FISH and FISHERIES

A scientific alternative to moratoria for rebuilding depleted international tuna stocks

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Abstract

There is considerable international concern and scientific debate about the current state and future of tuna stocks worldwide and the capacity of Regional Fisheries Management Organisations to manage the associated fisheries effectively. In some cases, this concern has extended to predictions of imminent collapse with minimal chances of recovery, even under a commercial catch moratorium. As a viable alternative to a full fishery closure, the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) has adopted a scientifically tested, adaptive rebuilding strategy for the depleted southern bluefin tuna (*Thunnus maccoyii*) stock. The management procedure (MP) adopted involves a harvest control rule that fully specifies the total allowable catch as a function of key indicators of stock status, adjusting future harvest levels every three years so as to meet the rebuilding targets agreed by CCSBT. It was chosen from a subset of candidate MPs selected following extensive simulation testing. This involved first selecting a wide range of plausible scenarios for stock status and input data, ranging from pessimistic to optimistic, against which the alternative candidate MPs were tested to ensure that they were robust to important uncertainties. This is the first time that a comprehensively evaluated MP has been adopted for an internationally managed tuna stock. Both the process and the outcomes have broad applicability to other internationally managed stocks.

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Introduction

There is considerable international concern and scientific debate on the current state and future prospects of tuna stocks worldwide, and what constitute effective policy and management measures for rebuilding those amongst these stocks which are heavily depleted (Polacheck 2002; Myers and Worm 2003; Sibert *et al.* 2006; Worm and Tittensor 2011; Fromentin *et al.* 2014). In the case of the highly prized bluefin tunas, Atlantic (*Thunnus thynnus*, Scombridae) and southern bluefin tuna (*Thunnus maccoyii*, Scombridae), stocks have been described by some as 'collapsed' with little chance of rebuilding (Collette *et al.* 2011). Proposed alternatives to current fisheries management measures include commercial catch moratoria and large-scale marine protected areas (Cullis-Suzuki and Pauly 2010a; Collette *et al.* 2011). For the most part, however, these recommendations have not been supported by rigorous scientific analysis of their likely performance, or realistic assessment of the governance, operational management and scientific monitoring issues that would need to be addressed for their effective implementation.

The tuna stocks of primary concern are highly migratory species that pass through the waters of individual countries as well as international waters as part of their life history. Under current international law, these stocks are managed via Regional Fisheries Management Organisations (RFMOs) (United Nations 1995) constituted of member states that may harvest the stocks. There are five tuna RFMOs worldwide, within which management measures (including moratoria) are formally negotiated and implemented. Catch and effort levels and related measures are typically decided by the Commission (the body within the RFMO responsible for decision-making) based on advice requested from its Scientific Committee and other subsidiary bodies of the Commission (e.g. Compliance Committee). The performance of RFMOs, and tuna RFMOs in particular, has been the subject of considerable discussion and review (Lodge 2007; MacKenzie *et al.* 2009; Cullis-Suzuki and Pauly 2010b), which has resulted in an active reform agenda.

Southern bluefin tuna, henceforth SBT, were first managed through informal tripartite agreements involving Australia, Japan and New Zealand since the early 1980s, and from 1993, under the CCSBT (Anonymous 1994). However, over much of this period management was, at most, able to halt the decline of the stock at a low level, currently estimated to be between 3 and 7% of unfished spawning biomass (SSB_0), but not to reverse this trend. This has resulted in agreement that the current spawning stock is below recognized limit reference levels. A difficulty in implementing timely corrective action, faced by other RFMOs in addition to the CCSBT, has been that the setting of annual catch limits requires a negotiated consensus of all members based on stock status advice. This tends to maintain *status quo*, as a no-change decision is often the only one able to achieve consensus. In contrast to annual stock assessments and negotiated catch limits, the adoption of a pre-agreed management procedure decision rule for setting the catch limit provides a default recommendation that is automatically adjusted in response to the observed indicators of stock status.

Such a management procedure (MP) has been scientifically evaluated under the auspices of the CCSBT and adopted as a rebuilding plan for the SBT stock and the international fishery that harvests it. This MP has been designed and refined by extensive simulation testing to rebuild the stock from its current historical low to the interim rebuilding target specified by the CCSBT (20% of SSB_0 by 2035) with a high probability (70%) (Anonymous 2011a). Given the state of the SBT stock, an essential part of the process was the specification of a wide range of plausible,

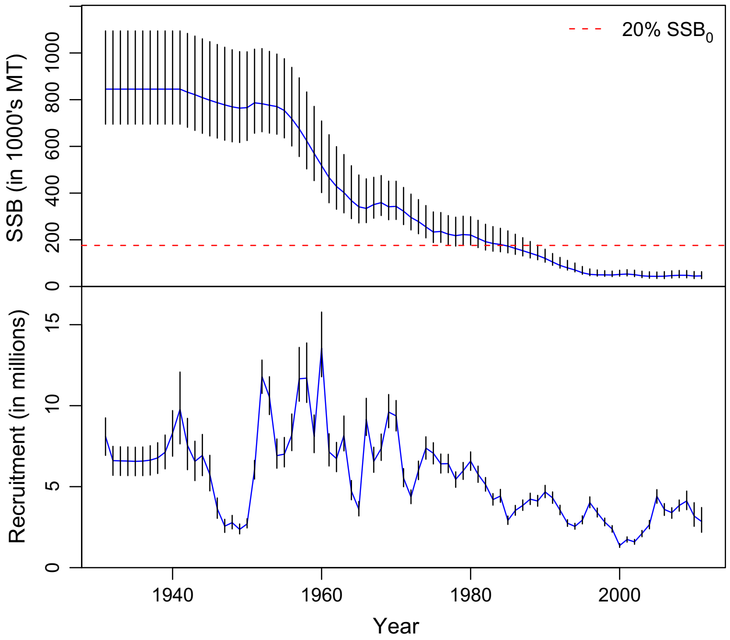

Figure 1 Historical estimates (median, blue line; 80% CI, black vertical lines) from 1931 to 2011 of spawning stock biomass (top, millions of tonnes) and recruitment (bottom, millions) for the reference set of operating models. The horizontal dotted line is 20% of SSB_0: the interim target rebuilding level.

optimistic and pessimistic data, stock and fishery scenarios to test the robustness of the candidate MPs and their relative ability to meet the agreed rebuilding target. The CCSBT adopted one of the candidate MPs and used it as a basis to set the catch limit (which covers all fisheries taking SBT) for the period 2012–2014 (Anonymous 2011b) and, more recently, for the 2015–2017 period (Anonymous 2013a); implementation of this MP to set catch limits will continue at three yearly intervals until mandatory review by 2017, except under pre-specified exceptional circumstances. This is the first time a fully specified and evaluated rebuilding plan has been agreed and implemented for an internationally managed tuna stock, and represents an important step towards managed rebuilding of these globally important fisheries. Here, we briefly review the development process of the MP conducted by the CCSBT.

Recent and current status of southern bluefin tuna

Southern Bluefin Tuna are a long-lived (to near 40 years), late-maturing (from about age 8 to 20) and highly migratory tuna found throughout the southern temperate oceans except for the more easterly regions of the South Pacific (Farley and Gunn 2007). The bluefin tuna species are all highly prized sashimi delicacies. Commercial surface and longline fisheries for SBT began in the 1950s, with annual catches reaching a maximum of 81 750t in 1961 and remaining relatively high until catch restrictions were first introduced in 1989. Since the turn of the century, both spawning biomass and median recruitment have been at historically low levels (Fig. 1 and Anonymous 2011a). The impetus for early management arrangements was the evidence of high fishing mortality rates and the demise of the purse seine surface fishery off the east coast of Australia in the mid-1980s (Caton 1991).

The 1990s were characterized by scientific debate over the status and productivity of the stock, the lack of agreement on appropriate methods for the assessment and the need (or not) for further reductions in global catches (Kolody *et al.* 2008). At the Commission level, the combination of the lack of consensus on scientific advice and the policy impasse on appropriate management action resulted in the absence of any official agreement on the global catch limit from 1989 to 2005, although each member country set its own quota. The impasse resulted in formal proceedings under the United Nations Law of the Sea in 1999

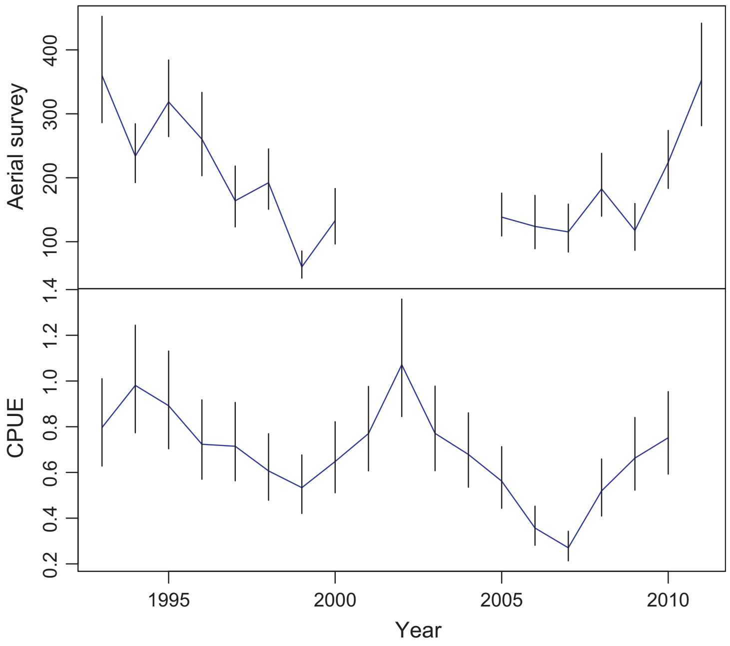

Figure 2 Scientific aerial survey (top, arbitrary units) and longline CPUE (bottom, numbers per thousand hooks) abundance indices (median and 80% CI).

over a proposal for experimental fishing (Polacheck 2002). The CCSBT response to the outcomes of these proceedings included a commitment to develop a formal rebuilding plan for the stock in the form of a fully tested MP.

Following a four-year development process, a MP was selected, recommended by the Scientific Committee and adopted by the CCSBT in 2005 (Anonymous 2005a; Butterworth 2008; Kolody *et al.* 2008; Kurota *et al.* 2010). However, this MP, which would have resulted in an immediate and substantial reduction in the catch limit, was not implemented as a result of indications which came to the fore at that time of substantial underreporting of SBT catches and potential bias in estimates of removals by the surface fishery in the previous 10- to 20-year period (Anonymous 2006a). Substantial uncertainty regarding the magnitude of the total SBT catch and its size composition over this period remains. Hence, the Scientific Committee is unable to conduct a stock assessment, in the conventional sense, and is restricted to using a range of scenarios for the historical catch and longline catch-per-unit-effort (CPUE) abundance series (Anonymous 2006a). Based on evidence of very low levels of incoming juveniles in the early 2000s (see Fig. 1), updated estimates of stock status and the substantial uncertainty in total removals in the previous two decades, global catches were reduced by 21% in 2006 (Anonymous 2006b) and 20% in 2009 (Anonymous 2009) to 9449t along with implementation of a comprehensive catch documentation scheme whose success will need to be monitored. The juvenile recruitment and longline CPUE trends (Fig. 2) have both recently shown a generally increasing trend.

The management procedure approach for SBT

An outcome of the technical and policy debates was a commitment within the CCSBT to continue to develop and evaluate a MP for rebuilding SBT (Anonymous 2007). Such a procedure consists of an agreed set of monitoring data, and methods for analysing those data for input to a harvest control rule (Rademeyer *et al.* 2007). The harvest control rule determines the recommended level of catch or effort based on the specified data and analysis. An advantage of this approach is that it is possible to prospectively evaluate the relative performance and robustness of candidate MPs to major uncertainties about the state and dynamics of the system. A set of plausible uncertainties are defined by the Scientific Committee as a reference set, against which candidate MPs can be tested. The weighting

Table 1 Summary of the SSB rebuilding and catch performance statistics for the management procedure adopted for the 3000t and 5000t maximum change options, with a 70% probability of rebuilding to 0.2 SSB_O by 2035, and catch limit changes every three years. Below $E(\circ)$ corresponds to the average value, $P(\circ)$ the probability, and the statistic P (C↑↓) relates to the probability that the catch limit will go down if it has previously gone up (calculated for the first four catch limit decisions from 2012 to 2021). Although the year 2035 is the rebuilding target date, the short-term performance measures are considered more informative. Results are presented for both the reference set and the pessimistic robustness scenarios.

Case, max. TAC change	$P(SSB_{2022} > 0.2SSB_0)$	$P(SSB_{2035} > 0.2SSB_0)$	$E(SSB_{2022}/SSB_{2011})$	$E(C_{2012–2022})$	P(C↑↓)
Reference, 3000	0.19	0.7	2.76	15 200	0.49
Reference, 5000	0.14	0.7	2.65	15 600	0.71
Pessimistic scenarios					
lowR, 3000	0.06	0.66	2.32	13 200	0.83
Upq, 3000	0.08	0.45	2.58	15 300	0.50
STwin, 3000	0.01	0.34	2.39	12 872	0.81
Omega75, 3000	0.06	0.48	2.74	13 304	0.74

of various parameter values and scenarios in both the reference set and robustness trials can be achieved in a number of ways; we do not detail how it was done for the SBT example here (Anonymous 2010a, 2011a), but rather refer readers to the MSE 'best practice' review in Punt *et al.* (2014) for more general guidance on this aspect. This is carried out using Monte Carlo simulation methods in a process commonly called management strategy evaluation (de la Mare (1986), Smith *et al.* (1999), see also the Appendix). In this manner, it is possible to identify the candidate MP that is most likely to meet the specified management objectives prior to its implementation. In addition, the participatory process under which candidate MPs are developed and evaluated means that there is a greater understanding and ownership of how the catch limit is calculated, the likely future performance under the MP adopted, and its sensitivity to different uncertainties. Once a MP is adopted, setting the annual catch limit is no longer an open-ended negotiation.

Rebuilding objectives and performance measures

The CCSBT set an interim rebuilding target of 20% of the unfished spawning biomass (henceforth, SSB_O) with a long-term rebuilding target of the biomass expected to produce maximum sustainable yield (Anonymous 2009), currently estimated to be 24% of SSB_O (Anonymous 2011a). Refining the technical specifications of objectives is commonly an iterative process as the performance of candidate MPs is evaluated (Kurota *et al.* 2010). In this case, the target rebuilding year (2035) was not decided by the Commission until the final MP had been selected and the trade-offs associated with different choices had been quantified. The Commission agreed that the probability of reaching the interim rebuilding target should be >50%, given the very low status of the stock and settled on 70%. In practice this meant that in the simulation evaluations of the candidate MPs, 70% of the population trajectories for the reference set would have a spawning biomass that was greater than, or equal to, 20% SSB_O by 2035. Performance measures included average future spawning biomass and catch, the relative risk of catch limit reductions following increases and the risk of further spawning biomass decline (see Fig. 3 and Table 1).

Management procedure development and evaluation

Two input data sets are used in the MP adopted (Anonymous (2010a) and see Appendix): (i) a scientific aerial survey of juvenile (ages 2–4) biomass in the Great Australian Bight, as an aggregated index of newborn fish entering the population 2–4 years previously (Fig. 2), and (ii) standardized CPUE of the Japanese longline fishery, as a measure of the relative abundance of exploitable fish, most of which are immature fish between ages 4 and 12 (Fig. 2). Given the primacy of the rebuilding objective, and to ensure a consistent comparison across candidate MPs, all were 'tuned' to a range of rebuilding targets (each defined by a

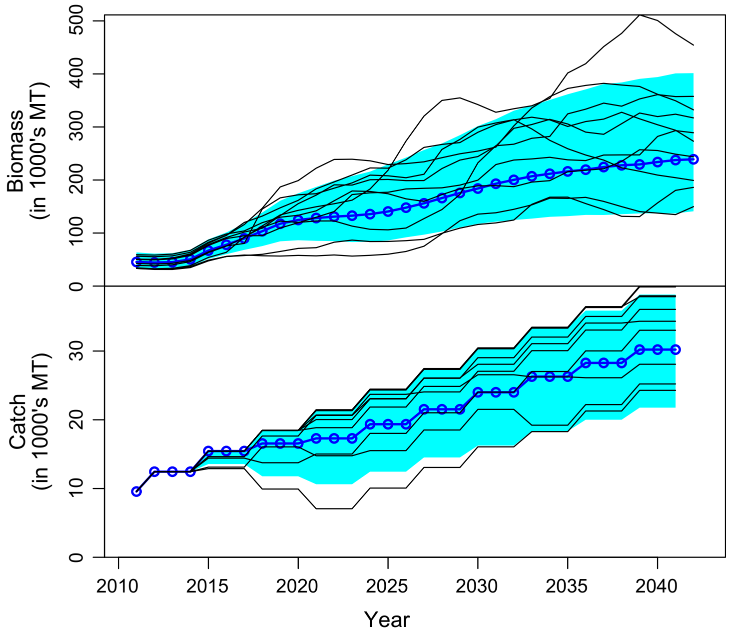

Figure 3 Predicted future spawning stock (top) and catch (bottom) for the MP adopted. The blue dotted line is the median, with the shaded region encompassing the 80% probability envelopes. To illustrate possible realized trajectories, which provide a better indication of variability over time, ten randomly chosen sample paths ('worms') are also plotted. The CCSBT restricted the TAC increase for the 2012–2015 TAC period to 1000t in 2012, a further 500t in 2013 followed by 1500t in 2014 should the MP still indicate that this increase can be taken under the data when updated in 2013.

combination of the year to achieve 0.2 SSB_0 and a target probability 0.7). This involved adjusting the key parameters of the harvest control rule to ensure the candidate MP would meet the rebuilding target for the reference set. In addition to the uncertainties incorporated in the reference set, several key robustness trials (more extreme, yet plausible, hypotheses about data, future processes and model structure) were agreed to further evaluate the robustness of the candidate MPs to important uncertainties. A variety of both optimistic and pessimistic scenarios – relative to the reference set – were specified, although the pessimistic ones were considered more important given the low status of the stock. The key robustness trials were as follows: (i) a short-term recruitment failure for four successive years following the implementation of the MP (lowR); (ii) a 35% positive bias in future longline CPUE, given recent fleet and spatial effort contraction (Upq); (iii) an alternative spatial interpretation of longline CPUE resulting in a much stronger decline in relative abundance (STwin); and (iv) a nonlinear relationship between longline CPUE and abundance so that proportional changes in actual abundance are greater than those observed in the CPUE (Omega75).

Adoption of the final management procedure

As noted, a wide range of candidate MPs were developed, tuned and then evaluated between 2009 and 2011 (Anonymous 2010a,b, 2011a). Only the performance of the MP adopted by the CCSBT, which combined elements of the two best performing candidates (Anonymous 2011a), is presented here (see Appendix). Each individual candidate MP performed marginally better than its rival on some robustness trials but not on others. A combined MP was discussed, then developed and tested, to obtain a procedure that performed better than the worst individual performer on each robustness trial. The approach of combining MPs in this manner to get better performance overall is not unique; the International Whaling Commission has followed the same path in developing its aboriginal whaling MPs (Anonymous 2003, 2005b). Table 1 summarizes the detailed performance of the MP adopted across the key robustness trials and for the agreed management targets and constraints (target year and probability of rebuilding; maximum, minimum and frequency of TAC changes) for the reference set.

Discussion

Suggested options for rebuilding many of the world's most important tuna stocks range from effective implementation of current measures, such as catch and/or effort limits (Lodge 2007; MacKenzie *et al.* 2009), to large-scale spatial closures (Gaines *et al.* 2010; Collette *et al.* 2011) and commercial moratoria for overexploited stocks (Collette *et al.* 2011). For SBT, large-scale fisheries closures and/or marine protected areas are unlikely to be a practical alternative for reducing fishing mortality on the stock. The scale and ontogenic nature of the annual migration (Pedersen *et al.* 2011) and dynamics of the longline fleets (Anonymous 2011a) are such that a spatial closure large enough to result in a substantial reduction in the annual fishing mortality would require large proportions of the Indian and Southern Oceans and the Java and Tasman Seas to be closed to targeted fishing. Furthermore, as appreciable catches of SBT are taken as by-catch in tropical tuna longline fisheries at the spawning ground south of Indonesia, these would also need to be taken into account in the design and implementation of such a measure. In addition to operational feasibility, even modest spatial closures would exacerbate the current uncertainty in the CPUE standardization, which relates to the spatial relationship between the stock and the longline fleet among seasons and years (Anonymous 2011a), and compromise the continuity of one of the main data series used to monitor and assess the stock. Even a full moratorium would not be expected to recover the stock to the interim recovery target until around 2022 (Fig. 4) as the speed at which the stock can rebuild – even in such an extreme case – is still heavily constrained by the species' late-maturity and longevity.

While, self-evidently, a commercial catch moratorium would result in faster rebuilding (Fig. 4), decision-makers are required to consider the costs and benefits of such action relative to the alternatives. These include the following: the management costs and feasibility of implementation and compliance, including the interaction with SBT by-catch in other fisheries; substantial social and economic impacts for associated fishing communities; and discontinuities in monitoring series for

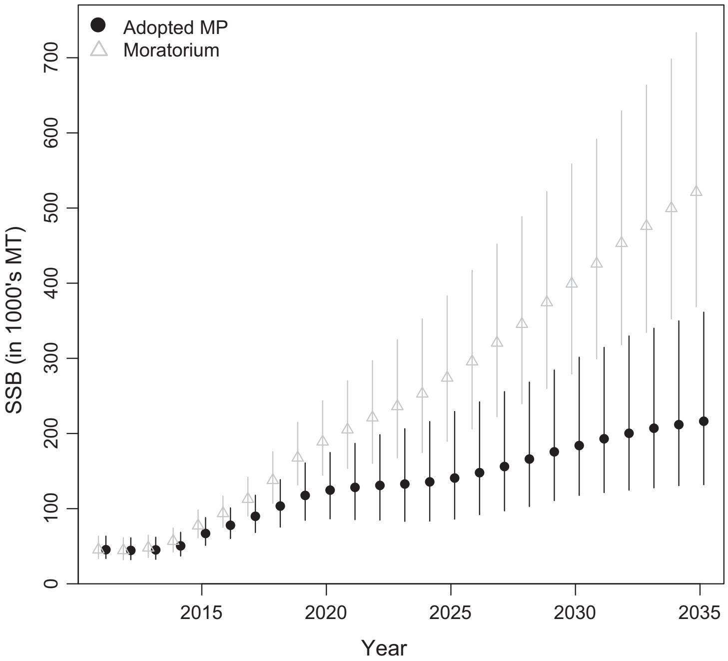

Figure 4 SSB rebuilding (median and 80% CI) performance comparison between the MP adopted (black) and a commercial catch moratorium (grey). A moratorium would be expected to meet the rebuilding target by 2022 instead of 2035, but there is little difference of import until after 2017. See also further discussion in the text.

assessing recovery and setting catch levels following the resumption of fishing. Our experience with international fisheries management organizations suggests that it would be very difficult to achieve the consensus decisions required for such actions. The results presented here indicate that there is a high probability of achieving rebuilding while maintaining a viable fishery, even for a heavily depleted stock, contingent on effective implementation and monitoring of the MP as tested.

Importantly, it is not possible to design and evaluate a MP for all possible future contingencies (Butterworth 2008; Kolody *et al.* 2008; Kurota *et al.* 2010). Hence, the need for rules that identify 'exceptional circumstances': events/conditions which are outside the bounds considered in the testing phase, or that provide new information which is cause to review the original performance of the MP. These pre-agreed rules and actions are an essential component of MP implementation, as they provide the framework for management decisions to continue to be made based on the MP adopted, while the implications of new information are investigated and appropriate responses (e.g. retuning or reviewing the form of MP) developed. In this way, they assist to avoid the decision paralysis that often occurs internationally under such circumstances.

Such a process has already been worked through within the CCSBT. A novel project to use genetic techniques to estimate the absolute size of the spawning population, termed close-kin genetics (Bravington *et al.* 2012), has recently been completed. Initial indications were that the spawning population of SBT is larger than previously estimated (Bravington *et al.* 2012) and the CCSBT instituted a process of taking these data into account when conditioning the SBT operating models (OMs) used to reflect the scenarios for which candidate MPs are tested (Hillary *et al.* 2012). This process was finalized at the 2014 Scientific Committee meeting, where the decision had to be made of whether exceptional circumstances had been triggered or not and whether the MP needed to be retuned to the agreed rebuilding targets. The decision was in fact that this was not necessary (Anonymous 2014). However, the main point here is that the MP framework that had been set in place was shown to be sufficiently flexible to deal with this type of eventuality without having to reopen the debate about status and appropriate catch limits given the new information, which is precisely where most management-related problems arise.

The SBT experiences to date are of clear value in relation to the management of other tuna fisheries. The process has highlighted: (i) the need for the transition from 'best assessment and short-term constant catch projections', to design and evaluation of robust candidate MPs that could meet Commissions' objectives; (ii) the value of transparent and collaborative model development and candidate MP testing; (iii) the central importance of verified catch and effort data and effective monitoring and compliance; (iv) the value of fisheries independent monitoring; and, most importantly, (v) commitments by Commissions to make difficult decisions on global catch limits based on the best scientific advice and implement binding and effective management measures both immediately and in the future.

There are a number of remaining uncertainties for SBT including environmental effects, ecosystem dynamics and impacts, and the characterization of the spatial dynamics of the population and fishery. The current OMs are not explicitly spatial, although various tagging experiments and analyses (Pedersen *et al.* 2011) have begun to reveal the complex spatiotemporal changes in population abundance over decadal timescales (Farley *et al.* 2007). Recent spatiotemporal trends in the longline fishery, in particular shifts in preference among historical grounds and contraction in the total distribution of effort (Anonymous 2011a), will require further study to ensure that the spatially aggregated longline CPUE input to the MP adequately captures trends in the exploitable biomass. The development of a spatial model will be an important future step to advance understanding of the underlying spatial dynamics of the SBT population and fishery, and for further evaluation of the robustness of the MP to alternative population, environmental and fishery hypotheses. More recently, the CCSBT SC has begun to reinvigorate its Scientific Research Program (Stobutzki *et al.* 2013), exploring not only extensions to the close-kin genetics project (Bravington and Davies 2013) but also how genetic mark–recapture methods (Preece *et al.* 2013) may be used to develop cost-effective monitoring for SBT in the future. In freeing member scientists from the annual assessment and catch limit negotiation process, they will be accorded more opportunity to investigate outstanding and important scientific issues in line with one of the benefits of moving to a MP approach (Butterworth 2007).

The adoption and implementation of a fully tested MP for the SBT fishery is a major step forward in the rebuilding of the population and the valuable international fishery that harvests it. Importantly, it is not the end of the process but the start of a new phase in the history of the fishery and CCSBT. The stock is currently estimated to be at a very low level with several very weak year classes over the past decade. Under the MP adopted, or even zero catches, it is likely to remain at very low levels for several more years as these year classes move through to the spawning population, before the more recent stronger year classes contribute to the predicted recovery in the spawning biomass (Figs 1, 3 and 4). The evaluation of the MP indicates that it should indeed be possible to rebuild the stock and fishery concurrently, even for pessimistic future scenarios, contingent on future continued elimination of illegal, unreported and unregulated (IUU) catches and accurate reporting of fishery data.

For the first MP decision in 2011, which concerned the TAC from 2012 to 2014, the MP indicated that the global TAC could be raised to 12 449t, given increasing trends in both the monitoring indices (Fig. 2). The CCSBT decided to limit this available increase in the TAC to 10 449t in 2012, 10 949t in 2013 and for 2014 the minimum of either 12 449t or whatever the MP predicted for 2015–2017 (Anonymous 2013a). In 2013, when the TAC calculations for the 2015–2017 were undertaken (Anonymous 2013b), the continued increasing trends in both the longline CPUE and aerial survey indices resulted in the MP calculating a TAC of 14 647t for the 2015–2017 period, thereby implicitly setting the 2014 TAC at 12 449t. Under an ‘ideal’ MP process, no decisions beyond the MP are made in relation to an appropriate TAC; the reality in this case was that the available increase in TAC calculated by the MP in 2011 was not taken fully, but rather phased in with additional conditions as detailed above.

The key point, however, remains that the catch limit must not be increased *above* that calculated by the MP, and even the conditions attached to the phased increase in the TAC were explicitly linked to what the MP would calculate for the following TAC period (2015–2017). The MP approach is adaptive, so it is right that when increases in TAC are calculated that they can – to the extent that the pertinent RFMO deems acceptable – be taken. In this case, the first two MP calculations permitted increases in TAC because they were being directly driven by consistent and apparent increases in the juvenile and subadult abundance. However, the real proof of the efficacy of the MP process in this case will stand or fall on what action the CCSBT takes if and when the MP indicates that a decrease in the TAC is required to meet the rebuilding target. Tempering increases in TAC clearly serves only to increase the probability of achieving the rebuilding target, whereas tempering decreases in TAC will clearly endanger the rebuilding program, so cannot be done defensibly within an adopted MP framework where the objectives are clear and agreed. Clearly, the MP approach as evidenced in the CCSBT example does not remove all freedom from the decision-making process with respect to setting catch limits, but it does mean that such freedom must be exercised consistent with the agreed performance objectives and remains influenced by what future data and the MP indicate. While this was not explored in depth in the CCSBT example in relation to future implementation uncertainty, the MP approach may, of course, be readily applied to ascertain over how wide a range of such uncertainty MP performance would be reasonably robust.

The development and adoption of an MP by the CCSBT marks a watershed for the management of a fish stock that crosses international boundaries and is managed by multiple countries. By settling on a single management rule based on data, CCSBT is in a position to avoid the problem of shifting goalposts that has plagued timely decision-making in some RFMOs: changing the catch limit to suit short-term goals while altering the target rebuilding period. Instead, adherence to the MP provides a high probability that SBT will be rebuilt. The MP approach to managing international fisheries has already been implemented in the International Whaling Commission (IWC) for aboriginal whaling (Anonymous 2003, 2005b) and the North Atlantic Fisheries Organisation (NAFO) for Greenland halibut (*Reinhardtius hippoglossoides*, Pleuronectidae) (Butterworth and Rademeyer 2010; NAFO 2010). More recently, the Indian Ocean Tuna Commission (IOTC) and the International Commission for the Conservation of Atlantic Tunas (ICCAT) have both committed to pursuing an MP approach to managing their tuna fisheries and the MSE approach to fisheries management is a key facet of the Global

Environment Facilities ‘Areas Beyond National Jurisdictions’ program (http://www.thegef.org/gef/abnj, last accessed 25th of March 2015).

We would, however, caution that the process does require considerable commitment of resources and scientific drive once commenced, if the later benefits from successful conclusion are to be realized, particularly at the international level. Both the IWC and CCSBT processes were facilitated by a strong core group of scientists providing continuity over a period of a number of years, where a number of these scientists were independent invitees whose participation was financed by the Commission; in particular this core included specialists to develop the key computing code required. In addition to the customary annual scientific committee meetings, further meetings of smaller working groups were required, both for scientific progress, and to explain the process to and interact with stakeholders. For SBT, the process was assisted by the scientific assumption that a single biological population (‘stock’) was involved (thus avoiding the complications of possible multiple stock structure and the associated uncertainties), and the smallish number of members of the Commission facilitated achieving a general understanding of the core concepts amongst managers. However, where such problems exist they can be overcome, as evidenced by application of this process in the much larger IWC. Moreover, any RFMO that has a core group of scientists able to either run complex stock assessment packages (ICCAT, Western and Central Pacific Fisheries Commission, IOTC, Inter-American Tropical Tuna Commission) or to design custom-written assessments (ICCAT and CCSBT) has the capability in-principle to develop suitable OMs and design and evaluate candidate MPs, and the RFMOs mentioned cover almost all the tuna and billfish stocks that are assessed at this time. The CCSBT was not a special case in this regard – what was required the most was the institutional will to take the MP route to get away from the assessment and management advice discussion cycle. Thus, we would advocate that this process be followed by other RFMOs; if the necessary resources can be committed, we suggest that the landscape of international fisheries management would be dramatically changed for the better.

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Appendix

Management strategy evaluation

Management strategy evaluation (MSE) is a framework for the simulation testing and evaluation of management procedures (MPs) – see the glossary in (Rademeyer *et al.* (2007)) for definitions of phraseology used in this field. In fisheries science, operating models simulate alternative plausible realities of a stock and fishery against which candidate MPs can be tested and their performances measured. Performance is measured relative to management objectives set by fishery managers after iterative interaction with developers. The trade-offs in performance for multiple competing objectives are evaluated before a MP is selected and implemented. The MSE methodology has been well described (de la Mare 1986; Rademeyer *et al.* 2007), but is not often carried through to adoption and MP implementation.

There are six steps involved (Punt and Donovan 2007):

1. Define management objectives and define performance measures. The CCSBT defined objectives for optimal resource use and conservation of the SBT stock. An interim rebuilding target of 0.2 SSB_0 was set as the primary objective; performance trade-offs were also examined for predicted future catch and biomass trends in both the shorter and the longer term.
2. Develop candidate management procedures and their data requirements. MPs define the data, analysis and rule (harvest control rule) used to calculate the catch limit (or effort). For SBT, a variety of rules were developed by scientists from member countries based on indices of relative abundance for the juvenile and adult components of the stock.
3. Develop operating models (OMs) that are conditioned on the historical data. The Scientific Committee, over many years, jointly specified and developed OMs and associated software that estimate and represent the population and fishery dynamics. A range of values or scenarios for key (although uncertain) historical data, life history and fishery parameters were used to incorporate a plausible range of uncertainty in the evaluations (Anonymous 2011a). The cross combination of the major sources of these uncertainties defined a core set of plausible OMs known as the 'reference set of OMs'. Other sources of uncertainty are also incorporated in a series of models used to conduct 'robustness tests'.
4. Simulation testing of candidate management procedures with operating models. The OMs are used to simulate the stock and fishery into the future. The candidate MPs are tested using them to set the future catch (or effort) levels in the fishery from simulated sampling of the data required for the MP. Monte Carlo replicates are used to sample across the stochastic processes in the OMs. Each candidate MP is tested against all the OMs defined in the reference set and in the robustness tests. The biomass and catch trends that result from the management of the simulated stock and fishery by each candidate MP are recorded and summarized for evaluation.
5. Evaluation and selection relative to performance measures. Candidate MPs were tuned so that they reached the rebuilding objective by a certain year with a defined probability. As all candidate MPs met this primary objective, the performances of these procedures were measured and compared in terms of catch and biomass over the time period that all candidate MPs operate. Long-term and short-term trends and variability in biomass and catch were key performance measures of interest. Summaries of performance statistics were provided to the commission for final selection. The rebuilding objective year and maximum amount of the catch limit change allowed in each three-year decision period were the final variables in the SBT MP agreed by the commission (Anonymous (2011b)).
6. Implementation of the management procedure. Implementation involves the commission setting global catch limits according to the MP harvest control rule, with guarantees that assumptions underlying the evaluations are not violated. This requires adequate catch monitoring and compliance activities. Meta-rules exist that define the criteria and actions under which the

implementation of the MP will be reviewed. These 'exceptional circumstances' provisions include where the population dynamics appear to be outside of the range of values under which the MP was evaluated or, for example, where one of the data sources used in the MP adopted becomes unavailable.

Basic specification of the management procedure adopted

The data used in the MP adopted for SBT are Japanese longline CPUE data and a scientific aerial survey of the biomass of the surface schools of juvenile tuna in the Great Australian Bight. Instead of using the raw indices in the harvest control rule, the MP first fits a population model to the two data sets. This is done for two reasons: (i) to deal with observation error directly and reduce uncertainty and (ii) to deal with the fact that the two indices observe similar year classes of fish, but at different times.

The model for the dynamics of juvenile biomass entering the adult population, J_y, and non-juvenile (i.e. subadult and adult), B_y, is very similar to that defined in (Trenkel 2008):

$$\begin{aligned} B_{y+1} &= J_y + g_y B_y, \\ J_y &= \exp(\mu_J + \varepsilon_y^J), \\ g_y &= \exp(\mu_g + \varepsilon_y^g), \\ \varepsilon_y^J &\sim N(0, \sigma_J^2), \\ \varepsilon_y^g &\sim N(0, \sigma_g^2), \end{aligned} \qquad (1)$$

where $N(\bigcirc)$ denotes the normal distribution. In this framework, there is a random effect structure for both the juvenile biomass, J_y, and the non-juvenile biomass net growth, g_y, and the non-juvenile biomass is the sum of the incoming juvenile biomass and the net growth of the preceding year's biomass. Estimated parameters are the means, $\mu_\bullet$, and the year-specific random effects, $\varepsilon^\bullet$. The adult biomass is assumed proportional to the longline CPUE data, with the juvenile biomass, J_y, entering the adult biomass assumed proportional to the aerial survey index in year $y-1$. A log-normal likelihood is assumed in both cases. As the estimation model in the MP can, in some sense, be interpreted as a simple stock assessment, a detailed analysis of the predictive performance of the model was conducted (Hillary and Preece (2011)). It was found that the model predicts the observed data well, given the model likelihood and priors, and so was adjudged to be a plausible model for the relative abundance dynamics over the age ranges observed by the two indices.

The harvest control rule has three components:

1. A trend-based effect whereby catch is increased or decreased based on the positive or negative trend in the log-scale adult biomass, $\ln B_y$.
2. A target-based effect whereby catch is increased or decreased based on whether the adult biomass is above or below a threshold level.
3. A precautionary juvenile biomass term whereby catch will be strongly decreased for levels of juvenile biomass, J_y, below a threshold level set using historical estimates and permitted to increase weakly when above it.

The trend-based effect defines a candidate new catch limit (TAC) as follows:

$$\mathrm{TAC}_{y+1}^1 = \mathrm{TAC}_y \times \left\{ \begin{array}{ll} 1 - k_1|\lambda|^\gamma & \lambda < 0 \\ 1 + k_2\lambda & \lambda \geq 0 \end{array} \right\} \qquad (2)$$

where λ is the slope in the regression of $\ln B_y$ for τ_B years (from years $y - \tau_B + 1$ to year y), k_1 and k_2 are gain parameters, and γ is an asymmetry parameter that permits stronger or weaker action for negative biomass trends depending on the value. The second TAC is defined as follows:

$$\mathrm{TAC}_{y+1}^2 = 0.5 \times (\mathrm{TAC}_y + C_y^{\mathrm{targ}}\Delta_y^J) \qquad (3)$$

where

$$C_y^{\mathrm{targ}} = \left\{ \begin{array}{ll} \delta\left[B_y/B^*\right]^{1-\varepsilon_b} & B_Y \geq B^* \\ \delta\left[B_y/B^*\right]^{1+\varepsilon_b} & B_Y < B^* \end{array} \right\} \qquad (4)$$

where ε_b represents the degree of asymmetry in the response to adult biomass levels above or below the target level B^* which is set at a value close to the level of Japanese longline CPUE observed when the stock was at the interim rebuilding target in the early 1980s (see Table 1). The recruitment adjustment Δ_y^J is defined as follows:

$$\Delta_y^J = \left\{ \begin{array}{ll} [\bar{J}/\Psi]^{1-\varepsilon_J} & \bar{J} \geq \psi \\ [\bar{J}/\Psi]^{1+\varepsilon_J} & \bar{J} < \psi \end{array} \right\}$$

and ε_J is also the degree of asymmetry in response to the current moving (arithmetic and of length τ_J) average juvenile biomass levels, $\bar{J}$, relative to the mean level of juvenile biomass, Ψ, seen for the years for which there are actual aerial survey data (1993–2011) and which are the lowest observed levels of historical juvenile abundance. The key control parameter is δ in (4) which is altered until the MP meets the tuning criteria $[PSSB_{2035} > 0.2*SSB_0) = 0.7]$ for the reference set. The actual catch limit set by the MP when a decision is made is simply the average value of the two candidate catch limits in (2) and (3). Table A1 details the parameter values used in the MP as adopted by the CCSBT.

Table A1 Key parameter values of the MP as adopted by the CCSBT.

Parameter	Value
δ	27 750t
k_1	1.5
k_2	3
γ	1
τ_B	7
τ_J	5
B^*	1.2
ε_b	0.25
ε_J	0.75