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Developing a management procedure robust to uncertainty for southern bluefin tuna: a somewhat frustrating struggle to bridge the gap between ideals and reality

Hiroyuki Kurota · Kazuhiko Hiramatsu · Norio Takahashi · Hiroshi Shono · Tomoyuki Itoh · Sachiko Tsuji

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Abstract Fisheries management is conducted to achieve sustainable use of fishery resources, mainly through regulation of fishing activities. For almost a decade, the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) struggled to reach agreement on a total allowable catch (TAC) for southern bluefin tuna (SBT) because of stock assessment uncertainties. To address this, in 2002 the CCSBT commenced development of a management procedure (MP), a pre-agreed set of rules to determine how the TAC will be adjusted as new monitoring data become available. The CCSBT Scientific Committee tested various candidate MPs using operating models which simulate fish population and fishery dynamics as well as incorporate process, observation, and model uncertainties. Candidate MPs were evaluated using performance measures related to the following management objectives: maximize catches, avoid stock collapse, and minimize interannual catch variation. Of the MPs explored, some relied solely on empirical data [i.e., adjusted TAC based on catch per unit effort (CPUE) trends], whereas others were more complicated, based on population models. In 2005, the CCSBT adopted a model-based MP that realized a moderate catch with low variability and avoided stock collapse. This MP struck a compromise between the risk-prone and risk-averse standpoints of the different stakeholders. However, despite this concerted scientific effort, the MP was not implemented because, shortly after its adoption, it became evident that historical catches may have been substantially underreported. This complication necessitates returning to near the beginning of the development process. MP approaches have various advantages and challenges to be explored further. However, it is essential to lessen human-introduced uncertainty (such as catch misreporting) by enhanced enforcement, and to increase management robustness to biological uncertainties by implementing MPs.

Keywords CCSBT · Fisheries management · Harvest control rule · Management strategy evaluation · Precautionary management

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H. Kurota (✉) · N. Takahashi · H. Shono · T. Itoh · S. Tsuji
National Research Institute of Far Seas Fisheries,
Fisheries Research Agency, 5-7-1 Orido, Shimizu,
Shizuoka, Shizuoka 424-8633, Japan
e-mail: kurota@affrc.go.jp

K. Hiramatsu
Atmosphere and Ocean Research Institute, University of Tokyo,
5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8564, Japan

S. Tsuji
Fisheries and Aquaculture Department, FAO,
Viale delle Terme di Caracalla, 00153 Rome, Italy

Introduction

Ecosystems are usually structurally complex, nonlinear, spatially and temporally variable, as well as difficult and costly to observe. Therefore, it is very difficult to predict their dynamics in response to human activities precisely. Addressing uncertainty is critical in disciplines related to population management of wild-living creatures such as conservation, harvesting, and pest control (Shea et al. 1998). Scientists have been confronting and struggling with uncertainty when analyzing ecological systems of interest and providing advice to policy-makers about impacts of management action (Hilborn and Mangel 1997; Ludwig et al. 2001; Ellison 2004; Clark 2005). Fisheries scientists in particular have been at the forefront of attempts to account for uncertainty in management, given strong demands from society and having learnt from several historical failures (Patterson et al. 2001; Harwood and Stokes 2003; Hill et al. 2007).

Management of marine resources to the satisfaction of all stakeholders is very difficult. Stock assessments, which quantitatively evaluate attributes of harvested population (i.e., stock) such as biomass and productivity and make predictions about stock reactions to alternative management options (Hilborn and Walters 1992), are inherently uncertain. Uncertainties arise from various sources such as limited information and knowledge not only of fish biology and ecological systems, but also of human activities. Basic life-history characteristics, which are often critical for reliable stock assessments, such as distribution, migration pattern, growth, lifespan, age at maturity, survival rate, and the stock–recruitment relationship, are not well known for many species (Walters and Martell 2004). In particular, in the case of highly migratory fish such as tunas and sharks, the costs of field surveys to cover wide distributions of the fish in distant waters are prohibitive; this makes it difficult to obtain reliable information on these basic life-history parameters and any fishery-independent index of stock abundance.

For these reasons, information from commercial fishing activities plays an important role in stock assessments. However, collection of reliable commercial data such as the number of fish caught by age (catch-at-age data), and even the total catch taken, is not always easy, due for example to poor data collection systems. In addition, commercial fishing data tend to include considerable sampling error (noise) and bias when used to provide an index of stock status, because the random sampling necessary to eliminate bias is rarely achieved in commercial fisheries. These uncertainties hamper clear understanding of past, current, and future stock status. Nonetheless, given that such uncertainties cannot be reduced to any great extent in the near future, the practical solution is to construct management systems that account for and are robust to uncertainty. Introduction of adaptive management, in which management measures change flexibly as new information about uncertain parameters is gained (i.e., updating a feedback policy), is one of the ways to deal with this issue of uncertainty (Walters and Hilborn 1976).

Another related problem in fisheries management is that of nonverifiability, which arises because it is hardly possible to test the validity of management options and mathematical models by designed experiments, as is usually the norm in other scientific disciplines. One set of methods devised to address this issue is operating model (OM) approaches (closed-loop evaluation; Walters and

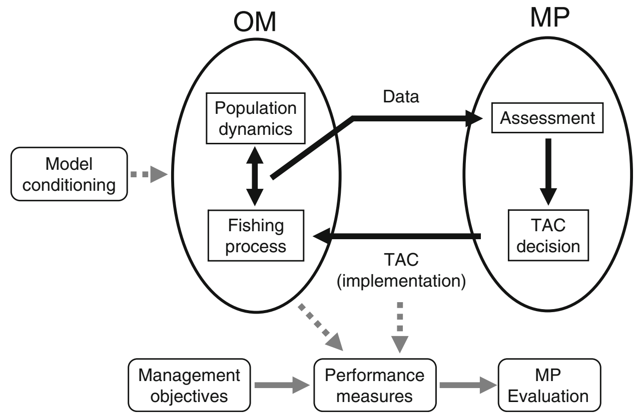

Fig. 1 Conceptual overview of MP development using OM approaches

Martell 2004), which have been developed in fisheries science (Hilborn and Walters 1992; IWC 1994; Punt 2006; Rice and Connolly 2007). Although the basic concept of OM approaches can be applied to various ecological phenomena, in the case of fisheries management, OMs simulate alternative plausible scenarios for the true population dynamics including fishing process and generate data that are used for simulation testing of management strategies (Fig. 1). In this approach, different model structures and parameter values (states of nature) can be defined in detail and manipulated explicitly. In this virtual world, a wide variety of situations incorporating a broad spectrum of uncertainties (regarding fish population, fishing process, data collection, and policy implementation as addressed in some closed-loop evaluations) can be treated as if everything was known. Therefore, experimental simulation trials can be conducted to examine the appropriateness of various management options under a wide range of uncertainties. Robustness of management to uncertainties can be verified by such exhaustive simulation studies.

A further problem in fisheries management is conflicts among management objectives, which reflect the different preferences amongst stakeholders (Hilborn 2007). Management objectives can be set in various ways, but in general these are categorized into three: conserving resources for the future, achieving high catches (often leading to maximizing profits) over a defined period of time, and minimizing socioeconomic dislocation (Punt 2006). Disparate time scales of these objectives can lead to trade-off relationships in the short and longer term. It is necessary to balance them carefully in order to reach agreement on the management objectives for a specific fishery. Within international fisheries management organizations in particular, negotiations among different countries with different preferred objectives often become complicated. In such cases, quantitative predictions (including the uncertainty) of the consequences of alternative management actions can provide managers and stakeholders with valuable information for decision-making based on scientifically rigorous analysis.

Uncertainty coupled with conflicts between management goals has led to serious difficulties in fisheries management. The Commission for the Conservation of Southern Bluefin Tuna (CCSBT) manages the southern bluefin tuna (SBT) fisheries by setting a global total allowable catch (TAC) and the fishing quotas for each country, but has often failed to reach agreement on catch limits. This international organization was founded in 1994 by Australia, Japan, and New Zealand; in 2002, Korea and Taiwan joined.[1] The Scientific Committee (SC), aided by its internal Stock Assessment Group (SAG), makes management recommendations to the Commission (the managers). However, debate between members over stock status due to large uncertainties in stock assessment results prevents management action, because the governing CCSBT Convention requires that all decisions are made by common consent, not by majority vote. In particular, in the late 1990s, there was a heated controversy regarding interpretation of catch per unit effort (CPUE), which is used as an index reflecting stock abundance. Japan carried out experimental fishing programs based on scientific designs to reduce the CPUE uncertainty, but Australia and New Zealand regarded them as commercial fishing and took Japan first to the International Tribunal of the Law of the Sea (ITLOS) and then to an Arbitral Tribunal. Eventually, in 2000, the Tribunal ruled that problems regarding SBT should be resolved internally, not by the Tribunal, and encouraged the members to normalize the Commission.

To resolve this deadlock situation, which brought the matter into court, in 2000 the CCSBT decided to start a scientific project to develop a management procedure (MP) in the SC (CCSBT 2000). In the CCSBT context, a MP is a set of rules that are agreed in advance and which dictate how the TAC for the fishery will be adjusted as new data are collected (CCSBT 2001). The phrase "agreed in advance" is an important feature to avoid ad hoc manipulation of TACs. An OM approach incorporating a wide variety of uncertainties was utilized to screen candidate MPs. This development process guarantees that MPs are explicitly precautionary if the robustness to uncertainties is ensured. Since the early 1990s, MPs have been used for management of hake and pelagic fish (sardine and anchovy) fisheries in South Africa (Plagányi et al. 2007). The revised management procedure (RMP) of the International Whaling Commission (IWC) is also well known as one of the first MPs developed using the OM approach (IWC 1994). Since then, MPs have been developed increasingly for marine resources (Stokes et al. 1999; Punt 2006; Rice and Connolly 2007; De Oliveira et al. 2008). A MP is sometimes referred to as a "management strategy," "harvest control rule" or "decision rule," although these are distinguished in some contexts (Rademeyer et al. 2007). The overall process of MP development is often called management strategy evaluation (MSE).

In terms of advantages, the CCSBT (2001) states that MPs guide the process of setting catch limits (TACs) in a manner which does not demand agreement on a preferred assessment approach. More generally, MPs that are more robust to uncertainty will provide a better chance of achieving management objectives. Furthermore, disagreement over stock assessment results can be diminished if a MP is demonstrated to be robust to different model assumptions (causing different assessment results). On the other hand, it is necessary for scientists, managers, and stakeholders to work intensively to make a number of (often difficult) decisions regarding specifications of OMs and MPs in advance. Additionally, the CCSBT project was the first MSE for highly migratory fish stocks. As a result, the project received much attention from other management organizations as it was seen as a new challenge. TACs that are robust to uncertainty are required for commercial fisheries around the world, because many of them are regulated mainly through catch limitations.

The development process for the MP as conducted in the CCSBT can be summarized as follows (CCSBT 2002a; Fig. 1): (1) Construct a set of OMs representing plausible population dynamics and fishing processes for SBT. OMs are fitted to historic fishing data and research results by estimating values for their parameters. (2) Project future resource dynamics using each MP. Future population dynamics and observed monitoring data are simulated by the OM. (3) Develop algorithms whereby candidate MPs determine a TAC based on available fishery monitoring data. (4) Evaluate the performance of each MP using several performance measures, which quantify the degree to which management objectives are met. (5) Select a preferred MP among the candidate MPs based on the performance measures. (6) Design an overall management process with the selected MP, including future review processes. Kolody et al. (2008) and Butterworth (2008a) thoroughly debate several topics regarding this MP development in the CCSBT, and De Oliveira et al. (2008) also briefly review this as well as other similar initiatives. However, there is no review which covers the whole process of this MP development in a comprehensive manner. In this paper, after briefly presenting SBT biology and fisheries, we review the process of MP

[1] Taiwan (as the Fishing Entity of Taiwan) is a member of the Extended Commission (EC) and Extended Scientific Committee (ESC). In this article, however, the EC and ESC are referred to as the Commission and SC, respectively, because the EC and ESC shall perform the same task as the Commission and SC. In 2008, Indonesia also joined the Commission.

development in the CCSBT outlined above. Following this, we discuss advantages and disadvantages, as well as future challenges for MP approaches, based on our valuable but somewhat frustrating experiences in the CCSBT.

SBT biology, fishery, and management

Southern bluefin tuna (SBT, *Thunnus maccoyii*) is large pelagic fish, reaching more than 2 m in length and 200 kg in weight (CCSBT 2007a). The species is distributed in the southern hemisphere, mainly in waters between 30° and 50° south, but is rarely found in the eastern Pacific. Direct age estimation studies using otoliths indicate that SBT mature after 8–12 years and live to 30 years or more (the maximum age from otolith studies is 42 years). The only known spawning ground is in the Indian Ocean, south of Indonesia, and thus SBT are considered to constitute a single stock as a management unit.

SBT is one of the most valuable fish in the world. The price for high-quality SBT at the Tokyo fish market is more than 50 US dollars per kilogram. The total value of SBT fisheries is estimated to be about one billion Australian dollars (CCSBT website, http://www.ccsbt.org/). Historically, Australia and Japan were the primary fishing countries. Industrial SBT fisheries started in the 1950s. The fisheries caught 80000 tons of SBT annually at their peak around 1960 and catch over 40000 tons continued until the early 1980s. However, concerns about stock decline were raised, and a regulation of setting TAC was introduced in 1985 by Japan, Australia, and New Zealand. By 1989, an official TAC was set at much less than the catch in the previous year. Since the 1990s, the reported annual catch has remained at about 15000 tons, including catches of emerging fishing countries such as Taiwan, Korea, and Indonesia. At present, the Australian purse seine fishery catches juveniles for farming in the Great Australian Bight. Japan, Korea, Taiwan, and New Zealand catch older juveniles and adults in high seas by longline. Indonesia also catches spawning adults as a by-catch from fisheries targeting other tunas such as yellowfin tuna. However, there has been very little catch by other countries and fleets. Currently, most SBT are exported to Japan to provide sushi and sashimi (thinly sliced, raw seafood).

Development processes of MP

MP development was carried out by CCSBT SC members, who consist of about 10–20 "national" scientists in member countries, an independent advisory panel (4 experienced specialists), and a consultant programmer. The advisory panel for the SC was officially established in 1999 to facilitate consensus among member countries. While a set of OMs was developed jointly by the SC, candidate MPs were proposed by scientists of member countries.

Construction of a set of OMs

The OM development took a step-by-step approach from a simple form to a more complicated one incorporating full stochasticity, according to a somewhat flexible timetable (CCSBT 2002a). OMs need to capture the key processes of the real dynamics of fishery system (fish stocks and fisheries) while also reflecting associated uncertainties. The development of OMs includes a process of "conditioning" them on past fisheries data. Conditioning is applied to estimate model parameters so that OMs are consistent with the information available for the resource, and the actual process of conditioning is similar to conventional stock assessments. The basic OM used for this project originates from a statistical age-structured model ("statistical catch-at-age model") developed for SBT stock assessment (Butterworth et al. 2003). The basic model specifications for this OM [CCSBT 2002a, 2003a, 2004a, 2005a; Haist et al. 2002; Haist 2004; see S1 in Electronic Supplementary Material (ESM) for the full model specification] assume that (1) the SBT constitutes a single stock, (2) population dynamics are propagated forward over time, (3) the stock–recruitment relationship can be modeled using a Beverton–Holt equation (Beverton and Holt 1957), which assumes a linear increase in juvenile instantaneous mortality rate as juvenile production increases, and incorporates a process error term to model annual recruitment variation, (4) natural mortality is age specific but time invariant, (5) age-specific selectivity of fishing changes slowly over time, and (6) growth curve changes over years but is fixed with known mean and variance of length–age relationship. Conditioning (parameter estimation) is based on the maximum-likelihood technique with a penalty on deviances from preferred values that corresponds to the role played by a prior distribution in Bayesian estimation.

For conditioning the OM, several types of historical fishery data and stock abundance indices were used: catch taken by each fishing fleet (the various fisheries are categorized into six fleets such as longliner and purseiner), CPUE of Japanese longline fishery, age or length composition of the catch (catch-at-age or catch-at-length data) for each fleet, and tag recapture data (CCSBT 2002a). For each set of observations, a likelihood function was defined which took account of observation error (e.g., log-normal for CPUE data, multinominal for age or length composition data, and Poisson for tag recapture). This statistically rigorous formulation can set relative weights for different kinds of observation data in parameter estimation based on the amount and quality of the data, so that final estimates constitute appropriately weighted averages over those that would arise from each dataset individually. Effective priors (in the form of penalty functions) for some estimable parameters were formulated on the basis of expert judgments.

One of the most crucial points in developing OMs is to adequately incorporate uncertainties. In this project, three main types of uncertainties were taken into account: parameter uncertainty, model uncertainty, and uncertainty concerning the future. One method to capture parameter uncertainty is to map posterior distributions. The SBT OM had more than 450 parameters that required estimation such as "steepness" of the stock–recruitment relationship, which is closely related to stock productivity (defined as the fraction of the average recruitment produced by the unfished stock, which is obtained when spawning biomass is 20% of the expected unfished spawning biomass), natural mortality rates, and recruitment levels. However, most parameters described fishing selectivity curves, and the variability was moderately constrained over time and across ages (so the effective number of parameters estimated was not that large. See Tables S1-1, 2 in ESM for a list of parameters). Estimates of uncertainty could not be achieved using Markov chain Monte Carlo methods due to convergence problems during the estimation process. As a result, a simpler "grid approach" was applied to integrate quasiquantitatively across a specified range of uncertainties for critical parameters (CCSBT 2004a; also see Table S1-3 in ESM for details).

In this grid approach, the SC first selected seven grid axes of uncertainty, including fundamental parameters (steepness, natural mortality at ages 0 and 10, nonlinearity of CPUE–abundance relationship), structural assumptions (the age range over which selectivity-at-age is normalized, sample size for age or length composition data in the multinominal likelihood), and dataset (i.e., standardized longline CPUE series used) (CCSBT 2004a). Next, several different fixed values or assumptions were preset for each axis, and a point estimate (from the maximum penalized likelihood) of parameters was obtained for each combination ("scenario"). The total number of scenarios considered eventually grew to 720 (=3 steepness × 3 age-0 mortality × 2 age-10 mortality × 2 CPUE-abundance × 2 selectivity age range × 2 sample size × 5 CPUE series). Finally, each scenario was assigned a weight depending on its plausibility relative to others. The weight for each scenario was calculated from the combination of a weight that was set for each value and assumption for each axis, which was determined from expert judgments and/or model fits to the observed data in a Bayesian framework (Punt and Hilborn 1997). The weight determined the number of replicates to be projected forward for the estimation result for each scenario to produce a total of 2000 replicates. This set of scenarios was called a "reference set" for the OM and used for evaluating the basic performance of MPs as a base-case OM combination.

Determination of the scenario weight is a very sensitive and difficult issue, particularly when weights (effectively informative priors) are determined by expert judgment. The weight placed on any given scenario is likely to impact overall OM projections and eventually management advice substantially (McAllister and Kirchner 2002; Parma 2002; Hill et al. 2007). The SC determined the weights for options on some uncertainty axes by a vote of the members after considerable discussion on uncertainty ranges and the plausibility of each scenario (CCSBT 2004a). In particular, steepness (stock productivity) needed to be examined in detail, because it was the parameter with the greatest influence on projections in the SBT case.

Spawning biomass was estimated from 1930 to 2004 for the reference set (Fig. 2; CCSBT 2005b). The range of these estimates is large, but it seems reasonable to presume that the real stock trajectory lies within this range. Stock biomass over recent years is substantially below the biomass estimated prior to industrialized fishing, and immediate action to promote steady stock rebuilding is required for optimal utilization. Results also indicated that recruitment had decreased substantially after about 2000 (recruitment estimates in 2000 and 2001 were about one-third relative to the average in the 1990s; CCSBT 2005b).

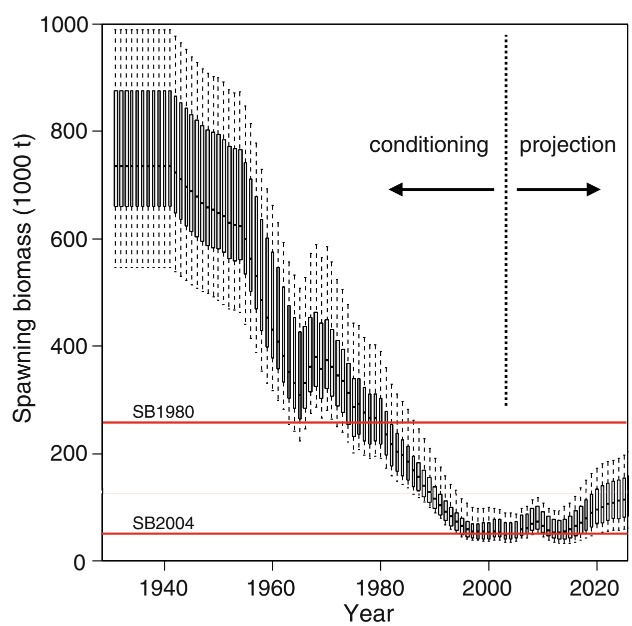

Fig. 2 An ensemble of conditioning results for OMs (from 1930 to 2003) and future projections under a MP (D&M) (from 2004 to 2025) (partially revised from CCSBT 2005b). The plot shows the 5th, 25th, 50th, 75th, and 95th percentiles for 2000 resampled scenarios. "SB1980" and "SB2004" represent spawning biomass in 1980 and 2004, respectively

This drop in recruitment was a serious concern that MPs needed to address. Based on this reference set, future projections were calculated to evaluate basic MP performance.

In addition to the reference set, scenarios were established to examine the robustness of MPs to further uncertainties and more extreme situations ("robustness test"). The SC acknowledged that these scenarios were less important or less likely than the reference set, but might be critical in some exceptional situations (e.g., extremely low recruitments in the future, possible underreporting of catch; also see the details and other scenarios in S1 in ESM). Approximately 20 further scenarios were proposed and examined in the process of MP development (e.g., CCSBT 2003b, 2005a). There was also considerable debate about how to use results of robustness tests. In this CCSBT exercise, however, most robustness test scenarios that were regarded as important were eventually incorporated into the reference set as default assumptions and grid axes. Only a couple of robustness tests regarding low recruitment in recent years and in the near future were defined in selecting a final MP. One of them was actually used to check the robustness of the MP to extremely low recruitment for several years.

Projections into the future

Projections were calculated over the period from 2004 to 2032 to evaluate MP performance (CCSBT 2003b, 2004b). This time horizon was selected to account for the long lifespan of SBT (which means that there is a time lag between the implementation of management measures and subsequent spawning stock recovery). For this exercise, most of the OMs assume that parameter values estimated from historical data applied to future fishery dynamics. This assumption of stationarity is somewhat tenuous for projections over very long timeframes because of possible changes within the fishery or environment.

In addition to the parameter value and model structure uncertainty consisting of the grid axes such as nonlinearity of CPUE–abundance relationship, two further sources of uncertainty were considered in the OM (CCSBT 2003b, 2005a). One was annual recruitment variation (process error in the stock–recruitment relationship), the standard deviation of which was assumed known, and the other was observation error in the longline CPUE, estimated during conditioning. Such variability needs to be included to prevent simulated data reflecting unrealistically precise information regarding stock status.

MPs were constructed to determine a TAC based on three sources of information provided each year by OMs: longline CPUE for ages 4 and above (age 4+), age composition, and catch of each fleet (or global TAC) (CCSBT 2002a). Age composition in catch is calculated from length composition in catch using the length-at-age growth curve that is assumed as known (for details, see S1 in ESM). In year t, the TAC for year $t + 2$ is determined based on the data up to year $t - 1$, except for the TAC, which is known for year t. Due to problems with the short period between Commission meetings and the commencement of the fishing season in some countries, the TAC calculated applies only to year $t + 2$ rather than to $t + 1$. In addition, in response to a request from the Commission to avoid frequent TAC changes, the SC decided to change TACs only every 3 years for base-case candidate MPs after examining the trade-off between the frequency of TAC changes and the risks of unintended stock decline.

Annual quotas were determined for each fleet by MPs (CCSBT 2002a). Thus it was possible to change quota allocations amongst fleets along with the global TAC. However, no candidate MP that incorporated the possibility of such changes in allocations was proposed to the SC. This omission of MPs might be because developers were not requested to explore such possibilities by managers, and implicitly concluded that it would be impossible to agree on any change in quota allocation at the Commission for political reasons. Therefore, all candidate MPs assumed fixed quota allocations set at recent proportions.

Development of candidate MPs

Candidate MPs developed through this MP exercise in the CCSBT were characterized into two major types that are also seen in other MSE exercises: empirical MPs and model-based MPs (Punt and Donovan 2007). As examples, the four candidates (two empirical and two model-based), which were selected in 2004 (CCSBT 2004b), are shown below (for details of the four MPs, see S2 in ESM).

(a) *HK5*. This empirical MP was developed by one of the authors ("Hiroyuki Kurota ver. 5"; Hiramatsu et al. 2004; Kurota 2005). This MP incorporates a feedback control system which sets the TAC as the minimum of the TAC values specified using the CPUE slope of age 4+ fish over a 10-year period (overall stock trend), and using the CPUE level of age 4 (recruitment index). Three parameters which control the behavior (performance) of the MP were tuned so that the TAC is governed by the stock trend in normal situations, but reduced more quickly and smoothly in the case of low recruitment to ensure conservation of the stock without short-term volatility of TACs. An advantage of this MP is that it is simple in terms of its formulation, and hence is easily understood by managers and stakeholders.

(b) *TAI*. TAI is an empirical MP developed by Sun (2005). In general, this MP sets TACs based on recent changes in CPUEs. Based on the developer's explanation, the main feature of this MP is that it incorporates a negative feedback component using the inverse demand relationship between price and TAC to minimize economic losses to fishermen resulting from abrupt, short-term TAC changes. To include this feature, this MP incorporates a component to diminish the amount of TAC changes.

(c) *D&M*. This population-model-based MP was developed by Doug Butterworth and Mitsuyo Mori ("Doug and Mitsuyo"; Butterworth and Mori 2003, 2005). The MP consists of two parts. In the first part, it estimates current biomass, the maximum sustainable yield (MSY), and biomass at the MSY (B_{msy}) using an age-aggregated Fox-type production model (Fox 1975), which uses past CPUEs and annual total catches as input. In the second part, the TAC is established from these estimates. The actual equation is somewhat complicated in order to incorporate components to deal with low recruitment and change TACs smoothly (see S2 in ESM), but in general, the TAC for the future consists of the sum of (1) a proportion of the current TAC and (2) the product of MSY and the current biomass relative to B_{msy}. If the current biomass is below B_{msy}, then the TAC is reduced to increase the biomass.

(d) *FXR*. FXR is a model-based MP developed by several Australian scientists (Basson et al. 2005). This MP is also based on the Fox-type production model, although components to utilize recruitment information and constrain large TAC changes were added later. In general, the same procedure is applied to estimate MSY and B_{msy} as in D&M. The major difference between the two MPs is that FXR determines TAC as the estimated MSY times the ratio of the current biomass and B_{msy}, irrespective of the current TAC.

Evaluation of MP performance

The extent to which any management objective specified by the CCSBT is likely to be met is an important consideration when evaluating the performance of candidate MPs. The management objective set in 1994 (when the CCSBT was established) was to recover the spawning biomass to its 1980 level by the year 2020 (CCSBT 1994). Through the MP development process, however, the CCSBT realized that it would be impossible to achieve this goal unless the TAC was substantially (and unacceptably) reduced. Thus, the CCSBT agreed to review this management objective in the process of MP development. As explained later, one result of the MP process was a recommendation by the SC that a new management objective be considered: for the biomass in 2022 to be at or above the biomass in 2004 with 90% probability. This should not be confused with what is referred to as "tuning" (that is, to set parameter values of MPs so as to meet a tentatively assumed target biomass) later in this section, which was required to compare MPs.

Discussion between scientists, managers, and stakeholders revealed three ideal objectives for the SBT management: (1) maximizing catches, (2) safeguarding the stock, and (3) minimizing interannual variation in catch and effort. Corresponding to the three objectives, over 20 performance measures were formulated to quantify MP performance; for example (1) the average catch anticipated over various projection periods, (2) the lower 10th percentile of stock abundance at the end of such periods, and (3) the average annual variation of catch. Determining the primary objective depends on individual preference and thus influences MP selection. At the early stage of the exercise, the SC noticed, as expected, a trade-off between maximizing catch and safeguarding the stock. This leads to a problem in comparing performance amongst different MPs. To resolve this issue, the SC decided that MPs (more specifically, control parameters of MPs) should be "tuned" to meet a target future biomass for the reference-set OMs. The tentatively set target was that the median of simulation results for spawning biomass in 2022 should increase by 10% relative to that in 2004 (10% decrease and 30% increase of spawning biomass in 2022 relative to 2004 were also set as sensitivity tests). These levels were proposed as targets that could be realistically accepted by the Commission to avoid a risk of stock collapse and substantial TAC reduction (CCSBT 2004b). This idea of tuning to remove one dimension from the trade-off facilitated comparisons of MP performance (Kolody et al. 2008).

More than 30 MPs were proposed to the SC through this MP development process and some of them were repeatedly improved to incorporate new ideas exchanged among scientists at SC meetings and MP workshops (CCSBT 2003a, b, 2004a, b, 2005b, c). Ten candidate MPs were ultimately submitted to the third MP workshop in 2004 (CCSBT 2004b). Comparisons amongst these MPs showed that the medians of biomass trajectories were similar and that the average catch over 20 years was almost identical amongst them (CCSBT 2004b). This arises from the fact that all these MPs were tuned to the same target biomass. However, the range of biomass variation and the catch trajectories over time were somewhat different amongst these MPs. Fifteen criteria based on performance measures (e.g., early TAC reduction, long-term TAC level, risk of low biomass; Table 1) showed that the MPs fell into four groups, and interestingly each group included MPs from the same

Table 1 An example of comparative performance of four MPs selected in the third meeting of the management procedure workshop

	Ideal	HK5_01	TAI_03	D&M_01[a]	FXR_01
Early TAC reductions	L	M	L/M	L	H
Longer-term TAC levels	H	M	L	L	H
Risk of low biomass	L	L/M	H	H	L
Increase in TAC at end of period	H	M	L	L	H
Range of TAC variation	?	M	L	L	H
Range of biomass variation	?	M/H	H	H	L
Post-2022 median biomass	H	M	H	H	L
Probability of low TAC	L	M	M	M	L
Interannual TAC variability and maximum of TAC change	L	L	H	L	H
TAC change reversals	L	L/M	H	L/M	M
Biomass under different selectivity assumptions	H	M	L	L	H
Biomass assuming no recruitment autocorrelation	H	H	L	M/L	M
Biomass assuming low recruitment	H	H	L	L	M
TAC assuming high stock productivity	H	M	L	L	H
Biomass assuming low stock productivity	H	M	L	L	M

L low, *M* medium, *H* high; for details, see CCSBT (2004b)

[a] D&M_03 (a variant of D&M), which was not included in the original table, was finally selected in the meeting

country (developer group). This suggests that the range of management objectives implicitly preferred by each group were surprisingly similar. Finally, four MPs (HK5, TAI, D&M, FXR) were selected from each category on the basis of their performance statistics (Table 1). These four MPs differed mainly as regards catch variation, particularly the extent of initial catch reduction, and their risk of low biomass, and this interrelation was considered an important trade-off (CCSBT 2004b). For example, the FXR MP had high catch variability and a low risk of biomass depletion. In contrast, the D&M MP had low catch variation but a higher risk of low biomass. The performance of HK5 was intermediate between these other two MPs (CCSBT 2004b).

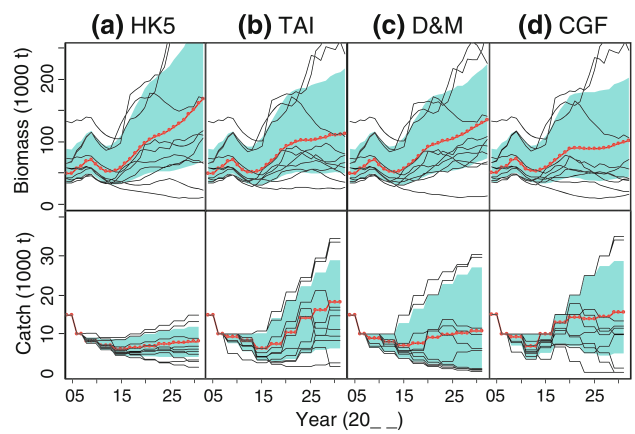

Fig. 3 Results of future projections (upper panel: catch, lower panel: spawning biomass) under the final four candidate MPs in the 2005 SC (partially revised from CCSBT 2005b; CGF is the former FXR); 2000 trajectories are represented by the 10th and 90th percentiles (*shaded area*), the median (*thick bold line with circles*), and 10 individual realizations (*thin lines*)

Selection of a preferred MP

After these four MPs had been selected, the SC was forced to modify the OMs to address two new problems (CCSBT 2004a, c, 2005a). One was that, as sometimes also occurs in fishery stock assessments, newly available CPUE data fell outside the range of predictions from the existing OMs. The other serious problem was that recruitments after 2000 were found to have dropped more drastically than was consistent with the assumptions of the original OM. The latter problem in due course led the SC to recommend a substantial TAC reduction to the Commission, with this to be implemented as soon as possible (in 2006 or 2007) and before routine MP application commenced (in 2008 or 2009; CCSBT 2005d).

Assuming such a significant TAC reduction, a final MP candidate was selected in 2005 by the SC from among the four MP finalists (CCSBT 2005d), although retuning of each MP was not carried out at that time because of time constraints. The SC acknowledged that all the MPs performed reasonably well. However, D&M showed better performance given the TAC reduction in 2006 compared with the other three MPs, in that catch variability was not large and catches increased steadily after stock rebuilding had been achieved (Fig. 3). For the CGF (former FXR) and the TAI MPs, catch variability was large; for HK5, catch stability was quite high, but the TAC did not increase after rebuilding the stock. The D&M MP struck a compromise between the risk-prone and risk-averse standpoints of the different stakeholders. This suggests that MP selection is dependent on which aspects of management objectives are emphasized (Kolody et al. 2008). The advisory panel played a central role in this selection, and other participants in the SC accepted their eventual proposal.

At the same meeting, the SC also recommended a new management objective in the form of a revised rebuilding target: "Using the D&M MP, the CCSBT achieves 90% probability that the biomass in 2022 will be at or above the biomass in 2004" (Fig. 2; CCSBT 2005d). Greatly reduced TACs would be needed over a long time to meet this criterion. Under the MP proposed, however, the future biomass level was estimated to be below the 1980 level by 2020 (the previous target for recovery).

Metarule and review process

In the simplest of applications, once a MP is implemented, it can be left to work indefinitely like clockwork or an autopilot (Butterworth 2007). In practice, however, the behavior of the MP selected and the continued validity of the OMs on which this selection was based should be reviewed regularly. The SC determined that fishery indicators (e.g., CPUE and the age composition of catch) and updated stock assessments including other methods and models than OMs be considered at regular intervals to ensure that the SBT resource had not moved outside the range over which the MP was designed to function (CCSBT 2005d). In general, the SC considers that stock status should be judged comprehensively based on a variety of assessments to avoid serious mistakes made possibly by sticking to one approach, although there is a risk that assessment results cannot be agreed on, as previously they were not. If such "exceptional circumstances" are confirmed, such as a sudden drop in recruitment of unexpectedly large extent, a "metarule" is to be invoked. The metarule is a prespecified process of actions (shown in the format of a flowchart; see CCSBT 2005d) for dealing with such exceptional circumstances. For example, conditions for convening urgent meetings and a process for alternative decision-making for TACs without using the MP are specified. Also included is a decision for revising OMs and MPs, if they are no longer regarded as reliable because, for example, of compelling new evidence about critical factors (e.g., demonstrated importance of spatial structure, multispecies interactions or oceanographic environment changes, and/or emergence of new fishing fleets). In this sense, for precautionary purposes, the metarule process makes allowance for the possibility that situations not envisaged in the existing OMs might occur in the future.

The overcatch issue and future development

In October 2005, the Commission adopted D&M as their chosen MP (CCSBT 2005e). Thus the CCSBT was able to complete the MP development process after 4 years of work. Soon after completion, however, an underreported catch (overcatch) issue was raised concerning the catches of the major fishing fleets over the past 10–20 years. A robustness test scenario assumed 15% underreporting of historical catch (CCSBT 2003a, 2005c), although this scenario was not examined in the final stage of MP development because this level of overcatch did not substantially deteriorate MP performance and, at that time, the low recent recruitment was recognized as a more serious issue. However, reports from special independent panels after their several-month investigation suggested that a substantially larger amount of possible past overcatches existed in both longline and purse seine fisheries (CCSBT 2006a, b). This overcatch issue was also likely to impact on the reliability of historical Japanese CPUE (CCSBT 2006c, d). In addition, a new fisheries regulation (an individual quota system) was introduced in Japan in 2006, and the CCSBT reduced the global TAC, including the Japanese quota, from 2007. These dramatic changes might change the characteristics of longline CPUE through changes of fishing tactics (e.g., target shifts to more valuable, larger fish to utilize limited quota more effectively). Since the D&M MP was highly dependent on both catch and longline CPUE inputs (as were most of the other MPs that had been considered), the anticipated performance as previously calculated for this MP became questionable. Consequently, in 2007 the Commission decided to relinquish the MP selected and redevelop another by about 2011 (CCSBT 2007b).

For the evaluation of next-generation MPs, in addition to adjustments of historical catch and CPUE series, updated OMs will incorporate (1) fishery-semi-independent data such as results of recent conventional tagging activities mainly for fish of ages 1–3 (CCSBT Secretariat 2008), and (2) fishery-independent stock abundance indices from scientific surveys such as an aerial survey for fish of ages 2–4 (Eveson et al. 2008) and a trolling survey for fish of age 1 (Itoh and Sakai 2008). This information will improve estimation of parameters such as recruitment and mortality of juvenile fish in the conditioning (CCSBT 2008a). These new datasets could reduce the dependence of stock assessment models on commercial fishing data, but may well also introduce new uncertainties. In principle, higher-cost information such as data from large-scale scientific research surveys is likely to provide more reliable indices of stock abundance, but it is uncertain whether they could continue on a regular basis because of the costs involved. For input data to MPs, it is essential to select information sources that are available and will definitely continue to be available in the future. The next-generation candidate MPs will utilize at least some of these new data sources as input, if they are regarded as valuable to know stock condition and available in the future.

Discussion

Unfortunately, the MP that had been developed and adopted in this exercise was not implemented due to the historical underreported catch issue. We feel a sense of crisis, given the consequences of such human-induced uncertainty. In principle, MPs are developed to be able to implement management measures that will prove robust to various uncertainties to ensure that overall objectives are attained. In practice, however, the range of uncertainties that can be examined in developing OMs and MPs is limited by the constraints of knowledge, human resources, finance, and time. Unreliable input data for OMs is likely to lead to unrealistic OMs, nonfunctional MPs, and eventually the failure of resource management. Rice and Connolly (2007) point out that there are many possibilities for inaccuracies and distortions in data from fisheries, whether their cause is accidental or purposeful, and they cause uncertainty in conducting assessments. Fishery-independent indices may be potentially valuable to monitor stock status, but the availability of such data is generally limited in terms of spatial and temporal coverage, so that stock assessment cannot help but depend on commercial fishing data to some extent. Therefore, it is crucial to lessen human-introduced uncertainty, such as underreporting of catches, by enhanced enforcement so that scientific efforts can concentrate on other sources of uncertainty (e.g., biological aspects).

The CCSBT SC acknowledged the importance of such implementation errors and explored a robustness test for historical and future underreporting of catch. However, the magnitude of underreporting is not fully understood and may have been substantially larger than the SC's expectation. Unfortunately the SC did not have substantiated reasons and information to justify more substantial underreporting as a possible scenario. In such a case, gaining agreement to assume more extreme underreporting scenarios is difficult given the CCSBT's understanding that each country monitors and reports catch correctly. This issue is potentially a major concern, common in international fisheries management organizations. As a potential solution, Kolody et al. (2008) emphasize the need for more proactive monitoring and compliance programs to collect and verify high-quality informative data. In 2006, to improve monitoring, the Japan Fisheries Agency introduced new regulations which consisted of (a) an individual quota system to allocate quotas for each vessel, (b) 100% landing inspections by government officials at ports, and (c) a requirement for individual tagging of each SBT subsequent to its catch. Furthermore, in 2008 the CCSBT adopted a catch documentation scheme (CDS), which requires catch certification and trade documentation for each SBT (CCSBT 2008b). These initiatives will definitely improve the quality of the data to be used for the development of the next-generation OMs/MPs in the CCSBT. However, unless such improvement can be achieved, it is necessary to consider human-introduced uncertainties more regularly and seriously in MP evaluations.

Nonetheless, we would argue that it is worth summarizing potential advantages and disadvantages of the MP approach, including challenges for the future (also see Punt 2006; Butterworth 2007; Punt and Donovan 2007), based on valuable, if frustrating, experiences as participants in the MP development exercise in the CCSBT. There are many aspects of this that would be apparent only to those involved in the actual development process.

Advantages of MP approaches and positive outcomes

The great merit of the MP approach is the determination of TACs which are robust to uncertainties by exhaustive pretesting of MP behavior using OMs. Verification of robustness of MP performance ensures that MPs incorporate the principles of precautionary and adaptive management. In this exercise, MP behavior was examined under a reference set consisting of many scenarios. These trials provided the impression that many of the proposed MPs were generally robust to various assumed uncertainties, although of course MPs with inappropriate feedback mechanisms (e.g., those too sensitive to CPUE changes) performed poorly. This apparent robustness may be due to a limited range of uncertainties explored in the exercise, but in the case of SBT, MPs with a reasonable feedback mechanism may be sufficient to deal with such uncertainties. Population dynamics of SBT are relatively stable due to their long lifespan, and this property of the stock may provide a degree of robustness to any MP. In fisheries management, uncertainty is sometimes emphasized too excessively, which delays decision-making and can sometimes lead to extreme management decisions such as moratoriums or retaining the status quo as the easiest way forward (Butterworth 2007, 2008b). This MP exercise showed that it is important to take "actions," that is, to test MP robustness using OMs with realistic levels of uncertainties, rather than to deliberate for an unnecessary long time.

Another strong point of MPs is to promote transparent and rapid decision-making for TACs. In principle, if a MP becomes available, TACs are determined automatically, so that confrontation among scientists, managers, and stakeholders can be avoided. Transparency in the process promotes agreement on management measures by removing skepticism amongst stakeholders. In addition, rapid decision-making with a short time lag between data collection and implementation is critical to secure sustainable use of marine resources.

Development and implementation of MPs leads to improvements in overall fishery management systems. In the case of SBT, a series of processes from data collection, stock assessment (OM construction), TAC decision (MP development), to implementation was specified in detail and improved over time to ensure that the MP development exercise proceeded smoothly. General understanding of SBT biology also advanced to provide more valuable information to the MP development process. Moreover, the development promoted interaction and collaboration among scientists, managers, and stakeholders. The CCSBT SC had many formal and informal meetings with managers and stakeholders in order to explain key concepts of the MP approach to and get feedback from them (e.g., CCSBT 2004d, 2005f). Such communications are indispensable for a general understanding of fisheries and developing common objectives (Kolody et al. 2008). A process that leads to agreed management goals provides benefits that may be more long-lasting than the MPs themselves (Punt 2006). These improvements may be regarded as side-benefits of MP development, but we consider that they were the greatest benefits of this CCSBT exercise.

The joint OM/MP development in the SC also contributed to some degree to normalization of the scientific process in the CCSBT. Before this exercise started, each member country tended to be overassertive in promoting their preferred stock assessment results. The collaborative process promoted discussion focused on the processes to analyze results, rather than on the results themselves. However, such collaboration can sometimes lead to disputes that get out of control, and increases the number of items for consideration (e.g., the number of scenarios to be examined and hence OMs to be developed). In the CCSBT exercise, the leadership provided by the independent advisory panel and the meeting chairs was indispensable in eliminating this risk and progressing this MP development steadily. In addition, a shared sense of crisis regarding SBT management and a high degree of interest from the public promoted this joint project.

Disadvantages of MP approaches and frustrating experiences

While OM approaches have several advantages, as mentioned above, it can prove very difficult to construct generally acceptable OMs. The SBT MP development process spent most time on the process of conditioning the OM (e.g., CCSBT 2002a–c, 2003a–c, 2004a–c, 2005a–c), and the CCSBT SC still continues to struggle with this delicate issue (e.g., CCSBT 2008a, c). The SC aimed to develop OMs with relatively complicated structures to describe the fishery dynamics in a realistic manner. In consequence, the SC modified the OMs, sometimes substantially, every time discrepancies were found between modeling predictions and new data, for example, when the next CPUE datum was found to lie outside the range predicted by the OMs (CCSBT 2004a). CCSBT experiences do confirm that unfortunately unexpected events can happen frequently. Flexible modification of OMs, if necessary, is justified, but this does raise anxieties about a never-ending process.

This frequent modification raises a concern that OMs can fail to cover sufficient uncertainties and quantify them properly. Particularly when scenario plausibility has to be determined by expert judgment, the associated necessary evaluation of plausibility is a sensitive issue. Although some CCSBT SC members had experience of MP developments for whales (IWC 1994) and local marine resources such as hake and lobster (Plagányi et al. 2007), standard development processes have not yet been established for the OM/MP approaches, particularly regarding methods to quantify uncertainty such as weighting scenarios (also see Butterworth 2008a; Kolody et al. 2008). The sources of uncertainty can be classified broadly into: (1) observation error, (2) model structure error, (3) process error, and (4) implementation error (Francis and Shotton 1997). In this exercise, the OM scenarios (reference set and robustness tests) were basically variants of a single model with different combinations of parameter values and model structural assumptions, although these spanned more uncertainties than is typical for traditional stock assessments. Ideally, several models with different model structures (e.g., spatio-temporal resolution for stock dynamics) and formulations (from simpler to more complicated) and datasets might be required to cover a wider set of uncertainties. Pascual et al. (1997) and Punt and Donovan (2007) point out the importance of taking model structure uncertainty into account when determining management options. In the case of the CCSBT exercise, some model structure uncertainties such as fishing selectivity normalization were considered, but we recognize that all potential structural uncertainties were not explored because the development process was partially limited by constraints of time, human resources, and knowledge to quantify uncertainty.

As mentioned above, however, extensive concerns over uncertainty could cast doubt on the possibility of stock management and produce deadlock in management decisions. Therefore, we would argue that the approach which the CCSBT followed provides a practical and balanced solution: apply a MP tested for ranges of assumed uncertainties, and invoke a metarule under unexpected circumstances. In this case, explicitly specifying what uncertainties are assumed or not in the development process is important. Monitoring stocks and fisheries is also indispensable, as indicated by the frequent OM modification that proved necessary in the CCSBT case. This compromise solution may be viewed as ambiguous and subjective, and overdependence on metarules may undermine the advantages of MPs (Kolody et al. 2008). However, we suggest that the compromise solution developed by the CCSBT is reasonable, because the reference set used to develop the MP covers a broad range of uncertainties and the occasions where the metarule might be invoked are limited by comparison. At the least, scientists need to pay more attention to the possibilities of underestimation (sometimes overestimation) of uncertainty, and ensure that managers and stakeholders are aware of these issues. Butterworth (2008a) emphasizes the importance of constructive and pragmatic scientific discussions in order to agree upon a way to deal with uncertainty. In fact, the CCSBT managed to reach agreement on approaches for dealing with these uncertainty-related issues.

Another important issue is financial and human resource costs. This exercise had nine major meetings (Stock Assessment Group/SC meetings and other targeted workshops, with each meeting taking from 1 to 2 weeks) over 4 years to complete the development process "tentatively." This is slightly shorter than the case of the IWC RMP case (6 years; Punt and Donovan 2007). For smooth progress, the leadership of the independent advisory panel and chairs was indispensable. However, the costs of holding the nine meetings (consultancy fees, travel expenses, etc.), although some topics other than MPs were discussed there, totaled about 2 million AUS dollars (CCSBT 2002d, 2003d, 2004e, 2005e). When the additional costs required for national scientists from the member countries are also considered, the MP development in the CCSBT was rather expensive, although it is reasonable to evaluate such cost in relation to the long-term cost (e.g., possible further stock decline) of not having made such efforts. To reduce financial and human resource costs, it is necessary to preset a clear timetable and specify tasks for each development stage, as the CCSBT actually did (CCSBT 2002a). The IWC also specifies a schedule that sets deadlines within a 2-year timeframe for the process of implementing the RMP (which is a generic management procedure) for a particular species and region (IWC 2005; Punt and Donovan 2007; Butterworth 2008b). In addition, experience and knowledge obtained from management strategy evaluation (MSE) projects need to be shared with scientists who work on similar projects for other wildlife resources. The authors needed considerable effort to understand the OM/MP approach at the early stages of the CCSBT exercise simply due to lack of actual experience. All meeting reports of the CCSBT stock assessment group (SAG), the Scientific Committee (SC), the MP workshops (MPWS), and the MP technical meeting (MPTM) during the MP development are available on the CCSBT website (http://www.ccsbt.org/). Recently, a free software package (Fisheries Library for R: FLR) has been developing as a general framework to evaluate fisheries management strategies (Kell et al. 2007). Such user-friendly software will also facilitate the construction of OMs and assist the development of MPs in an easier and less costly manner (Schnute et al. 2007), although it must still be difficult to apply such generic software to SBT at this stage.

Further future challenges

Fisheries management consists of many complex steps. Malfunctions at any point can affect performance of the other parts, and it is not possible to fix malfunctions at one point simply by doing a better job in another (Rice and Connolly 2007). This means that good modeling of stock dynamics is alone insufficient to provide meaningful advice on management. Ideally, useful evaluations should also consider the status and trends of economic, social, and cultural aspects of fisheries and fishing communities, not only the exploited stocks and related ecosystem components (Rice and Connolly 2007). This also indicates that reliable future projection may be harder to make than is customarily acknowledged, given rapid socioeconomic changes as seen in tuna industries; this contrasts with a basic premise of the OM/MP approach that it is possible to extrapolate past behavior into the future. To understand the somewhat intangible process of implementation, there needs to be more focus on human-related factors in the context of social-ecological systems. In particular, adaptive management including metarule invocation requires flexible responses in any overall management system in relation to stock status, social situation, and business environment (adaptive governance; Folke 2007).

SBT is considered to be one of the more readily manageable tuna species, because of its stable life history and the richness of the data associated with the fishery, even though past catch data was found to be uncertain. Similar MP development exercises have been proposed for Atlantic bluefin tuna in the International Commission for the Conservation of Atlantic Tunas (ICCAT) (ICCAT 2007) and tropical tunas and swordfish in the Western and Central Pacific Fisheries Commission (WCPFC) (Campbell and Basson 2008), though these proposals have not yet been accepted. Atlantic bluefin tuna has at least two spawning grounds in the Mediterranean Sea and the Gulf of Mexico, which leads to controversy associated with the extent of mixing of the two stocks in the Atlantic Ocean (Block et al. 2005; Kurota et al. 2009). Although associated OMs likely need to be more complicated than the SBT OMs to incorporate this uncertainty, it is interesting to examine the feasibility of MP application to such species/stocks with their more difficult management problems. Even if direct development of a MP is difficult due to substantially larger uncertainties, it would be valuable to examine various competing hypotheses about phenomena of interest using OMs. Such explorations can uncover critical factors for management and provide theoretical background to design new surveys and data collection schemes.

Unfortunately, the SBT population has already been greatly depleted, and immediate action to promote steady stock rebuilding is required (CCSBT 2008c). In general, it might be easier to develop effective MPs for healthier stocks and more stable fisheries. For these reasons, relatively more obstacles might be expected in developing and implementing a MP for SBT. Nevertheless, the CCSBT SC plans further efforts to redevelop a MP to better manage the SBT resource. Many fisheries and wildlife management endeavors may face somewhat similar management problems. We hope our efforts will be helpful to them.

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