WCPFC
MANAGEMENT OBJECTIVES WORKSHOP

Manila, Republic of the Philippines
28-29 November 2012

INTRODUCTION TO HARVEST CONTROL RULES FOR WCPO TUNA FISHERIES

MOW1-IP/06
14 Nov 2012
(WCPFC-SC8-2012/MI-WP-03)

A M Berger, S J Harley, G M Pilling, N Davies, J Hampton[1]

---

[1] Oceanic Fisheries Programme, SPC, B.P. D5, 98848 Noumea Cedex, New Caledonia

SCIENTIFIC COMMITTEE
EIGHTH REGULAR SESSION

Busan, Republic of Korea
7–15 August 2012

INTRODUCTION TO HARVEST CONTROL RULES FOR WCPO TUNA FISHERIES

WCPFC-SC8-2012/MI-WP-03

A M Berger, S J Harley, G M Pilling, N Davies, J Hampton[1]

---

[1] Oceanic Fisheries Programme, SPC, B.P. D5, 98848 Noumea Cedex, New Caledonia

Introduction to Harvest Control Rules for WCPO Tuna Fisheries

Executive Summary

This paper is one of a suite of three pieces of work contracted to inform the WCPFC Management Objectives Workshop currently scheduled for prior to WCPFC9 in late 2012. This paper focuses on harvest control rules (HCRs) and the other two papers focus on limit reference points (Harley et al. 2012, SC8-MI-WP-01) and target reference points (Pilling et al. 2012, SC8-MI-WP-02). The presentation of this work to SC8 will provide the feedback necessary to undertake further exploratory analyses (if necessary) and refine the material that will be presented to the participants of the MOW.

This particular paper aims to introduce the concept of harvest control rules for West-Central Pacific Ocean (WCPO) tuna management and to introduce some specific example HCRs applied to the skipjack (effort-based rules) and South Pacific albacore (catch-based rules) fisheries to demonstrate the process for evaluating alternative HCRs and linking results to the Kobe II strategy matrix. Questions that this paper should help to answer are:

- What are HCRs?
- How do HCRs fit in to the overall management process?
- How to compare and contrast alternative HCRs?

Harvest control rules identify a pre-agreed course of management action as a function of identified stock status and other economic or environmental conditions, relative to agreed reference points. Key features of HCRs are that they:

- provide a format to operationalize management objectives;
- integrate management parameters (e.g., target and limit reference points);
- specify pre-agreed management responses to changes in the status of the stock;
- increase transparency in how harvest management decisions are made; and
- provide a means for the development of rational fisheries management strategies through science-based decision-making.

The evaluation of alternative HCRs and eventual establishment of a harvest policy requires key inputs from stakeholders and managers <u>BEFORE</u> HCR management system evaluations can meaningfully be conducted. For each management system (e.g., WCPO skipjack tuna fishery) these include the need to:

- establish a clear set of management objectives;
- define management target and limit reference points consistent with those objectives;
- establish a set of performance metrics that correspond to the set of management objectives;
- define key system uncertainties that should be taken into account during analyses;
- identify alternative management options (e.g., type of harvest control measure, data to be used, or stock assessment procedures) ; and

- formulate candidate HCRs using the above information to be evaluated through simulation analyses.

Results from the illustrative examples highlight how the performance of alternative HCRs change when measured against different hypothetical management objectives, and how alternative HCRs can be comparatively evaluated by looking at key tradeoffs. These results emphasize some differences between HCRs that do not adjust harvest levels with stock status (more risk prone) and HCRs that do adjust (more risk averse) as well as some differences between the performance of effort-based and catch-based HCRs. Although designed to be illustrative, these examples provide insight into the process for developing HCRs for WCPO tuna fisheries.

A glossary of commonly used technical terms related to the development, evaluation, and application of HCRs can be found in Appendix 1.

Introduction

The purpose of this paper is to describe a general framework for developing harvest control rules (HCRs) for West-Central Pacific Ocean (WCPO) tuna management. The paper is comprised of two main sections. The first section aims to introduce the concept of HCRs, including how management objectives and reference points link to the HCR and how an appropriate HCR can be selected. The second section introduces some specific HCRs in the context of two examples, skipjack and South Pacific albacore, to demonstrate the process for evaluating alternative HCRs and linking results to the Kobe II strategy matrix. Results should be considered as illustrative only as the HCRs presented were not informed by specific management objectives.

The goal of this paper is to improve understanding of the process for developing and evaluating candidate HCRs for WCPO tuna fisheries. In particular, we present information relevant to three central questions and provide action items that require consideration to develop WCPO HCRs.

1) What are HCRs?
   Action: understand how HCRs operationalize management objectives
2) How do HCRs fit in to the overall management process?
   Action: decide upon target and limit reference points and metrics to evaluate HCR performance
3) How to compare and contrast alternative HCRs?
   Action: using information from #2, identify management options and key system uncertainties and decide upon a suite of candidate HCRs to test and evaluate

It is important to note that this paper is the third in a series of three related papers detailed by the Seventh Regular Session of the Scientific Committee (SC7) as important inputs to the Commission's Management Objectives Workshop (MOW) in Manila, 29-30 November 2012, and thus should be considered along with the first two (limit reference points; Harley et al. 2012, SC8-MI-WP-01; target reference points; Pilling et al., SC8-MI-WP-02). Further exploratory analyses (if necessary) will be presented to the participants of the MOW.

A general framework for developing harvest control rules

What are harvest control rules?

Harvest control rules identify a pre-agreed course of management action as a function of identified stock status and other economic or environmental conditions, relative to agreed reference points. Thus, HCRs formulate a procedure for making harvest policy decisions, such as converting the outcomes from a stock assessment (or some other form of assessment of the stock; e.g. level or trend in CPUE, etc.) into management actions (i.e. increasing, maintaining, or decreasing levels of fishing) to achieve the desired state. Pre-agreed harvest rules allow managers to act immediately when the state of the fishery degrades beyond acceptable limits (e.g., the LRP), which can otherwise be a time-consuming process for multi-jurisdictional fisheries. Without explicit rules to govern harvest levels, there is a tendency for exploitation rates to move towards levels that maximize short-term gains rather than levels that achieve long-term objectives (e.g., stable yields, maximizing catch rates, maintaining sufficient reproductive capacity, or preventing overfishing). Key features of HCRs are that they:

- provide a format to operationalize management objectives;
- integrate management parameters (e.g., target and limit reference points);
- specify pre-agreed responses to changes in the status of the stock;
- increase transparency in how harvest management decisions are made;
- and provide a means for the development of rational fisheries management plans through science-based decision-making.

Harvest control rules (including their component biological reference points) should be developed in the management planning stage with the involvement of all stakeholders. The success of HCRs is generally enhanced by involvement of stakeholders in the definition of the problem, including assumptions, and co-management (Ditchmont et al. 2010) as it facilitates trust and policy “buy in” (Smith et al. 1999; Gregory 2000). Candidate HCRs can then be evaluated for robustness to uncertainties in statistical estimates of stock status, environmental conditions, harvester behavior, and managers’ ability to change harvest levels (FAO 1995b). If harvest control rules are based on large amounts of uncertainty in terms of model, observation, process, or implementation errors (including estimation of reference points), then the formulation of the control rule should be more precautionary. If, on the other hand, inputs to harvest control rules are based on little uncertainty and/or if resulting controls are more stringent, then a less precautionary formulation of the control rule should be successful. Periodic reviews of the HCR are typically conducted to ensure that management objectives are being met, thereby allowing for adaptive changes to the policy as social, economic, biological, or ecosystem conditions change.

There are many types and configurations of HCRs (Deroba and Bence 2009), but most have three main components: a control measure, an indicator of the state of the system, and a functional relationship between the two. The control measure is the unit used to control the amount of fishing or resource extraction allowed according to the indicator, usually a measure of stock status, and is typically measured in catch (TAC), effort (TAE), or fishing mortality (TAF). Some of the more common HCR variants are described in Table 1. The functional relationship between the controlling measure and the indicator can range from very simple (constant rule; Table 1) to more complex (non-linear rule; Table 1) depending on the desired level of management response (“feedback”) to system changes and the inherent level of complexity associated with management objectives. For example, a HCR could feature a maximum percent change in the level of catch or fishing mortality allowed from year to year as part of a rebuilding plan in response to socio-economic considerations. It is important to note that HCRs that impose a particular functional relationship (e.g., constant rule) will translate into different management actions when using an absolute (catch or effort) control measure versus a rate-based (fishing mortality) control measure.

How do management objectives and reference points fit in?

Management objectives explicitly state the goals for the fishery, many of which naturally conflict with one another (e.g., maximizing TAC versus minimizing risk of low population levels). Reference points act as benchmarks for management action and to constrain conflicting objectives by balancing them at tolerable levels, usually in an attempt to promote population and fishery sustainability. Reference points alone are not sufficient to provide a scientific basis for making management decisions, so harvest control rules that use reference points are commonly applied. In essence, HCRs are the tool used to operationalize management objectives through the use of reference points in an attempt to best meet overall objectives. Therefore, clearly stated management objectives are critical because they guide the establishment of reference points and define the success of the selected harvest policy (Figure 1).

The role of managers and stakeholders will be to identify management objectives, candidate target reference points, options for harvest control rules, and the criteria against which their performance should be evaluated. The role of the scientific provider will be to identify appropriate biological limits to exploitation and to evaluate the performance of identified candidate harvest control rules.

The reference points which serve as limits, triggers, or targets can be parameters in harvest control rules (Figure 2). Limit reference points (LRP) are used in HCRs to provide a means of specifying scientific management advice in a more objective manner and is a point that the HCR should try to avoid or achieve with very low probability (see SC8-MI-WP-01). Target reference points (TRP) indicate the desired system state and are what the HCR aims to achieve with high probability (see SC8-MI-WP-02). Effectively, a stock that is below the target should be harvested at a lower rate than one above the target. A target reference point that is close to a limit reference point may give good management outcomes if there is accurate monitoring of the stock combined with quick and effective management responses built into the HCR as the target is exceeded or the limit is approached. But the same target reference point is likely to lead to poor management outcomes if the monitoring and management response is poorly directed, ineffective or slow. Trigger reference points (TrRP) are used to specify a particular change in management action, often acting as a buffer between the TRP and the LRP (Norris 2009). For example, a recovery plan could be built into the HCR as a management action that is ‘triggered’ as the stock approaches unsafe biological limits (i.e., the LRP). The overall performance of the reference point framework and a HCR must be considered within the structure of the fishery management system as a whole. For example, information delays from data collection processes and stock assessment evaluations need to be considered when designing a HCR, as do influences on other target species in multi-species fisheries and bycatch levels of non-target species.

How to select an appropriate harvest rule?

Identification of appropriate reference points and candidate harvest control rules is a major step in formalizing the goals and management of a fishery. However, fisheries systems are uncertain; there is imperfect knowledge of the status of stocks and their biology, uncertainty due to potential biases in the data sampled from the fishery, and uncertainty in the implementation of management decisions. As a result, it is highly desirable to test the combination of reference points and harvest control rules prior to implementation, to ensure that their use will achieve the targets on average and avoid the limits that are set for the population within the agreed level of risk. In effect, to conduct analyses that evaluate whether the proposed management system is robust to the uncertainties inherent within it. Therefore, identifying and quantifying the key management system uncertainties is critical. Control rules that do not specify an appropriate level of management action could result in a failure to achieve/avoid reference points (Norris 2009).

The decision-intensive process of developing a fishery management system along with the general call for science-based decision-making has resulted in an increased use of model-based approaches as decision support tools. Simulation analysis is one such tool that has been applied to many marine fisheries worldwide (e.g., Butterworth and Geromont 1997; Smith et al. 1999; Punt 2011) and has proven to be an effective tool for assessing the expected performance of alternative HCRs given system and management uncertainties, thus providing decision-makers the ability to compare and contrast alternative HCRs against the set of operational objectives (Walters and Hilborn 1976; De la Mare 1996; Sainsbury et al. 2000). These type of analyses are commonly performed through the use of 'management procedure/strategy evaluation' (MSE) simulations. Simulations that use stochastic projections more adequately capture system uncertainty and thus offer less risk-prone guidance then simulations that use deterministic projections (Lowe and Thompson 1993; Gibson and Myers 2004.

The goal of such analyses is not to make actual management decisions; rather it is to provide decision support by quantifying anticipated HCR performance against the suite of objectives. For each management objective, one or more statistics are agreed upon by managers and stakeholders to evaluate the success of achieving that objective. These are referred to as performance metrics (see Figure 1). For example, if a management objective was to maximize the expected economic value of annual harvests from the fishery, corresponding performance metrics could be average catch rate or total revenue/profit. Butterworth and Punt (1999) suggest that performance metrics should be chosen so that they can be easily interpreted among all stakeholders and managers.

Inevitably, tradeoffs arise when there are multiple management objectives. What might be a good harvest policy for one management objective may be less than desirable for another. Management objectives that aim to maximize harvest (or catch rates), minimize variation in harvest quota, and minimize risk of undesirable population states are examples of objectives that typically conflict. To resolve conflicts, tradeoffs among competing objectives can be examined. Some common tradeoffs assessed when evaluating alternative HCRs include (*sensu* Davies and Basson 2008):

- average long-term catch versus average long-term catch rate;

- average long-term catch versus probability of the stock being below the LRP;
- average long-term catch versus probability of the stock being above/below the TRP;
- average long-term catch rate versus inter-annual variation in catch; and
- average long-term effort versus stock rebuilding time to a target level.

Evaluating performance metrics (particularly tradeoffs) between candidate HCRs is a good way to assess contrast and ultimately provide support for the selection of a HCR rule that best balances all objectives. Software packages are being developed to facilitate and improve upon the visualization of tradeoffs among multiple objectives from simulations that incorporate key uncertainties associated with fisheries management systems (Booshehrian et al. 2012).

In the end, a decision must be made (not selecting a HCR or maintaining status quo management is still a decision!). The decision process can be very difficult, particularly given the number of uncertainties associated with fisheries management. Simulation analyses (e.g., MSE) that account for key uncertainties shows promise as a practical decision-aiding management tool. In order for analyses to be useful, it is critically important for stakeholders and managers to specify clear management objectives, identify key uncertainties, and develop corresponding performance metrics to evaluate the success of achieving those objectives given system uncertainty BEFORE meaningful analyses can be completed. In some cases, it may be necessary to not only specify management objectives, but also to assign a weight of importance to each objective to more precisely evaluate tradeoff diagnostics. Either way, this process results in quantitative indicators of anticipated management system performance to guide decision-making and the selection of an appropriate HCR.

Illustrative examples: Skipjack and South Pacific Albacore

Overview of approach

We provide two illustrative examples to demonstrate the process for evaluating alternative HCRs. The HCRs evaluated in this analysis (Table 2) were chosen to represent two general types of control rules, constant and sliding[2] (or “state-dependent”) at three different levels (based on 70%, 80%, and 90% of the level of catch or fishing mortality that would achieve MSY). The main difference between the two functional types of rules examined is that the sliding rules reduce harvest along a continuum when the stock falls below a threshold, whereas the constant rules do not adjust with stock status. Explicit descriptions of the control rules evaluated are shown in Table 2. Recall that these HCRs were selected as instructive examples to show contrast in outcomes, without specific reference to pre-specified management objectives.

Stock status and harvest policy related reference points were based on MSY-type indicators for these analyses. This was done solely to promote understanding of an HCR-based management system and the

---

[2] Using the simple linear form presented in Table 1. This type of rule is also referred to as a “broken-stick” (*sensu* Norris, 2009) or “hockey-stick” form.

interpretation of example results. The indicator used to depict the state of the skipjack and South Pacific albacore fishery (i.e., stock status) was the ratio of spawning stock biomass to spawning stock biomass at MSY (SB/SB_{MSY}). An effort-based harvest control measure (F/F_{MSY}) was used for the skipjack fishery, and a catch-based harvest control measure (Y/MSY) was used for the South Pacific albacore fishery. In no way does the use of the above measures preempt stakeholder or manager considerations of a system state indicator, the harvest control measure, or reference points when defining candidate HCRs.

A set of 200 stochastic simulations that projected skipjack and South Pacific albacore populations and associated fisheries forwards under a particular harvesting regime for 30 years were run for each of the 6 HCRs examined. Management interventions occurred every third year with changes in the TAC/TAE defined by the HCR based on stock status (SB/SB_{MSY}); the TAC/TAE was held constant in between interventions. Key uncertainties incorporated into the analysis for both species included process error in recruitment and assessment error in stock status (assumed a moderate level of assessment error; CV = 0.35). A brief overview of the analytical approach is provided in Appendix 2.

Highlighting some results

An evaluation of alternative HCRs is effectively a comparative analysis, with results highlighting anticipated outcomes, performance tradeoffs, and probabilities of achieving (or not achieving) specific objectives among those HCRs examined over longer timeframes. A host of informative results and summary graphics can be generated; we focus on a select few here. Supplementary figures and some additional examples of summary graphics are provided in Appendix 3 (A3).

One outcome of particular importance might be anticipated stock status at the end of the projection period under different control rules. Candidate HCRs would have had time to interact with the stock leading to a more stable characterization of long-term performance. Stock status results for skipjack and South Pacific albacore at the end of the projection period (year 30) were dependent upon the HCR applied (Figure 3; also Figures A3.1-A3.2). Sliding rules resulted in stock states that were more precautionary on average than corresponding Constant rules. However, there was more variability in stock status at the end of the projection period associated with Sliding rules. These results held for each of the three cases (70%, 80%, and 90% of MSY) examined and for both species (though more pronounced for skipjack and at higher %MSY levels).

The degree of difference in the performance metrics that were evaluated between the Constant and Sliding rules was influenced by the amount of time the stock was at low levels of stock status. Hence, differences were greatest when recruitment through the projected period was low and allowable harvest was high (Figure 4; also Figures A3.3-A3.4). This is because of the compensatory feature built into the Sliding HCRs at low stock sizes (i.e., harvest declines when stock status is low), which acts to reduce the probability of achieving an undesirable system state but at the cost of lower overall harvest (Figures A3.6-A3.7).

The rate of compensation built into the Sliding rules (i.e., slope of the falling limb) was highest for the Sliding 90% rule (lowest for the Sliding 70% rule). This suggests that although the Sliding 90% rule allows for higher levels of harvest compared to Sliding 80% and 70% rules, harvest will decrease more rapidly once the stock falls below the threshold level (beyond the TRP, for example) which could amount to increased inter-annual variation in allowable harvest (and effort; Figures 5; also Figures A3.8- A3.9).

Constant and Sliding rules performed more similarly for South Pacific albacore than they did for skipjack because in these simulations the South Pacific albacore stock infrequently approached levels low enough to trigger catch declines compared to skipjack which used a fishing mortality based control measure (F/F_{MSY}). In these analyses, we assumed catch and effort to be observed perfectly and the implementation of management actions to be adhered to perfectly, both strong assumptions. Incorporating other sources of uncertainty (such as these) will have an effect on the performance of HCRs, although the effect cannot be pre-judged. For example, reducing the assumed level of assessment uncertainty by nearly half (down to a CV of 0.20 from 0.35 assumed in this analysis) resulted in a change to HCR performance (Figure A3.10).

Examining tradeoffs between candidate HCRs is essential to identify differences in overall performance. Average annual catch, inter-annual variation in catch, and the proportion of vulnerable biomass removed increased with increasing exploitation levels (70%, 80%, and 90% of MSY) for both Constant and Sliding rules for each species (Figure 5). Comparing between rules, Constant rules at a given %MSY performed better than comparable Sliding rules in terms of higher average annual catch and lower average inter-annual variation in catch, but performed worse in terms of a higher proportion of vulnerable biomass removed (i.e. lower on average anticipated catch rates for Constant rules; Figure 5). Pair-wise evaluations of performance metrics to examine tradeoffs can also be useful (e.g., see Figures A3.8-A3.9). The probability of exceeding example reference points was generally higher and more variable with increasing levels of allowable harvest (regardless of rule type; Figures A3.6-A3.7). The probability of exceeding example reference points was higher when a Constant rule was applied instead of the corresponding Sliding rule for both species (Figures A3.6-A3.7), but much more so for skipjack.

Integration with the Kobe II strategy matrix

The use of a strategy matrix was recommended at the second global summit of Tuna RFMOs (Spain 2009) to convey management advice. A WCPF Commission paper prepared by Canada (Anonymous 2009) stated that:

> *Based on targets specified by the Commission for each species, the [strategy] matrix would present the specific management measures that would achieve the intended management target with a certain probability by a certain time. The probabilities and timeframes to be evaluated would be determined by the Commission. In the case of fisheries managed under TACs, the outputs would be the various TACs that would achieve a given result. In the case of fisheries managed by effort limitations, the outputs would be expressed as, for example, fishing effort levels or time/area closures, as specified by the Commission. It would also indicate where there are additional levels of uncertainty associated with data gaps. Managers would then be able to base management decisions upon the level of risk and the timeframe they determine are appropriate for a particular species and associated fisheries.*

The use of a strategy matrix should promote the application of the precautionary approach by explicitly laying out probabilities of meeting specified targets. Results from simulation analyses that evaluate alternative management procedures (e.g., HCRs) can be directly integrated into the Kobe II strategy matrix for setting management measures. We calculate probabilities of meeting some example management targets using a Kobe II type of strategy matrix for skipjack (Table 3) and South Pacific albacore (Table 4) for each of the HCRs examined. However, recall that "the Kobe II Strategy Matrix requires fishery managers first to determine the management objectives (probabilities, targets, time frames) before requesting work be conducted by the scientists" (Anonymous 2009).

Next Steps

The evaluation of alternative HCRs and eventual establishment of a harvest policy requires key inputs from stakeholders and managers. Several critical steps are necessary before HCR management system evaluations can meaningfully be conducted. For each management system (e.g., WCPO tuna stock) there is a need to:

1. establish a clear set of management objectives, of which contain specifics (quantities, probabilities, time frames, etc.);
2. define management target and limit reference points consistent with those objectives;
3. establish a set of performance metrics corresponding to each management objective;
4. define key system uncertainties that should be taken into account during analyses;
5. identify alternative management options; and
6. using the above, formulate candidate HCRs to be evaluated through simulation analyses.

Using input from the Scientific Committee, further examples will be developed for discussions at the next scheduled MOW.

References

Anonymous. 2009. CANADA – proposal for the establishment of a pilot project for using the Kobe II strategy matrix. WCPFC6-2009/DP31.

Booshehrian, M., Möller, T., Peterman, R.M., Munzner, T. "Vismon: Facilitating Analysis of Trade-Offs, Uncertainty, and Sensitivity *In* Fisheries Management Decision Making". Computer Graphics Forum (Proceedings of Eurographics Conference on Visualization 2012 (EuroVis 2012)), vol. 31, no. 3, pp. 1235-1244.

Butterworth, D. S., Geromont, H. F. 1997. Evaluation of a range of possible simple interim management procedures for the Namibian hake fishery. Report to the Ministry of Fisheries and Marine Resources, Namibia. 28 pp.

Butterworth, D.S., Punt, A.E. 1999. Experiences in the evaluation and implementation of management procedures. ICES J. Mar. Sc. 56, 985-998.

Davies, C., Basson, M. 2008. Approaches for identification of appropriate reference points and implementation of MSE within the WCPO. WCPFC-SC4-2008/GN-WP-10.

De la Mare, W. K. 1996. Some recent developments in the management of marine living resources, in: Floyd, R. B., Shepherd, A. W., De Barro, P. J. (Eds.), Frontiers of Population Ecology.CSIRO Publishing, Melbourne, Australia. pp. 599–616.

Deroba, J.J., Bence, J.R. 2008. A review of harvest policies: understanding relative performance of control rules. Fish. Res. 94, 210-223.

Ditchmont, C.M., Pascoe, S., Kompas, T., Punt, A.E. and Deng, R. (2010). On implementing maximum economic yield in commercial fisheries. PNAS 107, 16-21.

Food and Agriculture Organization (FAO). (1995). Code of conduct for responsible fisheries. FAO Mimeo. Rome, FAO. 41 p.

Gibson, A.J.F., Myers, R.A. 2004. Estimating reference fishing mortality rates from noisy spawner-recruit data. Can. J. Fish. Aquat. Sci. 61, 1771-1783.

Gregory, R. 2000. Using stakeholder values to make smarter environmental decisions. Environment 32, 34-44.

Harley, S.J., Berger, A.M., Pilling, G.M., Davies, N., Hampton, J. 2012. Evaluation of stock status of bigeye, skipjack, and yellowfin tunas and southwest Pacific striped marlin against potential limit reference points. WCPFC-SC8-2012/MI-WP-01.

Kleiber, P., Hampton, J., Davies, N., Hoyle, S., Fournier, D.A. 2012. MULTIFAN-CL User's Guide *(Developmental version)*. Most recent version: http://www. multifan-l.org/index.php?option= com_phocadownload&view=category&id=13&Itemid=116. Accessed July 4, 2012.

Lowe, S.A., Thompson, G.G. 1993 Accounting for uncertainty in the development of exploitation strategies for the atka mackerel resource of the Aleutian Islands. *In* Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, University of Alaska Sea Grant College Program Report Number 93-02, pp.203-231.

Norris, W. 2009. The application of reference point management in WCPO tuna fisheries: an introduction to theory and concepts. WCPFC-SC5-2005/ME-WP-01.

Pilling, G.M., Harley, S.J., Berger, A.M., Hampton, J. 2012. Consideration of target reference points for WCPO stocks with an emphasis on skipjack tuna. WCPFC-SC8-2012/MI-WP-02.

Punt, A.E. 2011. The impact of climate change on the performance of rebuilding strategies for overfished groundfish species on the U.S. west coast. Fish. Res. 109, 320-329.

Punt, A.E. 2006. The FAO precautionary approach after almost 10 years: have we progressed towards implementing simulation-tested feedback-control management systems for fisheries management? Nat. Res. Model. 19, 441-464.

Sainsbury, K.J., Punt, A.E., Smith, A.D.M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES J. Mar. Sci. 57, 731-741.

Smith, A.D.M., Sainsbury, K.J., Stevens, R.A. 1999. Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. ICES J. Mar. Sci. 56, 967-979.

Walters, C. J., Hilborn, R. 1976. Adaptive control of fishing systems. J. Fish. Res. Board Can. 33, 145–159.

Table 1. Description of common harvest control rules (HCRs). The control measure dictates the total amount of fishing or resource extraction to be allowed during the specified time period according to current stock status. Typical control measures include total allowable catch (TAC), total allowable effort (TAE), and total allowable fishing mortality (TAF). Typical indicators of stock status include absolute or relative measures of total abundance, biomass, or spawning biomass.

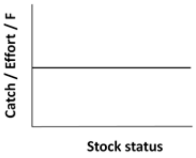
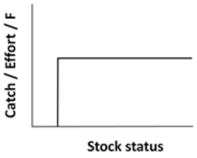
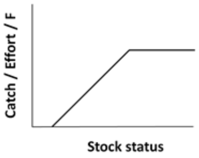
HCR	General Description	Graphic
Constant	A constant control rule maintains a single target value for the controlling measure, regardless of stock status. - TAC/TAE: promote stability but at the cost of either lower overall yields or higher levels of risk associated with reaching undesirable population states - TAF: harvest remains proportional to stock status	
Threshold	A threshold rule also maintains a single target value for the controlling measure up until a limit is reached at which point fishing ceases. - TAC/TAE: promote stability at healthy population sizes - reduces risk of fishery collapse - potential for fishing closures	
Step	A step rule incorporates discrete (or step-wise) increments in the control measure such that higher levels are permitted with improved stock status. - control measure adjusts with stock status - increased variation in yield - abrupt changes in the value of the control measure	
Sliding (simple linear)	A sliding (or "state-dependent" or "adjustable rate") rule allows for a continuous adjustment in the control measure. Higher levels are permitted with improved stock status. - moderate yields but generally with low levels of risk - increased variation in yield - gradual change in the value of the control measure	
Sliding (complex linear)	Same as above but linear combinations can be complex. - incorporate multiple transition points (e.g., according to limit, trigger, target, etc. management reference points) - contention from uncertainty in stock status when near transition points	
Sliding (non-linear)	Same as two above except continuous adjustment is non-linear. - smooth function - no major transition points so uncertainty in stock status tends to be less contentious	

Table 2. Description of example harvest control rules applied to the skipjack (effort-based rules) and South Pacific albacore (catch-based rules) fishery. Percentages refer to the percent of MSY (catch-based rules) and the percent of the fishing mortality rate that produces MSY (effort-based rules) allowed at the constant level. Graphical representations of these harvest control rules are shown in Figures 3 and 5. The state of the fishery is defined here as the ratio of spawning stock biomass to the spawning stock biomass at MSY (SB/SB_{MSY}).

Name	Description of harvest control rule
Constant (70%)	Constant catch or effort set at 70% of the level that would achieve the maximum sustainable yield (MSY), regardless of stock status.
Sliding (70%)	The level of catch or effort set according to the state of the fishery (i.e., stock status): $SB/SB_{MSY} \geq 1.2$ - a Constant(70%) rule $0.5 < SB/SB_{MSY} < 1.2$ - allowable catch/effort proportional to stock status (change is slow) $SB/SB_{MSY} \leq 0.5$ - fishery closure
Constant (80%)	Constant catch or effort set at 80% of the level that would achieve the maximum sustainable yield (MSY), regardless of stock status.
Sliding (80%)	The level of catch or effort set according to the state of the fishery (i.e., stock status): $SB/SB_{MSY} \geq 1.2$ - a Constant(80%) rule $0.5 < SB/SB_{MSY} < 1.2$ - allowable catch/effort proportional to stock status (change is moderate) $SB/SB_{MSY} \leq 0.5$ - fishery closure
Constant (90%)	Constant catch or effort set at 90% of the level that would achieve the maximum sustainable yield (MSY), regardless of stock status.
Sliding (90%)	The level of catch or effort set according to the state of the fishery (i.e., stock status): $SB/SB_{MSY} \geq 1.2$ - a Constant(90%) rule $0.5 < SB/SB_{MSY} < 1.2$ - allowable catch/effort proportional to stock status (change is rapid) $SB/SB_{MSY} \leq 0.5$ - fishery closure

Table 3. An example Kobe II strategy matrix for the example HCRs examined for the WCPO skipjack fishery. HCRs include three different levels (70%, 80%, and 90% of MSY) for Constant (CON) and Sliding (SLI) type of effort-based rules. See Table 2 for further descriptions of these HCRs.

Management target	**Time Frame**	**Probability of Meeting Target**						**Data Rich/ Data Poor**
		CON(70%)	SLI(70%)	CON(80%)	SLI(80%)	CON(90%)	SLI(90%)	
$F < 0.8F_{MSY}$	5 years	0.985	0.988	0.517	0.529	0.403	0.418	To be evaluated
	10 years	0.988	0.990	0.582	0.630	0.279	0.390	
	20 years	0.975	0.987	0.543	0.693	0.180	0.468	
	30 years	0.969	0.988	0.527	0.733	0.146	0.498	
$B > 1.2B_{MSY}$	5 years	1	1	1	1	1	1	To be evaluated
	10 years	0.980	0.983	0.936	0.951	0.889	0.915	
	20 years	0.969	0.978	0.903	0.940	0.802	0.890	
	30 years	0.966	0.982	0.883	0.938	0.756	0.883	
$SB > 1.2SB_{MSY}$	5 years	1	1	1	1	1	1	To be evaluated
	10 years	0.989	0.992	0.961	0.969	0.911	0.932	
	20 years	0.986	0.991	0.933	0.962	0.846	0.920	
	30 years	0.985	0.992	0.921	0.960	0.802	0.914	

Table 4. An example Kobe II strategy matrix for the example HCRs examined for the WCPO South Pacific albacore fishery. HCRs include three different levels (70%, 80%, and 90% of MSY) for Constant (CON) and Sliding (SLI) type of catch-based rules. See Table 2 for further descriptions of these HCRs.

Management target	**Time Frame**	**Probability of Meeting Target**						**Data Rich/ Data Poor**
		CON(70%)	SLI(70%)	CON(80%)	SLI(80%)	CON(90%)	SLI(90%)	
$F < 0.8F_{MSY}$	5 years	1	1	1	1	0.996	0.997	To be evaluated
	10 years	1	1	0.999	0.999	0.991	0.993	
	20 years	1	1	0.999	0.999	0.990	0.993	
	30 years	1	1	0.999	0.999	0.988	0.992	
$B > 1.2B_{MSY}$	5 years	0.995	0.995	0.992	0.993	0.986	0.988	To be evaluated
	10 years	0.987	0.988	0.979	0.981	0.963	0.967	
	20 years	0.985	0.987	0.976	0.978	0.965	0.970	
	30 years	0.982	0.984	0.972	0.974	0.961	0.966	
$SB > 1.2SB_{MSY}$	5 years	1	1	1	1	1	1	To be evaluated
	10 years	1	1	1	1	0.997	0.997	
	20 years	0.999	0.999	0.997	0.997	0.993	0.994	
	30 years	0.999	0.999	0.999	0.999	0.991	0.992	

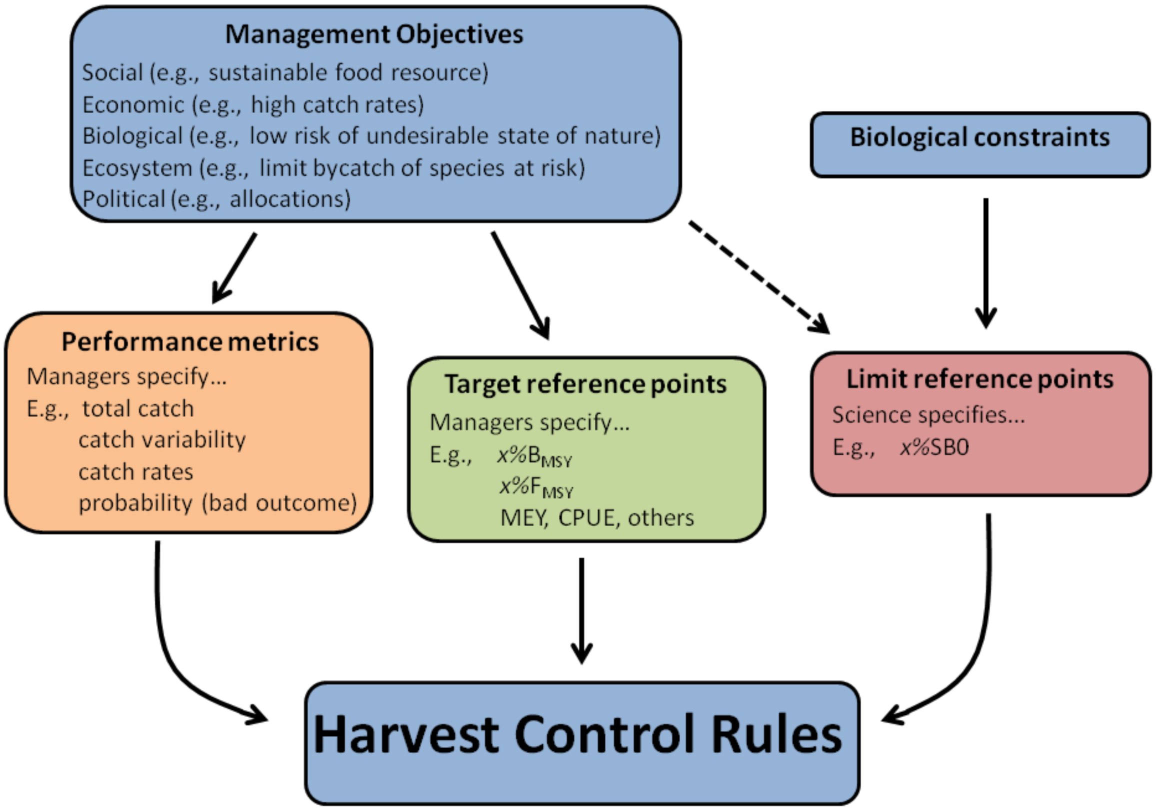


Figure 1. Conceptual model of how management objectives and biological constraints inform the development (reference points) and guide the selection (performance metrics) of harvest control rules. Abbreviations: B: biomass, SB: spawning biomass, F: fishing mortality, MSY: maximum sustainable yield, MEY: maximum economic yield, CPUE: catch-per-unit-effort.

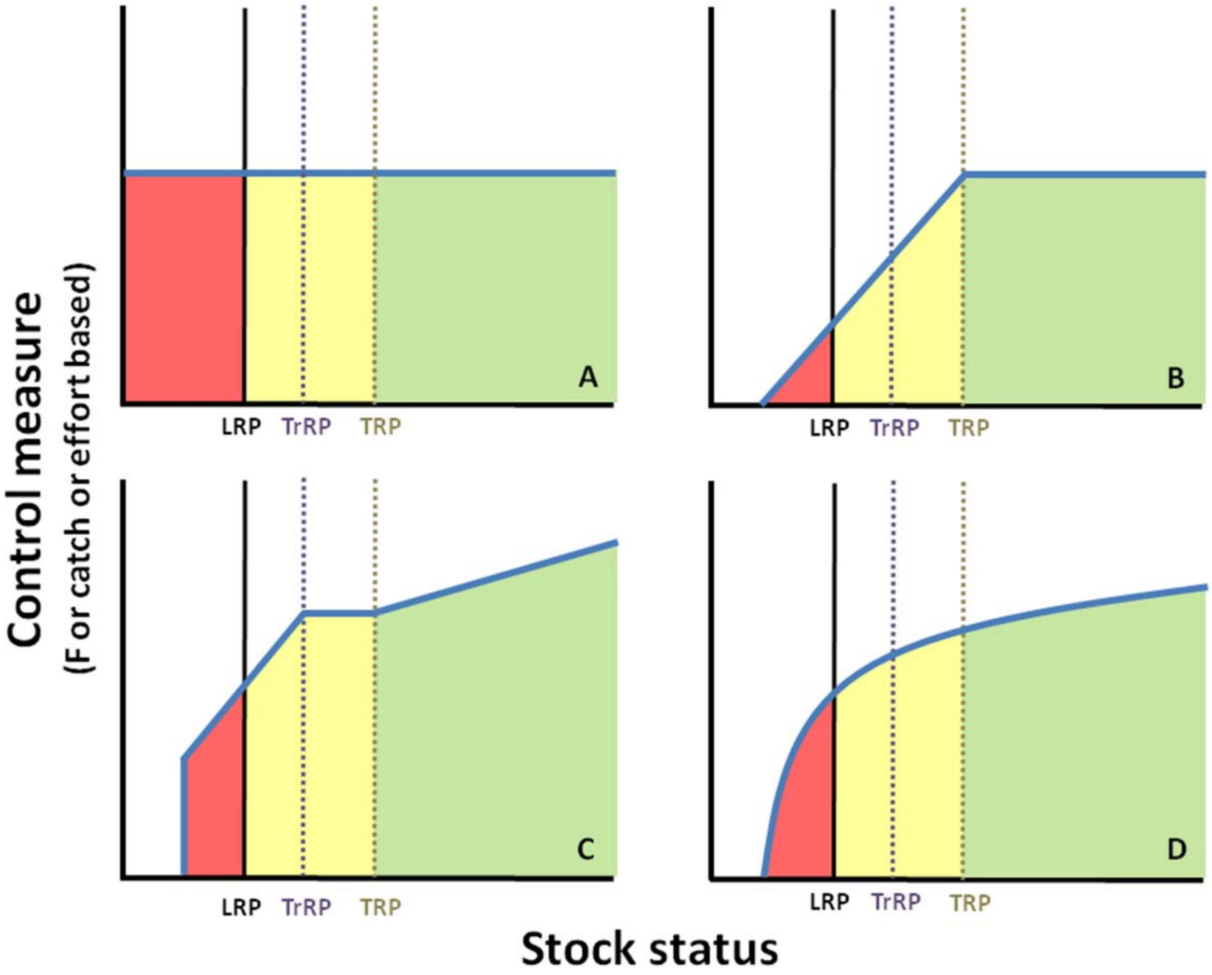


Figure 2. Example harvest control rules (solid blue line) to show how harvest rules can be developed in relation to pre-specified limit (LRP; solid black line), trigger (TrRP; purple dotted line), and target (TRP; brown dotted line) reference points to try and best meet management objectives. Allowable harvest is determined by 1) current stock status, 2) the pre-specified harvest control measure (e.g., the amount of fishing mortality relative to that which produces MSY or the yield relative to MSY), and 3) the functional form of the harvest control rule (panels A-D). Panel A is a Constant rule – does not adjust with stock status; Panel B is a Sliding rule that linearly adjusts with stock status once the TRP has been exceeded; Panel C is a Sliding rule that linearly adjusts at several points, including an adjustment as the TRP is approached and a steep adjustment once the TrRP is exceeded; and Panel D is a Sliding rule that non-linearly adjusts such that the amount of adjustment increases as stock status decreases. Rules B-D feature a fishery closure (to promote stock rebuilding) if the LRP is vastly exceeded.

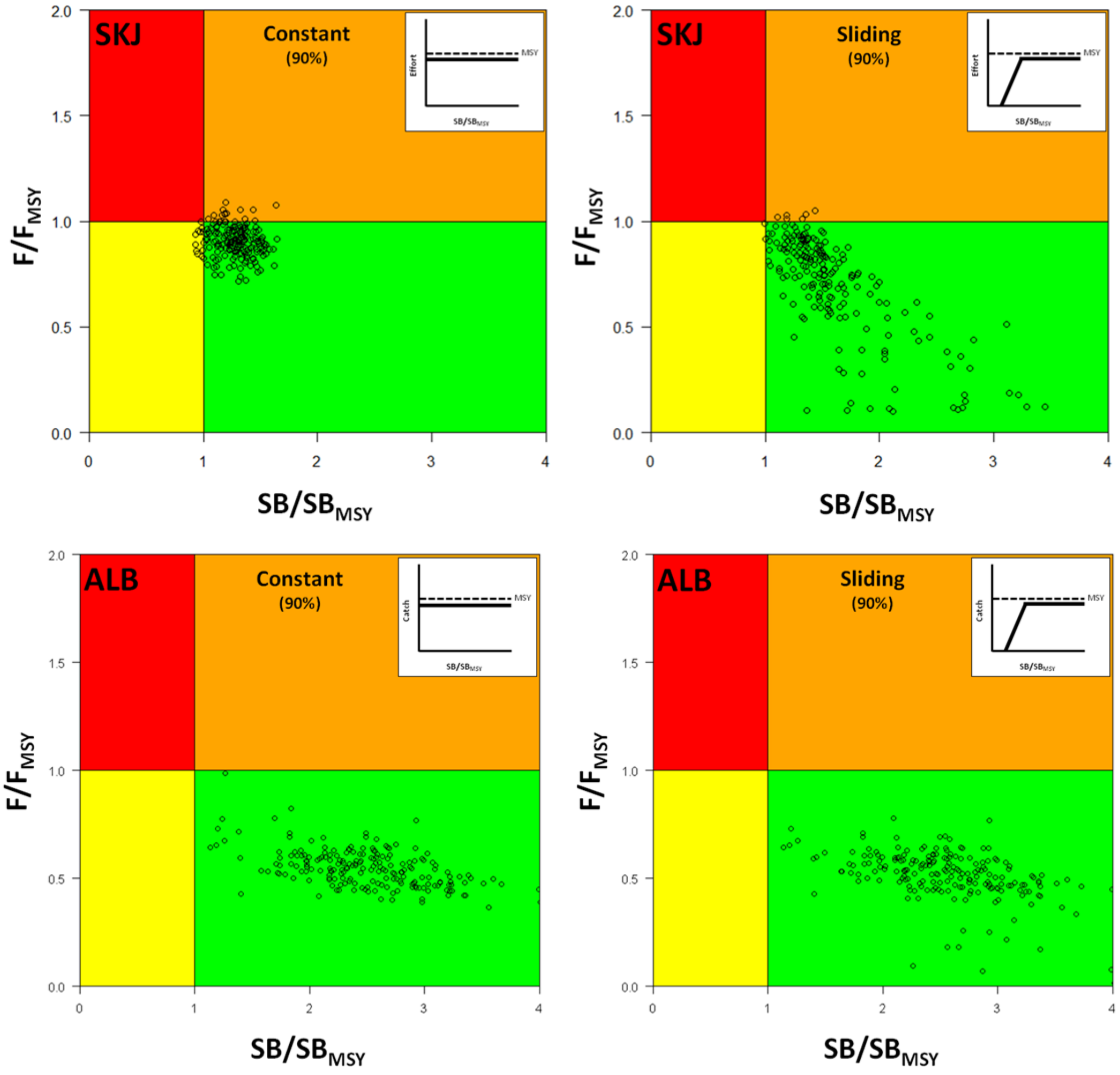


Figure 3. Stock status at the end of each projection period (points) under the Constant (90%) control rule (left) and the Sliding (90%) control rule (right) for skipjack tuna (top, effort control measure) and South Pacific albacore tuna (bottom, catch control measure). Each point represents the status at the end of the projection period from a single simulation. The spread of points represent variability in future stock status arising from recruitment variation and stock assessment error. A graphic representation of the harvest control rule evaluated is shown in the upper right corner.

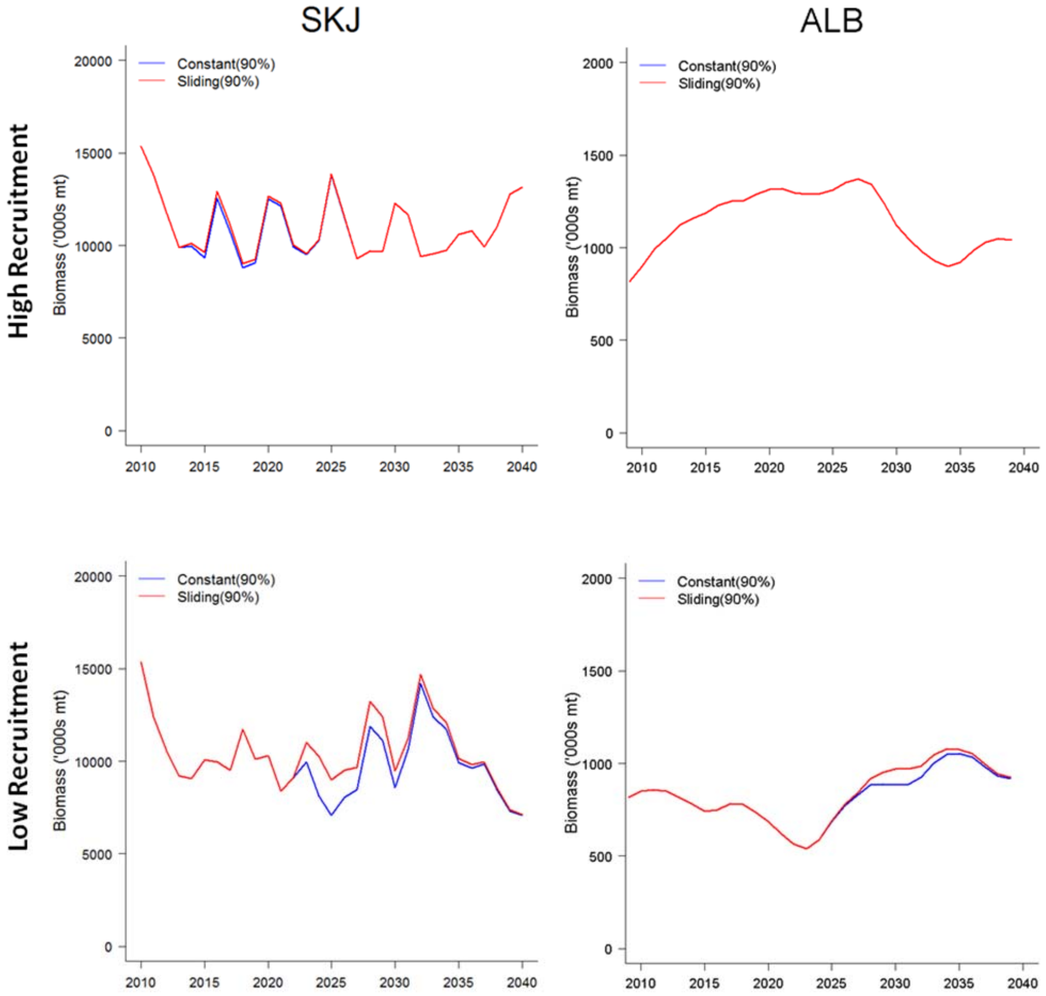


Figure 4. A single projected biomass trajectory for skipjack (left) and South Pacific albacore (right) using a Constant (90%) rule and a Sliding (90%) rule at two levels of assessed stochastic recruitment: high (97.5% quantile; top) and low (2.5% quantile; bottom).

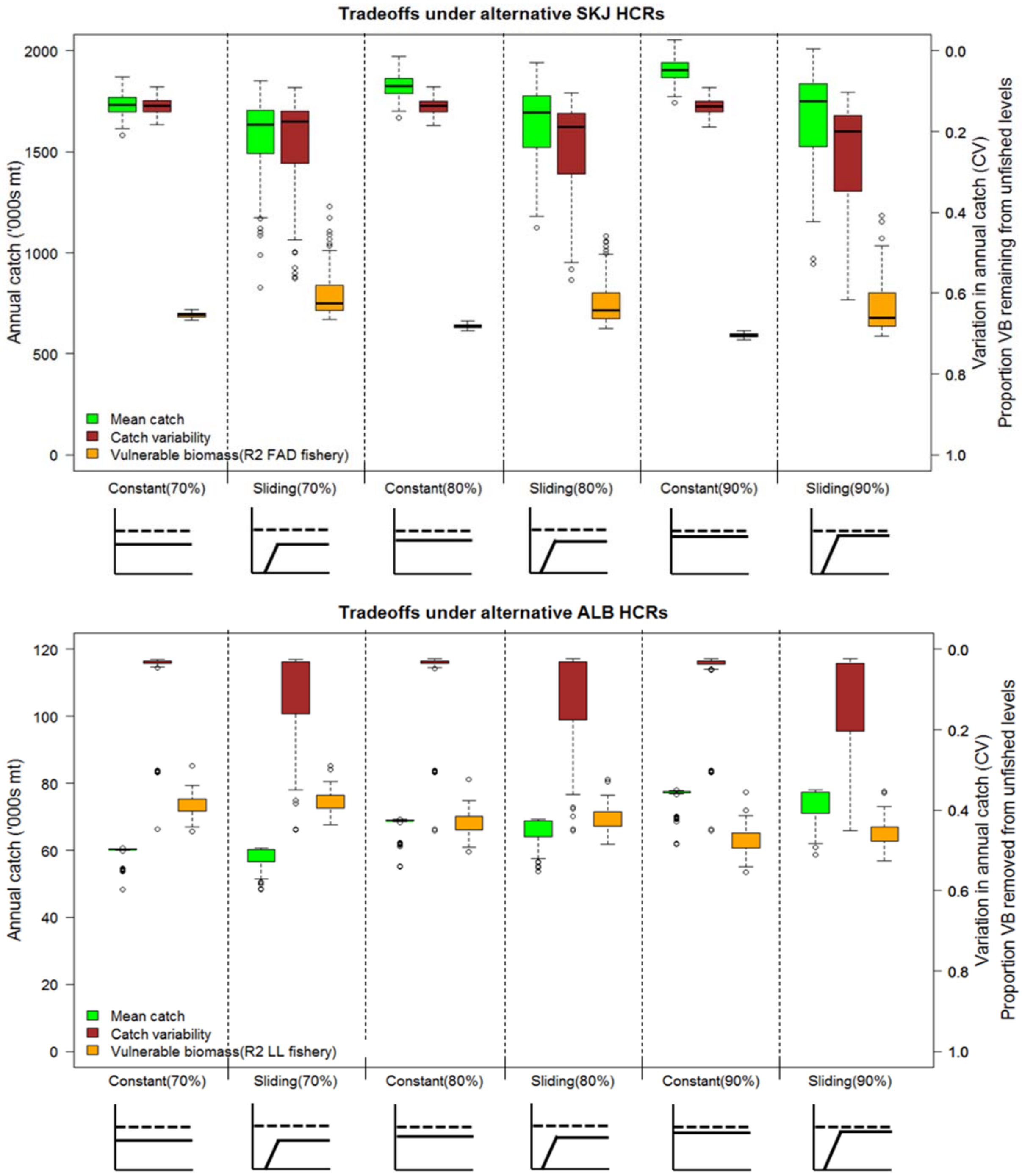


Figure 5. Boxplots showing tradeoffs among three performance metrics for skipjack (top) and South Pacific albacore (bottom): mean annual catch, inter-annual variation in catch, and proportion of vulnerable biomass removed from unfished levels. Relative differences in vulnerable biomass among harvest control rules are indicative of relative differences in catch rates that would result from those rules. Note that the right side axis has been inverted so that outcomes near the top of the graph are more desirable for all three performance metrics. A graphic representation of each example harvest control rule evaluated is shown along the lower axis. Median represented by the horizontal line of the box. Boxes represent the 25th, and 75th percentiles, whiskers show 5th and 95th percentiles.

Appendix 1: Terminology

Glossary of terms

The following is a list of definitions for technical terms used throughout this paper. Terms and definitions generally reflect those that are commonly used for the development and evaluation of fisheries harvest control rules.

Control measure: the unit used to control the amount of fishing or resource extraction allowed (e.g., catch or effort) according to some indicator (e.g., stock status).

Harvest control rule (HCR): specific course of action that indicates the specific amount of catch, effort, or fishing mortality based on some indicator of the current system state (e.g., stock status).

Harvest policy: general guidelines specifying how harvest levels should be set or how much fishing should be allowed.

Limit reference point (LRP): a benchmark which defines undesirable states of the system that should be avoided or achieved with very low probability.

Management objectives: the social, economic, biological, ecosystem, and political (or other) goals specified for the fishery.

Management options: alternative management procedures from which recommended management actions will be chosen.

Management procedures: a set of formal actions, usually consisting of data collection, stock assessment, and harvest control rules, to iteratively and adaptively manage a fishery.

Management strategy evaluation (MSE): a simulation-based analytical framework to evaluate performance of alternative management procedures when developing a fishery management system.

Performance metrics: a set of consistent statistics used to evaluate how well management objectives have been achieved.

Simulation: an imitation of a real world system used to gain insight into how the system operates.

Stochastic projections: provide an estimate of the distribution of potential future outcomes, integrating uncertainty in key inputs, from a particular set of management procedures.

Target reference point (TRP): a benchmark which assesses the performance of management in achieving one or more operational management objectives.

Total allowable catch (TAC): a type of control measure that specifies the maximum level of harvest that can be taken during the specified time frame.

Total allowable effort (TAE): a type of control measure that specifies the maximum level of effort that can be applied during the specified time frame.

Total allowable fishing mortality (TAF): a type of control measure that specifies the maximum fishing mortality rate that can be imposed during the specified time frame.

Trigger reference point (TrRP): a particular state of the system that triggers a predefined change in the management response.

Appendix 2: Brief overview of methodological approach

The HCRs examined in this paper were evaluated by using stochastic simulations as implemented in MULTIFAN-CL (Kleiber et. al. 2012). Simulations were used to compare how alternative catch-based (South Pacific albacore) and effort-based (skipjack) harvest control rules performed across a range of plausible conditions. Simulation analyses are useful because they allow for the quantification of relative performances among HCRs and against management objectives (Butterworth and Punt 1999). The general steps for each species included (*sensu* Punt 2006):

(1) Parameterize the MFCL projection model using information from the most recent MULTIFAN-CL stock assessment (2011 reference case albacore, see SC7-SA-WP-06; 2011 reference case skipjack, see SC7-SA-WP-04)
(2) Obtain current stock status information (e.g., SB_{latest}/SB_{MSY}) from most recent MULTIFAN-CL assessment
(3) Set catch or effort for the next management period (*currently set at 3 years*) based on the candidate HCR policy
(4) Project the population forward one management period under the policy prescribed fishery conditions (amount of catch or effort) with a particular set of recruitment values (more details below)
(5) Add random noise at the end of each management period to simulate uncertainty in our knowledge and ability to estimate stock status(a) and to effectively implement management(b)
    a. process uncertainty in the predicted stock status (CV assumed at 0.35)
    b. observation/implementation uncertainty in the prescribed fishery condition[3]
(6) Repeat steps 3-5 for each management period in the simulation (*currently set at 10*)
(7) Repeat steps 3-6 over many simulations (*currently set at 200*), each representing alternative plausible recruitment trajectories
(8) Calculate performance metrics across simulations[4]
(9) Repeat steps 3-7 over candidate HCRs (*currently set at 6*)

The full routine resulted in 200 individual 30-year stochastic projections from which performance metrics were then computed for each of the six candidate HCRs examined. The simulation operating model was developed and graphics produced using program R computing facilities (www.r-project.org/). Stochastic population projections were run using a currently unreleased version of MULTIFAN-CL.

Stochastic recruitment values used in the simulations for this paper were generated randomly by resampling estimated absolute historical recruitments (1972-2010). Development is currently underway to generate stochastic recruitment distributions from the product of a recruitment predictor and a set of log-normal deviates for use in stochastic projections. However, the inability to yet include this

---

[3] For analyses presented in this paper, observation/implementation uncertainty was not considered for ease of displaying and interpreting the implications of constant control rules and because of the need to define the distribution of such uncertainties.

[4] All performance metrics were calculated across the projected time series (30 years) for each simulation, except for stock status at the end of the projection period (year 30) shown in Figure 3. Alternatively, performance metrics could be calculated for the last year only or across years later in the time series, once the HCR has had time to interact with the population from the initial state.

development in the HCR analyses presented here has the potential to introduce bias into the results, particularly for HCR options where harvest approached or exceeded MSY due to recruitment being overestimated when stock size falls well below historical levels. For example, risk-related performance metrics (e.g., probability of exceeding the limit reference point) may be under-estimated, resulting in a management decision being more risk prone than expected. As such, <u>results presented here should be viewed as illustrative examples only</u>.

Appendix 3: Supplemental figures

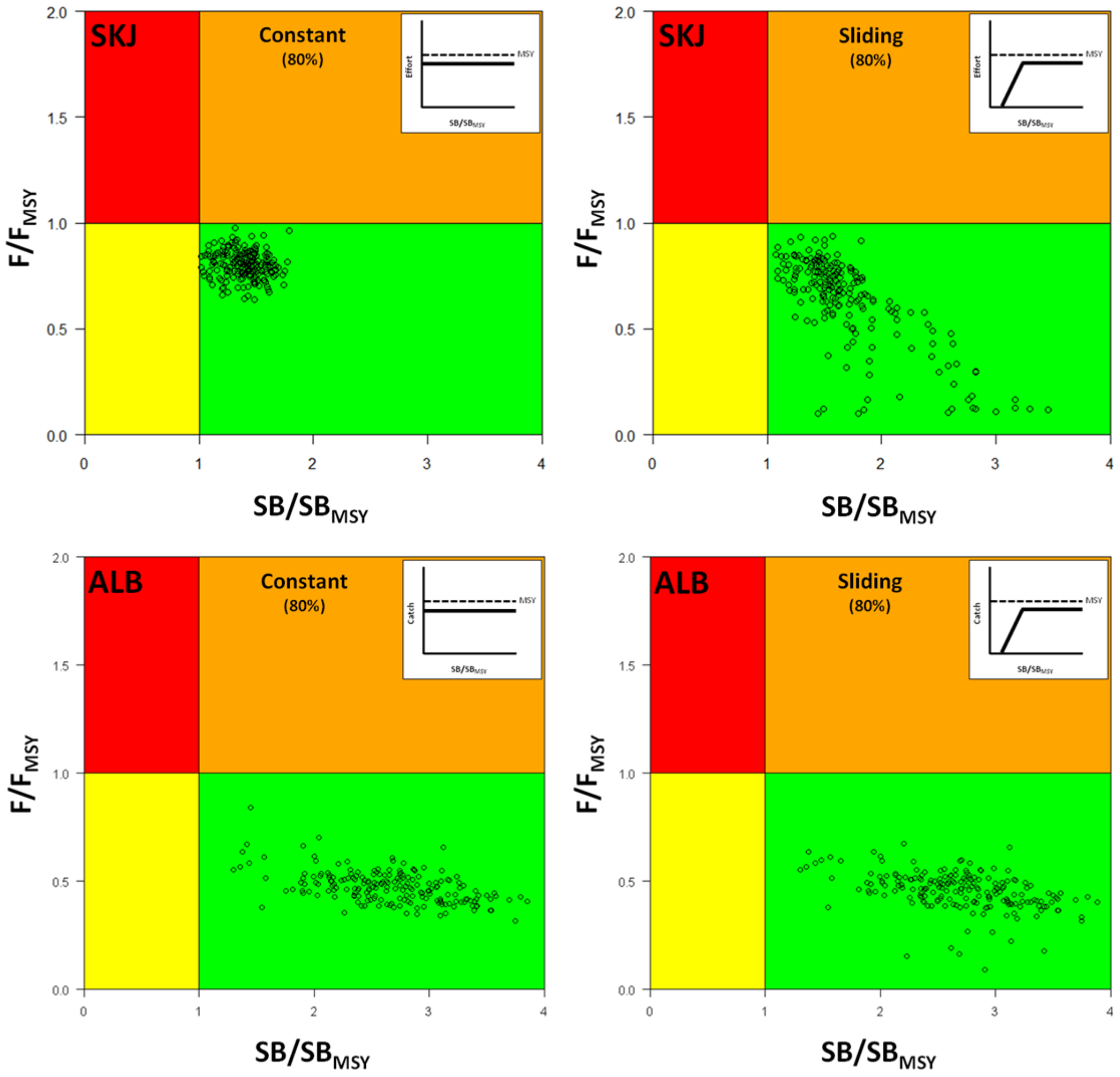


Figure A3.1. Stock status at the end of each projection period (points) under the Constant (80%) control rule (left) and the Sliding (80%) control rule (right) for skipjack tuna (top, effort control measure) and South Pacific albacore tuna (bottom, catch control measure). Each point represents the status at the end of the projection period from a single simulation. The spread of points represent variability in future stock status arising from recruitment variation and stock assessment error. A graphic representation of the harvest control rule evaluated is shown in the upper right corner.

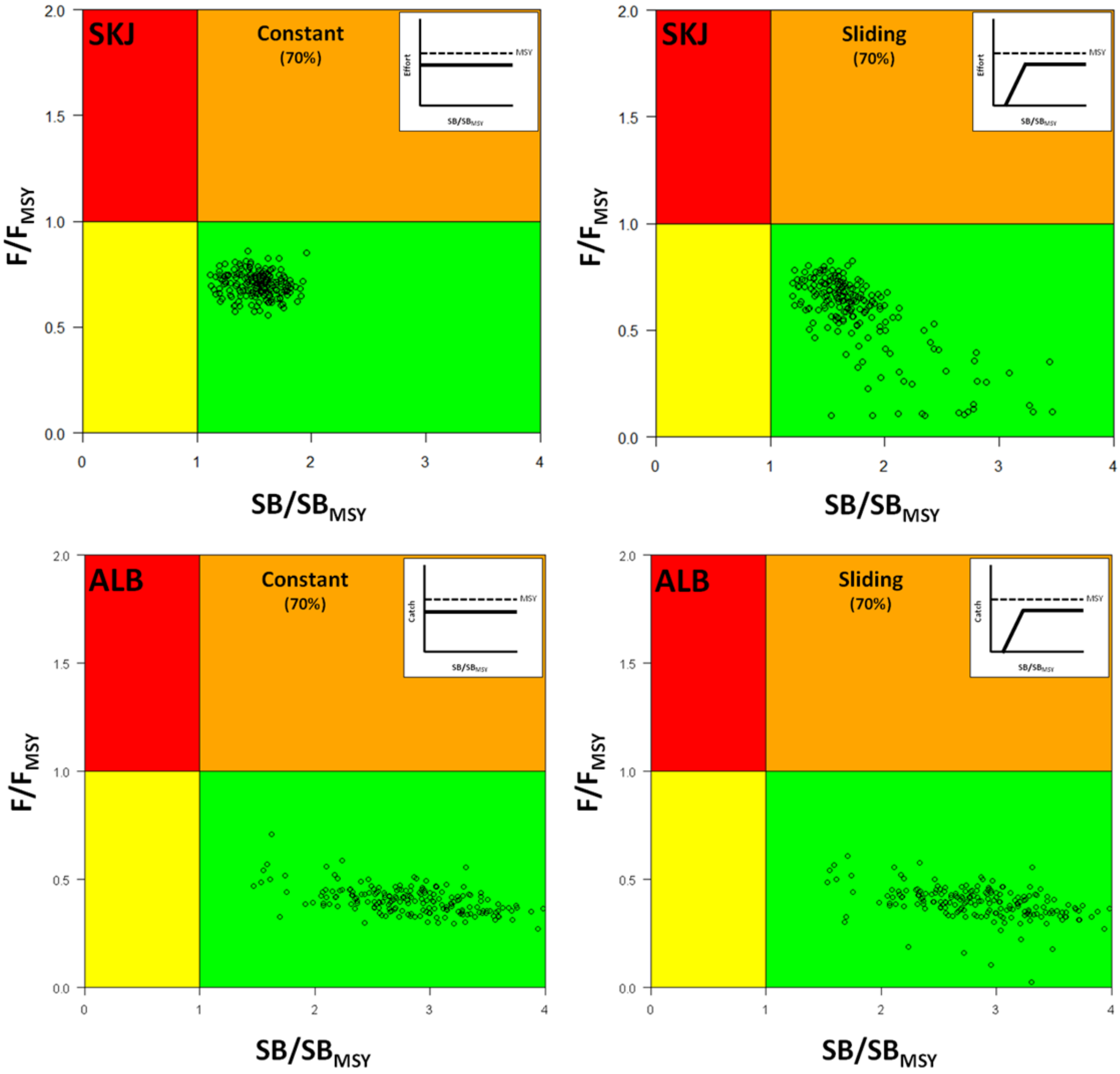


Figure A3.2. Stock status at the end of each projection period (points) under the Constant (70%) control rule (left) and the Sliding (70%) control rule (right) for skipjack tuna (top, effort control measure) and South Pacific albacore tuna (bottom, catch control measure). Each point represents the status at the end of the projection period from a single simulation. The spread of points represent variability in future stock status arising from recruitment variation and stock assessment error. A graphic representation of the harvest control rule evaluated is shown in the upper right corner.

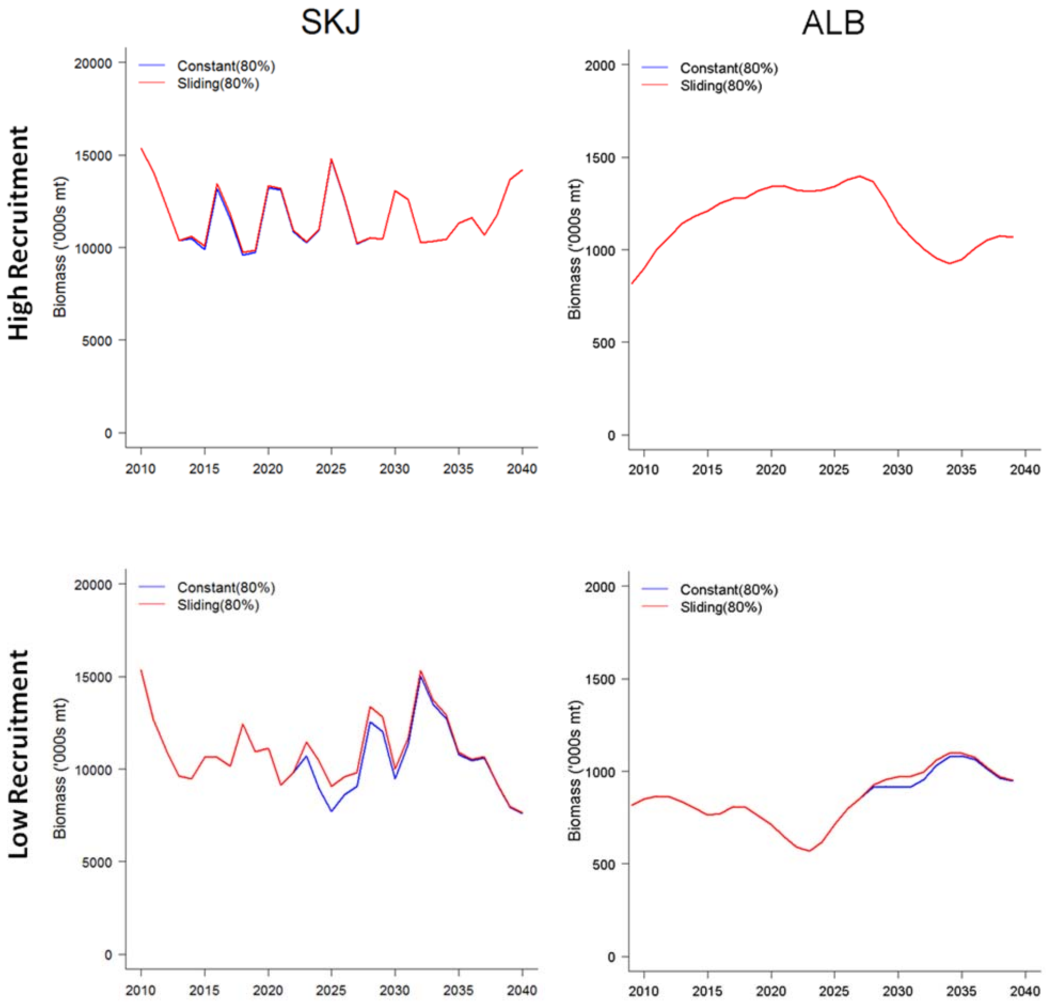


Figure A3.3. A single projected biomass trajectory for skipjack (left) and South Pacific albacore (right) using a Constant (80%) rule and a Sliding (80%) rule at two levels of assessed stochastic recruitment: high (97.5% quantile; top) and low (2.5% quantile; bottom).

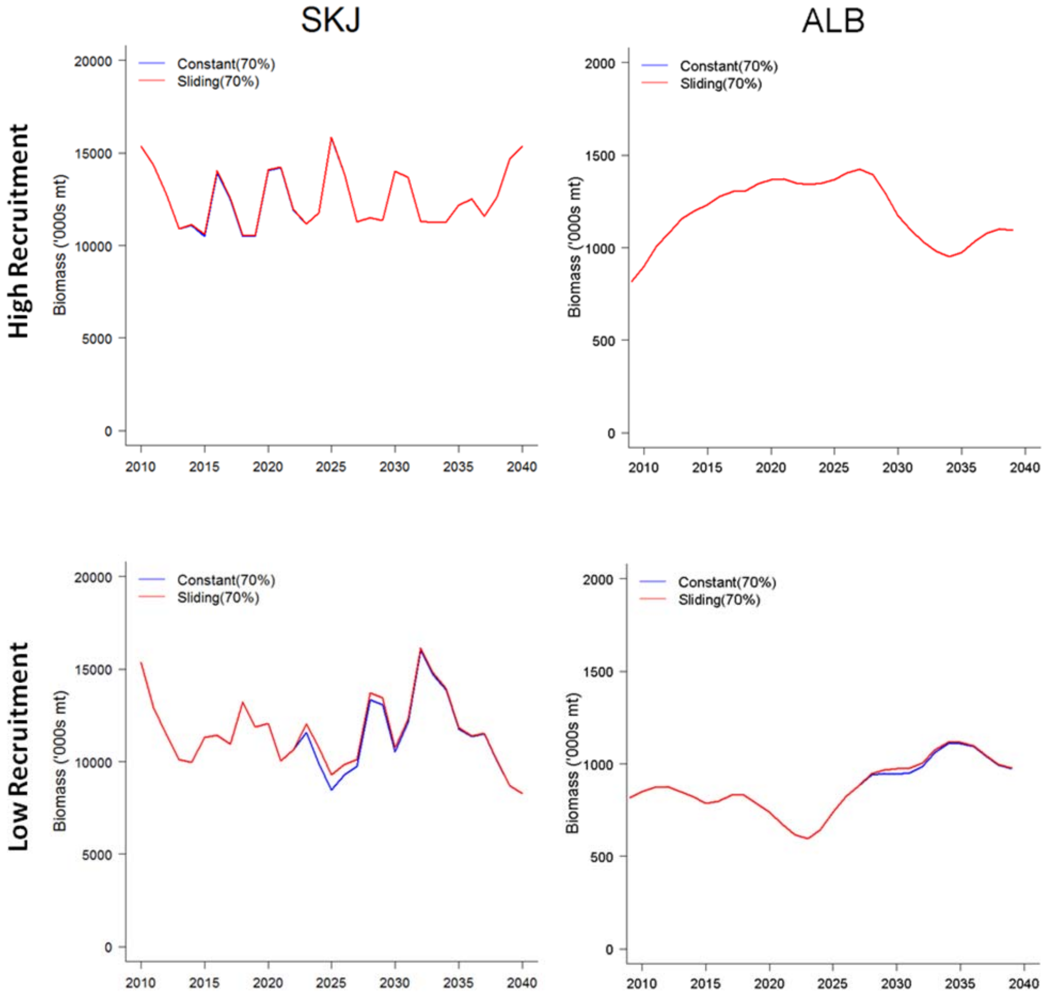


Figure A3.4. A single projected biomass trajectory for skipjack (left) and South Pacific albacore (right) using a Constant (70%) rule and a Sliding (70%) rule at two levels of assessed stochastic recruitment: high (97.5% quantile; top) and low (2.5% quantile; bottom).

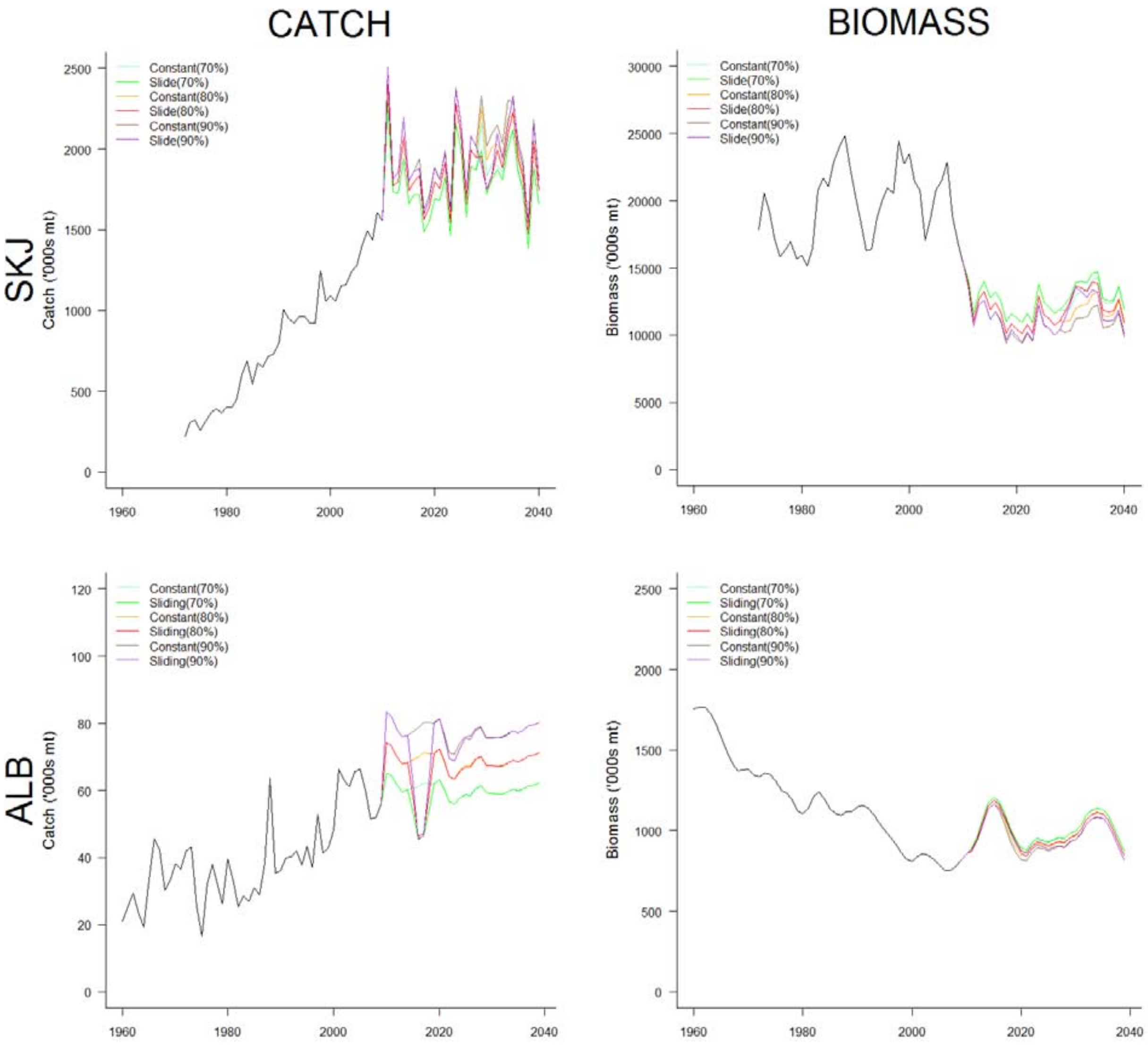


Figure A3.5. Time series of estimated (black line) and projected (colored lines) total catch and biomass for skipjack and South Pacific albacore. A single, randomly selected, projection is shown here for each of the example harvest control rules examined, representing one of the 200 stochastic recruitment trajectories used to compare rules for each species. An effort-based control measure was used for skipjack HCRs (top), and a catch-based control measure was used for South Pacific albacore HCRs (bottom). Descriptions of the example harvest control rules are given in Table 2 and graphical representations are shown in Figures 2 and 5.

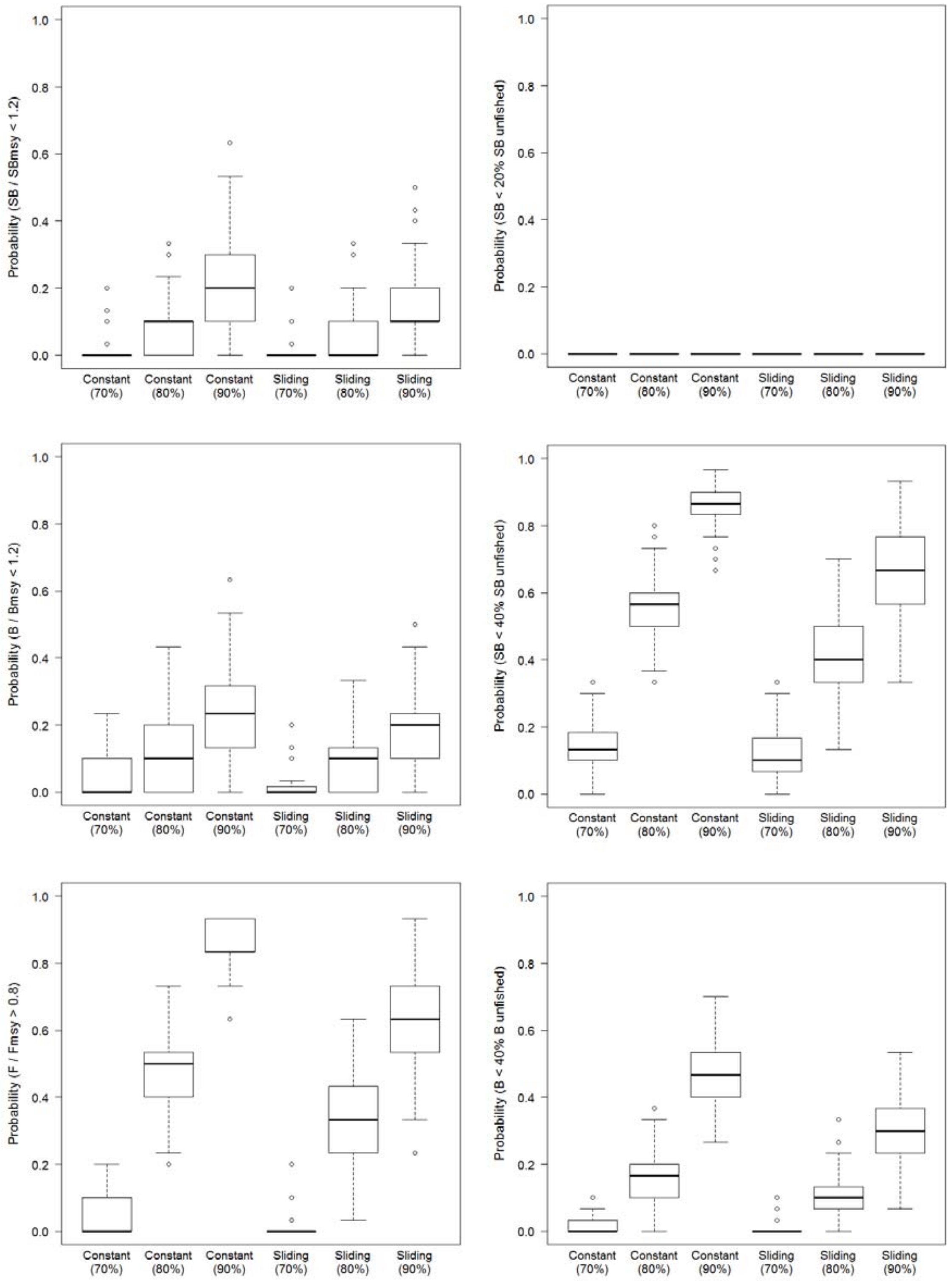


Figure A3.6. Boxplots showing the distribution across simulations for the probability of exceeding hypothetical skipjack target and limit reference points for each of the example HRCs examined. Median represented by the horizontal line of the box. Boxes represent the 25th, and 75th percentiles, whiskers show 5th and 95th percentiles.

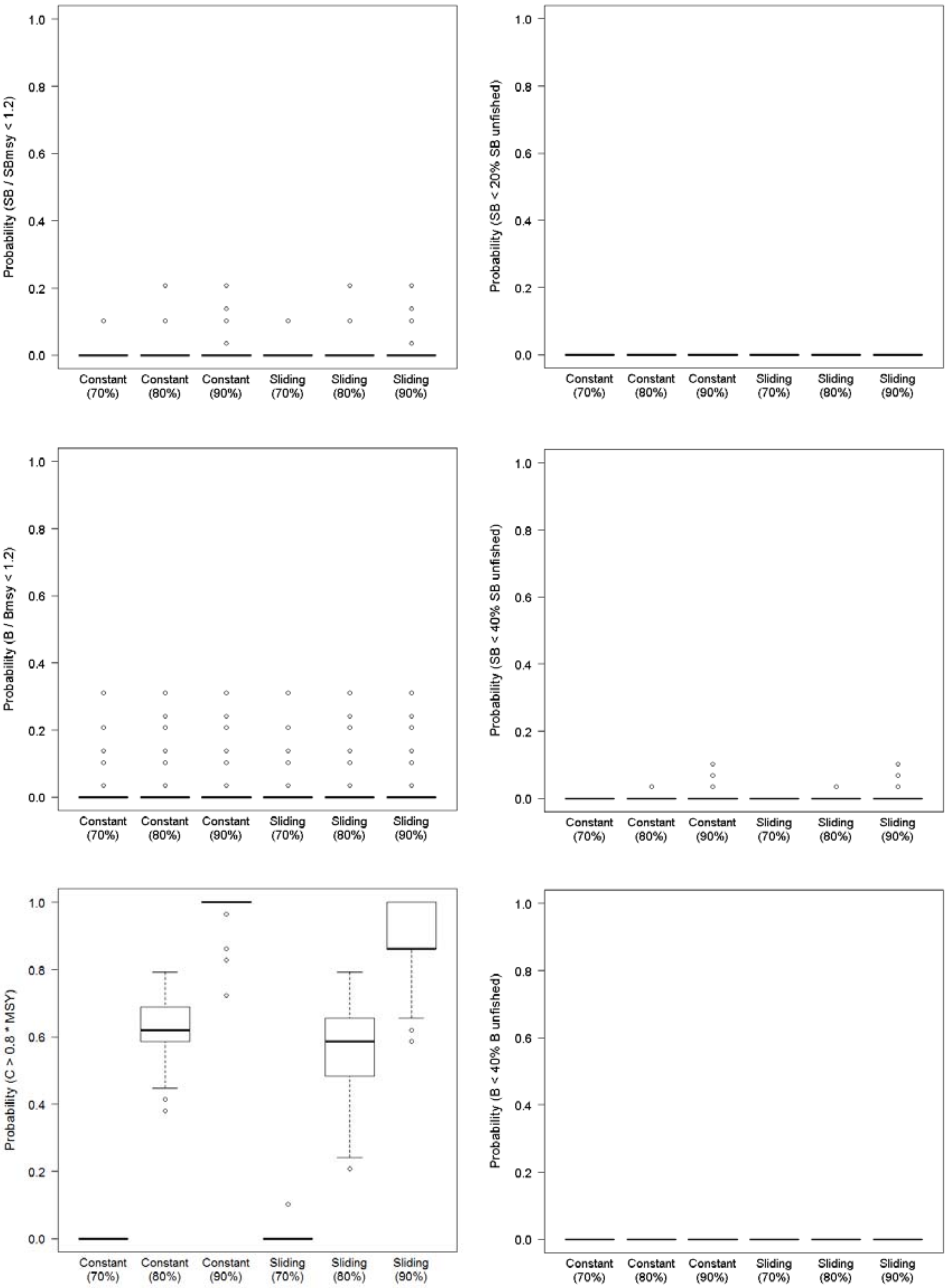


Figure A3.7. Boxplots showing the distribution across simulations for the probability of exceeding hypothetical South Pacific albacore target and limit reference points for each of the example HRCs examined. Median represented by the horizontal line of the box. Boxes represent the 25th, and 75th percentiles, whiskers show 5th and 95th percentiles.

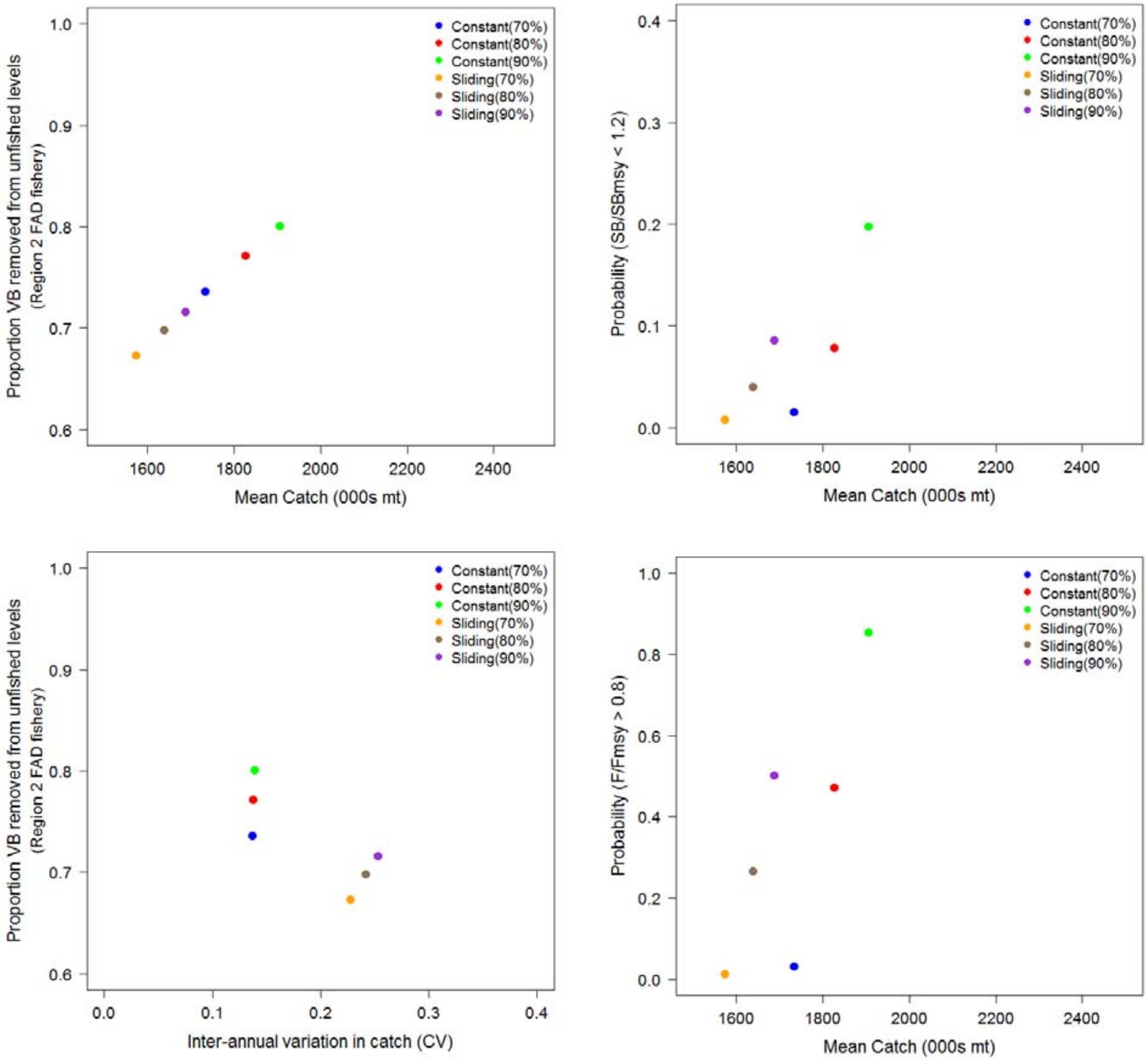


Figure A3.8. Two-dimensional tradeoff plots showing differences in some example skipjack performance metrics for the six HCRs evaluated.

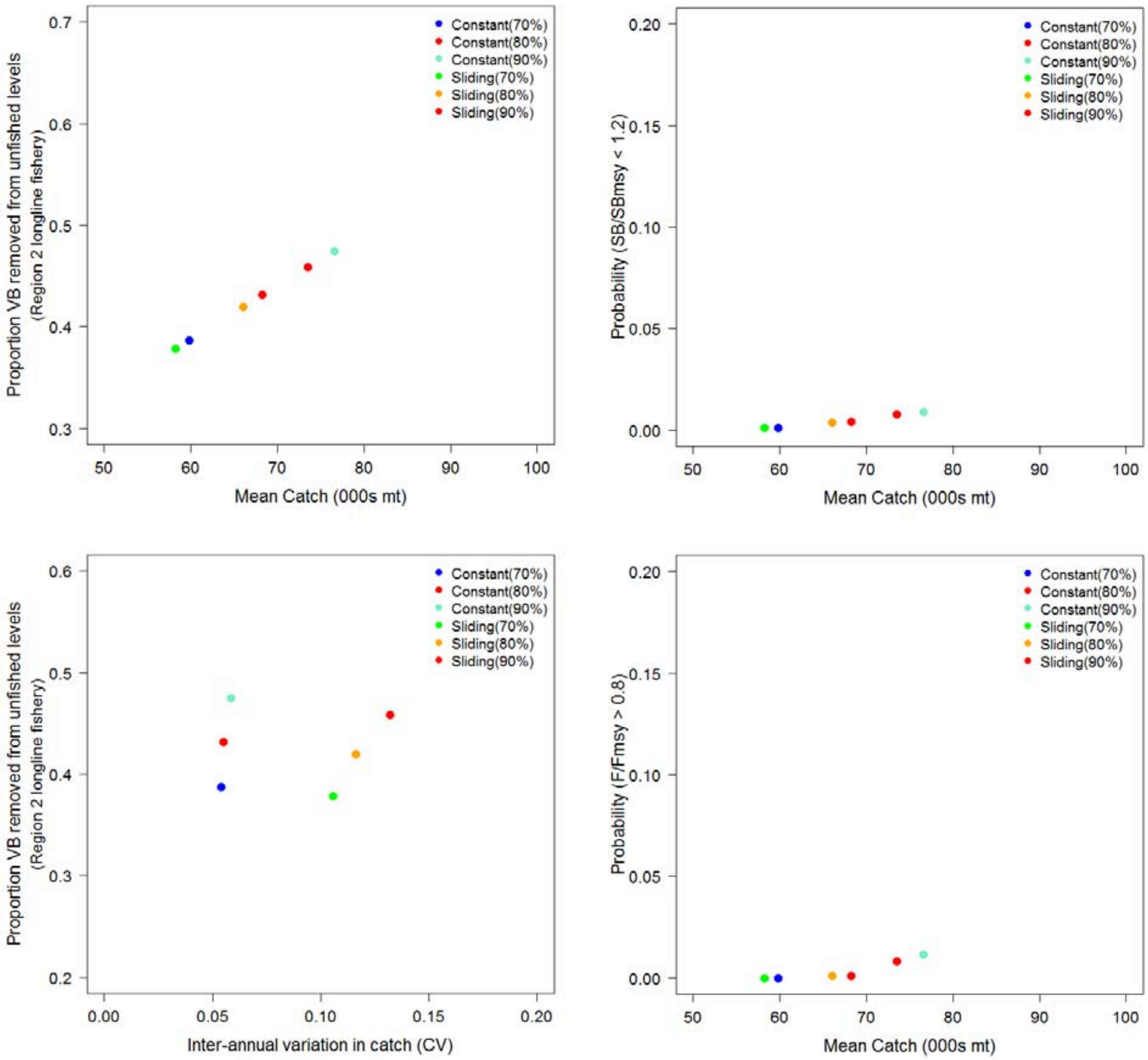


Figure A3.9. Two-dimensional tradeoff plots showing differences in some example South Pacific albacore performance metrics for the six HCRs evaluated.

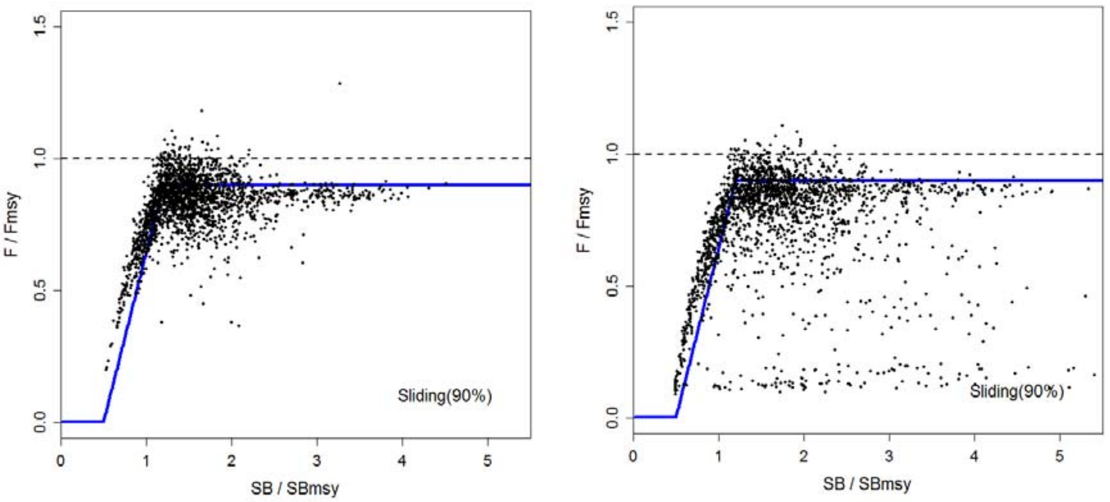


Figure A3.10. Individual realizations of effort-based management interventions (every 3 years for 30 years) across simulations (200) for the skipjack fishery according to the Sliding (90%) HCR. Scatter around control rules represents uncertainty due to recruitment variability (left and right panels the same level) and assessment uncertainty (CV=0.20, left panel; CV=0.35, right panel). In effect, the only difference between the two panels is from to the level of uncertainty associated with stock status (more uncertainty on the right) .