msy} within a period of one lifespan.

4. To prevent meaningless adjustments to the TACs, a rebuilding plan will only be implemented and subsequent TACs changed if catches need to be changed by more than 20% of the current or the original TAC levels respectively.

Study Stocks

Three stocks were chosen to represent the range of Atlantic tuna fisheries, i.e. North Atlantic albacore, Atlantic bigeye and East Atlantic skipjack.

Northern albacore

Albacore is a temperate/sub-tropical species widely distributed throughout the Atlantic Ocean and Mediterranean. Assessments are currently performed for two stocks (one in the South and one in the North Atlantic). The Northern stock has traditionally been exploited by a long line fishery for sub-adult (age ~ 4) and adult fish (age ≥ 5) and by a surface fishery targeting juvenile (age < 4) and sub-adult fish. The surface fishery historically comprised bait boats and trollers, but recently pelagic pair trawls and drift-nets have been introduced. The latter are, however, due to be phased out in January 2002.

Individuals mature at age five when they are about 90 cm in size. Maturity is assumed to be 50% at age five and 100% at older ages. Spawning is thought to occur at the beginning of the year (spring-summer months).

Routine assessments for the northern stock are performed using primarily ADAPT (Powers and Restrepo, 1992) but alternative approaches like ASAP (Legault and Restrepo, 1998) have been investigated. Both ADAPT and ASAP estimate that the current level of fishing mortality is above F_{msy}, 25 to 40% respectively (ICCAT, 1999b).

Management regulations currently in place for the northern stock limit the number of vessels to the average level of the period 93-95 and driftnet length to 2.5 km. Because of the results of the last assessment it is becoming increasingly likely that regulations will be implemented to reduce catches as well.

Bigeye

The distribution of bigeye tuna in the Atlantic Ocean extends between 50°N and 45°S. The stock is exploited by many different countries using three major gears: long-line, bait boat and purse seine. Growth is relatively fast, with fish reaching 100 cm by age three. At age three, 50% of fish are assumed mature and all are mature once they have reached age four.

Bigeye assessments are done assuming there is a single stock. Routine assessments are done with ADAPT, but other methods include forward Virtual Population Analysis and various forms of production models. No stock predictions have been made because of the contradictory results obtained from the different assessment models. The major regulations are a seasonal spatial closure on juvenile fishing grounds, a minimum size at 3.2 kg and a limit in the number of vessels to the average level of 1991-1992.

Skipjack

Skipjack, found in the tropical and subtropical areas of the Atlantic Ocean, are often associated with floating objects. This behaviour has been exploited by the two main fishing fleets, bait boat and purse seine fleets, since 1991, and it has led to increased catches during the last decade. Growth is highly variable throughout its range and this has precluded scientists from using size- or age-structured assessment models. The species spawns throughout the year.

Skipjack tuna assessments are done with generalised production model assuming two stocks exist, one in the east and another in the west. The seasonal spatial closure on bigeye juvenile fishing grounds also significantly affects skipjack.

Experimental design

Simulations are run as experiments, allowing the interaction between the management strategies and assumptions about the stock dynamics to be investigated.

Normally it is difficult to compare management procedures across species because data availability, fleet structure and assessment procedures are different between species. In order to be able to compare between species we have simplified the fishery systems and aggregated gears across national fleets and combined minor fleets. The fleets modelled are: longline, purse seine, baitboats, troll and "others", where others may include a combination of gears. The selection pattern of each of these fleets, however, is defined by the data existing for each stock.

In this study we are interested in comparing the performance of particular management strategies under different stock/fishery scenarios, where a management strategy is defined as the combination of a monitoring procedure, an assessment method and frequency, a reference point(s) and a harvest control rule. The monitoring procedure, assessment

method and harvest control rule were the same in all runs, but the method of setting the management target and frequency of assessments varied as follows:

Management strategies

F_{MSY} Proxy (3)	Assessment Frequency (2)
$F_{0.1}$	3 year cycle
$F_{30\%SPR}$	1/4 generation time
$F_{40\%SPR}$	

Generation time is calculated as the average age of the spawning stock weighted by the spawning potential of each age when only natural mortality is acting, i.e. the sum of age (A) times the proportion surviving to that age (S_A) times maturity at age (M_A) times weight-at-age (W_A), divided by the sum of survivors times maturity-at-age i.e.

$$\frac{\sum A \times S_A \times M_A \times W_A}{\sum S_A \times M_A \times W_A}$$

The stock/fishery scenarios considered aim to represent the combinations of life history characteristics, data availability and current stock status that may be encountered by ICCAT assessment working groups. They are defined by the 18 possible combinations of the following factors:

Stock scenarios

Stock (3)	Current Status (3)	Data Quality (2)
Northern Albacore	0.125 B_{Virgin}[1]	Poor (1 single abundance index for tuning)
Atlantic Bigeye	0.375 B_{Virgin}	Moderate (2 indices of abundance for tuning)
East Atlantic Skipjack	0.615 B_{Virgin}	

[1] 0.250 was used for skipjack because the value of 0.125 is incompatible with historical observations.

The combination of all possible management strategies and stock scenarios make 108 different treatments, all of which were run to allow the interactions to be investigated.

Model, estimation and measurement error were incorporated in the framework by explicitly modelling the assessment/management procedure. The management procedure is based upon VPA, a population model that reconstructs the stock history by making a backward projection assuming the total catch-at-age is known without error. It is also assumed that natural mortality and growth is constant and fixed. To initiate the backward projection the numbers- or fishing mortality-at-age of the oldest age in each cohort has to be estimated using catch per unit effort. In contrast, the operating model is a forward projection that includes process errors modelled as stochastic variations in natural mortality, recruitment, growth rate and selection. Therefore, the uncertainty in our ability to model the true system and to monitor catch, effort and biological data is explicitly included.

For each of the 108 combinations of treatments 100 replicate simulations were run, each associated with a random set of natural mortality, recruitment, growth and selection values.

The population and fleet parameters used in the experiments are presented in Appendix 1. Wherever possible the values used were the same as those used for the most recent assessment of each stock (ICCAT, 1999, 2000b and 2000c) and can be traced to comprehensive reviews of the biology of each stock (Bard, 1981; Bard and Capisano, 1991; Cayre *et al.*, 1988; Fonteneau and Marcille, 1991). In some cases values have had to be assumed since data were not available.

Analysis of performance

To simplify the comparison of overall performance of individual management strategies it was decided to analyse only two performance statistics: S_1, the ratio of SSB at the end of the rebuilding period to B_{MSY}; and S_2, the ratio of mean yield over the rebuilding period to MSY. The former is a measure of the success of a strategy in achieving the objective of maintaining the biomass of the stock at a level that will support MSY, whilst the later indicates how close the catches were to MSY during the rebuilding period. In as much as 100 stochastic simulations were run for each combination of treatments, only the median result is shown. The medians were used because the rebuilding plan is essentially concerned with targets rather than limits. Aiming at a target infers that the intention of managers is to be at a particular value, so it seems appropriate to use a measure of central tendency like the median. In contrast, aiming at a limit infers that the managers are trying to avoid a value with high probability, so an appropriate statistic may be a 90 or 95 percentile.

To identify significant main effects and interactions, an analysis of variance was performed on the two summary statistics. A stepwise selection procedure (SPlus version 6, Insightful Corp.) using both forward and backwards selection was used to

select significant terms as it was thought important that consistent methodology be applied across all stocks to select significant variables to aid in comparison. The resultant analyses of deviances are presented with tests for significance of the reported factors (marginal but non-significant factors are also included).

To compare the performance of management procedures across stocks and experimental treatments it is important to note the different starting status of exploitation of stocks at the beginning of the rebuilding period, as was shown at the beginning of the results section. A way to represent stock status is to show the yield prior to the start of the management procedure as a ratio of MSY (S_3) and the spawning stock biomass as a ratio of SSB_{msy} (S_4). A stock is closer to the target of management the closer both ratios are to 1. Note that, in our study, data were available up until 1997 and the first assessment was conducted in 1998. The year prior to the start of the procedure was therefore 1997.

RESULTS

The fishing mortality trends differ substantially between stocks. For albacore, overfishing ($F > F_{msy}$) has occurred during the whole history of the data if depletion is set to 0.125 and intermittently if depletion is set to 0.375. For bigeye, overfishing only occurs in the last few years when depletion is set to 0.125. For skipjack there is never overfishing.

The spawning stock biomass trends differ between the stocks and depletion levels. For albacore the stock is overfished ($SSB < SSB_{msy}$) for the greatest past of the history if depletion is set to 0.125, but not overfished at all for the other depletion levels. For bigeye, the stock is only overfished in the most recent years and when depletion is set to 0.125. For skipjack the stock is never overfished.

MSY estimates do not vary much for any stock within a depletion level, except for bigeye where a low observed catch in the mid 1980s changes the estimate substantially for a few years.

The stock recruitment relationships chosen exhibit strong compensation for bigeye and skipjack and weak compensation for albacore. As a result recruitment varied little in all the depletion scenarios for bigeye and skipjack, while for albacore there were substantial historical changes in recruitment, especially for depletion level 0.125 where recruitment has decreased by more than 50%.

Table 1 summarises the proxies for F_{msy}, MSY and B_{msy} estimated at the start of the management procedure. For albacore and bigeye $F_{40\%SPR}$ and $F_{30\%SPR}$ respectively are closest to F_{msy} for all depletion levels and thus can be used to estimate B_{msy} and MSY rather accurately. For skipjack, all of the proxy reference points underestimate F_{msy} and overestimate B_{msy}. However, all three proxies can be used to estimate MSY, although $F_{30\%SPR}$ gives the best results.

For all species and depletion levels, estimates of MSY are less dependent on the proxy used than B_{msy}

TABLE 1. – A comparison of proxies for MSY based reference points.

Albacore	F_{MSY}	0.125 MSY	B_{MSY}	F_{MSY}	0.375 MSY	B_{MSY}	F_{MSY}	0.625 MSY	B_{MSY}
Actual	0.25	31486080	131996024	0.26	37177141	157388291	0.27	56664532	241308515
$F_{0.1}$	0.50	37560399	53294963	0.53	54340154	75650740	0.55	91198088	125365428
$F_{30\%SPR}$	0.36	33562927	84495534	0.37	48309862	122949039	0.38	80808934	207055477
$F_{40\%SPR}$	0.27	29446637	112660714	0.28	42350145	163932050	0.29	70800335	276073880

Bigeye	F_{MSY}	0.125 MSY	B_{MSY}	F_{MSY}	0.375 MSY	B_{MSY}	F_{MSY}	0.625 MSY	B_{MSY}
Actual	0.29	76264	249192	0.24	91449	335564	0.23	140771	540449
$F_{0.1}$	0.21	73577	355591	0.17	90508	487229	0.17	140890	791646
$F_{30\%SPR}$	0.27	78203	276635	0.22	95962	381529	0.22	149230	622573
$F_{40\%SPR}$	0.20	72585	368847	0.17	89089	508705	0.16	138466	830098

Skipjack	F_{MSY}	0.250 MSY	B_{MSY}	F_{MSY}	0.375 MSY	B_{MSY}	F_{MSY}	0.625 MSY	B_{MSY}
Actual	2.64	105786	107616	2.61	123118	125757	2.59	194073	199195
$F_{0.1}$	1.13	100602	197086	1.14	118251	231464	1.14	188832	369224
$F_{30\%SPR}$	1.40	105798	170306	1.40	124299	200261	1.40	198372	319943
$F_{40\%SPR}$	0.92	94347	227075	0.92	110841	267015	0.92	176885	426590

Example Projections of Yield
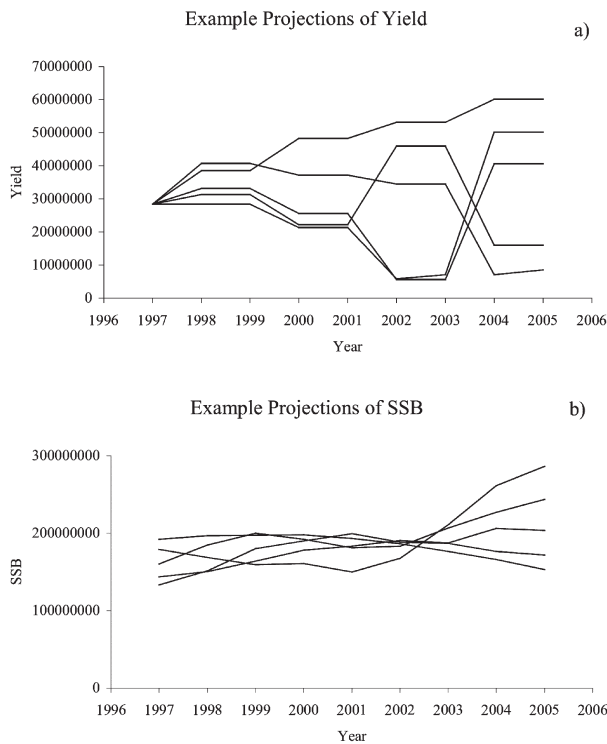

a)

Example Projections of SSB

b)

FIG. 4. – Examples of 5 model projections for albacore for selected simulations: a) yield, and b) spawning stock biomass.

or F_{msy}. The range of MSY values obtained from the different proxies varies by less than 25% for albacore and less than 12% for the other two species. B_{msy} and F_{msy} estimates obtained with different proxies, however, vary two or three times more than MSY estimates, probably because of the constant recruitment assumption used in their estimation. However, F_{msy} was found to be much less sensitive to the assumption about the level of depletion than either MSY or B_{msy}.

In the simulations the management strategy is a "constant catch policy" where the total allowable catch (TAC) is updated every time the stock is reassessed. This then leads to increasing yield variation over time (Fig. 4a), but in contrast it ensures that the level of variation in spawning stock biomass remains constant over time (Fig. 4b). This strategy aims therefore to reduce risk by ensuring that spawning stock biomass remains within a prescribed range.

The analyses of variance of S_1, the ratio of B at the end of the rebuilding period to B_{MSY}, and S_2, the ratio of mean yield over the rebuilding period to MSY, were able to separate, for each species, the most significant factors determining the performance of management.

For albacore, the analysis of S_1 indicated that the two most important factors for a successful management strategy were the carrying capacity of the stock and the proxy used for MSY (Table 2). Data quality and assessment frequency were also significant (> 5%) but not nearly as important as the previous two factors. The reason for the significant interaction between assessment frequency and carrying capacity was that, at the higher carrying capacity, a more frequent assessment policy resulted in the stock being closer to B_{msy} by the rebuilding year than it would have been with less frequent assessments. Analysis of S_2 revealed only three significant effects, which in order of significance were: carrying capacity, MSY proxy, and the quality of the data.

The analysis of S_1 for bigeye (Table 3) found that the most important effect was carrying capacity and the second was the proxy for MSY. There was a sig-

TABLE 2. – Albacore: Analysis of variance investigating significance of factors investigated for summary statistics, ratios of the SSB in the target rebuilding year to B_{MSY} and mean yield over the rebuilding period to MSY.

SSB in Rebuilding Year: B_{MSY}	DF	Deviance	Residual DF	Residual Deviance	F Value	PR > F
NULL			3598	1668.4		
MSY Proxy	2	105.6	3596	1562.8	162.2	0.0000
Assessment Frequency	1	1.1	3595	1561.7	3.2	0.0719
Data Quality	1	2.8	3594	1559.0	8.5	0.0036
Carrying capacity	2	387.8	3592	1171.2	595.7	0.0000
Assessment Frequency : Carrying capacity	2	2.5	3590	1168.7	3.8	0.0219

Mean Yield over rebuilding period: MSY	DF	Deviance	Residual DF	Residual Deviance	F Value	PR > F
NULL			3598	1670.0		
MSY Proxy	2	119.7	3596	1550.3	162.0	0.0000
Data Quality	1	4.8	3595	1545.4	13.1	0.0003
Carrying capacity	2	217.5	3593	1327.9	294.3	0.0000

TABLE 3. – Bigeye: Analysis of variance investigating significance of factors investigated for summary statistics, ratios of the SSB in the target rebuilding year to B_{MSY} and mean yield over the rebuilding period to MSY.

SSB in Rebuilding Year: B_{MSY}	DF	Deviance	Residual DF	Residual Deviance	F Value	PR > F
NULL			3958	4785,9		
MSY Proxy	2	99,7	3956	4686,2	64,4	0,0000
Data Quality	1	0,2	3955	4686,0	0,3	0,5907
Carrying capacity	2	1615,0	3953	3071,0	1043,3	0,0000
DataQuality :Carrying Capacity	2	12,9	3951	3058,1	8,4	0,0002

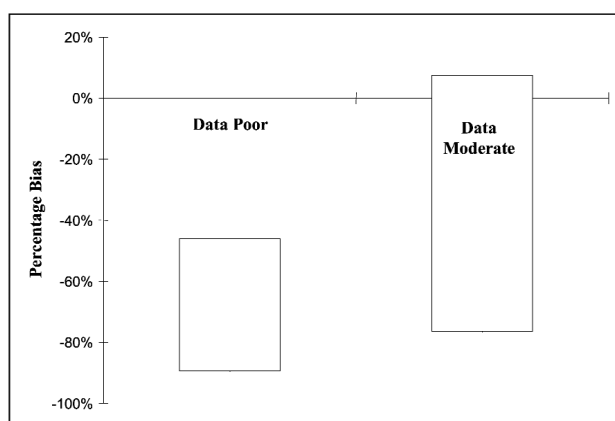| Mean Yield over rebuilding period : MSY	DF	Deviance	Residual DF	Residual Deviance	F Value	PR > F
NULL			3958	637,1		
MSY Proxy	2	4,7	3956	632,4	18,4	0,0000
Data Quality	1	9,5	3955	622,9	74,2	0,0000
Carrying capacity	2	113,6	3953	509,3	444,8	0,0000
Data Quality :Carrying Capacity	2	4,8	3951	504,5	18,8	0,0000

FIG. 5. – Bias in final year biomass estimated by the assessment model for a data rich and a data poor case for albacore. Boxes show the interquartile range for (estimated-true)/true.

nificant interaction between data quality and carrying capacity. The reason for the interaction was the greater bias in assessment based on the data poor than the data rich set. It should be noted that the effect of improving the data is not to increase precision but to reduce bias (Fig. 5). The analysis of S_2 only found three main effects to be significant, which, in order of significance, were carrying capac-ity, data quality, and the proxy used for MSY. In addition, there was a significant interaction between data quality and carrying capacity. This interaction occurred because bias was greater for the stock with the greatest carrying capacity.

Only carrying capacity and proxy for MSY were found to be significant in the analysis of S_1 for skipjack (Table 4). Three significant effects were found in the analysis of S_2 for skipjack, in order of significance these were proxy for MSY, carrying capacity and data quality. There were no significant interactions.

For stocks with high carrying capacities the stock is initially less likely to be overfished. In general, the most important factor for maintaining the stock at B_{msy} was the carrying capacity of the stock, followed by the proxy used to determine B_{msy}. These factors represent the dynamics of the stock over the long time scale. These factors were also important in determining mean yield, since management was set relative to the estimates of the two factors. Data quality was also important in determining mean yield. The stock assessment method used was VPA as implemented in ADAPT. Since the stock dynamics

TABLE 4. – Skipjack: Analysis of variance investigating significance of factors investigated for summary statistics, ratios of the SSB in the target rebuilding year to B_{MSY} and mean yield over the rebuilding period to MSY.

SSB in Rebuilding Year: B_{MSY}	DF	Deviance	Residual DF	Residual Deviance	F Value	PR > F
NULL			3551	3563,9		
MSY Proxy	2	37,4	3549	3526,5	20,3	0,0000
Carrying capacity	2	251,2	3547	3275,3	136,0	0,0000

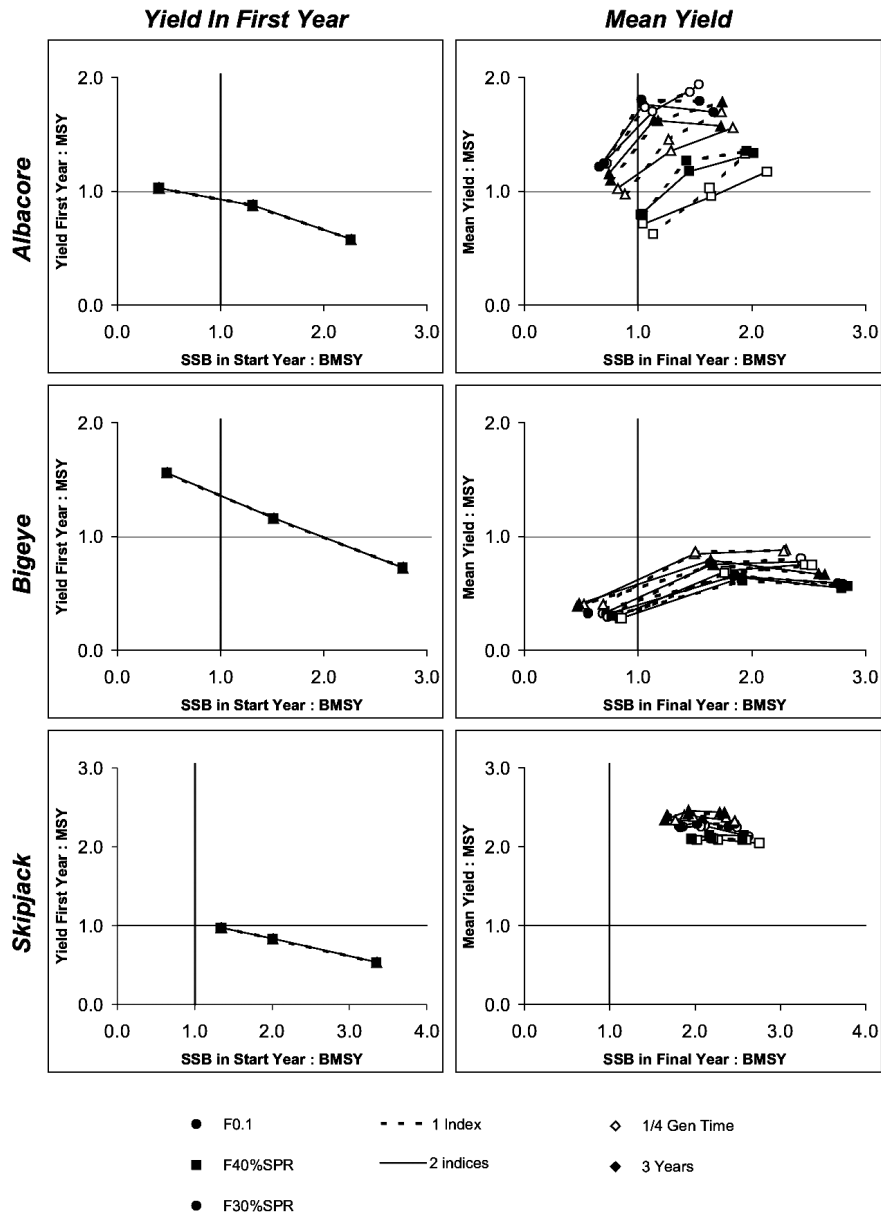| Mean Yield over rebuilding period : MSY	DF	Deviance	Residual DF	Residual Deviance	F Value	PR > F
NULL			3551	889,2		
MSY Proxy	2	43,7	3549	845,4	92,5	0,0000
Data Quality	1	1,0	3548	844,4	4,4	0,0364
Carrying capacity	2	6,0	3546	838,4	12,7	0,0000

FIG. 6. – Performance of a management procedure for three tuna stocks as a function of the different treatment scenarios. Left hand panels represent the status of the stock at the beginning of the procedure, and the right hand panels the status as a result of the procedure measured by the mean yield during the procedure and the SSB at the end of the procedure. All values are relative ratios of the MSY and SSB_{msy} targets. The shape of the symbol represents the type of proxy used, circles $F_{0.1}$, triangles $F_{30\%SPR}$ and squares $F_{40\%SPR}$. The colour of the symbol represents data quality, solid for two indices and open for one index. Lines connect treatments that are identical apart from the carrying capacity. The type of line represents the assessment cycle, hatched for every three years, solid for every 1/4 of a lifespan. The reference lines parallel to the x- and y-axes correspond to the MSY and B_{MSY} levels respectively.

of the assessment model and the operating model were similar, the convergence properties of VPA means that population estimates made by the assessment procedure are more uncertain in the recent period than in the long term. Setting yield is more influenced by short-term considerations whilst maintaining the stock at a level that will support MSY is more dependent on long-term considerations.

In summary, it is apparent that albacore, bigeye and skipjack are in a gradient from more to less like-

ly to be overfished in the initial year of the management procedure (Fig. 6). The management procedure only worked well for albacore but depended on the $F_{40\%}$ proxy chosen. For this species, if the stock was overfished, it recovered within one lifespan, and if the stock was underfished, it was able to increase yields and maintain SSB above SSB_{msy}. For bigeye, the procedure failed completely since if the stock was overfished it did not recover within one lifespan, and if it was underfished, it was unable to

increase yields. In fact, if the fishery was catching the target MSY level the procedure reduced catches below MSY. This effect could be just due to the presence of uncertainty in population parameters (process uncertainty). For skipjack, the procedure succeeded in reaching the targets as it allowed increases in yield and maintained SSB above SSB_{msy}. It could, however, be argued that if the goal of the skipjack fishery was to maximise yield whilst complying with the target, the management procedure failed by being too conservative and not allowing large enough increases in yield over the period of one lifespan.

DISCUSSION

Our study used ICCAT stocks as case studies; however, many of the conclusions of this study are likely to be relevant for other tuna stocks because the ICCAT management structure is representative of the structure of other international tuna commissions (Ward *et al.*, 2000). The management procedure selected in this study did not perform equally well for the three different stocks. This suggests that management strategies must be designed taking into account the biological characteristics of each specific tuna stock; it also suggests that a single strategy is unlikely to be appropriate for all ICCAT managed stocks (a conclusion also reached by Fromentin and Fonteneau, in press). In fact, such a management procedure may be too conservative for fast growing tunas like skipjack.

The performance of the management strategy was most sensitive to the carrying capacity of the stock and the type of proxy chosen as a reference point. The final status of the spawning stock and the yield stream obtained during the application of the strategy differed markedly, depending on the initial condition of the stock. The latter is not a surprising result because the procedure was not designed to produce an average level of yield but rather to drive this yield towards MSY. Also depending on the starting point, the average yield during the procedure would differ. The fact that the spawning stock at the end of one lifespan was so sensitive to the initial condition of the stock suggests that the procedure does not truly achieve its goal of achieving a target biomass, rather it operates as if B_{msy} was a limit indicator. In fact, it is unclear why the strategy performed poorly at rebuilding B, but relatively well at reaching MSY. In some cases, the choice of refer-ence point also affected performance. This highlights how the framework can reveal the real behaviour of a procedure. It also shows how important for the development of an appropriate management procedure it is to reduce the uncertainty about the current status of a stock, and its natural fluctuations over time (see e.g. Hjort 1914, Cushing 1982), and to determine the appropriate reference point for use during the assessment.

The type of assessment process does affect the strategy, but it seems that the type of proxy used for F_{msy} is more important than the frequency of assessments, so it is probably more productive to determine the right proxy to be used for a stock rather than to increase the frequency of assessments. This highlights how the framework developed can be used to determine the right balance between investment in tactical (periodic assessments) versus strategic research (development of assessment methods).

Our results suggest that the availability of more data tends to reduce bias rather than increase precision. This is an interesting result in light of the difficulty in obtaining fishery independent data for tunas. One of the advantages of fishery independent data is the reduction in biases, but our results suggest that such reduction may also be obtained through the use of more fishery dependent indices. It is important to note that it is not possible to say whether this sort of result reflects only these stocks and fisheries or if it is fairly general for all fisheries.

The current study has many limitations, including the fact that it only considers one type of management control. There are certainly many other types of controls that could be investigated with this framework, including constant catch strategies, or strategies that allow greater changes in catch between assessment cycles. Another limitation of this work is that it did not consider all the uncertainties present in the real world, some of which have been shown to affect the results of stock assessments. Examples of these effects are mis-reporting of catch (Fromentin, 2003), bias in estimates of biological parameters (Majkowski and Hampton, 1983; Bradford and Peterman, 1989; Tanaka, 1989; Clark, 1999; Hampton, 1999, Kell *et al.*, 1999), uncertainty with catch-at-age data because of ageing errors (Tyler *et al.*, 1989; Bradford, 1990; Beamish and McFarlane, 1995, Kell *et al.*, 2000) or because of the conversion from length to age through length slicing, and historic trends in population parameters.

Our framework only considers performance indicators related to the target species and ignores the

importance of other factors such as the effects of fishing on humans or on components of the environment other than the target species (Garcia *et al.*, 2000). Although it is clear that some of these factors are extremely important in the management of tunas, incorporating them into the simulation framework would require expanding of the operating and assessment models to include components of the fishery system that are presently very difficult to characterise quantitatively.

This research shows, like other studies (Ulltang, 1996), that the performance of the strategy was more dependent on the type of control (specifically the type of proxy used in the harvest control rule) than on the quality of the estimates of stock status. However, it remains to be seen whether this result depends on the fact that we only evaluated a constant catch strategy. Although much work has focused on estimation error that arises from trying to model the dynamic process during the assessment process, more work is needed to evaluate the robustness of current stock assessment and management procedures. In particular, attention should be given to the natural variation in dynamic processes, the error generated when collecting observations from a population, and error in implementing management actions.

This study aimed to elucidate general guidelines about assessment and management for a range of tuna stocks with different life histories before undertaking more detailed stock specific studies. The effects of many of these uncertainties on the performance of the management procedure for specific tuna fisheries will be investigated in the future with the framework. In particular, research will be carried out on the consequences of errors in catch and effort estimates induced by the response of fishing fleets to management, the effects of temporal trends in stock dynamics, the robustness of current practice to migration or movement of a stock across stock boundaries, and the problems created by spatial heterogeneity in tuna stocks. All this work will lead towards the development of general strategies based on life histories for stocks where data are limited.

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APPENDIX 1. DETAILS OF PARAMETERS USED IN THE FMSE SIMULATIONS.

Fleet parameters

Wherever possible four fleets were modelled for each stock: purse seine, long line, bait boat and another, which could be a fleet peculiar to a particular stock or else an aggregation of various fleets.

To make comparisons between stocks easier it was decided to have two indices of abundance per stock, so that both younger and older ages were represented. However, similar indices are not available for all the four stocks, as often indices are missing for particular age ranges and appropriate fleets. If more than two suitable indices were available, only two were chosen. If suitable indices did not exist for a particular fleet then indices were either generated by substituting an index for another fleet that fished on a similar age range or else by making assumptions about catch and effort trends. All indices are in numbers rather than biomass and were converted from biomass using catch- and weight-at-ages where necessary.

Albacore

The fleets used in the albacore simulation were long line, bait boat, troll and another. Selection pat-

Table 5. – Selection Pattern used in operating model

Age	Bait boat	Albacore Long line	Troll	Other	Age	Bait boat	Bigeye Long line	Purse seine	Age	Bait boat	Skipjack Long line	Purse seine
1	0.4169	0.0069	0.2586	0.1175	0	0.6225	0.0010	1.0000	0	0.0355	0.0841	0.0598
2	0.8666	0.0256	1.0000	1.0000	1	1.0000	0.0210	0.7251	1	1.0000	1.0000	1.0000
3	1.0000	0.4021	0.6411	0.5581	2	0.7164	0.1970	0.4501	2	0.5086	0.3124	0.4105
4	0.2972	0.7179	0.1030	0.2343	3	0.4178	0.6190	0.2404	3	0.4544	0.2440	0.3492
5	0.0707	1.0000	0.0188	0.1985	4	0.2015	1.0000	0.1438	4	0.4544	0.2440	0.3492
6	0.0832	0.8875	0.0116	0.4346	5	0.1072	0.9260	0.1310	5	0.4544	0.2440	0.3492
7	0.1519	0.8484	0.0138	0.7372	6	0.0594	0.6130	0.0968	6	0.4544	0.2440	0.3492
8	0.1893	0.9069	0.0088	0.6379	7	0.0551	0.6760	0.0105	7	0.4544	0.2440	0.3492
					8	0.0551	0.6760	0.0105	8	0.4544	0.2440	0.3492
					9	0.0551	0.6760	0.0105	9	0.4544	0.2440	0.3492
					10	0.0551	0.6760	0.0105	10	0.4544	0.2440	0.3492
					11	0.0551	0.6760	0.0105	11	0.4544	0.2440	0.3492

TABLE 6. – Historical series of yield used in operating model

	Albacore					Bigeye				Skipjack		
Year	Bait boat	Long line	Troll	Other	Year	Bait boat	Long line	Purse seine	Year	Bait boat	Long line	Purse seine
1975	17898752	10040400	9957222	5266524	1979	9591	27560	8824	1975	15095	19776	2386
1976	19750939	16657354	15077057	9181592	1980	12349	41678	9793	1976	26382	24831	4307
1977	15200661	15014529	18353465	7389131	1981	10124	41608	16454	1977	34734	44502	9905
1978	11186419	10153205	24312955	5156415	1982	6922	52026	14763	1978	39365	48694	4826
1979	16588059	8760365	24383801	4870286	1983	9796	33648	15833	1979	27560	8343	9591
1980	15729941	8433420	13106211	1882265	1984	11439	41599	16301	1980	41678	9204	12349
1981	12238526	8951480	11194713	2569742	1985	17651	48810	7757	1981	41608	15656	10124
1982	15286446	12315552	13009548	3074923	1986	15618	36796	9680	1982	52026	14476	6922
1983	18718277	16092773	13042920	4346404	1987	12631	3222	7734	1983	33648	15654	9796
1984	7069615	16724160	11136389	6950041	1988	9710	45541	8273	1984	41599	16063	11439
1985	11261641	17212216	10231739	3056898	1989	12672	55098	6964	1985	48810	7554	17651
1986	13996768	21410118	10960563	2077741	1990	18106	51333	9703	1986	36796	9286	15618
1987	16971719	7338482	11360235	1356888	1991	17750	61393	16588	1987	3222	7148	12631
1988	14975989	2947807	10691585	3373012	1992	16248	62271	17995	1988	45541	7859	9710
1989	14307712	1987595	10883586	4662522	1993	16467	62815	30289	1989	55098	6371	12672
1990	15608196	2436720	10512211	9015831	1994	20296	77885	31364	1990	51333	9407	18106
1991	8547369	5146809	9598768	6098818	1995	25552	74000	25347	1991	61393	16169	17750
1992	10564626	2901667	7707697	9821929	1996	19040	73660	26799	1992	62271	17467	16248
1993	12254428	7567995	6506703	14708150	1997	18721	66619	17551	1993	62815	29676	16467
1994	11689478	7379463	6257867	12048301					1994	77885	30434	20296
1995	9671020	4532638	10883094	15037840					1995	74000	24786	25552
1996	9395450	4128840	6952839	8494614					1996	73660	26446	19040
1997	9617038	3620043	8195789	7022856					1997	66619	17037	18721

terns (Table 5) were derived using the most recent selectivities patterns from the 1998 ASAP assessment (ICCAT, 1999). The indices of abundance used were Japanese long line ages 1 to 7 and Spanish trollers ages 2 and 3. Indices of abundance for the long line and other fleets were generated from these series by first calculating a relative effort measure and dividing the observed catches by the relevant index.

Bigeye

The fleets used in the bigeye simulation were purse seine, long line, bait boat and another. Selection patterns were derived from the partial Fs for the period 1991-1998 using a general selection pattern obtained by separable VPA (ICCAT, 2000a). The indices of abundance used were Japanese long line all ages and US long line ages 2 to 5. The US long line index is an index of abundance for ages 2 to 5 and so was used to substitute for a bait boat index where the maximum selectivity is at age 4. In this way indices of abundance were generated for the long line and the bait boat series by calculating a relative effort measure and dividing the observed catches by the relevant index.

Skipjack

The fleets used in the skipjack simulation were purse seine, long line, baitboat and another. Model parameters were obtained from ICCAT (2000b) when possible. Some parameters, however, were not

TABLE 7. – Biological parameter vectors used in operating model

	Albacore			Bigeye			Skipjack	
Age	M	Maturity	Age	M	Maturity	Age	M	Maturity
1	0.3	0.0	0	0.80	0.00	0	0.80	0.00
2	0.3	0.0	1	0.80	0.00	1	0.80	0.75
3	0.3	0.0	2	0.40	0.00	2	0.80	1.00
4	0.3	0.0	3	0.40	0.50	3	0.80	1.00
5	0.3	0.5	4	0.40	1.00	4	0.80	1.00
6	0.3	1.0	5	0.40	1.00	5	0.80	1.00
7	0.3	1.0	6	0.40	1.00	6	0.80	1.00
8	0.3	1.0	7	0.40	1.00	7	0.80	1.00
9	0.3	1.0	8	0.40	1.00	8	0.80	1.00
10	0.3	1.0	9	0.40	1.00	9	0.80	1.00
11	0.3	1.0	10	0.40	1.00	10	0.80	1.00
12	0.3	1.0	11	0.40	1.00	11	0.80	1.00

TABLE 8. – Growth (Von Bertalanffy) parameters used in operating model

Albacore			Bigeye			Skipjack	
Linf	124.74		Linf	285.37		Linf	80
K	0.23		K	0.11		K	0.3
t0	-0.9892		t0	-0.5		t0	-0.6
Cond Fact	1.3E-05		Cond Fact	2.4E-05		Cond Fact	7.5E-06
Power	3.107		Power	2.98		Power	3.253
CV			CV	0.00		CV	0.00
Instantaneous time of			*Instantaneous time of*			*Instantaneous time of*	
Spawning	0.5		Spawning	0.0		Spawning	0.5
Capture	0.5		Capture	0.5		Capture	0.5

available for this species and were obtained from Hampton (1999).

All biological parameters, selection patterns and yield time series are presented in Table 8.