Applying Management Strategy Evaluation to California Fisheries: Case Studies and Recommendations

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Written by:
Adrian Hordyk, University of British Columbia
David Newman, Natural Resources Defense Council
Tom Carruthers, University of British Columbia
Lisa Suatoni, Natural Resources Defense Council

Contributors:
Tom Barnes, California Department of Fish & Wildlife
Kathryn Crane, California Department of Fish & Wildlife
Heather Gliniak, California Department of Fish & Wildlife
Carlos Mireles, California Department of Fish & Wildlife
Derek Stein, California Department of Fish & Wildlife

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Acknowledgements

Since its inception, the Data-Limited Methods Toolkit (DLMtool) has evolved as a collaborative and open-source project. Its growth and continued improvement is due to the contributions of many scientists, managers, stakeholders, and funders who have provided constructive criticism, new ideas, identified software bugs, provided peer-review, and supported the work in countless other ways. For those whose contributions are not recognized explicitly below, we appreciate your help in shaping and promoting this public endeavor to improve the science and management of data-limited fisheries.

The concept of creating a flexible software package for data-limited fisheries emerged from a collaboration between the Natural Resources Defense Council (NRDC) and the University of British Columbia's Institute for the Oceans and Fisheries (UBC) beginning in 2012. The central question that spurred the initiative focused on a common dilemma: how to sustainably manage fisheries that lack traditional assessments of current population status and fishing mortality levels. We began grappling with this question within the context of the United States fisheries management system, which at the time was beginning to adopt mandatory annual catch limits for unassessed and data-limited stocks. To abide by the statutory deadline, U.S. fisheries managers scrambled to apply an assortment of methods for setting catch limits for scores of unassessed stocks. New methods were conceived, many untested, and rapidly applied to hundreds of fish species in a matter of a few years. At the time, there was no central repository of data-limited methods, and, more urgently, no way to transparently and consistently test the efficacy and applicability of different methods to different fisheries. To address this problem, NRDC and UBC conducted a comprehensive review of existing methods and used management strategy evaluation (MSE) to test how well these methods were likely to succeed or fail at sustainably managing a range of fishery types. We learned that the choice of method might work fine in one situation, but cause catastrophic results in another. Absent any consistent framework for evaluating this rapidly growing body of methods, we were unable to determine the appropriate management path for different fisheries in a proactive and scientifically-defensible way.

This realization led to the development of a prototype MSE tool that could be applied rapidly to fisheries anywhere. To test the concept, we convened a workshop with NOAA Fisheries in early 2014 where the first version of the DLMtool was showcased live to a room of seasoned scientists. The response was positive, but with ample ideas for improvement. Since that time, we have worked with scientists at governmental and academic institutions around the world to refine and improve the DLMtool through direct testing and application with real fisheries. To date, the DLMtool has been applied to dozens of fisheries, with each application providing crucial feedback on how to make it better.

This project with the California Department of Fish and Wildlife, aimed at demonstrating the use of MSE for California fisheries, has provided an important opportunity to test, scrutinize, and improve the DLMtool package, and to streamline its application for providing practical management advice. We are greatly indebted to the generous support provided by the Resources Legacy Fund and particularly the strategic advice and guidance of RLF's Program Manager, Mike Weber. We would also like to thank the people at the CDFW with whom we have had the good fortune to work, including Tom Barnes, Craig Shuman, and Chuck Valle. We particularly appreciate their openness to new ideas and approaches that has characterized this project and the broader effort to amend the Master Plan for Fisheries in California.

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Glossary

B_{MSY} – The biomass of a fish stock that provides the highest long-term average catch (maximum sustainable yield)

Bycatch – fish or other marine life that are taken in a fishery but which are not the target of the fishery, including dead and live discards

Catch-per-unit-effort (CPUE) – the amount of catch (in numbers or weight) taken by a single unit of fishing effort (also called catch rate, and often used as an indirect measure of abundance

Catchability – a constant of proportionality that defines the fraction of the stock that is caught by one unit of fishing effort.

Data-limited – (encompasses data-poor and data-moderate): a situation where data are insufficient to conduct a conventional stock assessment

Data-limited method (DLM) – a method, not derived from a conventional stock assessment model, for obtaining management advice from raw data (a.k.a., "management procedure")

Depletion – spawning stock biomass relative to the unfished (virgin) condition that existed prior to fishing

Discards – fish that are taken in a fishery but are not retained because they are of an undesirable species, size, sex, or quality, or because they are forbidden by law to be retained

Fishery Information – information about fish life history and habitat requirements; the status and trends of fish populations, fishing effort, and catch levels; fishery effects on fish age structure and on other marine living resources and users, and any other information related to the biology of a fish species or to taking in the fishery that is necessary to permit fisheries to be managed

F_{MSY} – the fishing mortality rate that will achieve maximum sustainable yield

Harvest control rule (HCR) – an interpretation of assessment model outputs for making management recommendations

Input control – a size limit, time-area closure, effort control

Management procedure (MP) – a reproducible approach that takes you from raw data to a management recommendation (a.k.a., "harvest strategy")

Management recommendation – a total allowable catch (TAC), total allowable effort (TAE), minimum size limit, marine reserve etc.

Management Strategy Evaluation (MSE) - a computer simulation approach for testing prospective management options over a wide range of possible future scenarios for the fish population and the fishery operating on it

Marine Life Management Act (MLMA) – the California state law governing marine fisheries management

Maximum sustainable yield (MSY) – the largest, long-term catch that can be taken under existing conditions

Observation model – a theoretical framework for generating data that may be biased and imprecise (the lens through which MPs "see" the operating model)

Operating model – a credible representation of fishing and population dynamics (the simulated reality)

Output control – a catch limit (OFL, TAC)

Performance metric – a predefined measure of the projected performance of different management strategies subject to a management strategy evaluation in terms of yield, biomass, fishing mortality rates, and other similar metrics, defined probabilistically over different time-periods of the MSE projection period

Selectivity – the proportion of individuals in any age or size class that are vulnerable to be caught by the fishing gear

Stock assessment – a process where one or more data streams of historical catch, effort, and population trends are analyzed using quantitative models and expert knowledge to estimate biological reference points, stock status relative to those reference points, and predict the impact of future catches on stock dynamics

Executive Summary

More than 80% of global catch is estimated to come from fisheries with little or no scientific information to guide management decisions (Costello et al., 2012). This leaves them vulnerable to overexploitation and declining yield over time. California is in a similar situation, with only about half of priority fish stocks managed under fishery management plans, and only a portion of those stocks having undergone formal stock assessments to inform management decisions. Many California fisheries are "data-limited," meaning they lack sufficient information on population status and biological and ecological characteristics to conduct a conventional stock assessment. Consequently, management decisions are often based on ad-hoc analyses and interpretations of available data, resulting in an inconsistent approach to management.

The California Department of Fish and Wildlife (CDFW) has embarked on a comprehensive program to address the challenges of fulfilling its mission to sustainably manage the state's marine fisheries. The mechanism for change is an amended Master Plan for Fisheries that provides specific guidance and associated tools for addressing the various chokepoints in developing fishery management plans and status reports for priority fisheries. This project, undertaken to inform the Master Plan amendment process, has been designed to test the potential role that management strategy evaluation (MSE) could play in providing reliable scientific management advice through the use methods that rely on fewer data than conventional stock assessments. Such methods range from simple rules that adjust management controls relative to changes in catch rates or the average size of the catch over time, to more complex approaches that more closely resemble conventional stocks assessments. While many such "data-limited methods" are readily available, the challenge has been to know which methods are most suitable for specific fisheries.

MSE enables users to test a range of management options in a quantitative manner, while being explicit about the uncertainties in the system. With the aid of computer simulation, MSE compares prospective management approaches over a wide range of possible scenarios. An MSE does not, by itself, provide a specific management recommendation like a catch-limit or effort control, but instead identifies those methods that are likely to provide the desired management performance. In contrast to stock assessments, which strive to identify our best understanding of the current stock status and dynamics of the fishery, MSE identifies management approaches that have a high likelihood of performing well across a range of uncertainty about stock status and the fishery system. MSE has been used by fisheries scientists since the 1970s, when it was originally developed by the International Whaling Commission to evaluate the various trade-offs involved in the management of marine mammals and to guide the decision process toward an appropriate management procedure.

To demonstrate how MSE may be used for data-limited fisheries in California, we applied a recently developed MSE software program called the Data-Limited Methods Toolkit (DLMtool)

(Carruthers et al., 2014) to four California fisheries in collaboration with the CDFW staff responsible for managing those fish stocks. The DLMtool is an open-source software package that uses computer simulations of real-world fisheries to help scientists and managers identify effective management methods under a range of assumptions regarding specific stock dynamics, fishing fleet behaviors, and the availability, precision, and accuracy of fisheries data. It is currently being applied to a range of fisheries in different fishery management regions (SEDAR, 2016; SEDAR 2016a; McNamee et al., 2015; Miller, 2015; Weidenmann, 2015).

With input from an expert working group of fisheries managers, scientists, industry representatives, and other stakeholders, we evaluated whether and how MSE (via use of the DLMtool) may be integrated into the state's management system.

The MSE framework within the DLMtool is comprised of three key components: 1) an operating model that is used to simulate the stock and fleet dynamics, 2) an assessment and harvest control rule model (containing "data-limited methods," also called "management procedures") that uses the simulated fishery data from the operating model to provide management recommendations (e.g., a total allowable catch or a control on fishing effort), and 3) an observation model that simulates the expected imprecision and bias in the fisheries data that are typically observed and used in management. The management recommendation from the method being tested is then fed back into the operating model, which is then projected forward one time step. This process of simulating the population dynamics of the fishery and the management process that impacts the simulated fish population is known as "closed-loop simulation." By repeating this process with a range of alternative management methods, MSE reveals the predicted impacts of specified management approaches to their fishery decades into the future and enables managers to choose an approach that best achieves their management objectives, as articulated through a set of well-defined performance metrics.

The four fisheries selected by CDFW as case studies for this project included barred sand bass (*Paralabrax nebulifer*), southern California halibut (*Paralichthys californicus*), southern red sea urchin (*Mesocentrotus franciscanus*), and warty sea cucumber (*Parastichopus parvimensis*). They were chosen to test the DLMtool's applicability to fisheries with different life-histories (two invertebrates and two finfish), data availability (from data-poor and unassessed to data-moderate and recently assessed), and fishery sectors (recreational, commercial, and mixed). The following process was used in applying the DLMtool to each stock:

1. Aggregating and processing currently available **fishery information**
2. Designing an **MSE operating model** that serves as the best available representation of the stock and fleet dynamics of the fishery and a realistic observation model that simulates imperfect knowledge of the system
3. Defining specific **performance metrics**, representing the management objectives for the fishery, that are used to evaluate different management procedures
4. Identifying acceptable and available **management procedures** from the MSE
5. Applying acceptable and available methods to obtain **management recommendations**

6. Analyzing the MSE results to determine the **value of additional information** to improve data collection and research programs

Decisions associated with the application of the DLMtool were stock-specific, as were the results. Summaries of the results for each case study are provided below.

Barred Sand Bass Case Study

To conduct the MSEs, CDFW identified performance limits and targets, below which management procedures were eliminated for consideration. For barred sand bass, management procedures were considered acceptable only if they had a greater than 80% probability that the biomass in years 11-50 and years 41-50 of the MSE projection period would be greater than $0.2B_0$ (20% of unfished biomass). The biomass target was specified at a 50% probability that biomass would exceed $0.4B_0$ in years 41-50 of the projection period.

A total of 86 management procedures were evaluated in the barred sand bass MSE (69 from the DLMtool package, plus an additional 17 custom methods). Many of the management procedures performed well relative to these management objectives. A total of 55 management procedures met all the performance limits and management targets. Fifteen of the methods that passed the performance metrics were custom input control methods that use size-based regulations, including minimum legal lengths or harvest slot limits.

The DLMtool MSE model currently assumes that size-based regulations are implemented perfectly and there is no fishing mortality on sub-legal fish. This assumption is invalid for fisheries where it is likely that sub-legal fish either are retained or discarded dead. Consequently, the minimum legal length methods included in this analysis may underestimate the risk associated with static size-based regulations, especially where it is unlikely that these regulations can be perfectly implemented.

Quantifying the risks of this implementation error requires specific data from the fishery, including an understanding of the selectivity of the fishing gear and an estimate of the fishing mortality rate on discarded fish. The DLMtool is currently being further developed to include this information and to quantify these risks. However, until such information is incorporated into the analysis, the results of size-based regulations examined for this study should be interpreted with caution.

The CDFW reported that post-release mortality for barred sand bass is low, however within the scope of this project it was not possible to quantify this. While the minimum legal length and slot limit methods were included in the analysis to examine their properties under ideal conditions, it was determined that it would be invalid to assume that these methods would be implemented perfectly. Therefore, size-limit methods were not considered acceptable or available for implementation with this fishery until the analysis can be updated to include data on discard mortality.

The barred sand bass fishery is comprised entirely of recreational fishers, both from private vessels and commercial passenger fishing vessels (CPFV). For a variety of reasons, CDFW currently lacks the capacity to implement catch limits in the recreational fishery, including a lack of administrative resources, challenges adopting in-season management with time-lagged catch data, and the current lack of regulatory authority to implement the necessary management measures. These limitations, combined with the lack of a time-series of total catch for the recreational fishery means that none of the 52 output control management procedures that were included in the barred sand bass evaluation were considered available with current data. Excluding output control methods and size-based input controls left 40 acceptable management procedures for barred sand bass, 11 of which that could be used with currently available data.

The five best-performing, available methods included: *ITe5*, a method that relies on an index target where effort is modified by up to 5% each management cycle according to the current index level (averaged over the last 5 years) relative to a historical target level; *ItargetE1*, a method that uses the same data as *ITe5*, but adjusts fishing effort based on recent trends in the population abundance; *LstepCE1*, which incrementally steps fishing effort up and down in response to the trend in the mean length of recent catches; and two methods that maintain constant effort policies, management measures that maintain effort at current levels (*curE*) and at 75% of current levels (*curE75*). Applying *ITe5*, the method with the highest projected long-term yield, to the currently available data resulted in a recommendation of a 5% reduction in fishing effort from current levels.

Southern California Halibut Case Study

The southern California halibut represents a stock with a large amount of fishery data and the benefit of a recent stock assessment to provide information on current stock status and estimates of the life history parameters. However, the stock also presents several challenges, including multiple fishing fleets, sparse or disparate fishery data sources, and a known, but currently undefined, portion of the stock that crosses the international border between the United States and Mexico. The CDFW staff selected a performance limit of an 80% probability that the biomass in years 11-50 and 41-50 of the MSE projection period would be greater than $0.125B_0$. The biomass target was specified at a 50% probability that biomass would exceed $0.25B_0$ in years 41-50.

Eighty management procedures were included in the MSE for California halibut, including 10 management procedures that were developed for this case study. A total of 24 management procedures satisfied the performance criteria for California halibut, including four methods involving static size limits. However, as discussed for barred sand bass, the version of the MSE model used for this analysis assumes there is no fishing mortality below the minimum legal length due to a lack of information on discard mortality for the stock and current limitations with DLMtool. The assumption of negligible fishing mortality below the regulated minimum size is unlikely to be valid in the California halibut fishery where trawl nets and other fishing gear are known to capture individuals below the regulated size, which are then discarded dead back to the sea, so these methods were excluded from further consideration. Of the 21 acceptable methods remaining, all but six of these were available to be used with the current data. Four of the acceptable and available methods were input controls and 11 output controls.

Output control methods performed well in the MSE in terms of high-long-term yield with biomass projections that exceeded CDFW's performance metrics. The best performing output control method (with regard to projected long-term yield) was *Itarget1*, which uses CPUE index and landings data to compute a recommended catch limit. When applied to currently available fishery data, this method would require a significant reduction in the initial median total allowable catch by about 60% of the current catch level, and then gradually increase catch levels as the population rebuilds to the target level. Yield was also projected to reduce in the initial years of the projections for the input control methods with the highest long-term yields.

The best-performing, available input control method, *ItargetE1,* is similar to the *Itarget1* method, but returns a management recommendation with a change in fishing effort instead of a TAC. Applying the *ItargetE1* method to the California halibut data resulted in a recommendation to reduce fishing effort by 15% from the current level.

The CDFW indicated that output control methods (e.g., TAC) may be difficult to implement in the multi-fleet California halibut fishery due to increased costs and administrative requirements, and that managing selectivity (e.g., size limits) and effort would be the preferred method of management for this fishery due to the ability to impose consistent management measures across multiple sectors of the fishery. However, the MSE results may provide an incentive to develop mechanisms to manage the fishery using output controls, although the results also suggest that effort controls (in addition to size limits) could also work for this fishery. Such methods may be considered easier to implement for the southern California halibut fishery than catch limits, although the practical application of an effort-based management control for the multi-fleet fishery would require careful consideration.

Red Sea Urchin Case Study

The red sea urchin fishery in southern California is targeted for the reproductive organs of mature individuals. It is currently managed with a minimum size limit of 3.25 inches. The capture of animals above the size of maturity reduces the risk of recruitment overfishing and contributes to the high number of methods tested in the MSE that meet the performance limits for the stock. The fishery is highly selective and fishing mortality on sub-legal individuals is not considered to be a significant issue, so the lack of implementation error in the MSE did not disqualify size-limit methods as was the case for barred sand bass and California halibut.

A considerable proportion of the red sea urchin biomass is believed to be within the network of marine protected areas (MPAs) that are closed to fishing. To test the impact of MPAs on the performance and selection of management procedures for the fishery, the DLMtool was modified to include a permanent closed spatial area. The MSE was run both with and without accounting for the MPA network. As expected, including the MPA in the operating model generally increased the probability of management procedures meeting the performance limits and targets. The CDFW selected a performance limit for red sea urchin with an 80% probability that the biomass in years 11-50 and 41-50 of the MSE projection period would be greater than $0.25B_0$. The biomass target was specified at a 50% probability that biomass would exceed $0.5B_0$ in years 41-50.

There were 24 acceptable methods for the red sea urchin fishery from the MSE that accounted for the MPA network, 23 of which were available with current fishery data. The *curE75* method (fixed effort at 75% of the current level) had the highest long-term yield of the effort-based methods. The *MLL3.375* (size-limit at 3.375 inches) and *MLL3.375_5.5* (slot limit between 3.375 and 5.5 inches) methods, had the highest long-term yield among all acceptable and available methods. Maintaining current fishing effort (*curE*) with the existing size limit of 3.25 inches had similar performance to the two increased size limit methods (*MLL3.375 and MLL3.375_5.5*), but just failed to meet the management target of a greater than 50% probability of biomass greater than $0.5B_0$ over the last 10 years of the projection period.

The *Islope1* and *Islope4* methods had essentially identical performance and the highest long-term yield of the nine output control management procedures. These methods use the slope of the relative abundance, as calculated by catch-per-unit-effort (CPUE), to provide a total allowable catch (TAC) level that is set in relation to the average catch over the five most recent years. The two methods differ in the responsiveness of the catch level to the slope in CPUE, with the *Islope1* method allowing larger adjustments from one management cycle to the next. When applied to currently available data for red sea urchin, the *Islope1* and *Islope4* methods produced median TACs of 8.81 and 8.78 million pounds, respectively, which are comparable to recent (2013) landings of 8.76 million pounds.

The choice by CDFW to use proxy values for B_{MSY} based on B_0 for the biomass targets for each of the four case study stocks led to a mismatch in the case of red sea urchin that caused the target to be unnecessarily restrictive. Theoretically, a biomass target of B_{MSY}, achieved by fishing at F_{MSY} over the long run, should also lead to the highest long-term yields. However, this can present conflicts in cases where proxies for B_{MSY} are selected that are inconsistent with B_{MSY} for the specific life-history and productivity parameters of the stock (as specified in the MSE operating model).

In the case of the red sea urchin, CDFW selected a performance target of greater than 50% probability that a management procedure would achieve a biomass target of at least 50% of the unfished level ($0.5B_0$) over the last 10 years of the projection period, as no established proxy reference points for invertebrate fisheries were found. The relationship between B_{MSY} to B_0 is related, among other things, to the steepness of the stock-recruitment relationship, the assumed values of which are specified in the MSE operating model. For red sea urchin, where steepness was assumed to be 0.4 – 0.6, B_{MSY} was below $0.5B_0$.

Fortunately, B_{MSY} is calculated in the MSE for each simulation, so the performance of the management procedures can be reported relative to the calculated B_{MSY} (even if current stock status relative to B_{MSY} is unknown for a stock in the real world outside of the MSE). We found that substituting the $0.5B_0$ biomass target with B_{MSY} as calculated by the model changes the performance of the methods considerably. In this case, 40 of the 41 methods that pass the minimum performance metrics have greater than 50% probability that the biomass in the final ten years of the projection period is greater than B_{MSY}, including maintaining current effort with the current size limit. This result emphasizes the importance of adequately exploring and understanding the implications of performance metrics before conducting the MSE and eliminating management procedures based on their performance.

As the effort data are recorded in paper form and manually entered into the CDFW database, there is a lag between the data being recorded and made available for analysis. For example, data was only available up to 2013, although the MSE conducted in this study assumed that data collected in one year was available to be used by the management procedure in the following year. The TAC-based methods that were identified as appropriate for this fishery rely on CPUE data to provide an index of abundance. It may be possible to expedite the entering and processing of the fishery catch and effort data by developing electronic data collection systems or other solutions to improve efficiency. However, these approaches may be expensive and difficult to implement for this fishery. If the lag in fishery data is likely to remain in the future, this reality should be included in the MSE model to understand the effects it may have on the performance of management procedures and the selection of methods that best meet the management objectives of the fishery.

The Working Group was also interested in examining the effects of a possible future increase in effort for red sea urchin because currently only about half of the 300 permits in the fishery are not actively used. To do so, we compared the effect of maintaining current fishing effort over time with the current size limit (*curE* method), with a scenario where fishing effort in the future increases by a biased random walk to a maximum of twice the current level (all 300 fishers become active). The median biomass in the current effort scenario (*curE*) initially increased to $0.5B_0$ until about 10 years into the projection, where it gradually began to decline to $0.46B_0$ in the final year. The median biomass in the scenario with increasing effort (*incE*) initially followed a similar trajectory, but the decline in biomass was markedly steeper, with depletion level of $0.36B_0$ in the final year. While the current effort scenario (*curE*) passed the requirements for both the performance limits, the median biomass in the last 10 years was below $0.50B_0$ and therefore the method did not meet the requirements for the management target, although by a very slim margin. In contrast, the increasing effort scenario had a much higher probability of dropping significantly below the management objective, with a greater than 20% chance that the biomass in the last 10 years was below $0.25B_0$.

Warty Sea Cucumber Case Study

The warty sea cucumber represented the case study with the most uncertainty about stock status and life history. The CDFW expressed some concern about the state of the warty sea cucumber fishery in southern California due to declining catch rates in recent years. The CDFW set a performance limit with an 80% probability that the biomass in years 11-50 and 41-50 of the projection period would be greater than $0.25B_0$. The biomass target was specified at a 50% probability that biomass would exceed $0.5B_0$ in years 41-50. The MSE results reflect the uncertainty in the dynamics of the warty sea cucumber stock, with most of the management procedures failing the management objectives, and many methods performing poorly.

A total of seventy-six management procedures were tested (73 DLMtool methods and three custom methods). Of these, only three methods passed the first performance limit of at least 80% probability that biomass in the last 10 years was greater than 0.25 of the unfished level (B_0). These included two output control methods (*Itarget4* and *HDAAC*) and one input control (*LtargetE4*), but only the former two (*Itarget4* and *HDAAC*) also satisfied the performance target at least an 80% probability of biomass above $0.25B_0$ in years 11 to 50 of the projection period, and thus were considered acceptable.

The two acceptable methods for warty sea cucumber have similar performance, where yield is reduced initially to about half of the current levels, with a corresponding decrease in fishing mortality, and the stock biomass rebuilds with a median biomass in the final years of the projection period just above $0.5B_0$ and above B_{MSY} as calculated by the MSE simulations. The initial reduction in catch is likely the result of three factors: a) the initial biomass is simulated below the management target, b) the biology of the warty sea cucumber is assumed to be unproductive (with wide bounds of uncertainty), and c) the choice of the performance limits and management targets, which require an 80% probability that the stock biomass is above $0.25B_0$ and a 50% probability that biomass is above $0.5B_0$. In contrast to the two acceptable methods, the MSE results indicate that the current effort scenario (*curE*) results in a continued decline in the biomass, a gradual decrease in yield, and an increasing trend in fishing mortality.

Of the two acceptable methods, only one (*Itarget4*) was available to be used with current data. The *Itarget4* method requires data on the relative index of abundance (CPUE) for at least the 10 most recent years and estimates of total catch in the five most recent years. The method works by calculating the ratio of the average CPUE in the last five years to the average CPUE in last 10 years, and recommends a new total allowable catch level as an adjustment to the average catch over the last five years. Catches for the warty sea cucumber have declined in recent years, from 494,000 pounds in 2011 to 136,000 pounds in 2015, with an average catch 250,000 pounds over the last five years of. The CPUE has also been declining in recent years, with the average CPUE over the last five years below the average CPUE from the last 10 years. Applying the *Itarget4* method to the warty sea cucumber CPUE data resulted in a median recommended TAC of 88,600 pounds.

Like the other methods that use an index of relative abundance, the recommended catch limit from the *Itarget4* method depends on the method used to generate the CPUE index. The process for recording and entering this data is identical to that used in the red sea urchin fishery, and the same issues regarding timing of data collection and analysis discussed above must be considered for this fishery. Alternative effort control methods that may be easier to implement and enforce, such as seasonal closures during spawning and closures that adjust based on CPUE trends, may provide viable alternative management options and should be further explored in the future.

The high uncertainty in the biology of the warty sea cucumber also contributed significantly to the uncertainty and poor performance of the management procedures. A significant source of uncertainty for this species is the natural mortality rate, which is essentially unknown, so a wide range was assumed from a search of the literature for other holothuroideans. Estimating natural mortality is difficult for most marine species, and especially so for invertebrates such as sea cucumbers. The network of MPAs in Southern California may provide useful information on growth and natural mortality for this species. In addition, it may be possible to use data from the protected areas to provide estimates of depletion, or relative indices of abundance, which may be used as fishery-independent data sources for managing the fishery. The CDFW is carrying out research programs to develop understanding of the biological attributes of the species, including growth and size at maturity. The results of these studies may be used to update the operating model parameters and reduce the uncertainty in the inputs for the MSE. Re-running the MSE with this updated information may increase the performance of some management procedures, and may result in the identification of appropriate alternatives for managing the fishery.

Although the minimum legal length methods did not meet all the minimum performance limits and management targets, the performance of these methods, particularly *MLL120* and *MLL100* suggests that increasing the size of first capture for warty sea cucumber would increase the probability of the stock meeting the performance objectives. Although both the size at maturity and the selectivity pattern of the warty sea cucumber is uncertain, it is clear that current fishing practices include the capture of immature individuals. The Working Group noted that implementing a minimum legal length (MLL) for the sea cucumber fishery may be difficult, particularly because it is difficult and time-consuming to measure sea cucumber, and the sea cucumber shape, length, and weight can change when brought to the surface. However, there may be alternative methods that can be used to regulate or provide incentives to minimize the fishing mortality on small sized individuals. While the potential mechanisms to modify the selectivity curve for this fishery are still being explored, we decided to run the MSE under alternative conditions to study the possible impact of implementing a size limit.

A second MSE was run for the warty sea cucumber with the assumption that some form of size-based regulation was implemented and the size at first capture was shifted to only include individuals that are likely to be mature. There were four acceptable methods in this alternative selectivity scenario (compared with two in the original MSE).

Recommendations

The results of this project demonstrate that MSE could provide an efficient and robust mechanism for deriving improved science-based management recommendations for California state-managed fisheries. Building an MSE framework into the state's management program could create a unified process for obtaining scientific advice that is more streamlined and cost effective than the current science program, one that relies on ad-hoc analyses of available data or, less frequently, on traditional integrated stock assessments. More consistent, widespread, and current scientific advice that explicitly characterizes the inherent risk and the probability of success would also improve the likelihood that California's high priority fisheries will be managed sustainably.

It is important to note that all simulation modelling is a simplification of a complex system and therefore open to misuse or abuse. Analysts and stakeholders should be aware of potential issues associated with the MSE approach, including creating self-fulfilling prophecies, where assumptions or hypotheses of the stock dynamics or the system in general are used to parameterize the operating model, and then the results of the MSE are used as evidence to support these hypotheses. Furthermore, it is important that analysts conducting the MSE and processing the fishery data are adequately trained in population dynamics and data analysis techniques, and are familiar with the processes involved in the sampling and collection of the fishery data. Finally, analysts and stakeholders should be aware of the assumptions of the MSE framework used for the analysis and understand that the results of the MSE are conditional on accepting that the MSE model has adequately captured the principal characteristics of the system. Therefore, plans for monitoring the resource should be developed when a new management procedure is implemented in a fishery, so the system can be monitored for signals that suggest it has moved outside the bounds simulated in the MSE, such as large scale environmental events, climate change, or changes in the productivity of the species.

With appropriate training, capacity building, and guidelines for use, CDFW has an opportunity to significantly enhance its science program's ability to inform management decisions. To incorporate the MSE process into the state's fishery management system, a first step would be to recognize MSE as an approved scientific framework for management in the revised Master Plan. To tailor an MSE framework to be consistent with the objectives and mandates of the MLMA, the state may want to delineate a consistent process by which MSE is applied to

California fisheries. The process that was applied in this demonstration project described in the report below, as well as the recommendations provided at the end of the report, may provide a basis for the process that California chooses to implement. The following recommendations, which are described in more detail at the end of the report, would help enable the CDFW to effectively integrate the MSE into the state's fishery management system.

<u>Training & Scientific Capacity Building</u>. The CDFW should consider developing its internal scientific capacity, either through a dedicated MSE team of CDFW scientists or through enhanced training of existing staff, combined with external support. In either case, we recommend a two-year transitional period wherein an external MSE team would work directly with CDFW to provide training for the core MSE experts, as well as more limited training for stock biologists who would be using DLMtool or a similar MSE framework to run management procedures. The alternative route would forego dedicated CDFW MSE staff in favor of enhanced training of existing environmental scientists, combined with external support from independent consulting scientists with expertise in MSE. While the latter approach would require more substantial trainings for a larger group of CDFW staff than the first option of a dedicated MSE team, and explicit prioritization in individual and departmental workplans to provide time and resources for such trainings, this approach could effectively build capacity more broadly and deeply throughout the marine fisheries program than the first option above, while relying on external consultants to support the MSEs.

<u>Defining Performance Metrics that Achieve CDFW's Management Objectives</u>. The definition of performance metrics to compare the relative performance of alternative methods is one of the most important aspects of the MSE approach. Different stakeholders may value different aspects of the fishery, and while it is possible to include a wide range of different performance metrics, it is important that the metrics used to select methods are considered carefully to ensure they are not in conflict with each other or have unintended consequences. The results of this study demonstrate the importance of developing and exploring the implications of potential performance metrics at the beginning of the MSE process. We recommend allocating sufficient time to develop performance metrics and emphasize that it is important that managers and stakeholders understand the properties of the performance metrics before the MSE analysis is conducted. There are myriad examples of different types of performance metrics that can be used, including those selected by CDFW for use in this MSE demonstration and many alternatives that are provided in the Discussion and Recommendations section of this report.

<u>Considering Data Quality and Governance Realities When Choosing Management Procedures</u>. Once the subset of acceptable and available management procedures has been identified through the MSE, the management agency experts, in this case CDFW, must then evaluate various factors for selecting the final management procedure that will be applied to current data to obtain management recommendations. While it may appear straightforward to simply select the MP with the highest long-term yield (remember that all of the remaining methods have passed the biological performance limits and targets), it is incumbent upon the scientists

most closely involved in the analysis to evaluate management procedures according to the quality of the data they rely on, the assumptions of the methods, and the applicability and practicality of particular management procedures within the current management regime.

Providing Scientific Peer Review & Triggers for Updating MSEs. Providing efficient and thorough scientific peer review of the MSE process is essential to ensuring that the resulting management recommendations are prudent and reliable. We recommend that any new MSE should undergo an independent review akin to the kind of evaluation done for a benchmark stock assessment. Once the results have been accepted and a management procedure selected for use in a fishery, routine updates of the fishery data used with the management procedure should occur on a predetermined, regular schedule (e.g., annually or biannually). This step should be reviewed through an internal mechanism in an expedited fashion. CFDW should also develop specific criteria, or triggers, for determining when an MSE update is necessary. Such triggers could include: when substantial new information on a stock's life-history, biology, productivity, or vulnerability becomes available; when pre-specified performance indicators, such as the anticipated amount of variability in catch or effort under a particular management procedure, diverge from the actual experience in the fishery over a period of time; changes in the management system that make different classes of management procedures possible (e.g., TAC instead of an effort control); evidence that an existing management type is not being adequately complied with, monitored, or enforced; or based on a predetermined time limit between updates (e.g., 5, 7, or 10 years).

Stakeholder Engagement. An MSE can be a powerful tool for engaging stakeholders in the process of identifying and understanding management objectives and trade-offs in how specific fisheries may be managed over time. The process also provides opportunities for input on questions of governance, such as how to design a management system that can provide high levels of compliance, can be implemented and monitored efficiently by the state, and achieves the objectives of the fishery as articulated in a specific set of performance metrics. Engaging stakeholders early in the process, especially when a new scientific process is being used for the first time, is important for educating stakeholders on how the process works and how and when they can provide important feedback into the process. Successful stakeholder engagement will enhance the credibility of the management system with the public, set expectations appropriately, and improve compliance and enforcement.

Collecting, Processing & Using Fishery Data in a Timely Manner. The Fishery Information Data Table is used for the application of management procedures, and thus the recommendation from a management procedure depends on the fishery data entered into the table.
It is important that the researchers who are familiar with the history and dynamics of the fishery are involved in the processing of the fishery data, particularly with time-series information. It is also very important for any scientist who is applying the DLMtool or similar MSE framework to be fluent in population dynamics, concepts of modelling fish stocks, and other fundamental aspects of fisheries science. Well documented and standardized data systems would ensure that data processing is consistent between years and not dependent on the knowledge or

experience of a single person within the organization. To best support the adaptive management process, we recommend that CDFW engage in a review of its fishery information databases to improve the efficiency and throughput for use in MSE and the stock assessment processes. We further recommend the development of a repository designed to house all processed fishery data in a single database, accessible by all authorized CDFW staff. The format of such a database could be made compatible with the DLMtool Fishery Information Data Tables, thereby saving time and redundancy in effort as the DLMtool is applied across multiple species.

Introduction

The lack of scientific knowledge of the amount and type of fishing occurring threatens the health and productivity of marine ecosystems around the world. It is estimated that more than 80% of global catch comes from fisheries with little or no scientific information to guide management decisions (Costello et al., 2012). In the United States, the population status of half of federally-managed stocks and stock complexes is unknown (NMFS, 2016). Among priority fish stocks in California, only about half are currently being managed under fishery management plans (Table 1) and only a portion of these stocks have been formally assessed. This may leave them vulnerable to overexploitation, especially in the face of climate change, ocean acidification, and other escalating environmental stressors.

Most California state fisheries are "data-limited," meaning they lack sufficient information on catch, population status, and biological and ecological characteristics to conduct conventional stock assessments (e.g., Stock Synthesis, Methot and Wetzel, 2013). The lack of assessments for data-limited fisheries adds to the already challenging task of selecting appropriate management strategies from among a large and diverse array of approaches that have recently been developed to address the challenges of managing stocks with few data. Recent requirements to adopt stock-specific management in the United States, Australia, and other countries have led to a flurry of scientific activity regarding the status and management of data-limited fisheries, including the development of myriad new methods for generating catch advice. The challenge, however, is to know which of these methods will work most effectively to manage a particular fishery given the large uncertainties in our understanding of the system.

Management strategy evaluation (MSE) presents a promising solution to the data-limited fisheries problem because it enables scientists to evaluate a range of management options in a quantitative manner while being explicit about uncertainties in the system. With the aid of computer simulation, MSE compares and evaluates prospective management approaches – from simple control rules that use few data, to more complex assessment models that require extensive data sets – over a wide range of possible scenarios for the fishery and fish population. This approach can be particularly useful in highly uncertain situations with limited available information.

A recently developed software package called the Data-Limited Methods Toolkit (DLMtool) (Carruthers et al., 2014) offers a flexible and extensible MSE function and analytic framework that can be readily tailored to data-limited fisheries. The DLMtool is open-source and it uses a standardized process to organize available fishery information, define management objectives, evaluate the performance of different management approaches, and apply high-performing methods to obtain concrete management guidance. It is currently being used for a range of fisheries in different management regions (e.g., SEDAR, 2016; SEDAR 2016a; McNamee et al., 2015; Miller, 2015; Weidenmann, 2015). The DLMtool also has been the subject of previous peer reviews (Carruthers et al., 2014; Carruthers et al. 2015; Sagarese et al., 2016).

This report presents the findings and recommendations of a demonstration project applying the DLMtool framework to four California-managed fisheries, which served as case studies for determining whether and how an MSE approach could facilitate improved fisheries management in the State.

Background

The goal of the project was to apply an MSE decision-making framework in collaboration with the California Department of Fish & Wildlife (CDWF) to identify the potential benefits and challenges to adopting the approach as part of the State's fisheries management process. To accomplish this, an external team of scientists and policy experts from the University of British Columbia (UBC) and the Natural Resources Defense Council (NRDC) worked closely with scientists and managers from the CDWF to familiarize them with the concepts of MSE and to customize the DLMtool software package to fit the scientific needs and policy requirements of the California's fishery management system. The primary purposes were for CDFW to gain knowledge of and experience with the DLMtool's functions and capabilities, and to determine whether and how the DLMtool may be integrated into the management system as part of the state's amended Master Plan for Fisheries. We convened a Working Group of independent scientists, fishermen, and conservationists to provide information on the fisheries being analyzed (both quantitative and qualitative), to identify management objectives, and to provide feedback on the results (see Appendix A for a list of Working Group members).

California's Marine Life Management Act

The State's Marine Life Management Act (MLMA) establishes a policy to ensure the conservation, restoration, and sustainable use of the State's living marine resources. California Fish & Game Code § 7050. The specific policy objectives of the Act (§ 7055(b)) include the following:

- To achieve sustainable use of fishery resources
- To facilitate long-term protection
- To ensure conservation
- To restore marine fishery habitats (if feasible)
- To prevent overfishing
- To rebuild depressed stocks

Sustainable use, which is identified as "the primary fishery management goal," is defined as:

> "…securing the fullest possible range of present and long-term economic, social, and ecological benefits, maintaining biological diversity, and, in the case

of fishery management based on maximum sustainable yield, taking in a fishery that does not exceed optimum yield." CA FGC § 99.5.

The MLMA mandates the use of fishery management plans that include measures that are necessary and appropriate for conservation and management of fisheries per the policies and requirements of the Act and based on the best scientific information available. CA FGC §§ 7072; 7082. These requirements include the specification of criteria for identifying when a fishery is overfished or subject to overfishing, and the adoption of measures to prevent, end, or otherwise appropriately address overfishing and to rebuild the fishery within a specified time period that shall be as short as possible, but not to exceed 10 years, except where the biology of the stock or environmental conditions dictate otherwise. CA FGC § 7086.[1] Notably for data-limited fisheries lacking stock assessments, both definitions provide for situations where maximum sustainable yield is unknown and where other proxies for sustainability may be considered.

The California Master Plan for Fisheries

To implement the MLMA's provisions, the law requires that the California Fish and Game Commission adopt a Master Plan to specify the process and resources needed to implement fishery management plans for all state-managed fisheries, and to do so with input from stakeholders, including fishermen, conservationists, and scientists. CA FGC § 7073(a). Specifically, the Master Plan must describe the research, monitoring, and data collection activities that CDFW conducts for marine fisheries. CA FGC § 7073(b)(3). The Master Plan must also prioritize the development of fishery management plans based on which species have the "greatest need for changes in conservation and management measures to comply with the policies and requirements" of the Act. CA FGC § 7073(b)(3).

The current Master Plan, adopted in December 2001, identified over 375 marine fishes, invertebrates, plants and algae managed by the State. Based on three distinct prioritization approaches (two for finfishes and one for invertebrates), the Plan selected ten groups, comprised of 29 species, as the highest priorities for conservation and management in addition to the two fisheries, comprised of 20 species, with fishery management plans already in progress at that time (Nearshore Finfishes and White Seabass), as well as the Abalone recovery

[1] Overfished is defined as a stock that has a "depressed" population and the principal means of rebuilding is by a reduction in fishing mortality. CA FGC § 97.5; CA FGC § 90.7 (defining "depressed" as "the condition of a fishery for which the best available scientific information, and other relevant information that the commission or department possesses or receives, indicates a declining population trend has occurred over a period of time appropriate to that fishery. With regard to fisheries for which management is based on maximum sustainable yield, or in which a natural mortality rate is available, 'depressed' means the condition of a fishery that exhibits declining fish population abundance levels below those consistent with maximum sustainable yield."). Overfishing is defined as a rate or level of fishing mortality that the best available scientific information, and other relevant information that the commission or department possesses or receives, indicates is not sustainable or that jeopardizes the capacity of to produce the maximum sustainable yield on a continuing basis. CA FGC § 98.

plan comprised of seven species. Market squid, another important California fish stock, was excluded from the list of priority stocks in the original Master Plan due to uncertain legislative activity regarding its management status, which has since been clarified. The only fishery management plans that have been completed to date are those that were in progress when the Master Plan was adopted (Market Squid, Nearshore Finfish, and White Seabass), as well as Spiny Lobster, which was completed in the first half of 2016. At least two additional management plans are currently under development for Red Abalone and Pacific Herring.

Table 1: Current list of priority stocks included in the California Master Plan for Fisheries.

PRIORITIZATION	FISHERY	SPECIES	FMP STATUS
FMPs in Process Prior to Master Plan	Abalone	Red abalone, Green abalone, Pink abalone, White abalone, Pinto abalone, Black abalone, and Flat abalone	Yes (Recovery Plan)
	Nearshore Finfishes	Black rockfish, Black-and-yellow rockfish, Blue rockfish, Brown rockfish, Cabezon, Calico rockfish, California scorpionfish, California sheepshead, China rockfish, Copper rockfish, Gopher rockfish, Grass rockfish, Kelp greenling, Kelp rockfish, Monkeyface prickleback, Olive rockfish, Quillback rockfish, Rock greenling, and Treefish	Yes
	White Seabass	White seabass	Yes
Top 3 Master Plan Priority Stocks	Sea Urchins	Red sea urchin and Purple sea urchin	No
	Halibut	California halibut	No
	Nearshore Sharks and Rays	Brown smoothhound, Gray smoothhound, Pacific angel shark, Shovelnose guitarfish, and Bat ray	No
Other Master Plan Priority Stocks	Lobster	California spiny lobster	Yes
	Surfperches	White seaperch, Redtail surfperch, Pile perch, Shiner perch, Walleye surfperch, Black perch, Barred surfperch, Rainbow surfperch, Striped seaperch, and Rubberlip seaperch	No
	Seabasses	Barred sand bass and Kelp bass	No
	Sea Cucumber	Giant red sea cucumber and Warty sea cucumber	No
	Subtidal Snails	Kellet’s whelk and Wavy top shell	No
	Intertidal Invertebrates	Tegula spp. and Giant (owl) limpet	No
	Kelp	Giant kelp and Bull kelp	No
	Squid	Market squid	Yes
Other FMPs	Herring	Pacific herring	In Process
	Red Abalone	Red abalone	In Process

What is Management Strategy Evaluation and How Does It Differ from Stock Assessment?

The central function of the DLMtool is to facilitate efficient yet customized management strategy evaluations (MSEs). MSE uses computer simulations to test prospective management options over a wide range of future scenarios of the fish population and the fishery operating on it. The aim is to identify robust management methods that perform well over all credible scenarios for the fishery. The management methods tested within an MSE can range from the simplest control rules to highly complex stock assessment models.

It is extremely difficult, perhaps impossible, to conduct large-scale experiments to directly evaluate the trade-offs associated with fisheries management. Even in well-studied fisheries, considerable uncertainty often exists regarding stock status and the dynamics of the fishery, making it difficult to attribute outcomes to distinct management actions. The advent of powerful and affordable computers has allowed for the development of the MSE approach (Butterworth, 2007; Punt et al., 2014; Smith, 1994). It was originally developed by the International Whaling Commission as a tool to evaluate the various trade-offs involved the management of marine mammals and to guide the decision process toward an appropriate management procedure. Since the late-1980s, MSE has become widely used in fisheries science and is routinely applied to evaluate the trade-offs in alternative management procedures of many of the world's fisheries.

An MSE makes it possible to consider a wide range of uncertainty in stock dynamics, fishing fleet dynamics, and data collection, which is particularly useful in a data-limited situation. An MSE does not, by itself, provide a specific management recommendation like a catch-limit or effort control, but instead identifies a *modus operandi* that is most likely to provide the desired management goals. The acceptable management approach identified through MSE can then be applied to current fishery data to provide specific management recommendations.

Importantly, the purpose of MSE is not to replace stock assessment, but rather to evaluate the efficacy and appropriateness of a range of methods (including simple data-limited approaches and more complex stock assessment models).[2] An MSE guides the selection of an appropriate method by simulating data under a variety of conditions, while an assessment model provides a basis for management advice utilizing actual data from the fishery. The fundamental equations underlying each approach are basically the same, but an MSE and an assessment (in their purest forms) are two distinct approaches designed to answer two different questions. In an MSE, the question being asked is: "what would happen to the population if…," while an assessment is trying to answer: "what is happening to the population now."

[2] The basic difference between a stock assessment and data-limited method is that the former produces estimates of current fishing mortality, depletion, and stock status (i.e., "status determination criteria"), while the latter uses signals in the available data to identify changes in management without necessarily calculating status determination criteria.

Both approaches start in similar ways by utilizing available information on the species life history (e.g., growth rate, maximum size) and characteristics of the fishery (e.g., gear selectivity, closed seasons) so the dynamics of the MSE or assessment are based on the species and fishery under consideration. In a strict assessment framework, as much fishery data (e.g., time series of landings, length/age structure, fishing effort) are used to solve for the parameters of primary interest (e.g., fishing mortality, depletion, stock status). The results of a successful assessment analysis will provide a representation of "what is happening in the population now," and how the population levels have responded in the past. Uncertainties in parameters are then evaluated through additional model runs to determine uncertainty in the results, and projections of future levels are explored through different management procedures (e.g., total allowable catch, minimum sizes) to provide management advice. If the fishery data are conflicted or unavailable, an assessment analysis may not be able to solve for the unknown parameters of interest, which is common in data-limited situations.

In an MSE, all information necessary to simulate the population and project it forward through time under different management procedures is provided with different degrees of uncertainty around each parameter, expressed as a range rather than a known quantity. Each simulation represents a different situation (e.g., an overfished or an underexploited population) based on the uncertainty specified by the analyst. Since an MSE is not solving for unknown information, it can be used when no or little data are available, and will always provide a solution which represents "what would happen if the species, fishery, and management procedures operate as specified." The MSE simulates the population repeatedly given the uncertainty specified in parameter inputs to evaluate how each management procedure performs under the range of these conditions.

The results of the MSE simulations allow for a more informed choice of an assessment or management approach, but the application of this approach using actual fishery data is still necessary to provide the management recommendations. While it is often not possible to fully condition a data-limited MSE on data from the fishery, it is important to identify a range of uncertainties that are considered plausible for the fishery with regard to stock and fleet dynamics. Additionally, the ranges for the observation uncertainty parameters and future fishing fleet dynamics, while difficult to estimate, should be carefully developed so that they cover a credible range for the fishery.

An MSE is usually comprised of three key components: 1) an operating model that is used to simulate the stock and fleet dynamics, 2) an assessment method and harvest control rule model (interchangeably referred to as "data-limited methods" or "management procedures") that uses the simulated fishery data from the operating model to provide management recommendations (e.g., a total allowable catch or a control on fishing effort), and 3) an observation model that simulates the expected imprecision and bias in how fisheries data are typically observed and used in management. The management recommendation is then fed back into the operating model and the model is projected forward one time-step. The process of simulating the population dynamics of the fishery along with the management process that feeds back and impacts the simulated fish population is known as "closed-loop simulation" (see Figure 1).

A benefit of the closed-loop simulation approach is that it allows direct comparison and evaluation of alternative management procedures against "perfect knowledge" of the system; something that is impossible in the real world (Walters and Martell, 2004). With the aid of computer simulation, it is possible to run many hundreds of simulations of the future system, each representing a different possible future "reality," accounting for uncertainty in knowledge of the stock and the fishery (i.e., errors in observation) as well as the uncertainty in future environmental and ecological conditions that are likely to affect the stock dynamics. Through these simulations, MSE reveals the relative impacts of specified management approaches to a fishery decades into the future, and enables managers to choose an approach that best achieves their management objectives, as articulated through a set of well-defined performance metrics.

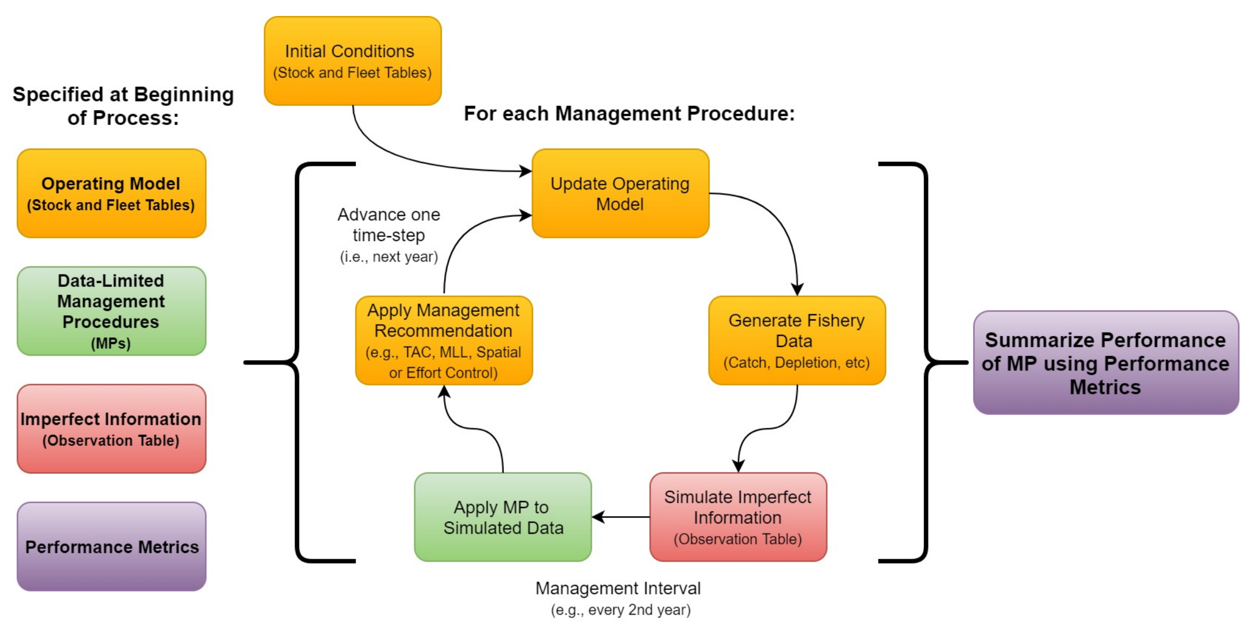

Figure 1: The general outline of the steps and components of a management strategy evaluation using the DLMtool. An operating model is parametrized with information on the fish stock and fishing fleet, which simulates the fishery dynamics and generates the fishery data. An observation model is then used to filter the simulated fishery data so that it represents real-world fishery data. A management procedure is then applied to the simulated fishery data, and a management recommendation is generated and applied back to the operating model. The model then advances one time-step (e.g., a year), and repeats the process for all years in the projection period. The process is repeated for each management procedure in the analysis. When complete, summary performance statistics, or performance metrics, are calculated for each management procedure, and compared to identify the methods that best met the management objectives for the fishery.

The Data-Limited Methods Toolkit (DLMtool)

Overview

The Data-Limited Methods Toolkit (DLMtool) is an open-source software package that uses computer simulations of real-world fisheries to help scientists and managers with three common objectives:

1. **To identify the relative performance of management methods** given the uncertainties associated with data-limited fisheries
2. **To compute explicit management recommendations** based on available data
3. **To analyze the value of information** to improve data collection and research programs

The simulation framework at the heart of the DLMtool enables users to conduct comprehensive management strategy evaluation (MSE) (see page 18 for a detailed description of MSE) to test the performance of numerous management procedures, or data-limited methods, under a range of assumptions and conditions regarding specific stock dynamics, fishing fleet behaviours, and the availability, precision, and accuracy of collected fisheries data. A management procedure is a set of instructions or rules on how the data should be analyzed to produce a management recommendation. Management procedures can vary in complexity and data requirements, from those which require no fishery data at all (e.g., set a constant size limit at 14 inches) to population dynamics models that use multiple indicators to determine a management recommendation (e.g., use information on total catch, species biology, and trends in catch-per-unit-effort to determine an appropriate management recommendation).

The DLMtool uses the MSE approach to simulate a fishery based on current knowledge of the system and to evaluate the performance of a range of alternative management procedures. The performance of different management procedures is gauged by clearly-defined management objectives for the fishery, which enable managers and stakeholders to identify those methods that have the highest probability of achieving those objectives and to consider the trade-offs involved in choosing among the best-performing methods.

The DLMtool also provides a straightforward way to apply the best available management procedure to the most current fishery information, as entered into a uniform spreadsheet. The DLMtool recognizes what management procedures can be used with currently available data and what additional data are needed to use potentially better-performing, but currently unavailable, methods. The DLMtool's diagnostic tools can also identify what data inputs different methods are most sensitive to, allowing the user to pay particular attention to the quality of those inputs. One of the key features of the DLMtool is the ability for users to design and test custom management procedures (including management that maintains current effort), new stock types, fishery dynamics, and performance criteria to best fit a specific fishery and management regime.

Although MSE has been used in fisheries science for many years, what has been lacking is an easily extensible framework that can be applied to a wide range of situations. Instead, fisheries scientists have tended to develop their own MSE frameworks for specific situations, and to test management procedures with their own MSE model. The DLMtool provides a single, open-source, and extensible platform which can be applied to a wide range of fisheries. This saves time and money as analysts do not need to develop their own MSE framework from scratch each time, and it provides a level playing field to test management procedures across different fisheries.

The idea of the DLMtool emerged from research examining the diversity of methods used for managing data-limited fisheries in the United States (Newman et al., 2015) and an MSE of their relative performance across a range of fisheries (Carruthers et al., 2014). In early 2014, a conceptual version of the DLMtool was presented at a workshop of experts from the National Marine Fisheries Service, state agencies, academic institutions, and non-governmental organizations to determine its utility and to refine its functionality. Since then, the DLMtool has been refined and expanded, in large part through testing and evaluation by independent scientists applying it to the fisheries they manage. The software is freely available at www.datalimitedtoolkit.org. It is programmed as an R package and uses parallel computing to make an efficient, powerful, and extensible MSE application accessible to users with personal computers.

The DLMtool Methodology

The DLMtool has been designed to facilitate a *process* of decision-making that is deliberate, transparent, and reproducible (i.e., independently testable). MSE is not intended to yield a single correct result, but rather to elicit a thoughtful discussion of management objectives that guide the evaluation of different possible management procedures and their inherent trade-offs, benefits, and risks. Ideally, this process begins with the involvement of a diverse group of knowledgeable stakeholders, including scientists, managers, fishermen, and conservationists. The following section describes the methodological framework for applying the DLMtool.

Step 1 – Aggregate and Process Fishery Information

Fishery information includes all knowledge about the biology and ecology of the target species, information on the status and historical trends in the stock, as well as details of trends in fishing effort, landings, changes in fleet dynamics, and anything else that relates to the exploitation of the species.[3] Information on species biology (e.g., growth, maturity schedule,

[3] The MLMA defines "essential fishery information" as "…information about fish life history and habitat requirements; the status and trends of fish populations, fishing effort, and catch levels; fishery effects on fish age

longevity) and the patterns of exploitation are important for developing even a qualitative understanding of the risks associated with operating a fishery. A quantitative evaluation of these risks requires additional information, including an understanding of the exploitation of the species (e.g., historical catch records, spatial distribution of stock and fleet), and an understanding of the life history and population structure (e.g., age or length composition) of the exploited stock.

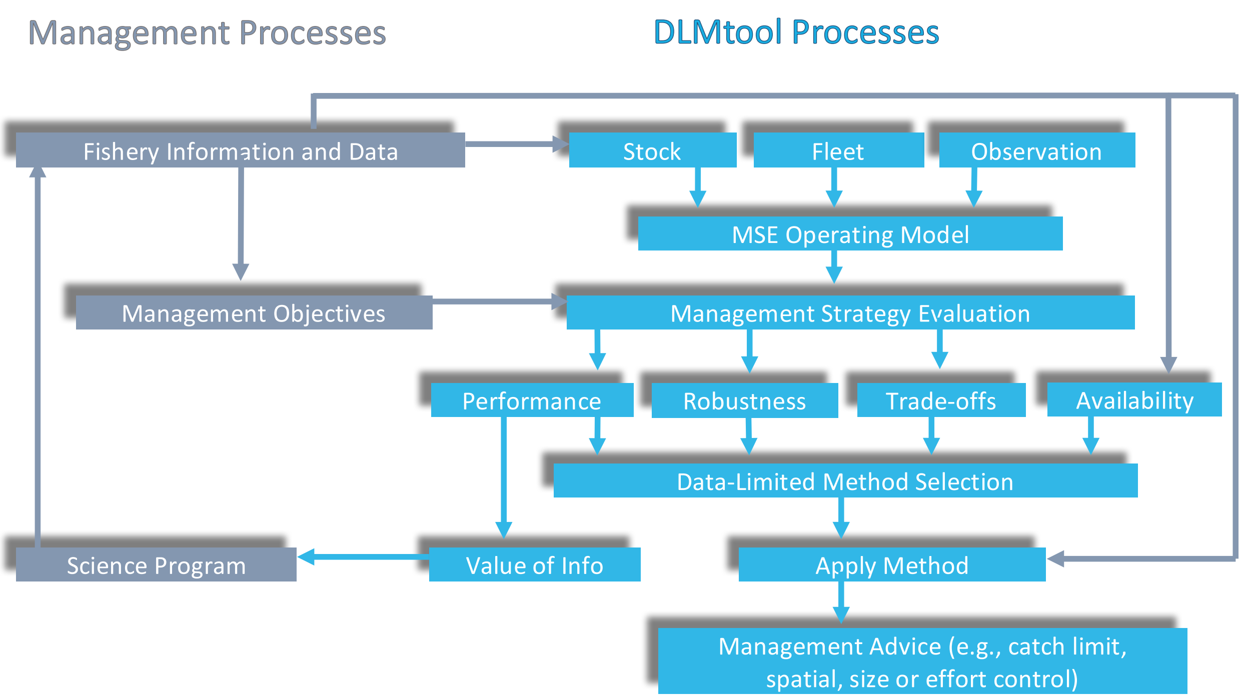

Figure 2: A flowchart of the DLMtool process showing the interaction between management functions and how they interact with the steps in the DLMtool framework.

Managers of data-limited fisheries are faced with the difficult task of making decisions regarding the regulation and operation of the fishery in the face of high uncertainty and insufficient information. Knowledge of fishery information is rarely complete, even in the most well-studied fisheries. There are more commonly large gaps in the understanding of the stock biology and status, and the dynamics of the fishing fleet, due to the highly dynamic nature of fish populations and the difficulty and expense in obtaining representative samples. The DLMtool is intended to assist managers and decision-makers through a framework that allows for a wide range of information on population and fishing dynamics, and the uncertainty surrounding the various components of the fishery, thus allowing managers to evaluate the relative performance of alternative management options against the management objectives.

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structure and on other marine living resources and users, and any other information related to the biology of a fish species or to taking in the fishery that is necessary to permit fisheries to be managed according to the requirements of this code." CA FGC § 93.

The DLMtool uses fishery information in two distinct, but related, ways: first, to create an operating model for the MSE (Step 2 below) and, second, to apply acceptable management procedures (Step 5 below). The fishery information used to condition the MSE operating model is stored in the MSE Operating Model Table (see Appendix B) and the information used for applying specific management procedures is contained in the Fishery Information Data Table (see Appendix D).

The process of aggregating fishery information and entering it into the DLMtool MSE Operating Model and Fishery Information Data Tables is described in detail below (see Steps 2 and 5). It begins with a questionnaire for managers and scientists (Appendix H) and a review of the relevant scientific literature on the fish species. The information gathered through this process is collected in a Fishery Information Summary document (see examples for this project's case study stocks at Appendices I through L), which should be treated as a living document that evolves as new information is discovered, collected, and/or processed. This process requires individuals who are trained in fishery science and population dynamics to understand what information is essential and what literature is relevant.

It may be helpful, but not necessary, to populate a Feasibility Table indicating the availability and rough quality of the major sources of fishery information (Appendix S). The Feasibility Table can be used to refine the list of potentially available methods at the preliminary MSE stage before all the underlying fishery information is processed and entered into the Fishery Information Data Table. This information may be used to identify management procedures that are clearly infeasible and provide little benefit to being included in the MSE. This may enable the analyst to conduct a preliminary MSE on a subset of management procedures that are likely to be implementable in the fishery, given the data that currently available. These results may be useful for providing preliminary MSE results that are relevant to the stakeholders, and used to guided discussion of other aspects of the MSE. A full review of available fishery data is required to populate the Data Table that is used to apply a chosen management procedure to the fishery, which will then supersede the more cursory information used in the initial Feasibility Table.

Step 2 – Design the MSE Operating Model

Once the fishery information has been identified and aggregated, the next step for using the DLMtool is to develop an operating model of the fishery by populating the MSE Operating Model Table. The DLMtool's operating model consists of a closed-loop simulation, which is used to construct the simulated population of the fishery, account for variability in population and fleet dynamics and uncertainty in the assessment and management process, and test different management procedures applied to the simulated fishery over a long time-horizon in a direct side-by-side comparison.

Constructing the Operating Model

The operating model consists of three distinct but interrelated sub-models:

- Population (Stock) Dynamics Model – This is a conventional age-structured, single sex, two-area spatial model used to generate various aspects of fish population dynamics. The initial year of the model begins at an unfished equilibrium biomass (B_0) and is fished at a fishing rate such that the spawning stock biomass in the final year of the exploitation history has been reduced to the new level of depletion (D). This historical simulation of the fishery from its pre-exploited state to the present provides the DLMtool with the simulated historical data necessary to project the fishery forward in time under the range of different management procedures being tested.
- Fleet Dynamics Model – This model determines the fishery's size-selectivity and temporal pattern of exploitation.
- Observation Model (Uncertainty) – Management procedures typically require some combination of inputs including estimates of the biological parameters, indices of abundance, or estimates of total catch. These parameters and metrics are often poorly known, especially for data-limited stocks. While the above two models generate the underlying state of the fish population and the fishing fleet, the observation model simulates the imperfect knowledge of the system like a lens through which we see the real world. This imperfect knowledge is then used in the management procedure to reflect the real-world situation where some estimates can be highly variable or biased.

Carruthers et al. (2014) provides a detailed description of the DLMtool operating model. For a complete description of the mathematical model, see Appendix A in Carruthers et al. (2014). An updated description of the most current version of the DLMtool model is under development and expected to be published by the end of 2017.

The parameters for the MSE operating model specify the characteristics and behaviors of the underlying sub-models above – stock, fleet, and observation, which relate to the stock dynamics, fleet dynamics, and observation of the fishery data, respectively. Together, they form the MSE operating model. Existing fishery information is incorporated in the MSE by means of the values for these parameters. For example, studies of fish biology (e.g., growth, maturity schedules, etc.) are an important and commonly researched data source that are often published in the scientific literature. Information on fish biology can be obtained by collating the published literature relating to the species and location, together with any available gray literature or analysis of additional data sets.

The DLMtool has been developed as a stochastic model, which attempts to account for multiple aspects of uncertainty, and each parameter requires a minimum and maximum value to represent the range of uncertainty. For example, the growth of the fish species requires information on the growth rate and the maximum size, as well as information on how the growth pattern is likely to vary between years. Each simulation run of the model draws a single value for each parameter from a uniform distribution, with hundreds of simulations accounting for the full range of uncertainty in all the parameters. Some aspects of a fishery may be well studied, so there may be high confidence in the values of the corresponding parameters. This low level of uncertainty is reflected in the MSE with a narrow range in the parameter values for those well-understood aspects of the fishery. Other parameters may be highly uncertain, so little or no data may exist to inform reasonable values. In situations where inputs are known to be correlated, this correlation can be preserved in the operating model by providing a table of sampled values. While this approach was outside the scope of this study, it is possible to incorporate correlated samples of parameter values, or samples from distributions other than the uniform, in the DLMtool operating model. Recent developments in the DLMtool have made it easier to include correlated parameters in the operating model, and we recommend this approach be explored in future applications.

The simulation model requires values for all parameters in the MSE operating model. Yet, by definition, data-limited fisheries lack some or perhaps most of this information. By specifying wide, but reasonable, ranges for these parameter inputs, the MSE can evaluate how different management procedures perform over a range of possible realities for the fishery, thus helping managers select methods that are robust to the uncertainty in many of the data inputs. Numerous methods exist to determine reasonable ranges for different parameters, including expert judgment and qualitative analysis of datasets, as well as “borrowing” information from other stocks or species (Punt et al. 2011). The DLMtool can test the sensitivity of the model to the different input parameters and identify parameters that contain high information value (i.e., those inputs have meaningful impact on the MSE results). Such results may be useful for prioritizing further research to reduce the uncertainty around important parameters (see Step 6).

The DLMtool has many default settings for the stock, fleet, and observation parameters that may be used initially to set up the model. For example, there are currently 12 default stocks covering a range of different life-history types including a long-lived rockfish, short-lived butterfish, albacore, and blue shark. There are 16 sets of default fleet parameters, ranging from targeted stocks with increasing exploitation history, to non-targeted species with dome-shaped selectivity. Finally, there are six sets of default observation parameters, ranging from perfect information to imprecise and biased estimates. It is expected that scientists and managers will examine the default input parameters and modify them to best reflect the fishery that the DLMtool is being applied to. Caution should be used when accepting default parameters without understanding the implications of the values that are being used. For example, it is possible that parameters in the observation model are instrumental in driving the relative performance of different methods, and analysts using the DLMtool should be educated in fisheries population dynamics modelling to fully understand these implications.

Tuning the Operating Model

The DLMtool has been designed for data-limited situations where very little information exists on the current stock status or the historical exploitation of the fishery. However, where such information does exist, it can be used to tune the MSE operating model so that the simulations more accurately reflect the historical exploitation pattern of the fishery. The fleet dynamics part of the MSE Operating Model Table contains a parameter that specifies the time period (years in the past) when the fishery commenced (the simulation model assumes that the stock biomass is at the unfished level (B_0) at this time). The patterns in historical fishing mortality (from the first year to the present) can be mapped as bands of trajectories using a function in the DLMtool (*ChooseEffort*) to reflect the knowledge of the trends in historical fishing effort. The fishing industry or other stakeholders may know that fishing effort was relatively constant for a period and then rapidly increased in a specific year, perhaps coinciding with a marked increase in price. This information can be incorporated into the operating model so that the simulated trends in fishing effort closely represent the reality of the fishery's stakeholders.

A second way that information on the fishery can be used to tune the operating model is the inclusion of historical changes in the selectivity pattern of the fishery. Regulated changes in the minimum size of capture may be documented for a fishery, or there may be knowledge relating to changes in the selectivity of the fishery due to changes in fishing gear. These break points in selectivity pattern can be mapped in a similar way to the fishing effort trajectories described above (using the *ChooseSelect* function) so that the historical selectivity pattern included in the simulation model reflects the history of the fishery. This is particularly important if there have been recent changes to the size-based management regulations, as was the case in this study for the barred sand bass.

In some cases, it may be impossible for the model to reach certain levels of depletion under the conditions specified. For example, if the size of capture is relatively high compared to the size of maturity and fishing effort has been low or declining in recent years, then it may be impossible for the model to simulate a stock that declines to very low biomass levels. Conversely, under other conditions, it may not be possible for the stock to end up at high levels of depletion (high stock size) without simulating very low or zero historical catches. In both these cases, the model parameterization is not consistent with the historical fisheries data, and simulating a population under the specified conditions is not possible. The DLMtool resolves this issue by re-sampling recruitment deviations and depletion until the selected depletion is reached. Importantly, if the MSE model repeatedly fails to reach the specified level of depletion, this is an indication that there may be some underlying conflicts or contradictions in the operating model parameters and these should be closely examined. Planned extensions of the DLMtool aim to develop specific functions to take all of the information contained in the operating model tables and derive plausible bounds for any unknown parameters.

It is important to distinguish between tuning the model to more accurately reflect historical exploitation patterns and conditioning the model with real data such as catch history and stock biomass. The MSE in the DLMtool is not conditioned with real data; that is, the absolute magnitude of the catches and stock biomass in the model do not reflect the actual catches and current biomass of the fishery. Actual fishery data is used later in the DLMtool process when acceptable management procedures are applied to the fishery (see Step 5 below).

Step 3 – Define Management Objectives

To evaluate the relative effectiveness of different management procedures, decision-makers must have clearly-defined management objectives. These management objectives are incorporated into the MSE process in the form of performance metrics, which provide the yardstick by which to compare the relative performance of different methods.

Using MSE to Examine Performance Trade-Offs

Fisheries managers are confronted with the difficult task of balancing exploitation to support robust fisheries while providing confidence in the sustainability of the resource and the overall health of the marine environment. There is often conflict in meeting these different management objectives and there is rarely an optimal management approach that fully satisfies all management objectives (Punt, in press). Walters and Martell (2004) explain that the task of modern fisheries management is to identify the various trade-offs among conflicting objectives and decide how to balance them in a satisfactory way.

A typical trade-off is the abundance of the target species versus the catch levels. Assuming no significant system-wide natural perturbations, a fish stock may be exploited sustainably if catches are set at low levels. However, such economic under-utilization of the resource is often undesirable. Alternatively, high catches may produce immediate short-term benefits, but may result in long-term decline or collapse of the stock. Additionally, there is often a trade-off between stock size and fishing effort, which results in lower catch rates (and lower profit) for individual fishers when a large number of fishers are active in the fishery (Walters and Martell, 2004). Other common trade-offs include the age and size at first capture, either delaying harvest until individuals are fewer in number (due to natural mortality) but larger in size, or capturing a large number of small sized fish (Punt, in press).

A strength of the MSE approach is the requirement that decision-makers specify clear objectives, which can be classified as either “conceptual” or “operational” (Punt et al., 2014). Conceptual objectives are typically high-level policy goals that may be broadly defined. However, to be included in an MSE, conceptual objectives must be translated into operational objectives (i.e., expressed as values for performance metrics). Such operational objectives, or performance metrics, may consist of both a reference point (e.g., biomass at some fraction of the equilibrium unfished level) as well as a measure of the acceptable associated risk (e.g., less than 10% chance that biomass declines below this reference level). It is not unusual that some of the management objectives are in conflict. A benefit of the MSE approach is to highlight these trade-offs among the different management objectives to guide the decision-making process. However, to characterize these trade-offs accurately, it is important that the performance metrics are quantifiable and thus compatible with the MSE framework (Punt, in press).

The most common performance metrics typically relate to the magnitude of the catch (i.e., yield) and the biomass of the target species. Table 2 presents examples of performance metrics that relate to catch and biomass of the target species. Other performance metrics may focus on additional aspects of the fishery, such as socio-economic trade-offs. While it may be possible to extend DLMtool to evaluate the socio-economic trade-offs (e.g., profit) of the fishery, this was beyond the scope of the current project.

Table 2: Example catch and biomass-based performance metrics that are often included in MSEs (modified from Table 5 in Punt, in press).

Performance Metric	Example
Short-term yield	Maximum total catch over first 10 years of projection period
Long-term yield	Average catch over final 10 years of projection period greater or equal to some level (e.g., MSY)
Inter-annual variability in catch	Variation in catch between years less than some threshold (e.g., 15%)
Probability of catch < threshold	Probability of catch declining below some absolute or relative threshold in any single year (or for X consecutive years)
Lowest catch	Lowest catch (absolute or relative) in projection years
Probability of catching large fish	Probability of catch including fish of size X or larger
Number of years catch < threshold	Probability of catch declining below some threshold (e.g., zero catch) in any given year
Average size of catch	Expected average size of fish in the catch
Catch rate	Highest average catch rate
Catch rate relative to reference catch rate	Probability of catch rate declining below some reference level in any (or some) year(s)
Biomass	Stock biomass (or spawning biomass) exceeding (or below) some absolute threshold
Biomass relative to unfished biomass	Probability of biomass declining below some fraction of the unfished biomass
Biomass relative to reference biomass	Probability of biomass declining below some fraction of a reference biomass (e.g., $0.5B_{MSY}$)
Biomass relative to initial biomass	Probability of stock size reaching some multiple (or fraction) of the initial (current) biomass
Rebuilding time	Average time before stock biomass rebuilds above some target reference level
Lowest biomass relative to unfished biomass	Probability of lowest biomass level in the projection years dropping below some fraction of the unfished level

Measuring Performance Quantitatively

The DLMtool automatically records all data from the MSE simulations in an object that can be analyzed to evaluate performance. A range of associated reference points are also calculated, such as those relating to biomass, fishing mortality rate, and the best yield that could be achieved over the projection period using the best fixed fishing rate scenario (a "best case" yardstick to judge the relative performance of the different management procedures). By storing these data, there are many possibilities for users to define their own performance metrics. However, the DLMtool includes several standard outputs that correspond with common fishery management objectives, including the following:

- **Biomass** relative to unfished biomass (B_0) or biomass at maximum sustainable yield (B_{MSY})
- **Fishing mortality rate** relative to fishing at maximum sustainable yield (F_{MSY})
- **Yield (short-term or long-term)** of a management procedure relative to the yield if the fishery were being exploited at F_{MSY}
- **Inter-annual variability in yield or effort** (e.g., fluctuations in yield from year-to-year)

Because the MSE runs many simulations of the fisheries performance under each management procedure being tested, the performance can be evaluated in comparison to a specific biomass threshold or target. For example, the management procedures can be ranked by the proportion of simulation runs where the fishing mortality rate (F) under a specific management procedure is higher than the F that is expected to produce the maximum sustainable yield (F_{MSY}). This is sometimes referred to as a "probability of overfishing" metric within the DLMtool, although it is important to remember that this does not reflect the probability of overfishing that may be occurring within the actual fishery; it instead refers to the likelihood that overfishing occurs within the simulated fishery of the MSE. Management procedures that have few runs where overfishing occurs (within the simulated MSE) are typically preferable to those that result in frequent excessive fishing mortality rates. An analyst or manager can also evaluate the simulated patterns of fishing mortality over different periods within the 50 year projections depending on management objectives (e.g., probability of overfishing in years 41-50 of the 50-year projection period).

Another performance metric included in DLMtool is the proportion of simulations where the stock biomass is above or below some biological reference point. For example, a minimum performance limit may be half the biomass at maximum sustainable yield (0.5 B_{MSY}), and the performance of the management procedures can be ranked by the proportion of simulations where the stock remains above this level. Management procedures that have a low probability of maintaining biomass above this limit may be considered too risky and therefore excluded from further examination.

There may be other performance metrics that are of interest to fishery managers and stakeholders in California. Stakeholder participation is critical when developing performance metrics to evaluate different biological scenarios or management procedures in a MSE. The DLMtool can be customized to track and display additional performance metrics as identified by stakeholders.

In addition to the single species trade-offs discussed above, managers may have concerns for multi-species interactions (e.g., ecosystem effects and bycatch). These trade-offs can be examined in multi-species or ecosystem models. However, specific multi-species and ecosystem objectives typically require considerably more information than is available in data-limited situations, and is outside the scope of this project and the current capacity of the DLMtool.

Step 4 – Identify Acceptable Methods

With the operating model and performance metrics defined, the next step in the process is to run the MSE. We recommend running a preliminary MSE to eliminate poorly-performing methods and to create a shortlist of promising management procedures for further evaluation. This initial step can be done using fewer simulations then the final MSE to save time, although it is important to ensure that enough simulations have been run for convergence of the model (see Figure 3). This point in the process also provides an opportunity to develop custom management procedures specific to the fishery. For example, current management measures, such as a minimum size limit and/or a seasonal area closure, can be added to the MSE and tested alongside the remaining management procedures that passed the initial simulation testing.

Using Performance Metrics to Identify Acceptable Management Procedures

The DLMtool currently has over 80 different management procedures that can be evaluated side-by-side (see Appendix E for a description of the management procedures currently contained in the DLMtool). This number is likely to grow as researchers continue to develop and contribute new methods. The management procedures typically have different data requirements and, in data-limited situations, only a subset of these 80-plus management procedures may be available for fisheries managers to use (the next step in the process determines what methods are available with current fishery information). Depending on data availability, fishery managers may still be left with a choice of dozens of different management procedures. The DLMtool has been designed to facilitate the process of selecting appropriate management procedures that meet the performance objectives chosen by fishery managers and stakeholders.

There are two main approaches to selecting among different management procedures that can be used in the DLMtool: “satisficing” and “trading-off” (Miller and Shelton, 2010). Satisficing requires the definition of reference points and acceptable risk thresholds that are used to determine which management procedures perform adequately and meet the minimum requirements of the fishery managers (Miller and Shelton, 2010). Some performance measures may be determined by policy, where management procedures that fail to meet these minimum performance limits are considered inadequate and removed from the list of candidate methods. For example, in Australia, $0.2B_0$ is commonly used as a minimum biomass limit and the harvest policy states that there must be 90% probability that the stock remains above this level (DAFF, 2007). All management procedures that meet the minimum criteria are deemed to *satisfice* the management objectives.

The satisficing method provides a useful tool for filtering out management procedures that do not meet the minimum requirements of the managers, and are thus unacceptable. However, it is often the case that there are multiple remaining management procedures that are determined to be acceptable, so decision-makers must still evaluate the trade-offs amongst the numerous acceptable management procedures that exceeded the limits. In such cases, performance metrics (sometimes the same ones as used in the satisficing process) can be used to determine which management procedures are preferable to others. For example, management procedures that produce a higher expected long-term yield are typically preferred over management procedures that produce less catch for the same level of risk. Likewise, for the same risk profile, management procedures that produce more stable catches (less inter-annual variability) are typically preferred to those where catches change dramatically between years.

The trade-off approach may also be used to identify methods which are “dominated” by other methods; that is, they perform worse than all other options with respect to all performance metrics, and thus would not be considered suitable for management. Identifying and removing these methods from the analysis allows the stakeholders to focus on the trade-off among the remaining management procedures.

The choice of a management procedure from the subset of “acceptable” methods is typically qualitative, as decision-makers must weigh the value of the various performance metrics (Punt, in press). Multi-criteria decision-making can be extremely difficult, as there is rarely a single optimal choice. Punt (in press) recommends that the number of trade-off metrics should be as small as possible, although he highlights that it is important to consider the interests and values of all stakeholders.

Satisficing criteria can represent either *minimum performance limits* or *performance targets*, both of which must be met for a method to be deemed acceptable. For example, the applicable fisheries law may require managers to avoid a stock becoming overfished (e.g., $0.5B_{MSY}$ or $0.2B_0$) and to manage biomass toward maximum sustainable yield or some proxy thereof (e.g., $1.0B_{MSY}$ or $0.4B_0$). In this example, the overfished threshold is a minimum performance limit *to be avoided*, while managing biomass around B_{MSY} is a target *to be achieved*, but not exceeded. Each performance measure that must be met, whether a minimum limit or a target, must include an appropriate risk threshold. These risk thresholds are defined probabilistically (e.g., 90% probability of exceeding $0.2B_0$). Minimum performance limits should have a high probability of being exceeded.

Managers can also choose to use a three-step process for evaluating the performance of different management procedures. The first step uses minimum performance limits to remove poorly-performing methods that do not pass the limits. An example would be to exclude any method that does not have at least an 80% probability of biomass exceeding an overfished threshold of $0.5B_{MSY}$ and an 80% probability of the fishing mortality being below $1.5F_{MSY}$. Once these poorly-performing methods are removed, the second step involves analyzing which remaining methods meet the performance targets (e.g., which methods have at least a 50% probability of achieving $1.0B_{MSY}$ over the last 10 years of the 50-year simulation projection). Managers are then left with methods that have a low likelihood of the stock becoming overfished and a high likelihood of the long-term biomass hovering around the B_{MSY} target. In step three, managers can then choose among the remaining methods based on their preference for maximizing yield and/or maintaining stable catch levels over time. This is the approach followed by the CDFW Working Group for this project, as is described in detail below.

The process of evaluating the management procedures against the performance metrics occurs after the management strategy evaluation simulation model has run. However, it is important that the performance metrics are specified prior to the completion of the MSE to ensure that the model records all the relevant information. *Furthermore, the management objectives and performance metrics must be defined prior to running the MSE to ensure a transparent decision-making process in selecting an appropriate management procedure (i.e., the MSE results should not be used to define the management objectives and performance metrics).*

Depicting Performance with DLMtool

The DLMtool has a wide range of functions for examining the MSE and visually comparing the relative performance of different management procedures. For example, the *CheckConverg* function can be used to verify that sufficient iterations have been run and the MSE has converged (Figure 3). This diagnostic test plots the relative performance of each management procedure by simulation number and indicates if the MSE results are stable. If the relative position of the management procedures continues to change, more simulations are required before the results can be further analyzed.

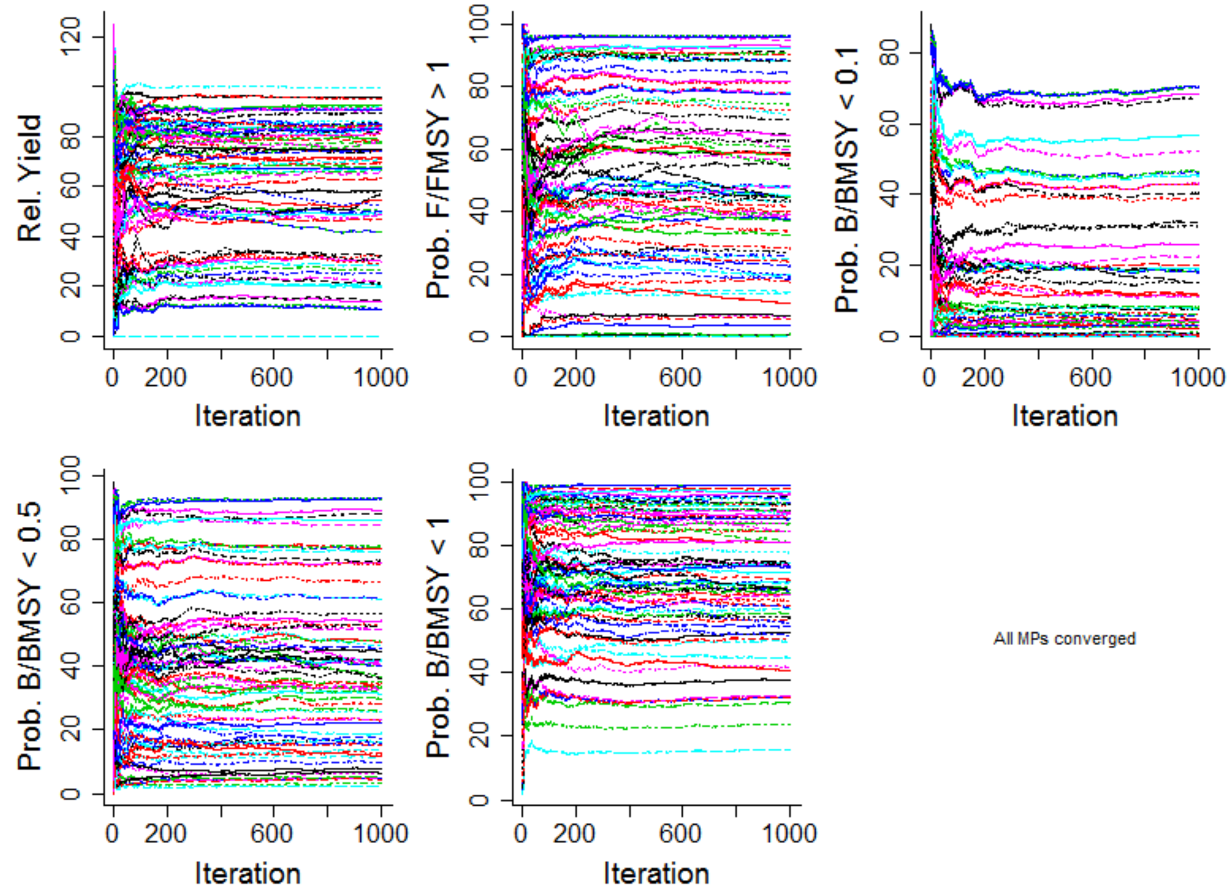

Figure 3: Convergence diagnostic plot for verifying that the results of the MSE are stable and the number of iterations in the MSE is sufficient. If the relative position of the management procedures (colored lines) is continuing to change, this is an indication that more iterations are required for the model to converge.

The performance of the management procedures against various performance metrics can be visualized using plotting routines in the DLMtool. For example, the behavior of individual management procedures can be examined using projection plots of performance (*Pplot*), as shown in Figure 4. Figure 5a shows an example trade-off plot created with the *TradePlot* function. This trade-off plot shows the performance of the management procedures with respect to four different performance metrics and indicates which methods pass the specified risk thresholds. The performance metrics and probability risk thresholds can be adjusted to match the concerns of the fishery managers.

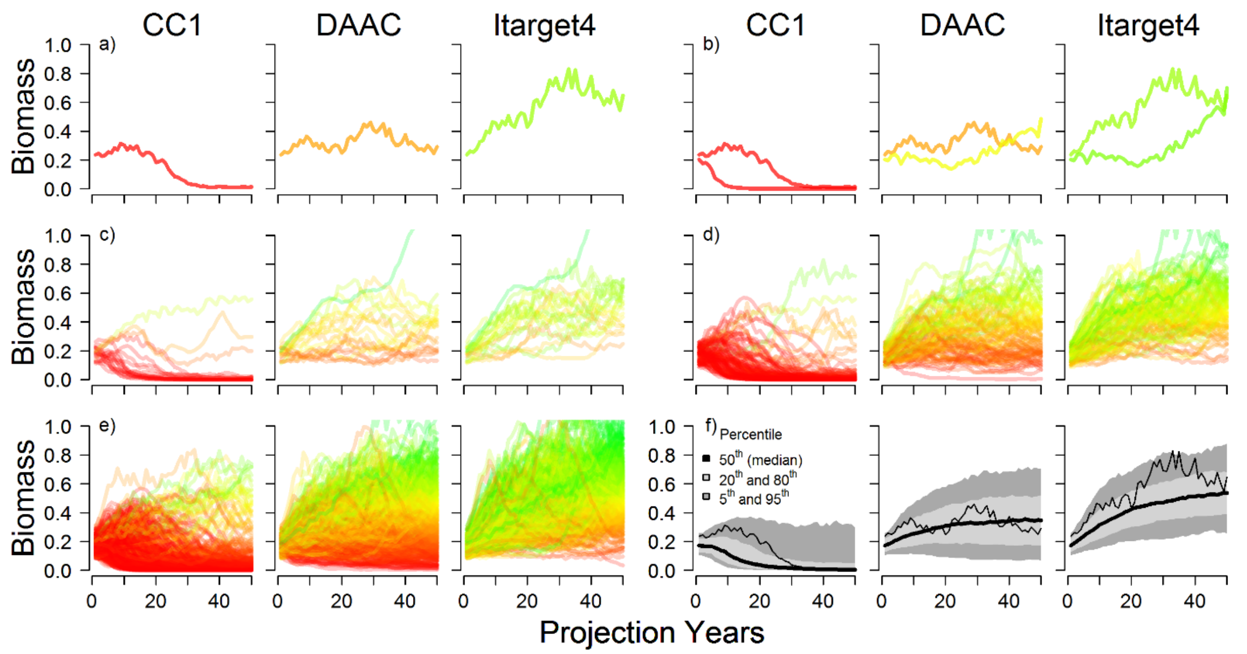

Figure 4: Example projection plots showing the trends in biomass (relative to unfished conditions) for three management procedures for a) a single simulation, b) 2 simulations, c) 20 simulations, d) 100 simulations, and e) all 1,000 simulations. Note the same starting point for a single simulation across the three management procedures. Panel f summarizes the performance of each management procedure across 1,000 simulations as the percentiles: 50th (median) with a solid black line and shading showing the 5th and 95th (dark gray) and 20th and 80th (light gray) percentiles. The thin black line in panel f shows the trajectory of a single simulation to demonstrate that the median of many simulations is less variable than any single simulation. The percentiles correspond to probabilities. For example, there is a 95% chance the biomass is above the lower bound of the dark gray polygon, an 80% chance it is above the lower bound of the light gray polygon, and a 50% chance it is above the median line.

Figure 5b is an alternative way to present the performance of the management procedures, and has been created using the *barplot* function. In this example, the risk threshold has been set at 80% and the two performance metrics are the probability that biomass in the last 10 years is (1) above half of biomass at maximum sustainable yield and (2) above 20% of the unfished biomass. Bars which exceed the probability threshold (top right) indicate methods that exceed the minimum performance criteria and would be considered as acceptable methods for applying to the fishery. Like the trade-off plot described above, the performance metrics, risk thresholds, and number of years over which the results are summarized, can be customized. Another alternative is the *Kplot* function, which creates Kobe plots for examining the proportion of time each management procedure spends in different parts of the Kobe space (Figure 6).

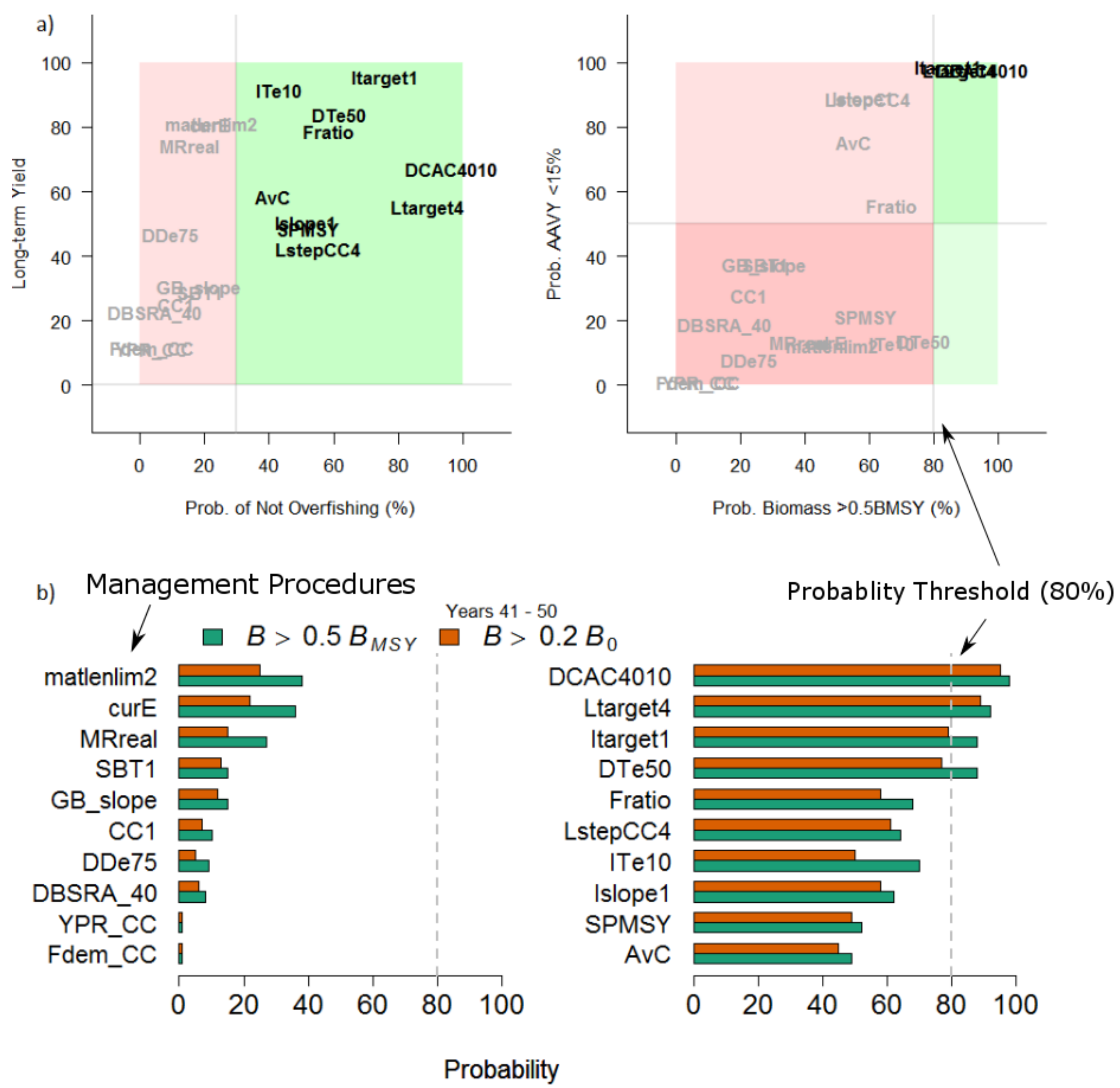

Figure 5: Example performance plots of twenty management procedures. Panel a) shows two trade-off plots showing the probability of not overfishing against average long-term yield, and the probability of biomass being above half of biomass at maximum sustainable yield against the probability that average annual variability in yield is less than 15%. The performance metrics on the x and y axes, and the risk thresholds for each axis, can be modified to suit the concerns of the fishery managers. Management procedures in dark shaded red areas of the plotting space failed to meet both performance metrics, while methods in the darker shaded green areas exceed the risk threshold for both. Panel b) shows a bar plot of two performance metrics for the twenty management procedures. Like the trade-off plot, the performance metrics and probability threshold can be adjusted to suit the needs of the fishery managers.

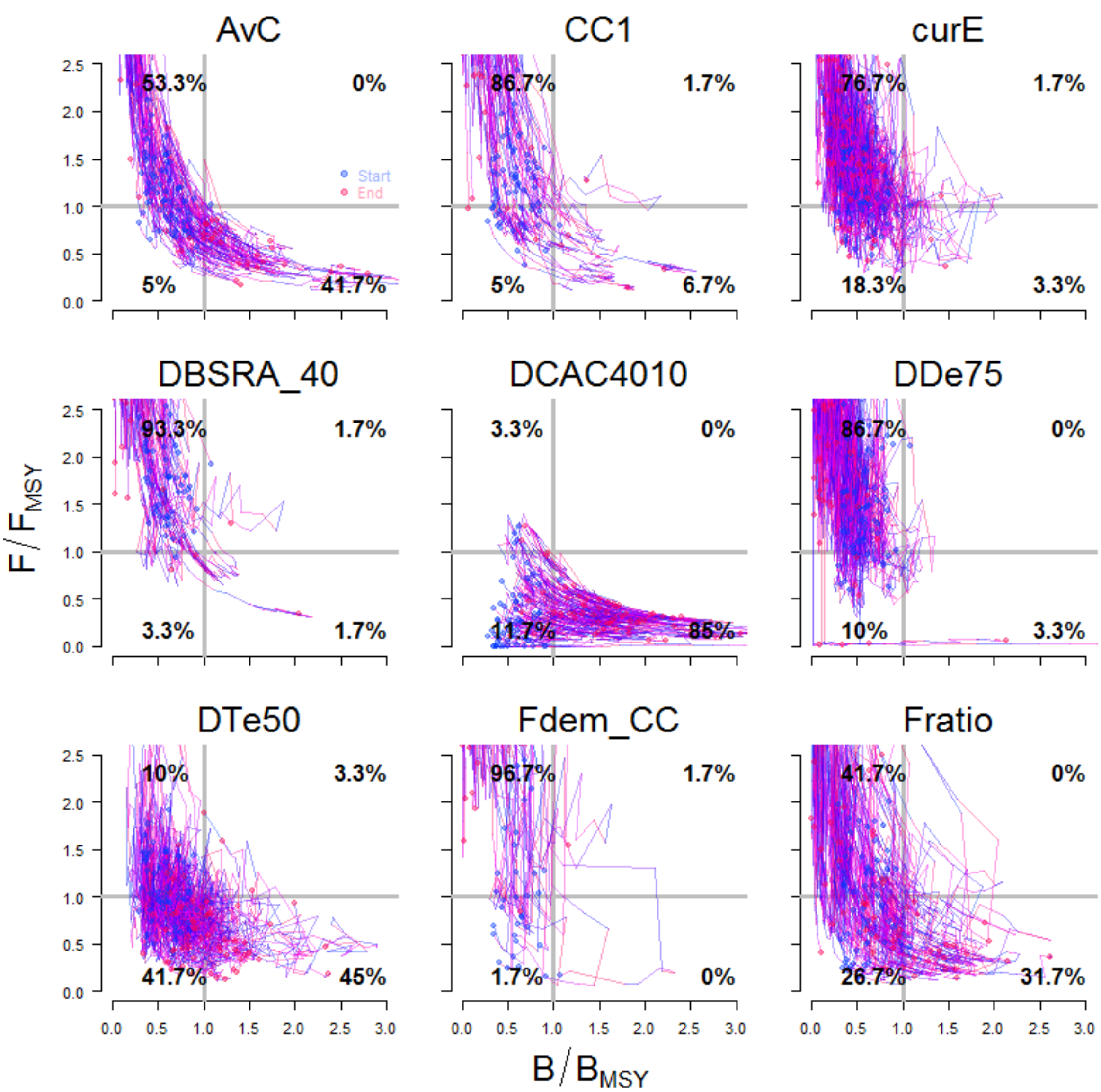

Figure 6: An example Kobe plot for nine management procedures. The Kobe plot can be used to examine the performance of individual management procedures, and indicates the proportion of time each method spends in the different parts of the Kobe plot space.

The DLMtool has various other plotting functions for the MSE results. Some of these plotting functions have been developed for specific applications of the DLMtool (e.g., *NOAA_plot*). The MSE results from the DLMtool are stored in a standard R object, and analysts who have some experience with R can be easily develop their own plotting routines. A full range of the plotting functions for MSE results can be displayed by using the *plotFun* function. To learn more about using plotting functions with DLMtool, see the User Manual at https://dlmtool.github.io/DLMtool/userguide/examining-the-mse-object.html#plotting-the-mse-results. MSE results can also be outputted from DLMtool in tabular form, with the probabilities of various performance metrics shown side-by-side for rapid review and comparison (see, e.g., Appendix N)

Step 5 – Apply the Best Available Methods for Management Recommendations

Any management procedure that does not satisfy the minimum performance limits and performance targets is eliminated from further consideration. The remaining management procedures can then be tested to determine whether they are feasible to apply with currently available fisheries information. To do this, DLMtool users must populate the Fisheries Information Data Table (referred to as a "DLM_data[4] object" in DLMtool) with all currently available fishery information (see Appendix D to see the input parameters). The Data Table includes all information relating to the fishery that can be used in the application of a management procedure and represents the best estimates and most up-to-date understanding of various aspects of the fishery. For example, information on historical catch and effort trends, and data on the size or age structure of the population, can be used by a management procedure to provide a management recommendation.

The data contained in the Fishery Information Data Table determines which management procedures *can* be used. For example, if a management procedure uses catch-per-unit-effort (CPUE) data to determine a management recommendation and this data does not exist for a specific fishery (perhaps due to a lack of effort data), then this management procedure cannot be used until the necessary data are added. On the other hand, management procedures which do not require any fishery data (e.g., a fixed size limit) are available irrespective of the amount of existing data. However, as noted below, governance and logistical limitations may prevent certain methods that are otherwise available from being implemented, monitored, and enforced.

The DLMtool includes a function to determine what management procedures are "available" with a given Fishery Information Data Table (*Can* function), which methods are "not available" (*Cant* function), and what additional data are required to make a currently unavailable method, available (*Needed* function). This information can be used to prioritize future data collection programs, particularly for management procedures that are currently "not available," but identified by the MSE to be suitable methods for achieving the management goals for the fishery.

It is important to distinguish between the MSE phase and application phase of the DLMtool process. The MSE phase uses the operating model parameters together with conventional fisheries population theory to simulate the dynamics of the fishery and to project the population into the future under a range of different conditions. The MSE includes many simulations, each representing a different possible future path for the fishery, that attempt to

[4] DLMtool version 3.2.2 was used in this analysis. Since version 4.1 the 'DLM_data' object has been renamed 'Data'

account for all the uncertainty and variability in future stock dynamics and environmental conditions. The MSE model *creates* fishery data for each year and each simulation in the model run. This fishery data is generated based on the current understanding of the stock biology, fishing fleet dynamics, and processes involved in collecting the fishery data (the stock, fleet, and observation parameter sections to the MSE Operating Model Table). Because the fishery data is generated with a simulation model, all data types are available (e.g., CPUE indices, recruitment trends, etc.) and all management procedures can be evaluated (even those that are "not available" for application in the real world).

In contrast, the method application phase only uses the Fishery Information Data Table, which contains the actual information that is available for the specific fishery. In some very data-limited situations the Data Table may contain very little information, which reflects the lack of data for the fishery. This data object can be updated over time as additional data is made available from ongoing research programs.

The list of acceptable methods from the MSE is then cross-referenced with those that are available with current data to create a final group of management procedures for managers to choose among. In choosing among the acceptable and available methods, managers and stakeholders must select methods that provide management advice consistent with the management controls for the fishery. The DLMtool contains three different classes of methods: input controls that prescribe effort controls (e.g., days-at-sea, size limits, bag/trip limits, seasonal closures); output controls (e.g., total allowable catch limits), and spatial controls (e.g., area closures or marine protected areas). Different management types may or may not be feasible due to the governance limitations and available resources of the management agency. It is important to recognize these limitations when selecting methods that are otherwise acceptable based on MSE performance and available with current data, because such acceptable and available methods still may not be feasible within the current governance framework. A final consideration in selecting an appropriate and feasible management procedure is for managers to consider any performance trade-offs apart from those used for minimum limits and targets. Such trade-offs could include relative short- and long-term yield and inter-annual variation in yield or effort.

Step 6 – Analyze the Value of Information

There are three ways in which the DLMtool can be used to quantify the value of future data collection. The first two, "post-hoc value of information analysis" and "cost of current uncertainties" focus on management procedures that currently can be applied given the data that are available. The third analysis, "value of new data," examines potential benefits of using management procedures that cannot currently be applied because the data they require are currently unavailable. See the Value of Information results section on page 91 for a detailed description of how we conducted these analyses for the CDFW project.

Assumptions & Limitations

Like all models, the DLMtool provides a simplification of reality. To approximate real fishery dynamics, DLMtool relies on multiple assumptions. Some of these assumptions are common to many fishery science models (e.g., age-structured population dynamics) and are a central to the structure of DLMtool. Other assumptions are a result of the way DLMtool was designed and developed, and may represent current limitations of DLMtool for applications to particular situations. It is possible to deal with some of these limitations by further development of the DLMtool, as was done for this project in many of ways described above. The CDFW Working Group has identified many recommended extensions and updates that would address those assumptions and limitations that are germane to California fisheries (see page 115). As new versions of the DLMtool are released, changes to the assumptions and limitations described below will be updated in the DLMtool User Guide (available at https://dlmtool.github.io/DLMtool/userguide/assumptions-of-dlmtool.html).

Biology

Short-Lived Species - Due to the problems with approximating fine-scale temporal dynamics with an annual model it is not advised to use the DLMtool for very short lived stocks (i.e., species with a longevity of 5 years or less). Technically, this could be dealt with by dividing all temporal parameters by a sub-year resolution. However, in this case the TAC would be set by sub year and the data would also be available at this fine-scale which is highly unlikely in a data-limited setting. An MSE model with monthly or weekly time-steps for the population dynamics is required for short-lived species, and may be developed in the future.

Density-Dependent Compensation – The DLMtool assumes there is no density-dependent compensation in fish growth or age/size of maturity, and natural mortality rate does not change directly in response to changes in stock size.

von Bertalanffy Growth – The growth model in the DLMtool is the von Bertalanffy growth curve. While this is the most commonly applied model to describe fish growth, it may not be the preferred growth model for some species. The consequences of assuming the von Bertalanffy growth model should be considered when using the DLMtool for species with alternative growth patterns. Alternative growth models are being considered for future developments of DLMtool.

Natural Mortality Rate at Age – The DLMtool currently assumes that natural mortality (M) is constant with age. Age-specific M is currently under development and will be added in future versions of the package.

Single-sex model – The DLMtool current assumes a single sex population dynamics model, so it does not account for female and male portions of the population separately. This may be an issue where there is strong sexual dimorphism in the population. A two-sex population dynamics model is being considered for future developments of the DLMtool.

MSE Model Assumptions

Idealized Observation Models for Catch Composition Data – The DLMtool currently simulates catch-composition data from the simulated catch composition data via a multinomial distribution and an effective sample size specified in the observation parameters. This observation model may be unrealistically well-behaved and favor those approaches that use these data. We are considering adding a growth-type-group model to improve the realism of simulated length composition data.

Implementation Error – The current version of the DLMtool does not contain any implementation error. The only imperfection between a management recommendation and the simulated TAC comes in the form of the MaxF argument that limits the maximum fishing mortality rate on any given age-class in the operating model. The default is 0.8 which is high for all but the shortest living fish species. An implementation error model is under development and will be included in a future version of the package.

Discard Mortality – Related to the previous point, the DLMtool assumes that there is no discard mortality or fishing mortality for fish that are below the length of selectivity. This is an important assumption, particularly when evaluating the impact of size-selectivity management methods such as a minimum legal length. This feature is also under development and will be included in the DLMtool soon.

Single Fishing Fleet – The DLMtool currently assumes a single fishing fleet that targets the stock. If the MSE is being conducted on a fishery with multiple fleets, the patterns in selectivity and fishing effort must be considered in aggregate and entered in the operating model parameters. A multi-fleet model is being considered for future DLMtool development.

Two-Box Model – The DLMtool uses a two-box spatial model and assumes homogeneous fishing and distribution of the fish stock. That is, growth and other life-history characteristics do not vary across the two spatial areas. Spatial targeting of the fishing fleet is currently being developed in the model.

Ontogenetic Habitat Shifts - Since the operating model simulates two areas, it is possible to prescribe a log-linear model that moves fish from one area to the other as they grow older. This could be used to simulate the ontogenetic shift of groupers from near shore waters to offshore reefs. This feature is currently under development.

Closed System – The DLMtool assumes that the population being modelled is in a closed system. There is no immigration or emigration, and a unit stock is assumed to be represented in the model and impacted by the management decisions. This assumption may be violated where the stock extends across management jurisdictions. Violations of this assumption may impact the interpretation of the MSE results, and these implications should be considered when applying the DLMtool. Although a unit stock is a central assumption of many modeling and assessment approaches, it may be possible to further develop the DLMtool to account for stocks that cross management boundaries.

Marine Protected Areas (MPAs) - MPAs can be evaluated as management actions in the DLMtool by closing one area to fishing in the future projections. Currently, it is not possible to include MPAs in future projections alongside other management methods such as a catch limit or effort control. Similarly, further development of the DLMtool is required to fully incorporate existing MPA networks into the MSE simulations.

Data and Method Application

Data Assumed to be Representative - The MSE model accounts for observation error in the simulated fishery data. However, the application of management procedures for management advice assumes that the provided fishery data is representative of the fishery and is the best available information on the stock. Processing of fishery data should take place before entering the data into the fishery data tables, and assumptions of the management procedures should be carefully evaluated when applying methods using the DLMtool.

The analysis described in this report was conducted with DLMtool version 3.2.2. DLMtool is undergoing continual development and many of the limitations described above will be addressed in future versions of the package.

Applying MSE to California Fisheries

The CDFW selected four fisheries to serve as case studies to test the DLMtool's applicability to different fishery types, including with regard to life-history, (two invertebrates and two finfish), data availability (from data-poor and unassessed to data-moderate and recently assessed), and fishery sectors (recreational, commercial, and mixed). The four case study stocks chosen were barred sand bass (*Paralabrax nebulifer*), southern California halibut (*Paralichthys californicus*), southern red sea urchin(*Mesocentrotus franciscanus*), and warty sea cucumber (*Parastichopus parvimensis*). The methodology that was used for conducting the MSE and the analyses of the results are presented below.

Aggregating Fishery Information

The first step in the process was to identify and analyze the fishery information for each stock, and to populate the parameters of the MSE Operating Model and the Fishery Information Data Tables (see Appendix M for the MSE Operating Model Tables for each stock). We began with a workshop with the CDFW scientists responsible for each species. The aim of this three-day workshop was to discuss the overall objectives of the project, to demonstrate the management strategy evaluation approach, and to describe the types of data and information that are required to use DLMtool. The following section describes the various additional steps in the process of gathering and processing fishery information for use in DLMtool.

Fishery Questionnaire

Following the initial workshop, a fishery questionnaire (see Appendix H) was distributed to the CDFW scientists to document the available information for each fishery. The first part of the questionnaire included general questions on the characteristics of the fishery (e.g., is the fishery seasonal or does fishing occur year round?), as well as specific questions on the historical and potentially feasible future management measures (e.g., have minimum or maximum size restrictions been placed on the catch?). The second part of the questionnaire focused more directly on data availability and was used to aggregate meta-data for each case study. For example, the questions asked if time-series of total catch exists for the fishery, and if so, for how many years? The purpose at this stage was not to collect the actual data, but to identify what data sources were available, who had access to the data, and what analyses or further additional steps were needed to process the data. Questions were also included on the species biology, including information on the natural mortality, growth, and maturity, as well as the characteristics of the fishing fleet, including selectivity and catchability. Where available, this information was used directly to populate the MSE Operating Model and Fishery Information Data Tables.

Scientific Literature

In addition to the fishery questionnaire, we conducted a review of the scientific literature to identify publications that contained information relevant to the case study stocks in California. The literature search focused on biological studies, including estimates of growth, natural mortality, maturity, and recruitment dynamics. Other relevant studies included estimated trends in abundance or exploitation patterns. Published studies of closely related or nearby species were also examined to inform the likely ranges for the biological parameters.

We also conducted an extensive search of the available gray literature for any information on the case study species. This included unpublished biological studies, stock assessment reports (where available) and other information relating to trends in population and fishing dynamics. Where available, fishery data from the CDFW was analyzed to provide estimates of various parameters.

Unanalyzed and unpublished data may be a valuable source of information for populating the parameter tables for the MSE, but should be carefully evaluated by the analysts to determine if it is reliable and representative. For example, information on the current age composition of the stock may be used to determine a crude estimate of current fishing mortality, which can be used to develop reasonable (although uncertain and thus wide) bounds for the current level of depletion. Maturity-at-size data is relatively easy to collect, and is often collected by researchers but remains unpublished until more biological research is complete. Information from within marine protected areas (MPAs) can also be useful, particularly for developing an understanding of the natural mortality rate and the expected unfished density for sedentary or relatively immobile species.

Fishery Information Summary Document

For each case study stock, we developed a Fishery Information Summary (FIS) document containing a synthesis of all the available information (from the CDFW responses to the questionnaire and the literature search) (see Appendices I through L for the FIS documents for the four case study stocks). These documents summarize the history of exploitation and management of the fishery. The FIS documents also provide details, with references to the published or gray literature, of the information pertaining to the parameters for the MSE Operating Model and Fishery Information Data Input tables. More information is often available than first anticipated for a data-limited stock. The process of consolidating the available information on the stock and the fishery in this way is useful for identifying the gaps in knowledge, as well as providing an in-depth overview of the current knowledge of the stock and fishery.

The FIS document for each species was developed in consultation with the biologists and subject matter experts from CDFW, and was revisited several times throughout the study as more information was obtained. A series of phone meetings and webinars were held between the DLMtool project team and the CDFW experts to discuss the contents of the summary document. Acceptable ranges for the parameters obtained from the scientific literature were discussed and agreed upon. These mostly related to the biological parameters such as growth and maturity, which were published for some of the species. The information gaps were discussed in detail, with a focus on the identification of additional potential data sources that could be explored further by the CDFW researchers. Multiple CDFW data sets were identified at this point and flagged for further analysis to obtain information on the unknown or uncertain parameters.

There was a lack of information for some of the MSE Operating Model parameters. Discussion with CDFW researchers was used to derive reasonable bounds for these values. For example, a range for the current level of depletion must be specified for the DLMtool MSE model. Apart from the California Halibut, where a stock assessment was carried out in 2010, no information regarding current levels of depletion exists for the case study stocks. Expert judgment was used to establish reasonable bounds for this parameter by evaluating knowledge of the exploitation history together with information on the selectivity pattern and vulnerability of the species. The DLMtool also assumes that growth is described by the von Bertalanffy growth function, which may not be appropriate for some species. In the case of the two invertebrate species, red sea urchin and sea cucumber, estimates of the von Bertalanffy growth parameters were highly uncertain. Growth for these species was assumed to follow a von Bertalanffy curve with wide bounds set for the K and L_∞ parameters based on published information of the longevity and life history of the species.

As is often the case for most stocks, but especially data-limited ones, information on the recruitment dynamics, including the steepness of the stock-recruit relationship, was also difficult to obtain. Bounds for these parameters were obtained from discussion with the species experts and published meta-analyses of stock-recruitment relationships for marine species (Myers, 2001, Thorson et al., 2014).

The observation error parameters of the MSE Operating Model Tables are perhaps the most difficult to elicit. These values are used to determine how the fishery information is simulated within the MSE model, with the aim of ensuring that the simulated fishery data realistically represent the variable and potentially biased data that is observed in the real world. Populating the observation error inputs involves specifying the uncertainty of unknown parameters, a task of considerable difficulty. In discussions with CDFW environmental scientists, we attempted to identify which data sources and parameters are likely to be most reliable, and which are most unreliable. In general, little information pertinent to observation error was available from the CDFW, so the parameters for the observation model were kept consistent across the four case studies, and were based on the values used by Carruthers et al. (2014). A description of where these values were modified is provided below.

As noted above, caution should be exercised when accepting default values in the operating model. Analysts conducting the MSE should be educated in fisheries science and population dynamics, and understand how the parameters in the operating model interact with the simulated stock and fleet dynamics and the observation process. Validating the observation process for a fishery requires familiarity with the data collection and analytical processes. Sufficient time and resources should be dedicated to understanding and populating the operating model parameters.

Working Group Meetings & Webinars

The initial values for the operating model were presented to the broader Working Group in a multi-day meeting in November of 2015. This information was presented in both graphical and tabular format, and allowed all members of the Working Group to comment and provide feedback on the parameter values. For example, graphics that showed simulated growth patterns, size compositions, and historical trends in exploitation from the MSE model were presented to the group to compare with their expert knowledge of the system. The Working Group meeting provided the opportunity for discussion of some of the more uncertain parameters, as well as the identification of potential additional data sources. Feedback from the Working Group was received in the weeks following the meeting and this information was used to update or refine the initial parameter values.

In February of 2016, Dr. Hordyk from the DLMtool team spent time meeting with the case study stock leads from CDFW to review all the available fishery information and to adjust parameter values for the MSE Operating Model Tables. These meetings also enabled the aggregation of available fishery information that could be used to populate the Fishery Information Data Tables for each stock. In March and June, we convened webinars with the entire Working Group presenting preliminary results from the MSE. The webinars provided Working Group members with a further opportunity to review the MSE and Data Tables, to ask questions about the process, and to provide feedback on the preliminary results. In November of 2016, a second Working Group meeting was held to review a draft of this report and to solicit feedback on the results and recommendations.

Feasibility Table

Discussions with CDFW experts and the broader Working Group identified the potential fishery information data sources that were available for each fishery, which are included in the FIS documents (see Appendices I through L). This information was used to populate a Feasibility Table for each case study stock. The Feasibility Table involves specifying the likely presence or absence of 15 broad data types (0 for absent, 1 for present) (see Appendix S). The Feasibility Table is used with a DLMtool function ("*Fease*") to identify which management procedures could potentially be used, and which are unlikely available due to insufficient data.

The Feasibility Table is an optional step in the DLMtool process that is not required to conduct the MSE and interpret the results. However, the complete analysis of the fishery data and the population of the Fishery Information Data Table can be time consuming, and the feasibility function allows an understanding of which management methods may potentially be available before the data analysis is complete. In this way, the Feasibility Table can be used early in the exploratory stages of the MSE and can use qualitative information on the potential availability of fishery data (i.e., presence/absence of different data types) to identify which management procedures are likely to be available for use and which are not available due to the absence of particular data streams. However, it must be emphasized that the Feasibility Table is not intended to replace a comprehensive data analysis, or eliminate data sources based on the crude presence/absence approach. Rather, the Feasibility Table can be used very early in the MSE development process to enable the analyst to generate preliminary results that are meaningful and relevant to the stakeholders before the comprehensive data review is complete. Once the Data Table is populated, the Feasibility Table becomes redundant and is no longer used to determine which management procedures are available to the fishery.

Designing MSE Operating Models

The parameter values for the MSE Operating Model were revised as new information became available, including feedback from CDFW and the broader Working Group. Recommended extensions to the DLMtool resulted in additional parameters requiring specification (see page 50 for a description of DLMtool extensions that were considered and adopted as part of this project). For example, the Working Group identified that the selectivity pattern for some case studies changed markedly throughout the history of the fishery as new regulations were adopted. In response, the DLMtool was modified to incorporate changes in the historical selectivity pattern, which introduced some new parameters. The information for these parameters was obtained through additional discussions with the CDFW experts and by revisiting the FIS documents. The final MSE Operating Model Table for each case study stock is included in Appendix M, and the basis for the parameters selected are explained in the FIS documents contained in Appendices I through L.

Crafting Performance Metrics that Align with Management Objectives

To evaluate the performance of the different management procedures included in the MSE, it is necessary to develop a suite of performance metrics. These performance metrics are related to the management objectives for each fishery, and used to rank the performance of each management procedure with respect to particular objectives, with the aim of identifying and removing methods that are unlikely to meet minimum performance criteria, and select the method that best meets the management objectives (see Step 3 on page 28 for more information on using performance metrics).

One of the main benefits of MSE, especially in the data-limited fisheries context, is the ability to evaluate the performance of different management methods with perfect knowledge of all the metrics that form the basis for fisheries laws and policies, and guide managers. Whereas in the real world, the stock status of a data-limited fishery is unknown, in the simulated world of the MSE, we can evaluate how a method is likely to perform in terms of biomass, fishing mortality rates, and other metrics, and then decide transparently whether a chosen management method is likely to achieve the performance mandated by law and expected by managers and stakeholders. Instead of having a calculation of the fishing mortality rate and/or biomass levels relative to MSY, as is typically the goal in more data-rich fisheries, MSE makes it possible to choose methods that are the most likely to attain the fishing mortality or biomass targets without ever computing the current rate or level for the fishery.

Minimum Performance Limits and Management Targets

The CDFW Working Group chose to use a three-step procedure for selecting acceptable management procedures. First, minimum performance limits were developed for each stock. These limits were used to eliminate methods considered too risky for management; for example, methods that result in the stock declining to unacceptably low levels in either the short or long-term, or methods that close the fishery (i.e., yield = 0) over a large proportion of the projection period, even at healthy biomass levels. The CDFW specified the minimum performance limits for each stock by considering the management objectives of the MLMA together with the current knowledge of the stock.

The CDFW Working Group selected minimum sustainable biomass limits and associated acceptable levels of risk for each stock (Table 3). The minimum biomass limits were analyzed over two overlapping time periods for the projections: years 11-50 and years 41-50. The rationale for using both time periods was to ensure that methods had a high probability of not falling below the biomass limits for the entire time period, while accounting for cases where biomass may start below the limit and need a reasonable time to rebuild. The second rationale for considering biomass levels over just the last 10 years of the fifty-year projection was to avoid a situation where the biomass is well above the minimum limit for most the projection period, but declining and ultimately crashing during the end of the period.

The second step involved removing methods which were unlikely to meet the management targets for the stock, defined as having a 50% probability that the biomass in the last ten years of the projection period (years 41 - 50) is above the target level (Table 3). Methods which met both the minimum performance limits and the management targets were termed "acceptable" options for managing the fishery. A requisite high probability was chosen for methods performing above the minimum limits and a median probability was used gauging whether methods would satisfy the performance targets. In other words, the acceptable methods have a low likelihood of the stock being depleted to low levels and a high probability that the stock biomass is maintained close to the management target.

Table 3: The minimum performance limits and performance targets selected by the CDFW Working Group for the four case study stocks.

	Barred Sand Bass	California Halibut	Red Sea Urchin	Warty Sea Cucumber
Step 1: Performance Limits				
80% probability biomass in years 11-50 *and* years 41-50 > minimum biomass specified for each stock	$0.2B_0$	$0.125B_0$	$0.25\ B_0$	$0.25B_0$
Step 2: Performance Targets				
50% probability biomass in years 41-50 > minimum biomass specified for each stock	$0.4B_0$	$0.25B_0$	$0.5B_0$	$0.5B_0$
Step 3: Trade-Offs Between Long-Term Yield and Variability in Catch/Effort				
Choose MPs using a stakeholder-driven decision that optimizes long-term yield, considering average annual variability in yield and effort (AAVY/AAVE)				

The third and last stage of the method selection process involved examining the various trade-offs among the remaining methods and selecting the method the best met the objectives for the stock. The Working Group decided that the trade-off between maximizing the expected long-term yield and minimizing the expected inter-annual variability in yield (defined in this study as the average annual absolute change in catch and expressed as a percentage) would be examined for each candidate method, and the preferred method would be selected by a stakeholder driven decision.

The two primary objectives for these fisheries are long-term biological sustainability of the stock and ensuring high long-term yield. The objectives were to manage the long-term biomass of the stock at or above the biomass corresponding to maximum sustainable yield (B_{MSY}), while minimizing the probability of the stock declining to undesirable levels. By definition, for a stock to rebuild to, or be maintained above, B_{MSY}, the fishing mortality rate must be below F_{MSY}. Therefore, long-term trends in biomass and fishing mortality rates are correlated and performance limits on the stock biomass achieve the same result as restrictions on fishing mortality.

It is important to note, however, that although not explicitly used as performance limits or management objectives, summary statistics of the fishing mortality rate, and other metrics, such as trends in future catches relative to the current conditions, can be examined for the management procedures that are selected as potential methods for managing the fishery. The stock-specific reasoning behind these Working Group choices on the performance metrics and acceptable risk thresholds are described below.

Barred Sand Bass

For barred sand bass, 0.4 of unfished biomass (B_0) was chosen as proxy for B_{MSY}, based on previous calculations for groundfish (PFMC, 2016). We chose the average over the last 40 years of the projection to avoid a scenario where the fishery is at unacceptable levels for most of the 50-year projection. The same metric with a different time series specified (last 10 years of the 50-year projection) was chosen to avoid a scenario in which the biomass crashes during at the end of the projection.

California Halibut

These values are based on the reference points for west coast flatfish in the Pacific Fishery Management Councils' Groundfish FMP and are included in several flatfish stock assessments (PFMC, 2016; Stawitz et al., 2016). The established proxy for B_{MSY} is $0.25B_0$, which was selected as the target performance metric for California halibut. $0.125\ B_0$ (the proxy for $0.5\ B_{MSY}$) was chosen as the performance limit, with a higher associated level of certainty to reflect the risk of exceeding this threshold.

Red Sea Urchin & Warty Sea Cucumber

For both species, limited information on life histories and expected population dynamics was available, so metrics were chosen based on the fundamental concepts of fisheries management. They represent conservative values to reflect the uncertainty of these data-limited species. The same values were chosen for red sea urchin to provide a means of comparison, since these two fisheries share similar dynamics and both species are echinoderms

Customizing the DLMtool for California Fisheries

The first CDFW Working Group meeting, held in November 2015, identified and discussed a range of potential customizations and extensions to the DLMtool that could prove useful for the DLMtool's application to California fisheries. In the months following the Working Group meeting, the DLMtool team incorporated many of these suggestions into the DLMtool, which are described in the following section. Custom management procedures were also developed specifically for each case study stock to test things such as the effect of maintaining current effort or stepped up changes in size limits (see page 53). Other extensions and further customizations to the DLMtool were recommended and explored, but were not implemented for this analysis due to limited time and resource. These are described in detail in the Discussion section starting at page 106).

Incorporating Historical Changes in Selectivity

The DLMtool models historical fishing as the aggregate behavior of all fishing operations combined. Prior to this project, it also assumed a constant historical selectivity pattern. This simplicity is appropriate in data-limited settings due to the lack of detailed quantitative knowledge of past fishing and the fact that such assumptions are computationally efficient. A problem arising in the California case studies (and elsewhere) is that changes in the composition of fishing practices can lead to time-varying changes in size selectivity (for example a recent reduction in the capacity of a fleet targeting juveniles). In response, the DLMtool was adapted by (1) allowing for temporally variable size selectivity in the structure of the operating model and (2) incorporating a new function (*ChooseSelect*) that allows users to sketch historical selectivity using a graphical user interface. This extension allows information on past management regulations or fishing practices to be used to tune the operating model to more realistically simulate the historical exploitation pattern of the fishery.

Cyclical or Stepped Recruitment Trends

The recruitment and population dynamics in the DLMtool operating model are simulated using process error and autocorrelation, which are typical for fishery population models. The CDFW Working Group identified long-term patterns in recruitment as a potentially important issue to evaluate with the DLMtool, particularly with respect to modeling the effects of climate change. The DLMtool was customized to include the option of a cyclical or stepped pattern in recruitment. Systematic patterns in recruitment can be included by specifying a range for the period and magnitude of recruitment shifts. This can be used for comparing the performance of management procedures under alternative states of nature.

Include "Data-Rich" Management Procedures for Comparison

The current DLMtool version includes some methods that are typically considered "data-rich," including the Delay-Difference model (*DD*), which assumes that the availability of a complete time-series of removals from the beginning of the fishery, a time-series of fishing effort, and estimates of the life-history information. These methods provide a direct comparison in the performance of data-rich assessment methods and simpler management procedures that require fewer data. The CDFW Working Group noted that including more "data-rich" management procedures, particularly Stock Synthesis 3 (SS3; Methot and Wetzel, 2013) in the suite of methods available in the DLMtool might be useful for a more realistic direct comparison using assessment models that are typically used in the region.

The implementation of this recommendation is very challenging, particularly because there is no clear "default" structure for a data-rich assessment approach, but rather a large range of possible alternative models that can be used. For example, should this include time varying selectivity? Should SS3 runs be rejected that did not converge? How should stochasticity in-model predictions be handled?

A second obstacle to incorporating SS3 into the DLMtool was that it takes too long to run to be viable in closed-loop MSE simulation (i.e., 20-80 seconds per run from writing the input file to reading the outputs). For 1,000 simulations and 20 projected assessments, a one-minute running time would take a total of 14 days to run (as opposed to 20 minutes for all other management procedures combined). A more streamlined Statistical Catch-at Age model is now being developed for the DLMtool, which should address this problem in the future, but proved to be beyond the scope of this project.

MSE Case Studies

The DLMtool was used to run the MSE for each of the California case studies (see page 18 for a description of MSE and page 24 for an explanation of how MSE is used in the DLMtool process). Each MSE included 1,000 simulations, and a projection period of 50 years. Since the case study fisheries had not been managed previously using such an approach, there was no clear guidance on the appropriate interval for management updates. Regular changes to management (e.g., changes to catch or effort limits) can be costly to implement and regulate. On the other hand, the performance of management procedures is likely to be degraded with a long duration between management actions. For this pilot project, a management update interval of four years was used for all four case studies. We recommend that the management interval in the MSE is considered and set for a duration that is appropriate for the fishery and management framework. The parameters for the operating models are provided in Appendix M and described in the FIS documents contained in Appendices I through L.

Management Procedures Evaluated

The version of the DLMtool used in this study included 86 built-in management procedures (22 input controls and 64 output controls) (see Appendix E for a complete list and description of all the management procedures contained in the DLMtool, and Appendix F for the data requirements for each method). Many of these management procedures are generalized methods that have been developed and used by institutions conducting stock assessments and published in the scientific literature. Some of the management procedures contained within the DLMtool exceeded the time-limit or repeatedly crashed during the MSEs, and thus were excluded from the analysis.

Additional management procedures (described below) were developed specifically for the California case study stocks in response to discussions with the CDFW Working Group. The practical implementation of some of the management procedures may be difficult under current conditions, but there is no cost to including them in the MSE. It is important to note, that the different customized management procedures developed for this demonstration were not intended to be exhaustive. The design and testing of new methods in future applications of the DLMtool is highly recommended.

Custom Management Procedures for Barred Sand Bass

A series of alternative size limits were developed for the barred sand bass MSE, including minimum legal length of 350, 360, 365, and 370 mm (current minimum legal length of 355 mm was also tested). Three alternative slot limits were also examined, with a fixed upper limit of 382 mm and lower limits of 350, 355, and 360 mm. Additional methods were developed that included a slot limit of 360-382 mm and an iterative effort-based control rule that adjusts annual fishing effort (e.g., days at sea) in response to trends in mean length or catch-per-unit-effort. Finally, we examined the effect of a closure of the barred sand bass fishery over the summer months (June - August) when the stock is known to form spawning aggregations. The method assumed a reduction of annual fishing effort to 55% of current levels, which was calculated from the monthly CPFV effort data from the last three years.

Custom Management Procedures for California Halibut

Size-based regulations were identified by the CDFW as a preferred management approach for California halibut. Seven different static size limits were tested in the management strategy evaluation (555, 585, 615, 645, 675, 705, and 735 mm; named *MLL555*, *MLL585*, etc). The purpose was to identify the effect of a range of size limits and to determine how well size-based regulations perform with respect to the management objectives. Three size-based management methods with logistic-shaped selectivity curves, which may more realistically reflect the selectivity pattern of a multi-fleet fishery (named *LogSel600*, *LogSel650*, and *LogSel750*, respectively), were also included.

Custom Management Procedures for Red Sea Urchin

Multiple different size-based methods were developed for red sea urchin. These methods included two minimum size limits that are larger than the existing minimum legal size of 82.5 mm (3.25 inch): 1) 85.7 mm limit (3.375 inch) and 2) 88.9 mm (3.5 inch). Two slot limits were also examined: 1) a lower limit of 85.7 mm and an upper limit of 139.7 mm (5.5 inch), and 2) a lower limit of 88.9 mm and an upper limit of 139.7 mm.

The above methods are static size regulations, where the size regulation is fixed for all future regulations. Four different iterative size regulation methods were also included, where an upper slot limit was 139.7 mm was fixed, and the lower size limit switched between 85.7 mm and 88.9 mm in response to trends in catch-per-unit-effort or mean length.

Custom Management Procedures for Warty Sea Cucumber

Managing the size of first capture was identified as a potential option for the warty sea cucumber. Sea cucumbers are difficult to measure, so a size-based regulation may be difficult to enforce. However, the protection of immature individuals from harvest using some form of size-based regulations has been demonstrated to be important for ensuring the biological sustainability of a stock.

Two additional size limit management procedures were included in the MSE for the warty sea cucumber: 1) a size limit of 100 mm (3.9 inch), and 2) 120 mm (4.7 inch). The intention for including these two methods was to examine how changing selectivity (however difficult to implement at the present time) affect the dynamics of the fishery in terms of yield and biomass. A method that prescribes a general 50% reduction in fishing effort was also included.

Note on Size-Based Regulations in DLMtool

The DLMtool MSE model currently assumes that size-based regulations (e.g., a minimum legal length) are implemented perfectly and there is no fishing mortality on sub-legal fish. This assumption is obviously invalid for fisheries where it is likely that sub-legal fish either are retained or discarded dead. Consequently, the minimum legal length methods included in this analysis may underestimate the risk associated with static size-based regulations, especially where it is unlikely that these regulations can be perfectly implemented.

Quantifying the risks of this implementation error requires specific data from the fishery, including an understanding of the selectivity of the fishing gear and an estimate of the fishing mortality rate on discarded fish. The DLMtool is currently being further developed to include this information and to quantify these risks. However, until such information is incorporated into the analysis, the results of size-based regulations examined for this study should be interpreted with caution.

The CDFW reported that post-release mortality for barred sand bass is low, however within the scope of this project it was not possible to quantify this. While the minimum legal length and slot limit methods were included in the analysis to examine their properties under ideal conditions, it was determined that it would not be valid to assume that these methods would be implemented perfectly. Therefore, these methods were not considered acceptable or available for implementation with this fishery.

The California halibut fishery is targeted by multiple fleets and a variety of different fishing gears. The assumption of no fishing mortality on sub-legal individuals is therefore invalid for this fishery. Like the barred sand bass case study, the size-based methods were included in the MSE to evaluate their properties under ideal conditions, but the results from these methods were not considered acceptable or available for use until such implementation error can be quantified within the MSE.

Because the red sea urchin fishery, where individuals are harvested by hand, is highly selective, the assumption of no fishing mortality on sub-legal animals was considered valid. However, the alternative size-selectivity scenario for the warty sea cucumber was not considered realistic to implement, and was included only as an exercise to examine the impacts of alternative selectivity pattern on the fishery.

Management Procedures Not Included in the Analysis

Not all the 86 management procedures included in the DLMtool could be included in the MSE for the case studies. For example, seven mean length methods (e.g., *BK_ML*, *DBSRA_ML*, *Fdem_ML*, etc.) crashed repeatedly and were dropped out of the MSE. Several methods (e.g., the *LBSPR* approaches) did not pass the time requirement and were not included in the MSE runs. Due to limited time and resources, and because the principal objective of this project was to evaluate the potential of the MSE approach for data-limited fisheries in California, it was not possible to include these methods in this analysis. Furthermore, initial exploratory analyses suggested that these methods performed poorly and were unlikely to meet the management objectives. The latest version of the DLMtool (version 4.1), released after this analysis was completed, has corrected the problems and improved the run-times of these methods.

The DLMtool also includes several reference methods (i.e., *FMSYref*, *FMSYref50*, *FMSYref75*, and *NFref*), which relate to fishing under conditions of perfect knowledge. These methods were included in the MSE, but are not presented in the results comparing the performance of alternative management procedures.

Identifying Acceptable & Available Methods

The management procedures were filtered down in the MSE to a smaller number of acceptable methods that met the performance metrics with the acceptable levels of risk. However, the management procedures have different data requirements, so not all the acceptable methods are available for use with current data for each stock. The DLMtool has a function to test which methods can be used with a given Fishery Information Data Table, and thus are considered available for use at the present time. If a management procedure is identified by the MSE as a suitable candidate for managing the fishery ("acceptable"), but is not available due to lack of data, the missing data streams can be identified and prioritized for future research. Among the list of acceptable methods, only methods that are also available can be used to derive current management recommendations.

Barred Sand Bass MSE Results

Acceptable Methods

Eighty-six methods were evaluated in the barred sand bass MSE, including sixty-nine pre-defined management procedures from the DLMtool and an additional 17 custom methods. Sixty-three methods met the requirements for the first performance metric of at least an 80% probability that biomass is above $0.20B_0$ in last 10 years of the projection period. Similarly, 66 methods passed the second performance limit of at least 80% probability that biomass is above $0.20B_0$ in last 40 years. All methods that passed the first performance limit also passed the second limit. Three methods, *DBSRA*, *DDe*, and *SLslope*, met the requirements for the second performance limit, but did not pass the first performance limit.

Fifty-six methods passed the requirements for the management objective of at least 50% probability that biomass is above $0.4B_0$ in the last 10 years of the fifty-year projection period. One method that passed the requirements for the management target did not pass the first performance limit (*SPslope*).

This resulted in 55 management procedures which met the requirements both the performance limits and management target. However, 15 of the methods that passed the performance metrics were custom input control methods that used size-based regulations including minimum legal lengths or harvest slot limits. As discussed in the section above, these methods were not considered acceptable candidates for this fishery due to the unrealistic assumptions about discard mortality and implementation error in the version of the DLMtool used for this analysis. Therefore, 40 of the 86 management procedures that were examined in the MSE were considered acceptable candidates for management of the barred sand bass fishery. A complete table of the MSE results for barred sand bass is available in Appendix N.

Available Methods

The barred sand bass fishery is comprised entirely of recreational fishers, both from private vessels and commercial passenger fishing vessels (CPFV). For a variety of reasons, CDFW currently lacks the capacity to implement catch limits in the recreational fishery, including a lack of administrative resources, challenges adopting in-season management with time-lagged catch data, and the current lack of regulatory authority to implement the necessary management measures. These limitations, combined with the lack of a time-series of total catch for the recreational fishery means that none of the 52 output control management procedures that were included in the barred sand bass evaluation were considered available with current data. Catch records from the CPFV fleet are available in logbooks and information on catches from private vessels can be derived from ongoing telephone surveys (although recent changes to the survey methodology have precluded the ability to construct a reliable time-series of total catch estimates at the present time). It may be possible to estimate total removals in the future and to dedicate the required administrative and regulatory resources necessary to make output controls an available option. But, given the lack of reliable long-term catch data and the lack of monitoring and enforcement capacity, output controls were not considered available for the barred sand bass case study.

Among the input control methods evaluated, three were not available due to the lack of data on total removals (*DDe*, *DDe75*, *DDes*) and two due to no information on the current level of depletion (*DTe40*, *DTe50*). Furthermore, the minimum legal length and harvest slot limits were not considered available for this fishery due to a lack of data on discard mortality and the retention of sub-legal sized fish (see Note on Size-Based Regulations in DLMtool section above). This resulted in 11 acceptable and available methods for barred sand bass (Table 4).

Table 4: The numerical results for the performance limits and target, B_{MSY} reference, and average annual variability in yield and effort for the 11 acceptable and available management procedures from the barred sand bass case study. The yield metric represents the average yield for each method in the MSE relative to the yield at F_{MSY}.

Management Procedure	Performance Limits: Prob. $B > 0.2\ B_0$		Performance Target: Prob. $B > 0.4\ B_0$	Reference: Prob. B > B_{MSY}	Long-Term Yield vs F_{MSY} ref (%)	Avg. Annual Var. Yield (%)	Avg. Annual Var. Effort (%)
	Yrs 41-50	Yrs 11-50	Yrs 41-50				
ITe5	0.94	0.96	0.55	0.66	98	22	1
curE	0.96	0.97	0.69	0.77	86	22	0
LstepCE1	0.96	0.97	0.71	0.79	80	22	1
curE75	0.98	0.98	0.77	0.84	79	22	0
ItargetE1	0.95	0.97	0.72	0.79	76	22	3
LstepCE2	0.96	0.97	0.73	0.80	74	22	1
BSB_Scls	0.99	0.99	0.84	0.89	70	22	0
curE50	0.99	0.99	0.86	0.90	67	22	0
LtargetE1	0.98	0.99	0.86	0.90	51	22	3
ItargetE4	0.99	0.99	0.91	0.94	37	22	4
LtargetE4	1.00	1.00	0.97	0.97	20	22	5

Trade-Offs Among Acceptable and Available Methods

There was a clear trade-off with respect to the expected long-term yield and the probability of the biomass in the last 10 years being above $0.4B_0$ for the 11 acceptable and available methods (Figure 7). There was also considerable variation in the expected long-term yield for these methods. For example, three of the methods had long-term yield of ~50% or lower relative to the potential yield with perfect management, and a corresponding high probability of high biomass (lower right corner of Figure 7). These methods were methods that used trends in mean length or catch-per-unit-effort to adjust fishing effort (*LtargetE1*, *LtargetE4* and *ItargetE4*). This suggests that these methods may be overly conservative for this fishery, with low long-term yields and reduced fishing effort.

Two of the methods represent generic reductions in fishing effort (*curE75* and *curE50*; 75% and 50% of current fishing effort, respectively). A seasonal closure of the fishery over three summer months (June to August; *BSB_Scls*) was modelled as a reduction in fishing effort to 55% of the current level. Currently, most fishing occurs during these months, and this reduction in fishing effort corresponds to a decrease in expected long-term yield (Figure 7).

The *LstepCE1* and *LstepCE2* methods, which adjust fishing effort based on trends in mean length, and the *ItargetE1* method, which adjusts effort based on trends in an index of abundance, had similar performance, with higher expected long-term yield and lower probability of biomass being above 40% of the unfished level compared to the more precautionary methods (Figure 7).

The *curE* method, which represents fishing effort held constant at the current level, had the second highest long-term yield. An iterative effort control method (*ITe5*; method that adjusts fishing effort by up to 5% in response to trends in the index of abundance over the five most recent years) had the highest expected long-term yield (Figure 7).

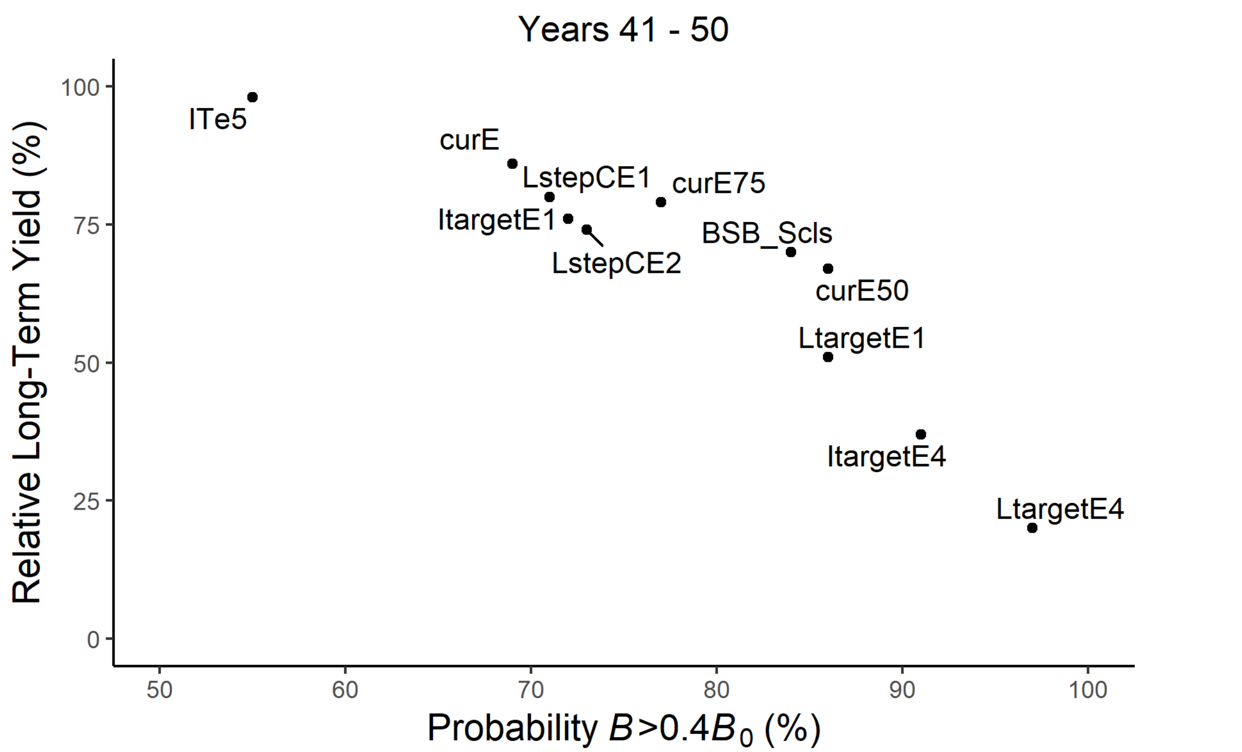

Figure 7: Trade-off between the probability that biomass is above 0.4B_0 in the last 10 years of the projection and the expected long-term yield for 11 acceptable and available methods in the barred sand bass MSE. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

The CDFW Working Group determined that the decision for selecting the best method should be a stakeholder-driven process that evaluated the trade-off between the expected long-term yield and the average annual variability in yield and effort among acceptable and available methods. As all acceptable methods were effort-based input controls, there was little difference in the variability in yield between the methods (Figure 8a). The variability in fishing effort was more significant between the different methods, however, all methods had an average less than 5% (Figure 8b).

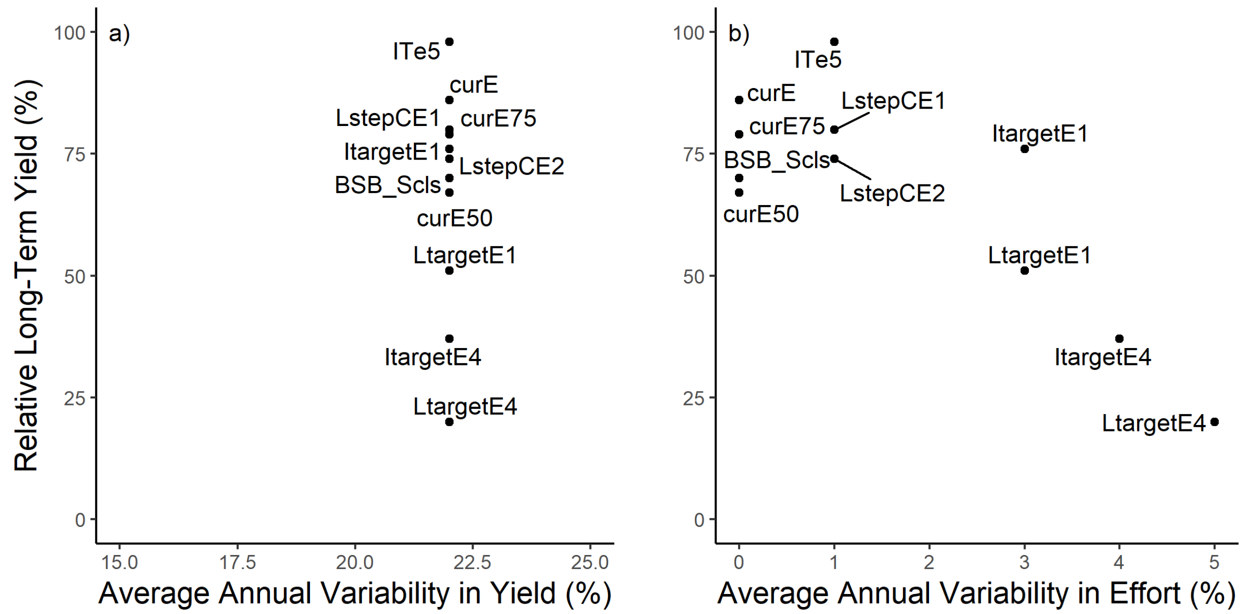

Figure 8: Trade-offs between average annual variability in yield (AAVY), average annual variability in effort (AAVE), and long-term yield for the 11 acceptable and available methods for the barred sand bass MSE. The acceptable and available methods were all effort-based input control methods, and there was very little difference in performance between the methods. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

An inverse relationship exists between variability in annual yield and fishing effort. Output control methods regulate a catch limit, and often have built-in limits on how much the recommendation can change between years. Fishing effort will vary between years, and natural variations in productivity and recent trends in exploitation can affect the availability of the biomass and the effort required to catch the total allowable catch (TAC). Therefore, output control methods with a TAC will typically have relatively low variability in yield, and a correspondingly higher annual variability in effort.

Effort control methods have the reverse behavior, where fishing effort is regulated and relatively stable between years, but the yield can vary between years in response to the availability of the stock. It should be noted that the management strategy evaluation model assumes that the TAC is fully caught in every year (where possible) which can result in high fishing effort in years where the biomass is low relative to the TAC. The fishing industry will usually cease fishing when it becomes unprofitable, and there may be some years where the TAC is not fully caught. Therefore, the estimates of average annual variability in effort may be over-estimated in some of these situations.

Projection Plots of Selected Methods

Figure 9 shows the projection plots for four acceptable and available methods with high long-term yield. The lower bound of the gray polygon shows the 20th percentile of the distribution for each year, which corresponds to an 80% probability that the metric is above this point. Likewise, the median biomass, corresponding to the 50th percentile or 50% probability, is above $0.4B_0$, which was required for these methods to pass the management targets.

The *curE* method, which maintains current fishing effort with the current size limit, does not use any data or management response, but assumes that future fishing effort will remain static at the current levels. The *ITe5* method is an index target MP, where effort is modified by up to 5% each management cycle according to the current index level (averaged over the last 5 years), relative to a historical target level. The *ItargetE1* method uses the same data, an index of abundance, but adjusts fishing effort based on recent trends in the population abundance. The *LstepCE1* method incrementally steps fishing effort up and down in response to the trend in mean length in the recent catches.

The median biomass was above B_{MSY}, and fishing mortality well below F_{MSY} for all four methods. The median biomass and yield increased from the current level for all four methods. The iterative effort control method (*ITe5*; up to 5% changes in fishing effort in response to trends in relative abundance) was the only method that increased fishing effort in response to the stock being above the target level, and resulted in the highest long-term yield (Figure 9).

It is important to note that the median line shown in the projection plots represents the median trend over many simulations, each representing a different trajectory. The median line means that, in any given year, half of the projections are above this point and half are below. While the median of many possible futures appears relatively stable, in reality, there is only one, not 1,000, future trends. This means that actual future trends in biomass, fishing mortality, or yield, will not follow the stable median line directly, but will vary between years due to various factors affecting the fishing and stock dynamics (e.g., environmental variability). The trajectory of a single simulation is shown in Figure 9 to demonstrate the higher variability of the individual simulations compared to the median line.

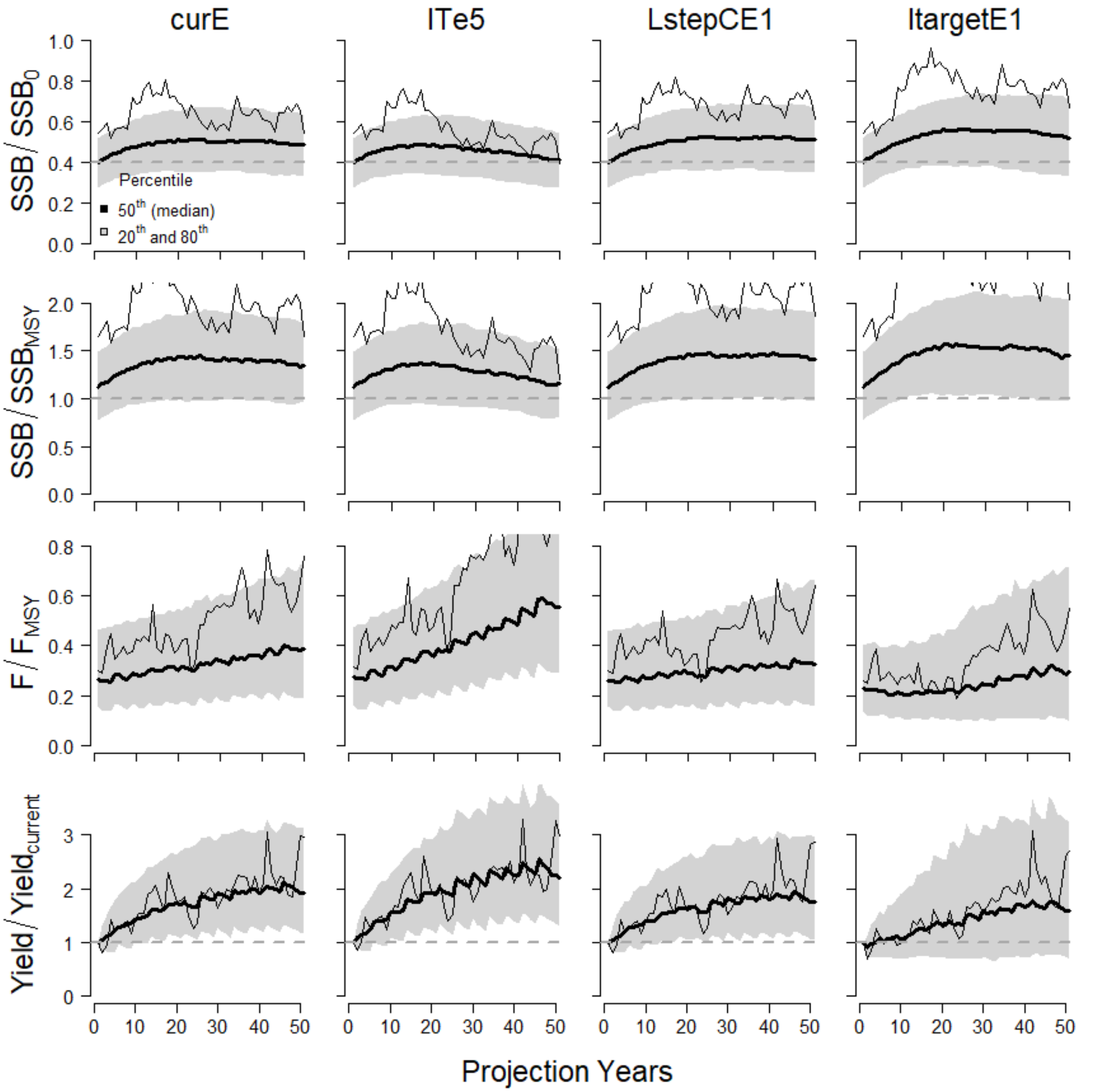

Figure 9: The projection plots (20th, 50th (median), and 80% percentiles) for the biomass relative to unfished conditions (*SSB/SSB_0*), spawning biomass relative to *SSB_{MSY}*, fishing mortality relative to *F_{MSY}*, and expected yield relative to yield in current year for four top performing methods in the barred sand bass MSE. The *curE* method represents management that maintains current effort and the existing minimum legal length. The thin black line in each panel shows the trajectory of a single simulation to demonstrate that the median of many simulations is less variable than any single simulation.

California Halibut MSE Results

Acceptable Methods

Eighty management procedures were included in the MSE for California halibut, including 10 management procedures that were developed for this case study. The customized management procedures included a series of alternative minimum size limits and selectivity patterns, as this form of management was identified by the CDFW Working Group as the preferred method for managing this fishery. As discussed on page 55, these methods were examined but not considered available due to the unquantified risk associated with discard mortality on sub-legal individuals.

Twenty-eight methods met the requirements for the first performance metric of biomass greater than $0.125B_0$ in the last 10 years of the projection period. Twenty-nine methods passed the second performance metric of 80% probability that the biomass was above $0.125B_0$ in the last 40 years of the projection period. The *MLL615* and *DCAC_40* methods passed the second performance metric (82% and 80%, respectively), but failed the first performance metric (both 77%). Similarly, the *ITe10* method passed the first performance limit (80%) but just failed the second (79%).

Thirty-seven methods met the management target of at least 50% probability that the biomass in the final 10 years was above $0.25B_0$. However, 12 of these 37 methods did not pass one or both of the performance limits. Furthermore, 4 size-based methods met the requirements of both the performance limits and the management objective but were not considered acceptable due to the unrealistic assumption of no discard mortality. Therefore, there were a total of 21 acceptable methods from California halibut MSE. A complete table of the MSE results for California halibut is provided in Appendix O.

Available Methods

Fifteen of the 21 acceptable methods were also available to be used with the current data for California halibut. Two of the acceptable methods that are currently unavailable (*Ltarget4* and *LtargetE4*) require a time-series of mean length and another four acceptable methods (delay-difference models (*DD*, and *DD4010*) and stock-reduction analysis methods (*DBSRA4010* and *SPSRA*)) require a time-series of catch and effort from the beginning of exploitation period, data which are not available for California halibut. Although some length composition data do exist for this fishery, the sample sizes are relatively small and there are some concerns about the representativeness of the data. Additionally, growth is strongly sexually dimorphic in California halibut, and, until recently, information on the sex of the samples was not recorded.

The size-limit methods were considered unavailable due to a lack of data on fishing mortality of sub-legal sized fish (see Note on Size-Based Regulations in DLMtool section above). It is important to note that even if the data existed to account for these issues such that they could be considered available for management, the results suggest that, even under the idealized conditions modelled here (ignoring post-release mortality), size-based regulations must be significantly higher than the current selectivity of the fishery to meet the management objectives, and thus likely incompatible with an economically-viable fishery.

This resulted in a total of 15 acceptable and available management procedures for the Califronia halibut MSE, 4 of which were input control methods and the remaining 11 were output control methods (Table 5).

Table 5: The numerical results for the performance limits and target, B_{MSY} reference, and average annual variability in yield and effort for the 15 acceptable and available management procedures from the California halibut case study. The yield metric represents the average yield for each method in the MSE relative to the yield at F_{MSY}.

Management Procedure	Performance Limits: Prob. B > 0.12.5 B_0		Performance Target: Prob. B > 0.25 B_0	Reference: Prob. B > B_{MSY}	Long-Term Yield vs F_{MSY} ref (%)	Avg. Annual Var. Yield (%)	Avg. Annual Var. Effort (%)
	Years 41-50	Years 11-50	Years 41-50				
Itarget1	0.93	0.93	0.65	0.47	95	5	11
ItargetE1	0.89	0.89	0.55	0.39	92	22	3
DepF	0.91	0.90	0.62	0.49	87	14	19
DTe40	0.90	0.86	0.54	0.37	87	22	2
DAAC	0.90	0.91	0.68	0.57	85	4	10
Fratio4010	0.96	0.96	0.72	0.58	85	15	21
DTe50	0.93	0.88	0.62	0.44	84	21	2
MCD	0.98	0.98	0.88	0.79	75	4	9
MCD4010	0.99	0.99	0.89	0.82	71	6	11
DCAC	0.81	0.83	0.68	0.60	70	1	14
Itarget4	0.99	0.99	0.94	0.89	68	3	9
DCAC4010	0.99	0.99	0.91	0.86	67	3	10
ItargetE4	0.99	0.97	0.90	0.80	67	22	4
HDAAC	1.00	1.00	0.98	0.94	51	3	9
CC4	0.83	0.85	0.80	0.77	22	5	13

Trade-Offs Among Acceptable and Available Methods

The CDFW indicated that output control methods would be difficult to implement in the multi-fleet California halibut fishery due to increased costs and administrative burdens, and stated that managing selectivity was the preferred method of management for this fishery due to the ability to impose consistent management measures across multiple sectors of the fishery. However, they agreed that it would be useful to evaluate output controls within the MSE, even if the application of these methods would be difficult to implement.

Most of the acceptable and available methods had long-term yields above 60% of that possible with perfect management (Figure 10). The *CC4* method, a constant catch MP, was an exception, and had the lowest yield and no marked increase in probability of meeting the management objective. This MP performs markedly worse than the other candidates in both dimensions (i.e., it was dominated by the other methods) and is not considered a suitable method for management compared to the other alternatives. The *HDAAC* method, which is a variant of the *DCAC* method, had the highest probability of biomass being above the management target, and, excluding *CC4*, the lowest expected long-term yield (Figure 10).

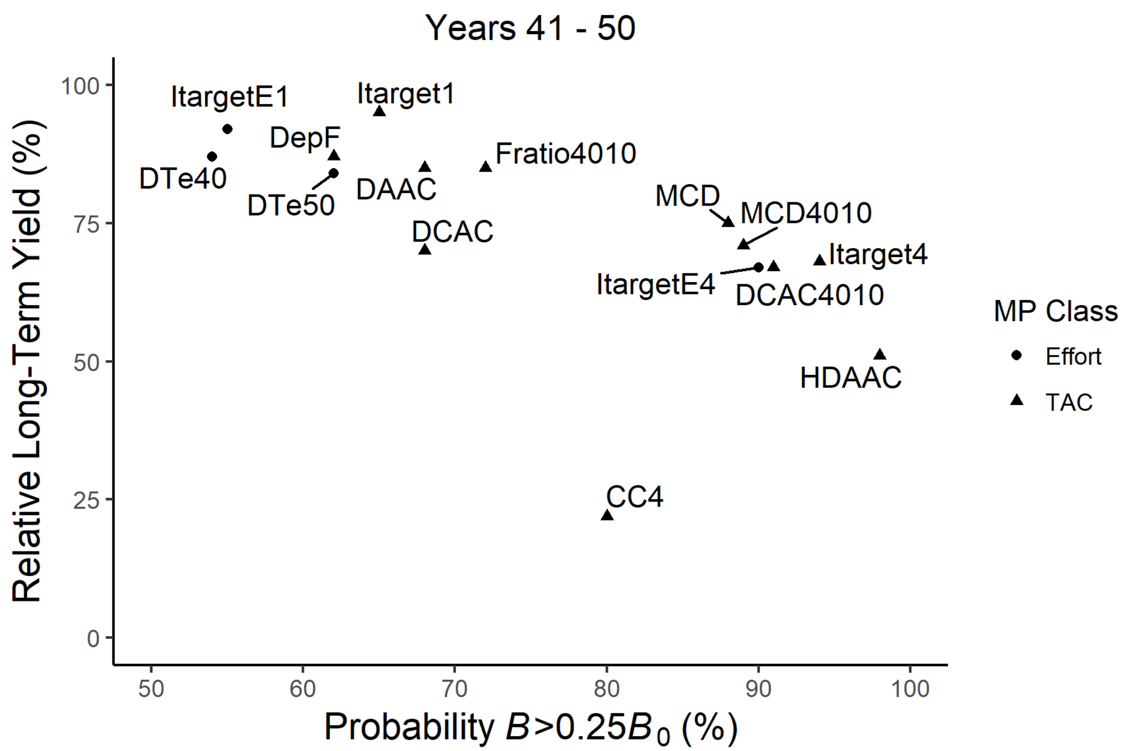

Figure 10: Trade-off between the probability that biomass is above $0.25B_0$ in the last 10 years of the projection and the expected long-term yield for 15 acceptable and available methods in the California halibut MSE. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

There were seven MPs with an average long-term yield greater than 75% of that expected from fishing exactly at F_{MSY}. These included three input control management procedures: *ItargetE1*, *DTe40*, and *DTe50* (circles in top left of Figure 10), and 4 out control methods: *Itarget1*, *DepF*, *DAAC*, and *Fratio4010*. The remaining six methods, which had an expected long-term yield of less than 75%, included *Itarget4* and *ItargetE4* (more precautionary variants of *Itarget1* and *ItargetE1* respectively), *DCAC* and *DCAC4010* (*DCAC* with a 40-10 harvest control rule), and two variants of a method based on estimates of current depletion (*MCD* and *MCD4010*).

The trade-off between both average annual variability in yield and average annual variability in effort and the expected long-term yield revealed that there were seven dominated methods (*CC4*, *DCAC4010*, *DepF*, *Fratio4010*, *HDAAC*, *ItargetE4*, and *MCD4010*), meaning they performed worse than the other candidates in all three dimensions (i.e., lower yield and higher expected variability in both yield and effort). Given the stakeholders desire to maximum yield while minimizing variability in yield and effort, these methods were not selected over the other acceptable and available methods. Figure 11 shows the trade-off between both average annual variability in yield and average annual variability in effort and the expected long-term yield for only the remaining 8 top-performing methods.

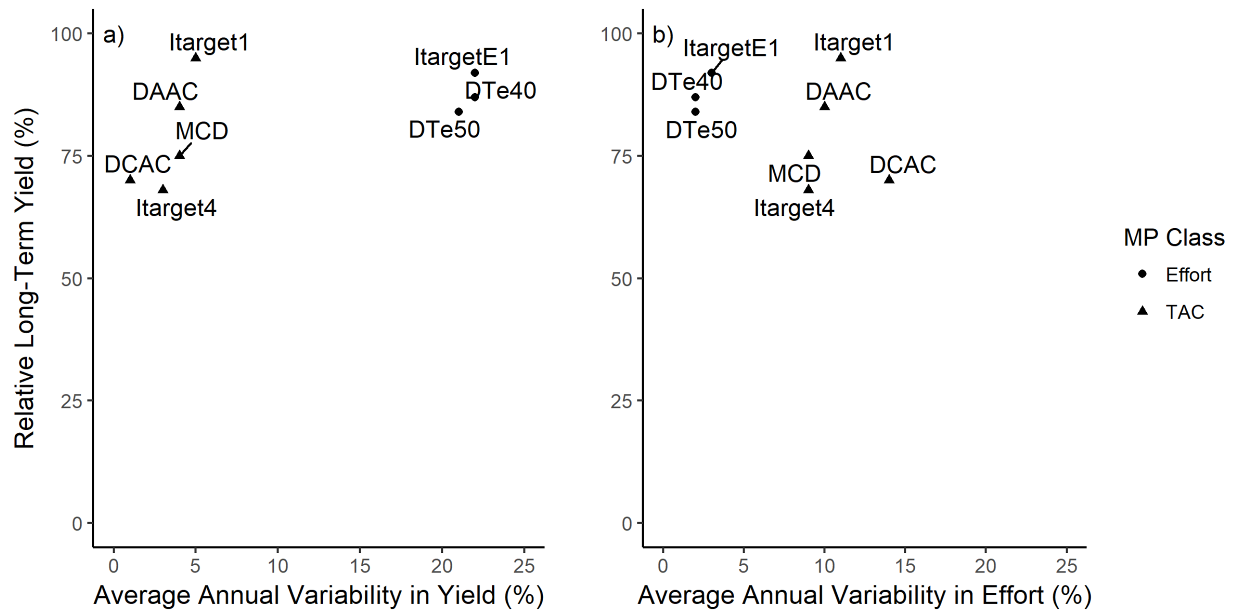

Figure 11: Trade-offs between Average Annual Variability in Yield (AAVY), Average Annual Variability in Effort (AAVE), and Long-Term Yield for 8 acceptable and available methods for the California halibut MSE. Seven acceptable and available methods are dominated (i.e., perform worse in all dimensions) and have not been shown in the plot. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

As expected, the input control methods had higher variability in yield (Figure 11a), but lower variability in effort compared to the output control methods (Figure 11b). The final choice for the most appropriate method would depend on how the stakeholders value this trade-off, together with the practical implications for applying each method. For purposes of this demonstration, the output and input controls with the highest yield and lowest variability, in yield and effort respectively, were selected at the methods to be applied for this fishery. These were *Itarget1* (output control) and *ItargetE1* (input control).

Projection Plots of Selected Methods

Figure 12 shows the projection plots of the *curE* method, which assumes constant fishing effort at the current level, the two acceptable and available output control methods with the highest expected long-term yield (*Itarget1* and *DAAC*) and the input control method with the highest expected long-term yield, (*ItargetE1*). The *Itarget1* and *ItargetE1* methods use information from an index of abundance and provide management recommendations in terms of a catch limit and effort adjustment, respectively. The *DAAC* method uses data on current depletion and the ratio of B_{MSY}/B_0 to provide a catch recommendation.

The output control methods (*Itarget1* and *DAAC*) both reduced the initial median TAC to about 50-60% of the current catch level, and gradually stepped up the catches as the population rebuilt to the target level (Figure 12). This resulted in a general increase in the biomass of the stock, with the median biomass in the final year close to B_{MSY} for both methods.

Yield and fishing mortality were also initially reduced by the *ItargetE1* method, although at a slower rate compared to the output controls. The median biomass in the final year stabilized very close to the management target of $0.25B_0$, but was below B_{MSY} for this method (Figure 12). Also shown for comparison in Figure 12 is the projection of simulations that maintain current fishing effort with other existing management measures (*curE*). These results suggest that continual fishing at the current level of fishing effort is likely to lead to a long-term decline in the abundance of the stock.

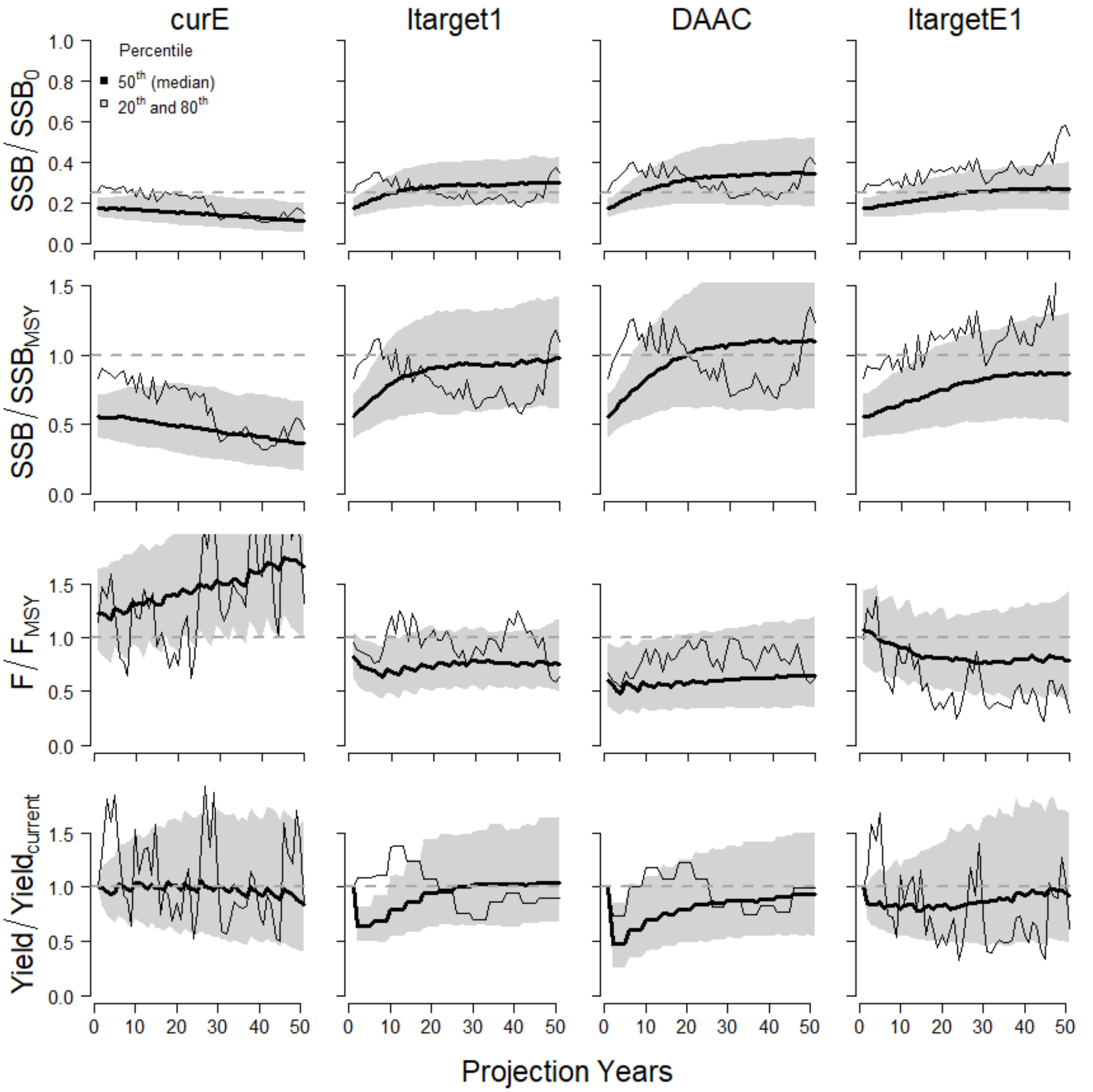

Figure 12: The projection plots (20th, 50th (median), and 80% percentiles) for the biomass relative to unfished conditions (*SSB/SSB₀*), spawning biomass relative to *SSB_MSY*, fishing mortality relative to *F_MSY*, and expected yield relative to yield in current year for four methods in the California halibut MSE. The *curE* method represents management that maintains current effort and the existing minimum legal length and is included as a reference. The *Itarget1* and *DAAC* methods are the two output controls with the highest expected long-term yield. The *ItargetE1* method is a variant of the *Itarget1* method, and provides adjustments to fishing effort based on trends in the index of abundance. The thin black line in each panel shows the trajectory of a single simulation to demonstrate that the median of many simulations is less variable than any single simulation.

Red Sea Urchin MSE Results

Eighty management procedures were included in the MSE for red sea urchin, including eight management procedures developed for this case study. The customized management procedures included a series of alternative minimum size limits and harvest slot limits, as suggested by the CDFW Working Group. Because of the highly selective nature of the dive fishery, we assumed no fishing mortality on sub-legal individuals, so the lack of implementation error in the MSE did not disqualify size-limit methods as was the case for barred sand bass and California halibut.

Although the DLMtool can include spatial restrictions on fishing effort as a future management option, the version used for this analysis did not include the ability to account for historical marine protected areas (MPAs). While it is possible to modify the DLMtool to include information about an existing MPA network, these modifications were beyond the scope of this project. In lieu of directly modelling historical MPAs, the existence of the MPA network in Southern California was considered when specifying the bounds for the current level of depletion for the operating model. The CDFW Working Group believed that, based on the size and habitat of the MPAs, 15-25% of the red sea urchin stock in Southern California is inside the MPA network, so are not accessed by the sea urchin fishing industry. This information, together with the number of years that the MPAs have been in place, and the relatively immobile nature of the species, suggests that a considerable proportion of the red sea urchin biomass is not vulnerable to fishing. Furthermore, the current minimum legal length for sea urchin in Southern California has been above the size of maturity since the late 1980s, which suggests that a proportion of the spawning biomass on the fished grounds is also protected. The information was used to set the bounds for the current level of depletion in the operating model to 0.3 – 0.6, representing a stock that is currently 30% to 60% of the unfished level. The lower bound for this range was based on the assumption that the MPA network and minimum legal length together protect 15 – 25% of the unfished biomass, and the remaining biomass is available to the fishery. If the presence of the MPA network was ignored in the MSE, the lower bound for the level of depletion may be set to a lower value, which would negatively affect the performance of all methods (i.e., higher risk of biomass declining to low levels).

One shortcoming of this approach, however, is that it does not account for the presence of no-take zones in the future projections. To test the impact of the MPA network on method performance, two MSEs were conducted for this stock. In the initial analysis, the MSE was conducted using the default DLMtool model, where the closed area is not included in the future projections for all management procedures. In the second analysis, the DLMtool was modified to include a permanent closed spatial area in addition to the input and output control management procedures in the future projections.

Acceptable Methods - Ignoring Existing MPAs in Future Projections

Using the standard DLMtool model (excluding the existing MPAs in future projections), 30 of the 80 methods included in the red sea urchin MSE met the minimum performance limit of at least 80% probability that the biomass in the last 10 years of the projection period was above $0.25B_0$. Similarly, 35 methods met the requirements for the second performance limits, of at least 80% probability that the biomass was above $0.25B_0$ in the last 40 years of the projection. Five methods (*CC4*, *Islope1*, *Islope4*, *ITe10*, and *ITe5*) met only the requirements for the second performance limit and failed the first performance limit.

Twelve methods met the requirement for the management target for the red sea urchin of at least 50% probability that biomass in the last 10 years was above $0.5B_0$. However, one method (*CC4*) that passed the management target did not meet the requirements for both performance limits. Furthermore, 19 methods that passed both performance limits did not meet the specified management target. These methods included the current fishing effort scenario (*curE*), as well as alternative size and harvest slot limit methods (*MLL3.5*, *MLL3.75*, *MLL3.5_5.5*, *MLL3.375_5.5*). Additionally, two methods that included a closed spatial area in the future projections, *MRreal* (current effort and size limit and MPA) and *MRnoreal* (introduction of MPA with corresponding reduction in effort), did not meet the requirements for the management target (33% and 45%, respectively).

Acceptable Methods - Accounting for Existing MPAs in Future Projections

Including the MPAs in future projections improved the performance of all management procedures with respect to the minimum performance limits, with 35 and 40 methods meeting the requirements for the first and second performance limits, respectively (compared with 30 and 35 methods in the base case MSE). Likewise, 24 methods met the requirements for the management target (compared with 12 methods in the base case MSE). The results from the second MSE run, which included the MPA, were used for the rest of the analysis. Consequently, there were 24 acceptable methods for the red sea urchin fishery. See Appendix P for a complete table of the MSE results for red sea urchin.

Figure 13 compares the performance of the management procedures with respect to the performance limits and management targets for the scenario where the MPA was (y-axis) and was not (x-axis) accounted for in the operating model. These results show that including the MPA in the operating model generally increased the probability of management procedures meeting the performance limits and targets. The effect was particularly noticeable for the two performance limits, where poorly-performing methods did worse (lower probability) when the MPA was not included in the operating model. These results suggest that including the MPA in the operating model improves the performance of poorly-performing management procedures, but had less of an effect for well-performing management procedures where the biomass was maintained at higher levels via harvest control rules. The MPA effect was also

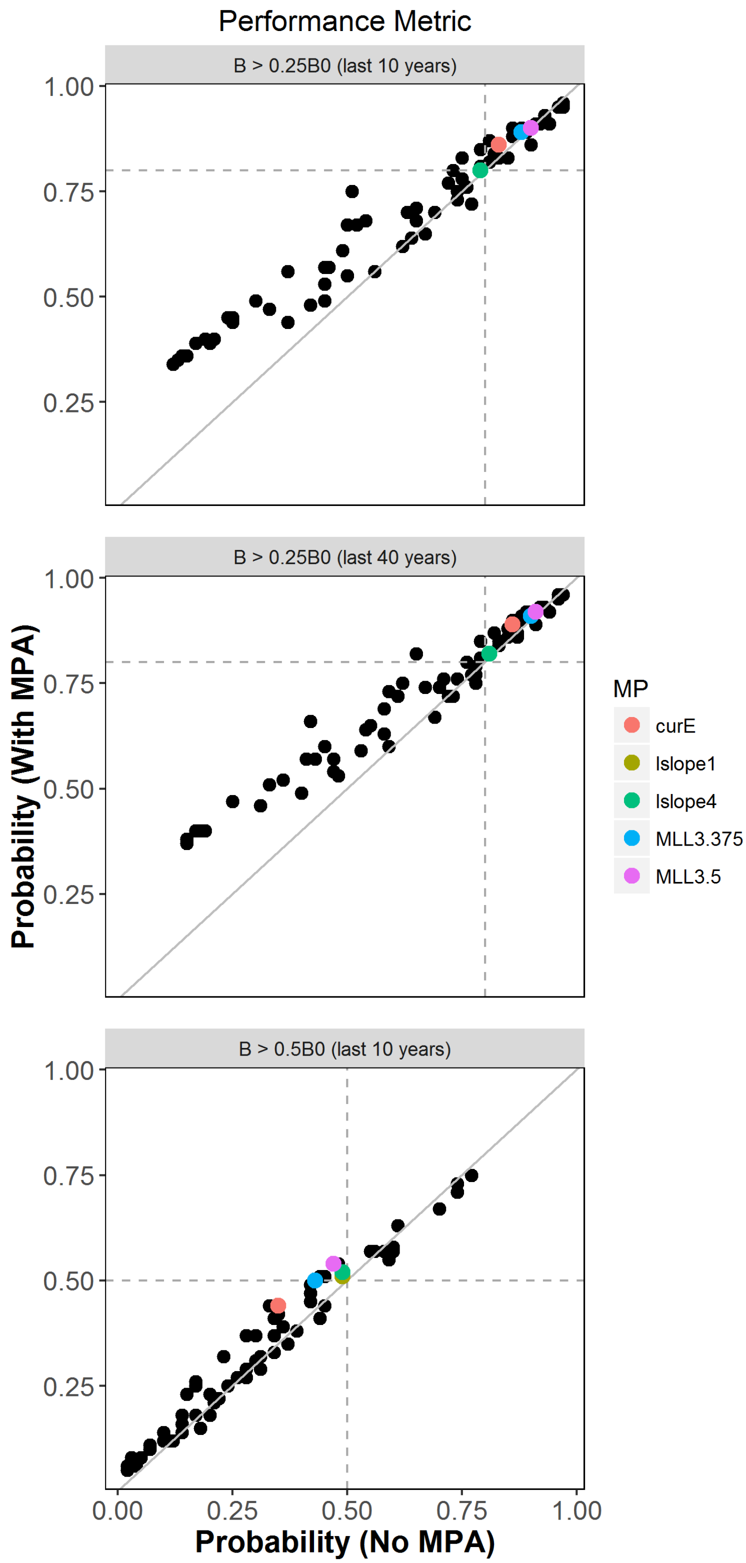

Figure 13: Comparison of biomass-based performance of management procedures for red sea urchin with and without marine protected areas factored in. The top five performing methods, including the current size limit (*curE*) which did not pass the management objective in either scenario, are shown in color.

noticeable for the management objective, where the four well-performing methods identified in the run with the MPA (Islope1, Islope4, MLL3.375, and MLL3.5) all failed to meet the 50% probability threshold when the MPA was not included. Maintaining the current size limit and fishing effort (curE) had greater than 80% probability for both performance limits in both the scenarios (with and without the MPA). However, this method just failed to meet the management objective of at least 50% probability that the biomass was above $0.5B_0$ in both scenarios.

Available Methods

Of the 24 acceptable methods, one method (*HDAAC*) was not available. This method requires an estimate of the current level of depletion, which is not known for the red sea urchin stock in southern California. This resulted in 23 acceptable and available methods, 14 of which were input controls (effort controls and alternative size limits), and nine of which were output controls (Table 6).

Table 6: The numerical results for the performance limits and target, B_{MSY} reference, and average annual variability in yield and effort for the 23 acceptable and available management procedures from the red sea urchin case study. The yield metric represents the average yield for each method in the MSE relative to the yield at F_{MSY}.

Management Procedure	Performance Limits: Prob. $B > 0.25\ B_0$		Performance Target: Prob. $B > 0.5\ B_0$	Reference: Prob. B > B_{MSY}	Long-Term Yield vs F_{MSY} ref (%)	Avg. Annual Var. Yield (%)	Avg. Annual Var. Effort (%)
	Years 41-50	Years 11-50	Years 41-50				
ItargSL1	0.89	0.92	0.51	0.72	74	23	0
ItargSL4	0.89	0.92	0.51	0.72	74	23	0
LtargSL1	0.89	0.91	0.51	0.72	74	23	0
LtargSL4	0.89	0.91	0.51	0.72	74	23	0
MLL3.375	0.89	0.91	0.50	0.72	74	23	0
MLL3.375_5.5	0.89	0.91	0.50	0.72	74	23	0
MLL3.5	0.90	0.92	0.54	0.74	73	23	0
MLL3.5_5.5	0.90	0.92	0.54	0.74	73	23	0
curE75	0.89	0.92	0.51	0.72	71	22	0
Islope1	0.80	0.82	0.51	0.66	58	2	11
Islope4	0.80	0.82	0.52	0.66	58	2	11
LstepCE2	0.90	0.91	0.54	0.74	58	22	2
Itarget1	0.91	0.92	0.58	0.76	56	5	12
Ltarget1	0.83	0.87	0.57	0.71	56	5	15
ItargetE1	0.91	0.93	0.57	0.77	54	22	3
LstepCC1	0.84	0.84	0.57	0.71	49	2	11
LstepCC4	0.84	0.84	0.57	0.71	49	2	11
CC4	0.81	0.86	0.55	0.68	46	5	16
LtargetE1	0.93	0.93	0.63	0.80	46	22	3

Management Procedure	Performance Limits: Prob. $B > 0.25\ B_0$		Performance Target: Prob. $B > 0.5\ B_0$	Reference: Prob. B > B_{MSY}	Long-Term Yield vs F_{MSY} ref (%)	Avg. Annual Var. Yield (%)	Avg. Annual Var. Effort (%)
	Years 41-50	Years 11-50	Years 41-50				
Ltarget4	0.91	0.93	0.67	0.81	43	4	12
Itarget4	0.95	0.96	0.71	0.86	36	3	10
ItargetE4	0.95	0.95	0.73	0.87	25	23	5
LtargetE4	0.96	0.96	0.75	0.88	19	23	5

Trade-Offs Among Acceptable and Available Methods

Figure 14 shows the trade-off between expected long-term yield and the probability of meeting the management objective for the 23 acceptable and available methods, separated for display purposes by management type. The *curE75* method (fixed effort at 75% of the current level) had the highest long-term yield of the effort-based methods (Figure 14, left). The *LstepCE2* (iterative effort control that responds to trends in mean length) had similar performance with respect to the probability of meeting the management objective, but a lower expected long-term yield. The remaining four effort-based methods were increasingly more precautionary, with higher probability of meeting the management objective, and lower expected long-term yields (Figure 14, left). As the *LtargetE1* and *LtargetE4* method had the lowest expected long-term yield, and had very precautionary behaviour compared to the other acceptable methods, they were not included in the further analysis.

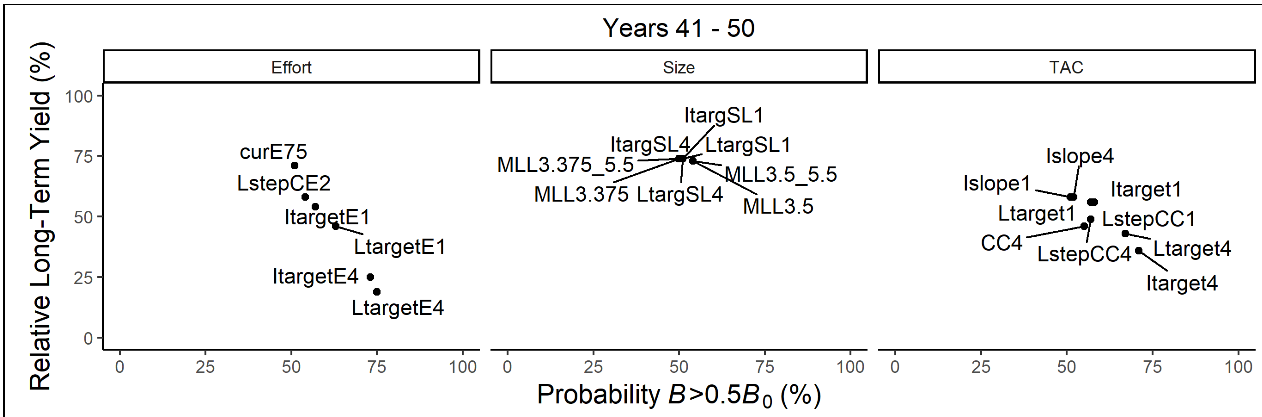

Figure 14: Trade-offs between the probability that biomass is above $0.5B_0$ in the last 10 years of the projection and the expected long-term yield for the 6 effort-based (left), 8 size-based (center), and 9 output control (right) acceptable and available methods in the red sea urchin halibut MSE. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

The size-based methods (minimum legal lengths and harvest slot limits) had the highest long-term yield, and essentially identical performance across the 8 size-based management procedures (Figure 14, center). Because the performance of these methods was so similar, the *MLL3.375* method was selected to represent these methods in further analysis.

The *Islope1* and *Islope4* methods had essentially identical performance and the highest long-term yield of the nine output control management procedures (Figure 14, right). The remaining seven methods showed a trade-off between the expected long-term yield and the probability of meeting the management objective, with the highest probability and lowest expected long-term yield from the *Ltarget4* and *Itarget4* methods. These methods were the more precautionary version of other acceptable methods (*Ltarget1* and *Itarget1*), so they were not included in the further analysis.

Figure 15 shows the trade-off between the average annual variability in yield and effort and the expected long-term yield for the well-performing acceptable and available methods. This result shows the same pattern seen in the other case studies, where effort-based controls have higher variability in yield but very low inter-annual variability in effort. Conversely, the output controls all have low inter-annual variability in yield, but show increased variability in effort compared to the effort controls (Figure 15).

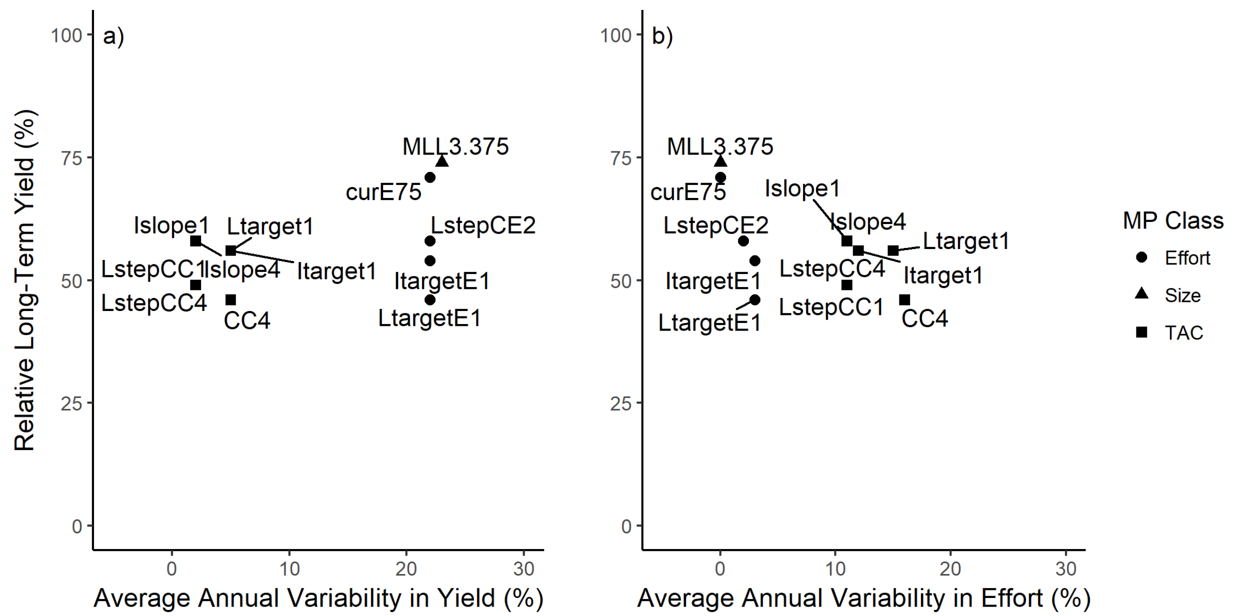

Figure 15: Trade-offs between Average Annual Variability in Yield (AAVY), Average Annual Variability in Effort (AAVE), and Long-Term Yield for 12 acceptable and available methods for the red sea urchin MSE. Seven acceptable and available size-based methods have essentially identical performance to the *MLL3.375* method and have not been shown in the plot. The *Itarget4*, *Ltarget4*, *ItargetE4*, and *LtargetE4* methods are also not shown, as they have the lowest expected long-term yield compared to other methods using the same class of management. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

Projection Plots of Selected Methods

Figure 16 shows the projection plots of the *curE* method, which assumes constant fishing effort at the current level, the two acceptable and available output control methods with the highest expected long-term yield (*Islope1* and *Islope4*), an effort-based method with high expected long-term yield (*LstepCE2*), and a static size limit with effort held at the current level (*MLL3.375*). The performance of the *Islope1* and *Islope4* methods was very similar, with the median biomass rebuilding above $0.5B_0$, and a gradual decline in yield over the 50-year projection period. The effort-based input controls had similar performance to the two output control methods, with median biomass increasing to $0.5B_0$, approximately $1.3B_{MSY}$ (Figure 16). Median fishing mortality was below $0.5F_{MSY}$ for the entire projection, and the median biomass above B_{MSY}, for these three methods, and both median yield and fishing mortality continued to gradually decline throughout the projection period.

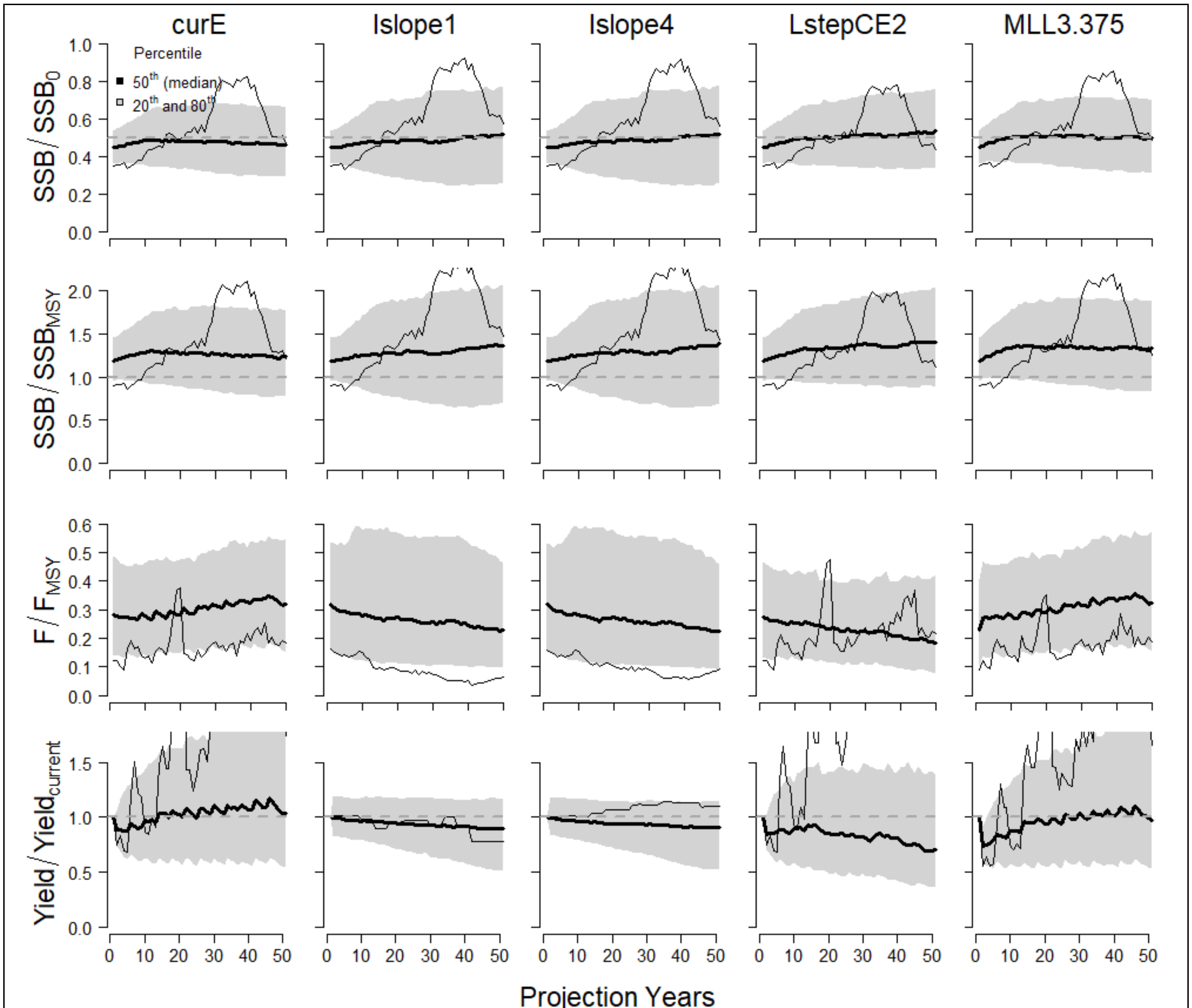

Figure 16: The projection plots (20th, 50th (median), and 80% percentiles) for the biomass relative to unfished conditions (*SSB/SSB_0*), spawning biomass relative to *SSB_{MSY}*, fishing mortality relative to *F_{MSY}*, and expected yield relative to yield in current year for four methods in the red sea urchin MSE. The *curE* method represents management that maintains current effort and the existing minimum legal length and is included as a reference. The *Islope1* and *Islope4* methods are the two output controls with the highest expected long-term yield and have almost identical performance. The *LstepCE2* method is an input control method that adjusts fishing effort in response to trends in mean length. The *MLL3.375* method represents a static size limit and fishing effort held constant at the current level. The thin black line in each panel shows the trajectory of a single simulation to demonstrate that the median of many simulations is less variable than any single simulation.

The minimum legal length method (*MLL3.375*), which assumed fishing effort stayed constant at the current level and a 3.375 inch size limit, resulted in an initial decrease in yield as the smaller sized individuals were no longer available to be caught (Figure 16). However, unlike the output control methods, yield continued to increase throughout the 50-year projection period. The *curE* method had similar performance to the increased size limit method, but failed to meet the requirements of the management objective, as the median biomass in the last 10 years of the projection period was below $0.5B_0$.

Evaluating the Impacts of Increased Fishing Effort

There are currently 300 licenses in the red sea urchin fishery, but only about 150 of the permit holders are currently active. The Working Group was interested in examining the effects of the latent effort becoming active in the fishery in the future. To do so, we compared a scenario where effort is maintained at a stable level over time (*curE* method) with a scenario where fishing effort in the future increases by a biased random walk to a maximum of twice the current level (all 300 fishers become active).

The median biomass in the current effort scenario (*curE*) initially increased to $0.5B_0$ until about 10 years into the projection, where it gradually began to decline to $0.46B_0$ in the final year (Figure 17). The median biomass in the increasing effort scenario (*incE*) initially followed a similar trajectory, but the decline in biomass was markedly steeper, with depletion level of $0.36B_0$ in the final year (Figure 17). While the scenario that maintains current fishing effort (*curE*) passed the requirements for both the performance limits, the median biomass in the last 10 years was below $0.50B_0$ and therefore the method did not meet the requirements for the management target, although by a very slim margin. In contrast, the increasing effort scenario had a much higher probability of dropping significantly below the management objective, with a greater than 20% chance that the biomass in the last 10 years was below $0.25B_0$ (Figure 17).

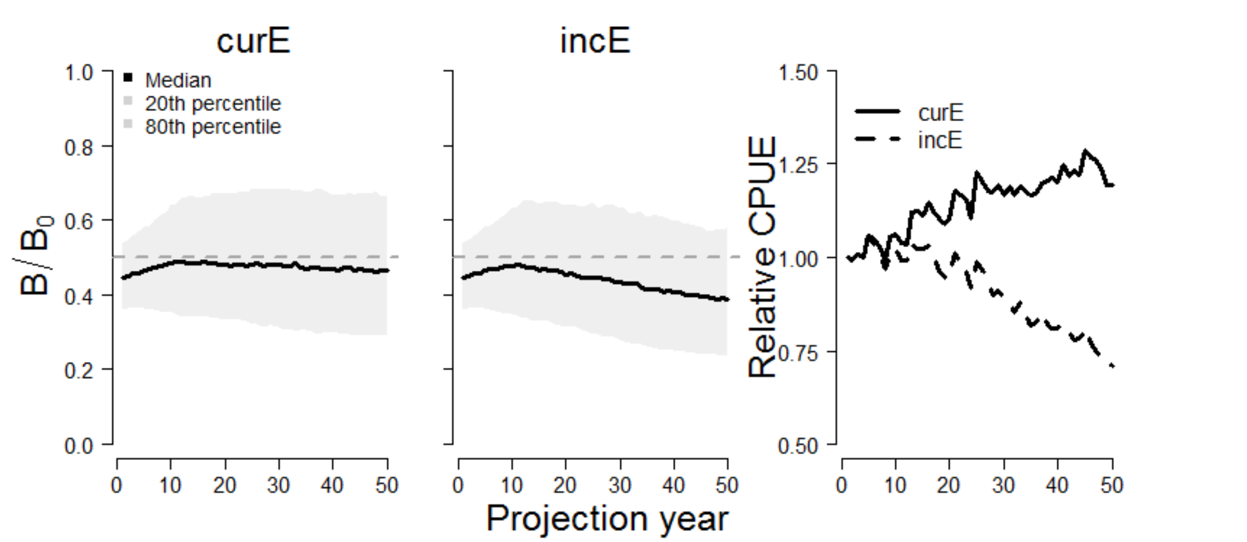

Figure 17: The projection plots (20th, 50th (median), and 80% percentiles) for the biomass relative to unfished conditions (B/B_0) for the current effort and size limit scenario (*curE*), and a scenario where fishing effort increases in the future (*incE*; current size limit and effort increases up to twice the current level). The dashed gray line indicates $0.5B_0$. Also shown are the relative average catch rates (CPUE) for the two scenarios over the 50-year projection period.

The yield was higher in the scenario with increasing effort compared to when fishing effort was stable at the current level (results not shown). However, there was a marked difference in the catch rates between the two scenarios, with catch rates continuing to increase in the *curE* scenario to about 1.25 the current level, but declining to less than 75% of the current catch rates in the scenario with increasing effort (Figure 17).

Warty Sea Cucumber MSE Results

Acceptable Methods

A total of 76 management procedures were tested (73 DLMtool methods and three custom methods) for the warty sea cucumber. Of these, only three methods passed the first performance limit of at least 80% probability that biomass in the last 10 years was greater than 0.25 of the unfished level (B_0). These included two output control methods (*HDAAC* and *Itarget4*) and one input control method (*LtargetE4*) (see Appendix E for a description of the different management procedures). Two methods (*HDAAC* and *Itarget4*) also met the second requirement of at least an 80% probability of biomass above $0.25B_0$ in years 11 to 50 of the projection period.

Three methods met the management target of at least 50% probability that the biomass in the last 10 years of the projection period is above $0.5B_0$ (*HDAAC*, *Itarget4*, and *LtargetE4*). However, the *LtargetE4* method did not pass one of the performance limits. The two remaining methods (*HDAAC* and *Itarget4*) met both the performance limits and the management targets, and were therefore considered acceptable. See Appendix Q for a complete table of the MSE results for warty sea cucumber.

Available Methods

The *HDAAC* method requires an estimate of natural mortality (*M*) and current depletion, estimates of which are not currently available for the warty sea cucumber in southern California. This resulted in a single acceptable and available method for this stock, *Itarget4*, which uses a relative index of abundance to iteratively adjust the recommended catch limit to achieve a target catch rate (Table 7).

Table 7: The numerical results for the performance limits and target, B_{MSY} reference, and average annual variability in yield and effort for the two acceptable management procedures from the warty sea cucumber case study. Note that the *HDAAC* method (italics) is not available due to insufficient data. The yield metric represents the average yield for each method in the MSE relative to the yield at F_{MSY}.

Management Procedure	Performance Limits: Prob. B > 0.25 B_0		Performance Target: Prob. B > 0.5 B_0	Reference: Prob. B > B_{MSY}	Long-Term Yield vs F_{MSY} ref (%)	Avg. Annual Var. Yield (%)	Avg. Annual Var. Effort (%)
	Years 41-50	Years 11-50	Years 41-50				
Itarget4	0.83	0.83	0.53	0.67	70	5	12
HDAAC	*0.85*	*0.85*	*0.53*	*0.67*	*61*	*6*	*11*

Trade-Offs Among Acceptable Methods

Although only a single method (*Itarget4*) was both acceptable and available for warty sea cucumber, the trade-offs among the two acceptable methods can be examined to determine if the unavailable method (*HDAAC*) may provide preferable performance, and thus warrant the collection of the data necessary for its use (an estimate of depletion and natural mortality rate). The results suggest that the two acceptable methods have similar performance with respect to the average annual variability in yield and effort, with approximately 5% inter-annual variability in yield (Figure 18a), and approximately 10% average inter-annual variability in effort (Figure 18b). In this case, neither of the methods outperforms the other with respect to these metrics, so this information may not useful to decide between the two.

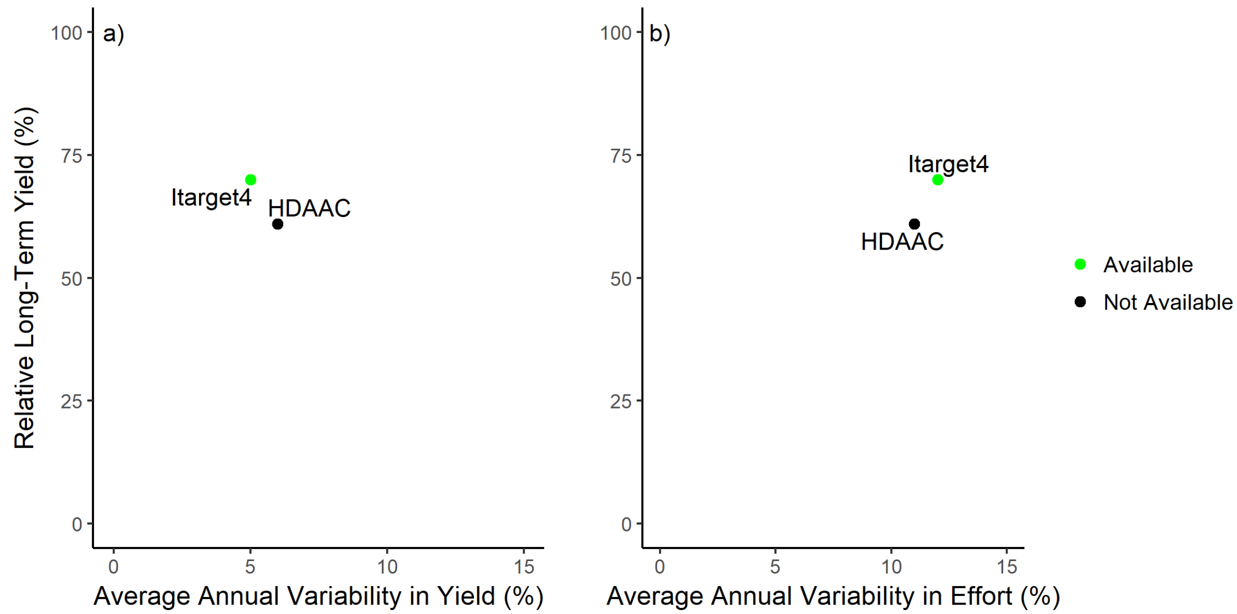

Figure 18: Trade-offs between a) Average Annual Variability in Yield (AAVY) and b) Average Annual Variability in Effort (AAVE) and Long-Term Yield for the two acceptable methods from the warty sea cucumber MSE: *Itarget4* (green; available) and HDAAC (black; not available). The center of the text labels indicates the point on the x-axis that corresponds to the performance of each method. Long-term yield on the y-axis is relative to the yield obtained with a constant fishing mortality rate of F_{MSY} (i.e., perfect management).

Projection Plots of Selected Methods

Figure 19 shows the projections from the MSE model of the biomass, fishing mortality, and yield over the 50-year projection period for scenario that maintains current fishing effort (*curE*), and the two acceptable methods. The two acceptable output control methods have similar performance, where yield is reduced initially to about half of the current levels, with a corresponding decrease in fishing mortality, and the stock biomass rebuilds with a median biomass in the final years of the projection period just above $0.5B_0$ and above B_{MSY} (Figure 19). For both methods, projected yield is initially reduced from current levels, which enables the population to rebuild, although for most simulations, not all the way back to current levels, which are simulated between a wide range of 0.05 and $0.4B_0$ (below the management target of $0.5B_0$). The initial reduction in catch is likely the result of three factors: a) the initial biomass is simulated below the management target, b) the biology of the warty sea cucumber is assumed to be unproductive (with wide bounds of uncertainty), and c) the choice of the performance limits and management targets, which require an 80% probability that the stock biomass is above $0.25B_0$ and a 50% probability that biomass is above $0.5B_0$. In contrast to the two acceptable methods, the MSE results indicate that maintaining current fishing effort over time (*curE*) results in a continued decline in the biomass, a gradual decrease in yield, and an increasing trend in fishing mortality.

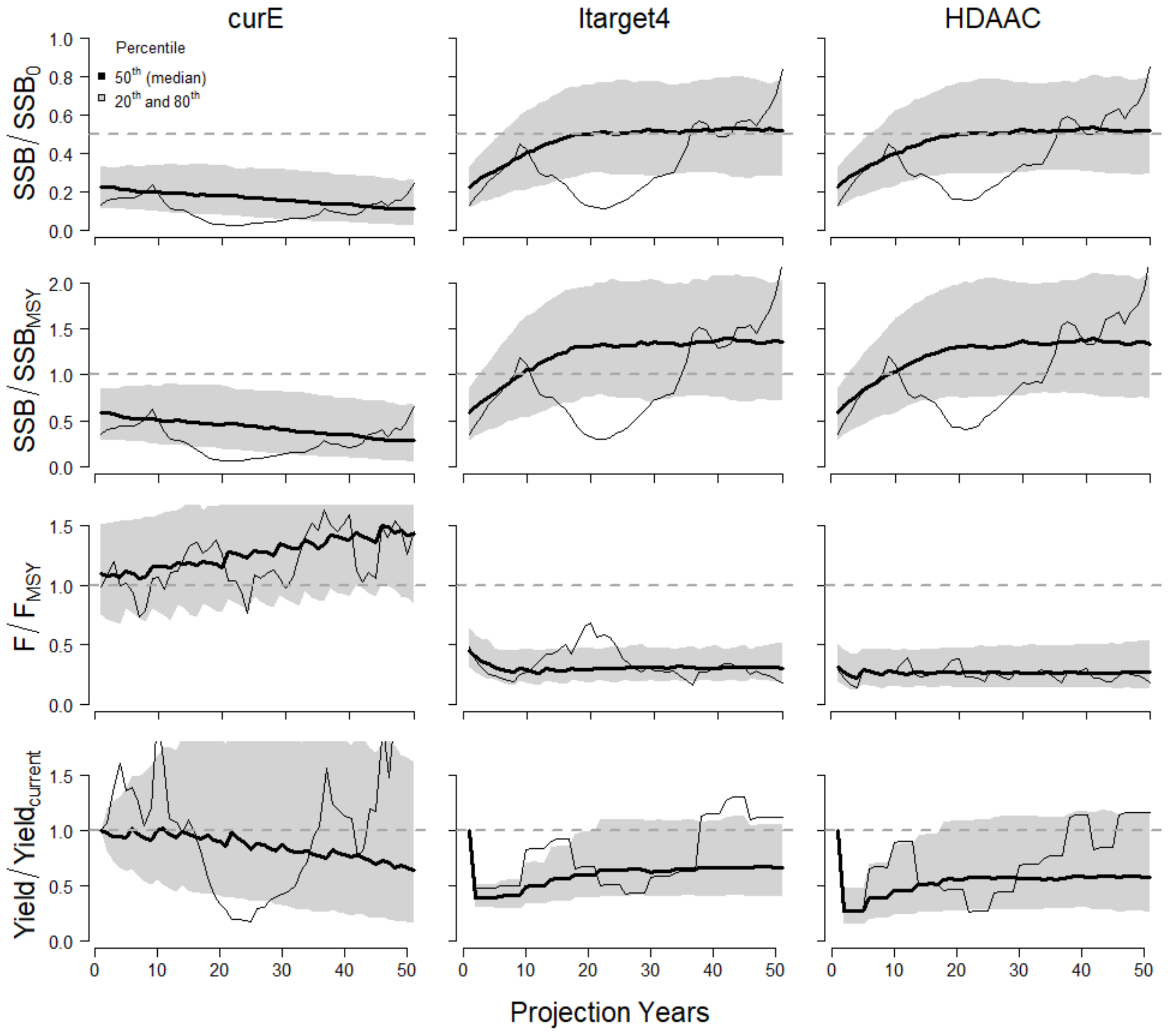

Figure 19: The MSE projection plots (20th, 50th (median), and 80% percentiles) for the biomass relative to unfished conditions (B/B_0; top left), biomass relative to B_{MSY} (B/B_{MSY}; top right), fishing mortality relative to F_{MSY} (F/B_{MSY}; bottom left), and expected yield relative to yield in current year (bottom right) for the current effort scenario (*curE*) and the two acceptable output controls. Note that the *HDAAC* method is not available due to insufficient data. The thin black line shows the trajectory of a single simulation.

Testing an Alternative Scenario for Warty Sea Cucumber – Managing Selectivity

Although the minimum legal length methods did not meet the minimum performance limits and management targets, the performance of these methods, particularly *MLL120* and *MLL100* suggests that increasing the size of first capture for warty sea cucumber would increase the probability of the stock meeting the performance objectives. Although both the size-at-maturity and the selectivity pattern for warty sea cucumber are uncertain, it is clear that current fishing practices include the capture of immature individuals. This information was simulated by setting the operating model parameters to include a selectivity-at-length curve that overlaps with the maturity-at-length curve (Figure 20).

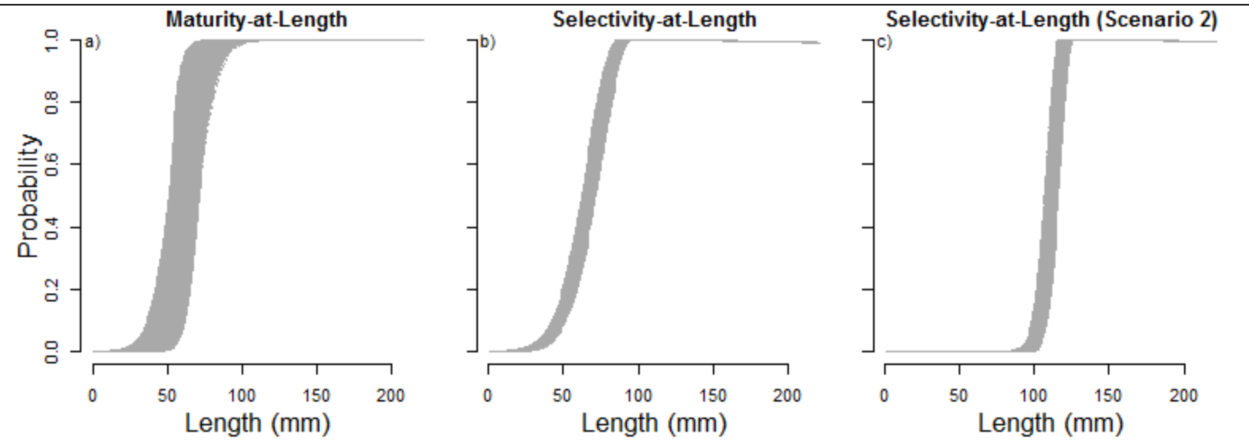

Figure 20: The a) range of maturity-at-length curves defined in the operating model of the MSE run for warty sea cucumber, b) the range of selectivity-at-length curves used in the base run of the MSE, and c) the range of selectivity-at-length curves used in the alternative scenario where the selectivity curve has been shifted to the right to avoid the capture of immature individuals.

The CDFW Working Group noted that implementing a minimum legal length (MLL) for the sea cucumber fishery may be challenging, because it is difficult and time-consuming to measure sea cucumbers, which significantly change shape, length, and weight when brought to the surface. However, there may be alternative methods that can be used to regulate or provide incentives to minimize the fishing mortality on small sized individuals. While the potential mechanisms to modify the selectivity curve for this fishery are still being explored, we decided to run the MSE under alternative conditions to study the possible impact of implementing a size limit. Note, however, that this analysis assumed that there was no fishing mortality on individuals below the minimum legal length, which is unlikely to be true in the fishery. Therefore, the results of this analysis are for explanatory purposes only. Information on the selectivity of the fishery and the fishing mortality of released sea cucumber would have to be known before the risks of this approach can be quantified using MSE.

Alternative Selectivity Scenario – Acceptable Methods

A second MSE was run for warty sea cucumber to test the effects of implementing a size-based regulation where the size at first capture was shifted above the size of maturity (Figure 20c). For the alternative selectivity scenario MSE, seven methods met the management target of a 50% probability that biomass being above $0.5B_0$ in the last 10 years of the projection period. Two of the seven methods did not meet the requirements of the performance limits (*LstepCC1* & *LstepCC4*). Thus, there were a total of five acceptable methods in this alternative selectivity scenario (compared with two in the original MSE). However, three of the five acceptable methods were not available due to insufficient data. Therefore, the alternative selectivity scenario resulted in two acceptable and available management procedures: the output control method that was acceptable and available in the initial analysis (*Itarget4*) and the effort-based version of this method (*ItargetE4*) (Table 8). As there are only a small number of acceptable methods, the trade-offs between variability in yield and effort, and expected long-term yield are not plotted but can be examined in Table 8. See Appendix R for a complete table of the MSE results for alternative scenario of the warty sea cucumber.

Table 8: The numerical results for the performance limits and target, B_{MSY} reference, and average annual variability in yield and effort for the 5 acceptable management procedures from the alternative scenario with increased selectivity for warty sea cucumber case study. Note that the *HDAAC*, *Ltarget4*, and *LtargetE4* methods are not available due to insufficient data. The yield metric represents the average yield for each method in the MSE relative to the yield at F_{MSY}.

Management Procedure	Performance Limits: Prob. ***B*** > 0.25 B_0		Performance Target: Prob. ***B*** > 0.5 B_0	Reference: Prob. B > B_{MSY}	Long-Term Yield vs F_{MSY} ref (%)	Avg. Annual Var. Yield (%)	Avg. Annual Var. Effort (%)
	Years 41-50	Years 11-50	Years 41-50				
ItargetE4	0.82	0.80	0.51	0.65	63	23	4
Itarget4	0.89	0.86	0.59	0.73	61	5	14
HDAAC	*0.89*	*0.87*	*0.57*	*0.72*	*57*	*6*	*14*
Ltarget4	*0.84*	*0.80*	*0.59*	*0.70*	*46*	*6*	*19*
LtargetE4	*0.90*	*0.83*	*0.61*	*0.75*	*43*	*23*	*4*

Alternative Selectivity Scenario – Comparison with Base Case

The result of this alternative selectivity scenario, where length at first capture was assumed to be higher, suggests that the output control method *Itarget4* and the effort-based modification of this method, *ItargetE4*, are the only two methods that are acceptable and available. However, although they are currently unavailable due to insufficient data, several more methods passed the requirements for performance limits and management targets in the alternative scenario with increased size at capture. The probabilities of meeting the performance metrics were increased for all the remaining methods, indicating that managing selectivity is important to reduce risk to the stock. Finally, this alternative scenario examined a somewhat arbitrary size-selection curve, assuming that size of first capture was increased to around 100 mm. Information on the practical implications of regulating and enforcing a size limit, or incentivizing the shift in selectivity in other ways, could be used to determine alternative size selection curves.

Management Procedure Application to Case Study Stocks

Once the acceptable and available management procedures have been identified through the MSE, the next step is to apply one or more of these methods using current fishery data to provide specific management recommendations for each stock. It is important to note that this step is distinct from the MSE, which is to evaluate the performance of a suite of alternative management methods and to identify the methods that are most likely to meet the long-term management objectives for the stock. Because the data in an MSE framework are simulated, all the candidate methods can be tested, regardless of the actual data available for the stock. Once a candidate method has been selected for use in the fishery, then actual fishery data are used to compute a specific management action, like a catch limit or effort control.

The Fishery Information Data Table contains the actual fishery data (e.g., catch, index of abundance, trends in recruitment, etc.) for a specific fishery. Unlike the simulated data used in the MSE, the Fishery Information Data Table may not be complete, and in some cases, only a subset of the acceptable methods identified in the MSE can be applied to the data.

Populating the Fishery Information Data Table

For this demonstration project, the process of populating the Fishery Information Data Table began after the operating model parameters had been completed. An in-person meeting was held with each CDFW species expert in February of 2016 to begin collating and analyzing the fishery data that had previously been identified in the fishery questionnaire, but not yet analyzed or processed. In many cases, the careful analysis of these data provided more information than initially anticipated, which was useful in revising the operating model parameters for the MSE.

Efforts were made to aggregate all the data sources identified in the original meta-data. Each data source was examined in detail and a determination was made whether these data could be used in the Fishery Information Data Tables. In some cases, data did exist, but could not be used, either because we were unable to access the data sets for this project or because time constraints meant it was not possible to conduct an extensive analysis and processing of the data. The objective of this study was to *demonstrate* the MSE approach and the selection and application of a management procedure. However, before the MSE approach is considered for use in management, we strongly recommend a comprehensive data review, including the processing and analysis of all available and relevant data by analysts who are familiar with data collection processes for the fishery. The data sources for each case study, how they were processed, and the reasons why they were included or excluded from the Data Table are discussed in detail in the Fishery Information Summaries contained in Appendices I through L.

Barred Sand Bass Management Procedure Application

Four input control methods were identified as those most likely to meet the long-term management objectives for the barred sand bass fishery. Only input control methods were available, predominantly due to the absence of reliable total catch information for this species. The MSE results indicate that the *ITe5* method had the highest expected long-term yield of the acceptable and available methods. This method uses the ratio of the current index of abundance (averaged over last 5 years) to a target reference level to provide a recommended adjustment for fishing effort (up to a maximum of 5% change per year). A reference target of 1 was assumed, corresponding to the catch-per-unit-effort in the late 1980s through to the mid-1990s (dashed black line in Figure 21). The current relative abundance (averaged over last five years) was 0.59 (blue line in Figure 21). Applying the *ITe5* method to the Data Table for the barred sand bass resulted in a recommendation of a 5% reduction in fishing effort from current levels. This analysis assumed that the current minimum legal length of 355 mm remained unchanged in the future.

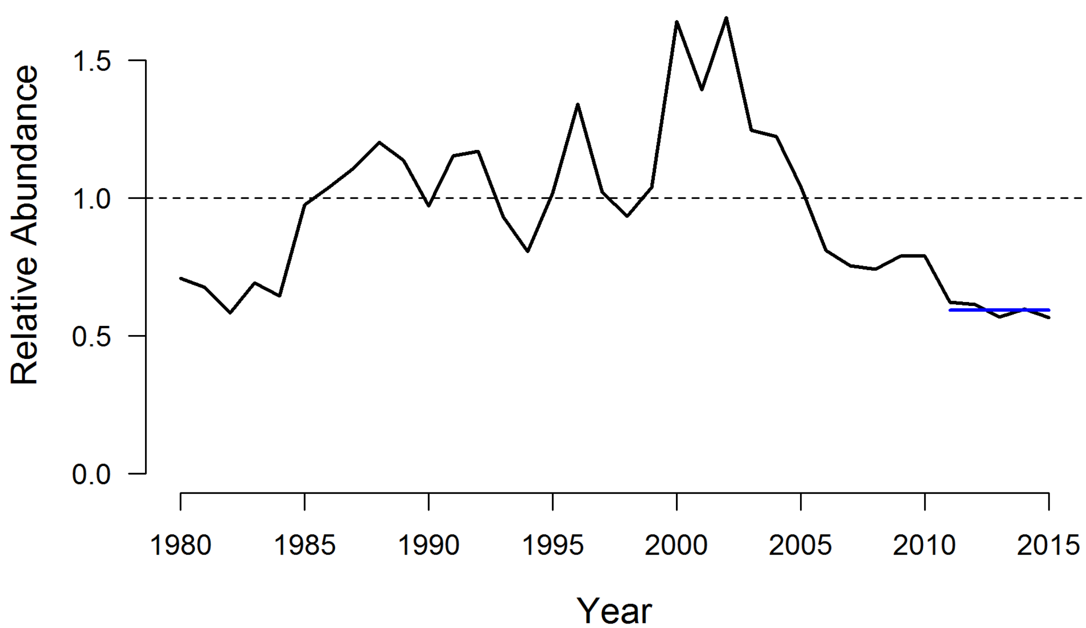

Figure 21: Index of abundance (CPUE) for the barred sand bass that was used with the *ITe5* method for a management recommendation. A reference target level of 1 was assumed (dashed black line). The average CPUE over the last 5 years is shown as a blue line. The *ITe5* method recommends up to a 5% change in fishing effort based on the distance between the average recent CPUE (blue line) and the target (dashed black line).

It is important to reiterate here that this analysis did not include implementation error, and the MSE model assumed that effort regulations, with up to a 5% change in fishing effort, were able to be implemented perfectly in the fishery. The ability of a management agency to have such fine-scale control over fishing effort must be considered before a method such as this is accepted for management. Future developments of the DLMtool will include an implementation error model.

The recommendation from the *ITe5* method is sensitive to the reference target level and the index of abundance in recent years. Therefore, the choice of the method used to standardize the catch-per-unit-effort data may influence the resulting management recommendation. Furthermore, the choice of the target reference level was selected for demonstration purposes, and an appropriate target level of catch-per-unit-effort should be chosen by managers and stakeholders of the fishery. However, the *ITe5* method in this case recommended the maximum reduction in fishing effort (5%), and this is unlikely to be reduced if the current catch-per-unit-effort is well below the target level.

California Halibut Management Procedure Application

The *Itarget1* method was the acceptable and available output control method that projected the highest long-term yield for California halibut. This method relies on two main sources of information: the CPUE index and the landings data, together with the assumed error for these data sources. The recommended TAC from this method is sensitive to the method that is used to standardize the CPUE index. The *Itarget1* method requires data on the relative index of abundance (CPUE) for at least the 10 of the most recent years, and estimates of total catch from the last five years.

Figure 22 shows the total catch for the California halibut from 2004 to 2015, the relative index of abundance (CPUE) calculated from the Commercial Passenger Fishing Vessels (CPFV) fleet, and the distribution of total allowable catch levels from the *Itarget1* method. Catches have been declining, while the CPUE has been relatively stable over the last 12 years, with the average CPUE over the last 10 years (dashed blue line) essentially identical to the average CPUE over the last five years (solid blue line; Figure 22). The recommended TAC from the *Itarget1* method ranged from 59 to 103 tons, with a median value of 79 tons.

The acceptable and available input control method *ItargetE1* is similar to the *Itarget1* method, but returns a management recommendation in terms of a change in fishing effort instead of a TAC. Applying the *ItargetE1* method to the California halibut data resulted in a recommendation to reduce fishing effort by 15% from the current level.

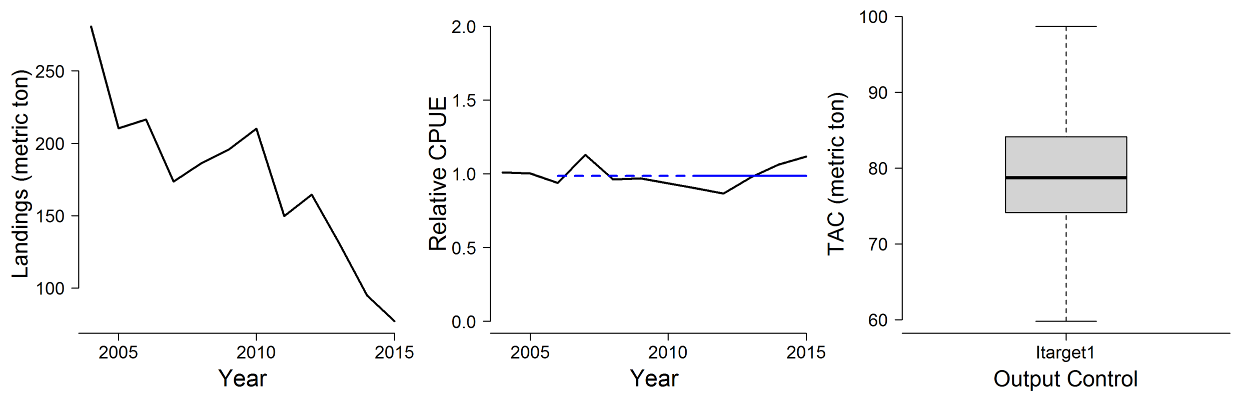

Figure 22: The total landings of California halibut from Southern California (2004 – 2015), the index of relative abundance, and a boxplot showing the distribution of TAC recommendations from the *Itarget1* method (median 79 tons). The dashed blue line shows the average CPUE over the last 10 years, and solid blue line the average CPUE over the last 5 years.

The Working Group noted that the CPFV data may not be suitable for generating an index of relative abundance, due to the likely presence of hyper-stability in a charter-fishing fleet. However, there was insufficient catch and effort data from sectors of the fishery to construct alternative indices of abundance, a finding that was also reported in the recent stock assessment for this stock (Maunder et al., 2011). Therefore, additional work should focus on developing a representative index of abundance if these methods are to be used in the management of this fishery.

Red Sea Urchin Management Procedure Application

The MSE results for red sea urchin revealed that the two acceptable output control methods with the highest long-term yield were *Islope1* and *Islope4*. The projection and trade-off plots showed that the performance of these two methods was similar, with the *Islope1* method having a marginally higher long-term yield. These methods use the slope of the relative abundance (CPUE) over the last five years to provide a total allowable catch level that is set in relation to the average catch over the five most recent years. The two methods differ in the responsiveness of the catch level to the slope in CPUE, with the *Islope1* method allowing larger adjustments from one management cycle to the next.

The index of relative abundance for the red sea urchin in Southern California was estimated for the years where effort data were available (1998 to 2013; Figure 23). The index of abundance was relatively flat in recent years, with a slightly positive slope over the last five years (blue line Figure 23). Total landings in the last year of the CPUE index (2013) was 8.76 million pounds (Figure 23). When applied to this data set, both the *Islope1* and *Islope4* methods returned a similar recommendation, a median TAC of 8.81 and 8.78 million pounds respectively (Figure 23).

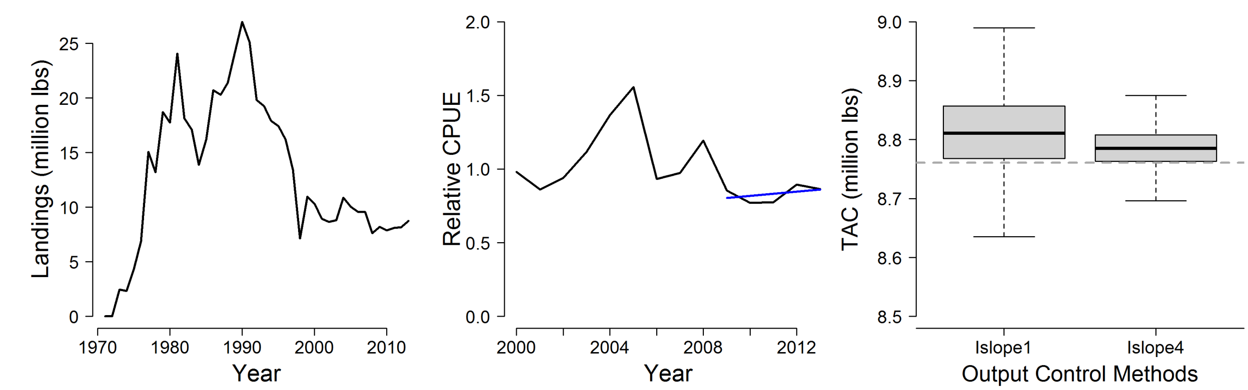

Figure 23: The reported landings of red sea urchin from Southern California (1970 – 2013), the index of relative abundance (1998 – 2013; blue line showing the slope over last 5 years), and the distribution of recommended TAC from the *Islope1* and *Islope4* methods (dashed gray line shows the 2013 landings).

The recommended TAC from the *Islope1* and *Islope4* methods are dependent on the landings data included in the Data Table, particularly for the previous 5 years. The DLMtool assumes that the most recent CPUE data corresponds to the most recent landings data. Because effort data were not available for the last two years, the CPUE index only went to 2013, and therefore the average landings were only used up to 2013. Total landings from 2014 and 2015 were slightly lower than that from 2013, so if these data were included the calculation of average catch over the last five years may be slightly lower.

The two output control methods are also sensitive to the CPUE index that is included in the Data Table and therefore on the method used to standardize and construct this index. The CPUE index is relatively flat over the last five years, so the *Islope1* and *Islope4* methods recommended a catch limit that is slightly (~0.5%) larger than recent catches. Updating the CPUE index to include the most recent years of data (2014 and 2015, and perhaps 2016) may result in an increased slope in the CPUE index (either increasing or decreasing). Furthermore, alternative methods of standardizing the CPUE index may also result in a different trend in relative abundance in recent years, and thus impact the TAC recommendations from these methods.

The two best performing input control methods for the red sea urchin were the *MLL3.375* and *MLL3.5*, representing minimal legal lengths of 3.375 and 3.5 inches, respectively. The current size limit for the red sea urchin in Southern California is 3.25 inches. The implementation of these methods is relatively straightforward and does not require or depend on any information in the Data Table. However, like the other species examined in this study, the MSE model assumed that there was no fishing mortality on sub-legal individuals. This assumption was considered valid for red sea urchin given the highly selective nature of the dive fishery.

Warty Sea Cucumber Management Procedure Application

The MSE results found that the *Itarget4* method was the only acceptable and available management procedure for the warty sea cucumber fishery in Southern California. This method requires data on the relative index of abundance (CPUE) for at least the 10 most recent years and estimates of total catch in the five most recent years. The method works by calculating the ratio of the average CPUE in the last five years to the average CPUE in last 10 years, and recommends a new total allowable catch level as an adjustment to the average catch over the last five years.

Catches for the warty sea cucumber have declined in the recent years, from 494,000 pounds in 2011 to 136,000 pounds in 2015, with an average catch over the last five years of 250,000 pounds (Figure 24). The CPUE has also been declining in recent years, with the average CPUE over the last five years (solid blue line in Figure 24) below the average CPUE from the last 10 years (dashed blue line in Figure 24). Applying the *Itarget4* method to the Data Table for the warty sea cucumber resulted in a median recommended TAC of 88,600 pounds (Figure 24).

The *Itarget4* method uses two sources of information from the Data Table, the landings and CPUE index. Like the other methods that use an index of relative abundance, the recommended catch limit from the *Itarget4* method depends on the method used to generate the CPUE index.

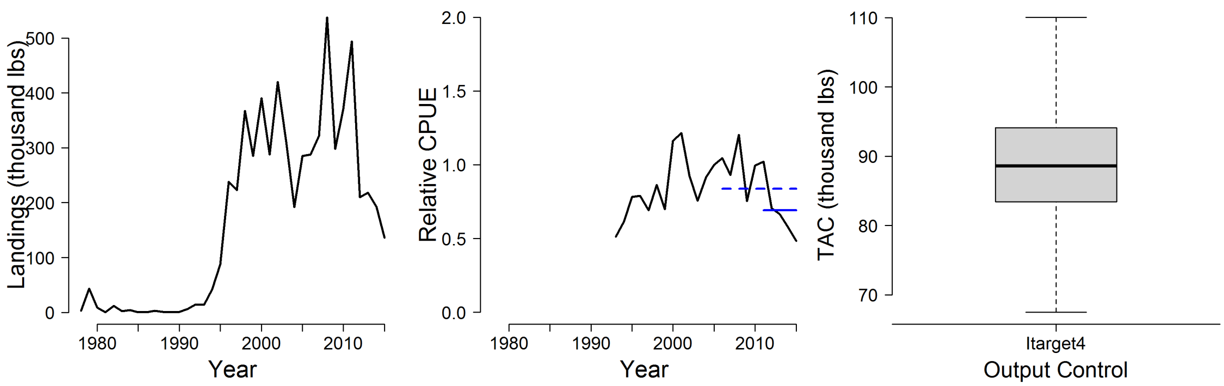

Figure 24: The reported landings of warty sea cucumber from Southern California (1978 – 2015), the index of relative abundance (1993 – 2015; blue line showing the slope over last 5 years), and the distribution of recommended TAC from the *Islope1* and *Islope4* methods (dashed gray line shows the 2013 landings).

Value of Information Analysis

There are three ways in which the DLMtool can be used to quantify the value of future data collection. The first two, "post-hoc value of information analysis" and "cost of current uncertainties" focus on management procedures that currently can be applied given the data that are available.

In post-hoc value of information analysis, the simulations are examined to identify which observation processes (e.g. bias in annual catches, error in annual catches) were most strongly correlated with management procedure performance. Assuming an MP will be adopted, this analysis can be used to prioritize collection of those data that are most likely to improve that MP's performance in the future.

The cost of current uncertainties is similar to post-hoc value of information analysis in that it examines correlations among simulation conditions and performance. However, cost of current uncertainties examines the parameters that determine the conditions of the operating models (e.g. natural mortality rate, changes in fishing efficiency) rather than the observation processes (e.g. bias in annual catch data). Analysis of the cost of current uncertainties attempts to identify the areas of OM specification that were the primary drivers of MP performance and could be used to prioritize research to improve knowledge in aspects of fishery dynamics. The third analysis, "value of new data," examines potential benefits of using management procedures that cannot currently be applied because the data they require are currently unavailable.

The operating models of these MSEs included large amounts of uncertainty in population and fishery dynamics, and simulated relatively poor quality data. This resulted in the selection of MPs that were robust to these uncertainties and therefore did not show conclusive value in the collection of additional data. Due to the lack of guidance provided by the value of information analyses, a brief summary is provided here and the detailed results are provided in Appendix T. Value of information analysis remains an emerging field of MSE for data-limited stocks and should be a priority for investigation in future projects.

In general, the quality of simulated data (post-hoc value of information analysis) determined management procedure performance less than the range of simulated conditions (cost of current uncertainties). This indicates that research may be best spent developing new management procedures or undertaking additional research to help narrow the plausible states of nature represented by the operating models.

Where possible, greater precision in our knowledge of current stock depletion would help to select management procedures for red sea urchin and warty sea cucumber (where the management procedures that were selected are sensitive to this simulation input). If, for example, it can be ruled out that red sea urchin is currently above 45% of unfished spawning biomass levels, then managers can have greater confidence in the selected management procedures. Conversely, if stock levels are found to be less than 45% of unfished, then the MSE may lead to the selection of alternative management procedures.

In the case of California halibut, age at maturity was a key driver of MP performance. The best performing MPs might not have been selected if ages at maturity were simulated higher than age 6. This points to potential cost of this uncertainty that may be addressed by further research.

For barred sand bass, red sea urchin and warty sea cucumber, the long-term yields obtained by input control management procedures were often determined most strongly by catchability increases (improved fishing efficiency). However, the relationship was not in the direction that many might expect. Relative to MSY fishing, these MPs can be expected to provide higher long term yield when fishing efficiency increases the most (i.e., between 1-2% per year). While the mechanism behind this is not clear, it is likely that increases in efficiency are allowing for a pattern in fishing that allows stocks to reach productive levels in the medium term after which higher fishing rates lead to higher catches (and possibly stock declines) over the longer term. While reference MSY yields come from a constant rate of fishing, the input controls are benefitting from a rate that is increasing due to simulated gains in fishing efficiency.

Given the current quality of simulated data and the range of operating models, there was only one instance where a management procedure might have provided better yield were it available for use. This finding indicates that further work into customized management procedures for California stocks may be an important priority; it may be better to get the best out of the data that are currently available before investing in a substantially improved program of data collection.

Discussion & Recommendations

Recent advances in the science and management of data-limited fisheries offer significant potential to improve fisheries management in California. The CDFW MSE Project has provided an opportunity to evaluate the efficacy and applicability of incorporating MSE into an integrated scientific and management framework for California fisheries. The results demonstrate how MSE could provide an efficient and robust mechanism for deriving science-based management recommendations for data-limited stocks based on rigorous examination of different management approaches in the face of uncertainty. Adopting an MSE framework with a standardized approach could create a unified process for obtaining scientific advice that is more streamlined and cost effective than a science program that relies solely on traditional stock assessments. More consistent, widespread, and current scientific advice would also improve the likelihood that California's high priority fisheries will be managed sustainably, and in a manner consistent with the mandates of the MLMA. The following section of the report includes a discussion of the project's findings and recommendations that are specific to the four case study stocks and, more generally, regarding how CDFW could create the necessary framework and scientific capacity for adopting MSE into its management system.

Discussion of Case Study Stocks

Barred Sand Bass

The MSE results for the barred sand bass indicated that many of the management procedures met the requirements of the performance limits and management targets chosen by CDFW for this demonstration project. This included the method that maintains current fishing effort (*curE*), which had similar performance to the size-limit based methods that were evaluated in the MSE. The barred sand bass fishery is currently managed with a minimum size limit, which was last increased from 304 mm to 355 mm in 2013, and a bag limit, which was also changed in 2013 from 10 to five fish per day. The size limit is considerably higher than the size of maturity for this species (219-239 mm), which reduces the risk of recruitment overfishing and contributes significantly to the high number of well performing methods for this fishery.

The performance of the methods that maintain stable effort over time and the minimum legal length methods considered in the MSE are dependent on the assumption that there is negligible fishing mortality on sub-legal individuals. Observations from CDFW that post-release mortality rates are low in this fishery support this assumption. However, the fishing mortality rates of sub-legal individuals does not appear to have been formally investigated in a scientific study and, as this is a critical assumption of the MSE model, the alternative size limit methods were not considered available in this study. It is important to validate the assumption of negligible post-release mortality before interpreting the MSE results for management advice. If static size limit based methods are being considered for management of the fishery, it is critical to quantify the associated risks by accounting for post-release fishing mortality and implementation error of size-based regulations. This requires additional information on the selectivity of the fishing gear (not just the retention by the fishers), as well an understanding of the fishing mortality rate on discarded fish.

Many management procedures have been developed to respond dynamically to signals in data streams and therefore aim to detect potential problems in the fishery and adjust management accordingly. However, static methods (e.g., constant catch, effort, or fixed size limits), as tested in the MSE, are data-free and do not use any data streams to track trends in population abundance. Although they have been included in the MSE, the results of static controls should be interpreted with caution, and analysts and stakeholders should be confident that the full range of uncertainties (e.g., future increases in fishing effort or catchability) have been explored in the MSE before recommending these methods for management.

The impact of a seasonal closure on the barred sand bass fishery was approximated in this MSE by assuming that there was a direct relationship between the length of the closed season and the reduction in fishing effort. In practice, fishing effort often does not decrease linearly with the length of a closed season, as there may be incidental catch during the closed season when fishers are targeting other species, or fishing effort may increase in the open season months. The seasonal closure examined in this MSE provide preliminary results on the likely impacts of such a policy. However, if managers are considering this approach, we recommend that the relationship between fishing effort and fishing season be examined in detail, and the implementation error be included in the model before accepting the MSE results for management advice.

None of the 52 acceptable output control methods were available to be used for this fishery. This was predominantly due to the absence of reliable records of total catch for barred sand bass. Records on catch do exist from logbooks and surveys of the commercial passenger fishing vessel (CPFV) fleet and surveys of the private recreational fishers. However, additional standardization and analysis is required before these data can be used to estimate total catches, especially for recent years. In addition to the issue of insufficient data, output controls were not considered to be a feasible management option by the CDFW for barred sand bass because it is targeted exclusively by recreational fishers and catch limits are difficult to implement and monitor for CDFW at the present time. This case study demonstrates the importance of evaluating feasible management controls when conducting an MSE. While all management types can be included in the MSE, and the performance examined in the outputs, only methods which are considered possible to implement should be considered when developing management advice from the MSE results.

Southern California Halibut

The southern California halibut case study represents a stock with a large amount of fishery data and the benefit of a recent stock assessment to provide information on current stock status and estimates of the life history parameters. However, the stock also presents many challenges, including multiple fishing fleets, sparse or disparate fishery data sources, and a known, but currently undefined, portion of the stock that crosses the international border between the United States and Mexico. Furthermore, the CDFW currently considers output controls to be impractical for this fishery, preferring to manage the fishery using size-based regulations.

While the size-based methods examined in this MSE depend on the same assumption regarding fishing mortality on sub-legal individuals as discussed above, the results suggest that to achieve the management objectives for this fishery (under the unrealistic assumption of perfect implementation) the size limit must be increased considerably from the current regulations. Including the post-release mortality on sub-legal individuals that are caught by the fishery but discarded back to the water is likely to shift the acceptable selectivity curve even further toward larger size fish. Upon examining the results, this large increase in size limit was considered impractical by the CDFW Working Group, particularly because it would exclude some sectors of the fishery completely. Furthermore, the assumption of negligible fishing mortality below the regulated minimum size is unlikely to hold true for this fishery, where trawl nets and other fishing gears are known to capture individuals below the regulated size, which would then be discarded dead back to the sea. Therefore, these methods were not considered available candidate management procedures in this study.

The results highlight the need for management procedures that are not only likely to meet management objectives, but also can be implemented feasibly with the data requirements and management constraints of the fishery. The MSE demonstrates that catch limits could meet the management objectives for this stock, although issues of high-grading and discarding must still be examined in more detail to determine how such issues could be minimized and accounted for. This may provide an incentive to develop mechanisms to manage the fishery using output controls. Likewise, effort controls could work for this fishery. Such methods may be considered easier to implement for the southern California halibut fishery than catch limits, although the practical application of an effort-based management control for the multi-fleet fishery would require careful consideration. For example, effort-based controls assume that current fishing effort can be quantified and that mechanisms exist for managers to have fine-scale control on the amount of fishing effort in the future.

California halibut exhibit strong sexual dimorphism, with females growing significantly larger than males. The DLMtool version used for this study was a single-sex model that does not account for sexual dimorphism in growth or other life history characteristics. For simplicity, we used the female life history parameters for this study, although this approach has several short-comings. The results of the size limit methods are likely to be biased because the growth of the smaller-sized males in the population is not adequately accounted for. Furthermore, the application of a management procedure using female growth parameters in the Data Table may introduce bias as the actual catch or abundance data comes from a population made up of both male and female fish. It is possible to develop the DLMtool model to account for sexual dimorphism, and we recommend this approach if the model is going to be used for species with strong differences in growth or other life history characteristics between male and female fish. Alternatively, it may be possible to use the mean values of male and female growth parameters, together with larger associated CVs, to account for this difference in growth. This approach should be explored in more detail and analysts should be aware of these issues when using the DLMtool for species with sexual dimorphism.

Red Sea Urchin

The red sea urchin fishery in southern California is targeted for the reproductive organs of mature individuals and currently managed with a minimum legal length of 3.25 inches. Like the barred sand bass discussed above, the capture of animals above the size of maturity reduces the risk of recruitment overfishing and contributes to the high number of methods that meet the performance limits for the stock. The MSE demonstrated that the stock has high resilience, and that catch limits, effort controls, and size regulations may all meet the management objectives for this stock.

A considerable proportion of the sea urchin biomass is believed to be within areas closed to fishing activity, and as the species is understood to be relatively sedentary, the MSE results demonstrated that including the MPA in the simulation model increased the performance of all the management procedures. This demonstrates the importance of accounting for the conservation benefits of MPAs for this stock.

The red sea urchin in Southern California is targeted by a single commercial dive fleet, which hand picks the individuals from the sea. The fishery is highly selective and fishing mortality on sub-legal individuals is not considered to be a significant issue. Total catch and effort data exist for this fleet, with divers estimating their daily catch and recording total dive hours for each trip. Furthermore, the landing receipts from the processors are used to estimate total landings.

As the effort data are recorded in paper form and manually entered into the CDFW database, there is a lag between the data being recorded and made available for analysis. For example, data was only available up to 2013, although the MSE conducted in this study assumed that data collected in one year was available to be used by the management procedure in the following year. The TAC-based methods that were identified as appropriate for this fishery rely on CPUE data to provide an index of abundance. It may be possible to expedite the entering and processing of the fishery catch and effort data by developing electronic data collection systems or other solutions to improve efficiency. However, these approaches may be expensive and difficult to implement for this fishery. If the lag in fishery data is likely to remain in the future, this reality should be included in the MSE model to understand the effects it may have on the performance of management procedures and the selection of methods that best meet the management objectives of the fishery. We intend to add this feature to the DLMtool, and analysts should be aware of lags between data collection and application in management procedures, and include this lag in future MSE analyses.

Warty Sea Cucumber

The warty sea cucumber represented the case study with the most uncertainty about stock status and life history. The CDFW expressed some concern about the state of the warty sea cucumber fishery in southern California, particularly regarding declining catch rates in recent years. The MSE results reflect the uncertainty in the dynamics of the warty sea cucumber stock, with most of the management procedures failing the management objectives, and many methods performing poorly.

The high uncertainty in the biology of the warty sea cucumber also contributed significantly to the uncertainty and poor performance of the management procedures. A significant source of uncertainty for this species is the natural mortality rate, which is essentially unknown and a wide range was assumed from a search of the literature for other holothuroideans. Estimating natural mortality is difficult for most marine species, and especially so for invertebrates such as sea cucumber.

The network of MPAs in southern California may provide useful information on growth and natural mortality for this species. In addition, it may be possible to use data from the protected areas to provide estimates of depletion, or relative indices of abundance, which may be used as fishery-independent data sources for managing the fishery. The CDFW is actively carrying out research programs to develop understanding of the biological attributes of the species, including growth and size at maturity. The results of these studies may be used to update the operating model parameters and reduce the uncertainty in the inputs for the MSE. Re-running the MSE with this updated information may change the performance of some management procedures, and may result in the identification of appropriate alternatives for managing the fishery.

Like the red sea urchin, the warty sea cucumber is exploited by a commercial dive fleet and has the potential to be highly selective. There is market demand for small size individuals, and some fishers are targeting very small, immature sea cucumber. Explorations of alternative operating models could demonstrate that much of this poor performance, where few management procedures were able to meet the management objectives, was due to the apparent harvesting of very small individuals, and an increase in the size of capture is likely to improve the performance of most methods. However, the practical application of size-based regulations for this fishery is considered difficult.

Sufficient catch and effort data exists for this fishery to apply the single output control method that was identified as acceptable in this study. The process for recording and entering these data is identical to that used in the red sea urchin fishery, and the same issues regarding timing of data collection and analysis discussed above must be considered. Alternative effort control methods that may be easier to implement and enforce, such as seasonal closures during spawning and closures that adjust based on CPUE trends. As mentioned in earlier sections, the implementation of effort controls assumes that managers can measure and regulate fishing effort. Furthermore, the MSE results assume that effort controls are implemented perfectly. These assumptions should be carefully examined in the context of the fishery, and implementation error included in future MSE analyses before these results are used to inform management decisions.

Recommendations for the MSE Approach

All simulation modelling is a simplification of a complex system and therefore open to misuse or abuse. Analysts and stakeholders should be aware of potential issues associated with the MSE approach. For example, it is possible for simulation models to be used as a self-fulfilling prophecy, where assumptions or hypotheses of the stock dynamics or the system in general are used to parameterize the operating model, and then the results of the MSE are used as evidence to support these hypotheses. To avoid this circular reasoning, it is important the MSE analysis follows a defined process, where all operating model parameters are specified carefully, and the bounds on the parameters appropriately reflect the uncertainty in the system. The basis for each parameter must be supported and cited, and any changes to parameters after an initial MSE is conducted must also be clearly articulated.

Furthermore, it is important that analysts conducting the MSE and processing the fishery data are adequately trained in population dynamics and data analysis techniques, and are familiar with the processes involved in the sampling and collection of the fishery data. Although software such as the DLMtool make it easy to run an MSE analysis, analysts and stakeholders should be cautioned against treating the MSE analysis as a “button pushing” exercise, and instead devote sufficient time and resources to the time-consuming task of understanding the fishery data and populating the operating model parameters in a way that reflects as complete an understanding of the system as possible.

Finally, analysts and stakeholders should be aware of the assumptions of the MSE framework used for the analysis and understand that the results of the MSE are conditional on accepting that the MSE model has adequately captured the principal characteristics of the system. Therefore, plans for monitoring the resource should be developed when a new management procedure is implemented in a fishery, so the system can be monitored for signals that suggest it has moved outside the bounds simulated in the MSE, such as large scale environmental events, climate change, or changes in the productivity of the species.

The impacts of climate change or other long-term changes in productivity can be approximated and examined within the MSE model. It is possible to include long-term trends in natural mortality, growth, or recruitment, that may be used to understand the likely effects of changes in productivity caused by climate change or other environmental drivers. We reiterate here that adequate training in population dynamics modelling is essential to examine the impacts of these stressors on the performance of the methods, and emphasize that sufficient time and resources should be allocated to this aspect of the analysis if managers and stakeholder wish to investigate the impacts of climate change or other ecosystem effects using a single stock MSE model such as the DLMtool.

Incorporating MSE into the Master Plan for Fisheries

The California Marine Life Management Act (MLMA) requires that fisheries management decisions are based on the best scientific information available and that such information be subject to external peer review (FGC §§ 7062, 7072). Management strategy evaluation provides a method of quantitative scientific analysis and related decision-making framework that can be readily reviewed and tested by independent experts. Adoption of such a framework could be used to address a number of objectives and requirements under the MLMA, including: confidence that fisheries are managed sustainably (FGC §§ 7056(a)-(c)), that socio-economic interests of fishing communities are accounted for in the management process (FGC §§ 7056(e), (i), (j).), that decision-making is based on the best scientific information available (FGC § 7056(g).), that the process is inclusive and adequately incorporates input from stakeholders (FGC § 7056(h).), and that the management process is adaptive over time (FGC §§ 7056(l), (m).).

Should the CDFW choose to incorporate MSE into the state's fisheries management system, a first step would be to formally recognize MSE as an approved scientific framework for evaluating candidate management strategies. This could be included directly in the amended Master Plan for Fisheries (e.g., "management strategy evaluation may be used as long as both the underlying tools or models have been adequately peer reviewed and the process for incorporating them in the management of the state's marine resources has been demonstrated to satisfy the requirements of the MLMA").

To tailor an MSE framework to be consistent with the objectives and mandates of the MLMA, it is important that CDFW prescribe a process for developing and adopting the performance metrics by which different data-limited management procedures will be evaluated and selected for use in management. This could be done using a pre-designated set of performance metrics or through specific guidance on selecting among a range of acceptable performance metrics on a fishery-by-fishery basis. The pre-designated metrics could also be designed broadly, while still allowing the specific management limits and targets to vary by fishery, depending on life-history and other factors. We recommend that the process of designing performance metrics be open and transparent, with stakeholders well represented and full opportunity for notice and comment from the public.

In addition, the state should delineate a consistent process by which an MSE framework is applied to California fisheries for each of the key steps in the process: (1) management strategy evaluation and method identification; (2) method application and management recommendations; and (3) value of information analysis and future data collection.

Some key questions that need specific resolutions for consistent application of MSE across multiple fisheries include:

- What CDFW staff would be responsible for conducting MSEs and what types of training and support are needed to ensure sustained implementation is successful?
- How should CDFW translate its management objectives into specific performance metrics that can be used to select optimal management procedures?
- How should a CDFW choose a single management procedure among a group of acceptable and available ones?
- What types of peer review are required for a new MSE or an updated application of an existing MSE output?
- At what points in the process must stakeholders be brought in?
- How can the MSE process help to improve data processing and organization?

Recommendations to these questions are provided below.

Training & Scientific Capacity Building

Developing internal scientific capacity, either through a dedicated MSE team of CDFW scientists or through enhanced training of existing staff, is an essential step toward applying MSE to CDFW's priority fisheries.

Building an Internal CDFW MSE Team

One option for building scientific capacity at CDFW would be to create a dedicated team of scientists to assist other environmental scientists in applying MSEs to state fisheries. This team could work directly with stock environmental scientists to aggregate fishery information, design operating models for each fishery, run management strategy evaluations, and present the results to decision-makers. This could provide the basis for the selection of an approved management procedure for each stock, with the analysis documented in a fishery management plan or associated report. The MSE for each stock should be updated periodically, especially as information that may impact the resulting selection of acceptable management procedures becomes available.

CDFW environmental scientists, working with CDFW MSE experts and following necessary trainings, could then process all relevant fishery data and apply the approved management procedure to derive current management recommendations. This information could be included initially in the fishery management plan, but in subsequent years could be adopted for management through some sort of streamlined regulatory process that has been authorized by the Fish and Game Commission and delegated to CDFW to implement on a regular basis. The internal CDFW MSE team should also be responsible for conducting value of information analyses for each fishery. The findings of these analyses should be used to develop and refine a specific data collection plan that prioritizes the types and quality of data to be collected and processed. Recognizing that CDFW may not have the resources to dedicate one or two scientists to create this core MSE team, an alternative discussed by the Working Group would involve building the capacity of existing CDFW stock leads and related staff. This approach would require expanded training on basic fisheries population dynamics theory, as well as the features and development of an MSE model.

We recommend a two-year transitional period wherein an external MSE expert would work directly with CDFW to provide training for the core MSE experts, as well as more limited training for stock biologists who would be using MSE outputs to inform fishery management plans and enhances status reports. The individuals hired or reassigned to form the CDFW MSE team must have a background in fisheries population dynamics, experience managing and processing fisheries data, and knowledge of the R programming language. Additionally, scientists who are familiar with the data collection processes (e.g., sampling, data pre-processing, and storage) and other aspects of the fishery (e.g., stock and fleet dynamics) must be involved in the MSE process, and lead the analysis of the fishery data and the population of the operating model parameters.

Capacity-Building & External Support to CDFW

The alternative route would forego dedicated CDFW MSE staff in favor of training and capacity building of existing environmental scientists, combined with external support from independent consulting scientists. The current responsibilities of CDFW environmental scientists includes nearly every aspect of the science program for each stock, from data collection and processing to stock assessment and the development of fishery management plans and associated regulatory materials. Many of these scientists have marine biology educational and training experiences, but may not also have much, if any, experience in fisheries populations dynamics. There also appears to be a lack of fluency in statistical software programming, such as R. Despite these challenges and limitations, the CDFW staff that collaborated on this project proved engaged, interested, and capable of learning how MSE could support their productivity in the future.

As part of the November 2016 meeting, we conducted a two-day training with CDFW staff to provide further exposure and a more detailed, hands-on tutorial for the main functions of the DLMtool. By the end of the two days, the staff were more familiarized with the mechanics of building operating models, running MSEs, analyzing results, and selecting acceptable management procedures. In discussions toward the end of the meeting, CDFW staff reported that the training was helpful and provided confidence that more extensive training and capacity building could enable them to operate the DLMtool or a similar MSE framework for their stocks.

While this would require more substantial trainings for a larger group of CDFW staff than the first option of a dedicated MSE team, as well as explicit prioritization in individual and departmental workplans to provide time and resources for such trainings, this approach could effectively build capacity more broadly and deeply throughout the marine fisheries program than the first option above. Based on feedback from the Working Group, we recommend a series of trainings in four discreet areas: fisheries science, with an emphasis on population dynamics and statistical modelling; data processing and standardization; R software training, and immersive DLMtool trainings and mentoring. We also recommend that the MSE trainings are done in sequence with the steps in the process outlined in this report using real fisheries, so the process not only provides skills and expertise to CDFW staff, but also results that can directly inform the management system in the near term. This type of sequential training would enable all the staff to be working through similar challenges with their stocks at the same time, alongside the MSE experts conducting the training.

Defining Performance Metrics that Achieve CDFW's Management Objectives

The definition of performance metrics to compare the relative performance of alternative methods is one of the most important aspects of the MSE approach. Different stakeholders may value different aspects of the fishery, and while it is possible to include a wide range of different performance metrics, it is important that the metrics used to select methods are considered carefully to ensure they are not in conflict or have unintended consequences. The performance metrics used in this study were developed by the CDFW Working Group through an initial workshop and numerous follow-up webinars and conference calls (see Table 3).

The results of this study demonstrate the importance of developing and exploring the implications of potential performance metrics at the beginning of the MSE process. We recommend allocating sufficient time to develop performance metrics and emphasize that it is important that managers and stakeholders understand the properties of the performance metrics before the MSE analysis is conducted. One approach that we recommend is to use a series of reference MPs (such as fishing exactly at F_{MSY}, or some fraction of F_{MSY}) to examine the properties of any proposed performance limits. This allows managers and other stakeholders to see, given the assumptions and parameterizations of the operating model, how achievable the performance metrics are even under ideal or perfect conditions. Agreeing on a set of performance metrics and the process that will be used to eliminate and select methods is critical before the full MSE analysis is carried out.

Proxy B_{MSY} Reference Points and Long-Term Yield

For purposes of this project, CDFW chose to use proxy values for B_{MSY} as reference points for each of the four stocks. Theoretically, a biomass target of B_{MSY}, achieved by fishing at F_{MSY} over the long run, should also lead to the highest long-term yields. However, this proved to present conflicts in cases where proxies for B_{MSY} were selected that were inconsistent with B_{MSY} for the specific life-history and productivity parameters of the stock (as specified in the MSE operating model).

This is demonstrated in the case of the red sea urchin, where CDFW selected a performance target of greater than 50% probability that a management procedure would achieve a biomass target of at least 50% of the unfished level ($0.5B_0$) over the last 10 years of the projection period. The $0.5B_0$ target level was chosen as a proxy for the biomass at maximum sustainable yield (B_{MSY}), as no established proxy reference points for invertebrate fisheries were found. However, the relationship of B_{MSY} to B_0 is related, among other things, to the steepness of the stock-recruitment relationship, the assumed values of which are specified in the operating model parameter table. Furthermore, B_{MSY} is calculated in the MSE for each simulation, and the performance of the management procedures can be reported relative to the calculated B_{MSY}. In the case of the red sea urchin, where steepness was assumed to be 0.4 – 0.6, B_{MSY} was below $0.5B_0$.

Figure 25a shows a scatterplot of the probability that biomass is greater than $0.5B_0$ against the expected long-term yield for the 41 methods that passed the two minimum performance limits in the red sea urchin MSE. Because $0.5B_0$ is above B_{MSY} in this case, the methods with the highest long-term yield have less than 50% probability of being above $0.5B_0$ and are thus not considered acceptable methods. The desire to select methods with the highest long-term yield, while simultaneously having >50% probability of being above $0.5B_0$, means that the methods that are identified as best performing will be located close to the boundary of acceptable and unacceptable methods (Figure 25a). In other words, according to these criteria, the best performing methods (highest yield) will have just over the required 50% probability, while similarly performing methods that fall just below the 50% probability threshold will be considered unacceptable.

Substituting the $0.5B_0$ biomass target with B_{MSY} calculated by the model considerably changes the apparent performance of the methods (Figure 25b). In this case, 40 of the 41 methods that pass the minimum performance metrics have greater than 50% probability that the biomass in the final ten years of the projection period is greater than B_{MSY}, and, if this performance metric was used, would be consider acceptable. This result highlights the importance of ensuring that the chosen performance metrics (e.g., target biomass) are internally consistent with parameters of the operating model (e.g., steepness). If managers and stakeholders choose to select a method based on the highest expected long-term yield, then they are implicitly stating that the biomass should be at, or around, the most productive level; i.e., B_{MSY}. If, on the other hand, the management objective is for the stock to be managed to some specified non-B_{MSY} biomass target, then the performance metrics should be defined in such a way that are not in conflict. For example, if managers wish for a method to drive the stock above B_{MSY}, the highest long-term yield should not be used as a metric for selecting methods (yield can still be examined in trade-off plots), but rather methods can be ranked on the proximity of the median biomass to the desired level, and methods that are closest to the target level considered the "best performing."

We intend this only to be a demonstration of the relationship between B_0 and B_{MSY} and to highlight that a desire to select management procedures based on highest expected yield may be problematic if other performance metrics eliminate MPs that drive the stock to the B_{MSY} level. Managers may wish to choose performance metrics relative to B_0 for numerous reasons, and this approach can be used to eliminate or select management procedures. However, caution should be exercised in developing the performance metrics to avoid selecting methods that fall right on the boundary between acceptable and non-acceptable methods. This issue is discussed in more detail in the next section.

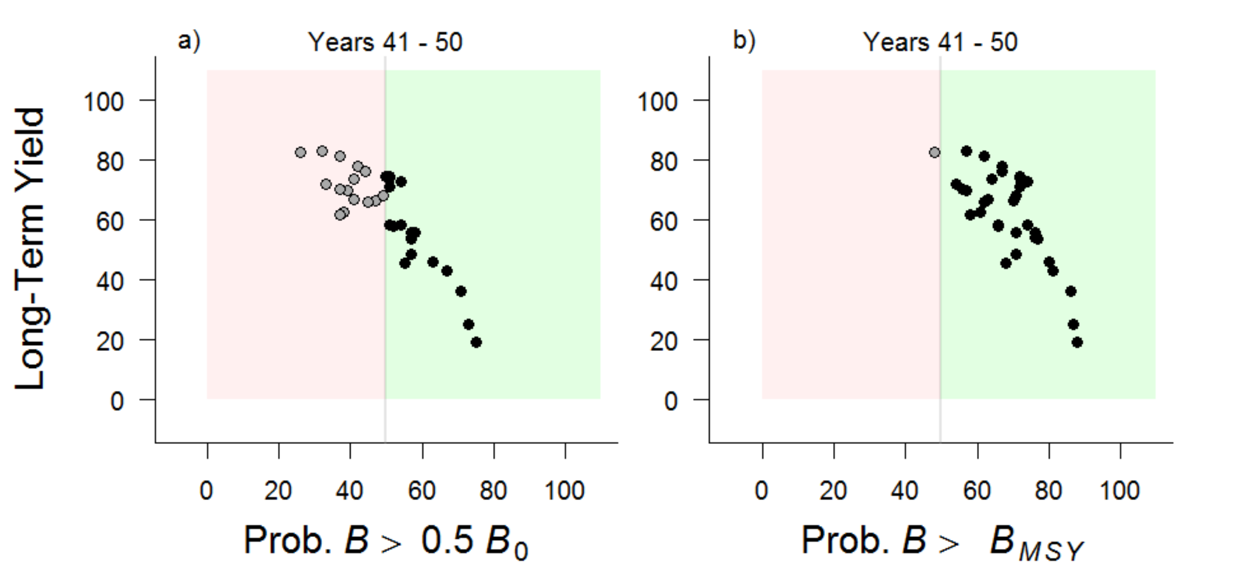

Figure 25: The probability that biomass in the last ten years is a) above half of the unfished level ($0.5B_0$) and b) above biomass at maximum sustainable yield (B_{MSY}), and the expected long-term yield for the 41 methods in the red sea urchin MSE that passed the two minimum performance limits. The gray circles (red background) are methods which do not meet the required 50% probability. The solid black circles (green background) are methods which exceed the required 50% probability. Of these acceptable methods, according to the $0.5B_0$ performance metric, the methods with the highest long-term yield also have the lowest probability of being above $0.5B_0$, and the 'best' methods fall almost exactly on the boundary. When B_{MSY} is used, almost all of the 41 methods have greater than 50% probability of being above B_{MSY}.

Hard Cut-Offs for Targets

While the performance limits are designed to eliminate methods with pathological performance, the aim of the second step in the performance metrics was to identify methods that were most likely to meet the management objectives. However, in several of the case studies examined in this project, the management objectives proved to be more restrictive than the performance limits. Switching from proxy B_{MSY} biomass targets to B_{MSY} calculated in the model, as described above, leads to fewer methods being eliminated by the management objective requirement. However, managers may have valid reasons for selecting performance metrics relative to B_0, and these should not be disregarded. The hard cut-off used to exclude otherwise well performing methods can still be problematic due to the stochastic nature of the MSE. In other words, re-running the MSE model may result in slightly different probabilities, potentially changing the number of acceptable and not acceptable methods.

For example, Figure 26a shows that the probability of biomass being above $0.5B_0$ is very close to 50% for a number of methods. While MSE models typically have a large number of simulations, the resulting probabilities can vary by small amounts between different model runs, which can have important implications for the interpretation of the results. In this case, a method may be considered the 'best performing' (given the performance metrics used in this study) or not acceptable depending on which side of the 50% probability boundary it falls. However, the fundamental problem of including or excluding methods arbitrarily based on the stochastic results of the MSE remains. For example, one of the 41 methods that passed the performance limits had less than the required 50% probability and would be considered not acceptable (Figure 26b).

One way to deal with this issue may be to quantify the variability in the calculated probabilities that arises from the stochastic MSE. This variability, referred to as Monte Carlo error, can be quantified by calculating the performance metric while increasing the number of simulations and using the resulting estimated variance to identify methods that are not statistically significantly different from the specified threshold. For example, we calculated the probability of the biomass being above $0.5B_0$ and B_{MSY} in the last 10 years with the number of simulations in the MSE ranging from 701 to 1,000. Diagnostic tests proved that the MSE has converged well before 700 simulations, and therefore the remaining variability in the calculated probabilities was due to Monte Carlo error. We calculated the mean and standard deviation of the probability for each method for the 300 runs, and plotted the mean and ninety-five percent simulation intervals (95% of simulations within this range) for the 41 methods (Figure 26). This analysis shows that the Monte Carlo error is relatively small for the calculated probabilities. When the $0.5B_0$ performance metric was used, the ninety-five percent simulation intervals for several of the borderline methods revealed that the probabilities for these methods were not significantly different from 50% (Figure 26a). Although the same principal applies to any performance metrics, when the B_{MSY} performance metric was used, the probability for the single excluded method remained significantly lower than 50% (Figure 26b) and thus would still be considered not acceptable.

While accounting for the Monte Carlo error may assist with how to deal with borderline methods, it does not address the issue of using a hard cut-off limit for management targets that are intended to be achieved, but not necessarily exceeded (unlike management limits that represent thresholds of unacceptable performance that must be exceeded). For example, the single method in Figure 26b with probability significantly below 50% fails to meet the requirement for the management objective and would be considered not acceptable. However, it may be argued that the performance of a method with 48% probability of biomass being above B_{MSY} is not qualitatively different from a method with slightly higher probability. Sainsbury (2008) notes that reference points can encourage an over-simplistic view where risk is considered to change abruptly at particular thresholds. When using hard cut-offs to define thresholds for management targets, managers and other stakeholders should be aware that they are implicitly stating that methods that fall just short of the stated management target are too risky to consider as potential methods for management. Alternatively, managers could consider using a hard cut-off for minimum performance thresholds that eliminate methods that are entirely unacceptable and then examine the trade-offs in the remaining methods to identify those that best meet the management objectives.

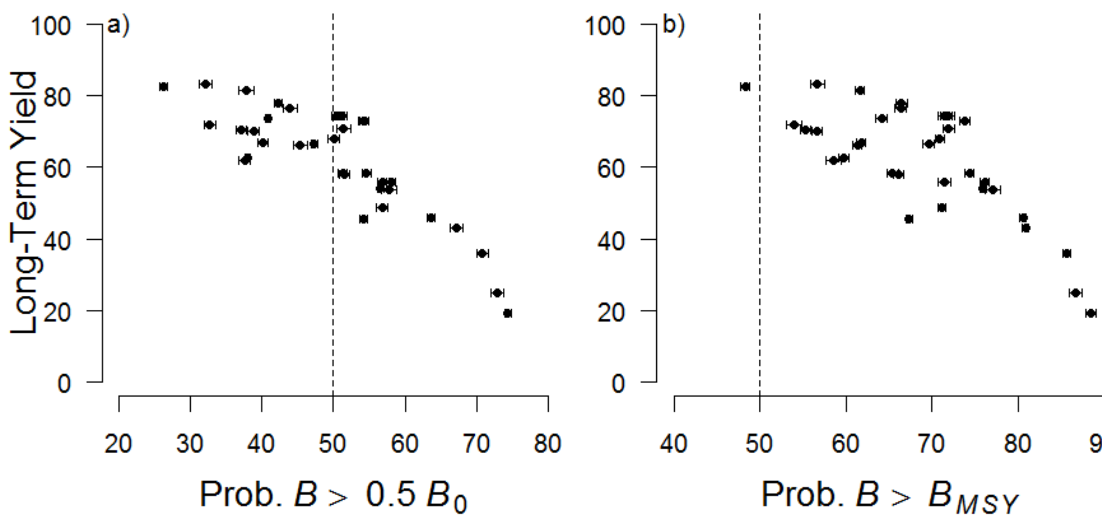

Figure 26: The mean probability (points) and ninety-five percent simulation intervals (lines; 95% of simulations within this range) that biomass in the last ten years is a) above half of the unfished level ($0.5B_0$) and b) above biomass at maximum sustainable yield (B_{MSY}), and the expected long-term yield for 300 different simulations of the red sea urchin MSE.

Demonstrating a Bracketing Approach

An alternative approach that avoids the issue of hard cut-offs for management targets is to use bracketing to eliminate undesirable methods and focus the analysis on the trade-offs of the remaining methods. Using this approach, minimum performance limits are used to exclude methods that are considered too risky to be candidates for management, as was done with the first performance metric used for the four California case studies. Because these poorly performing methods often result in low biomass (i.e., below B_{MSY}) they are not likely to have high long-term yields and thus the conflict between the biomass reference point and the desire to maximize long-term yield described above is not expected to be an issue. Any number of performance limits can be included in this step to eliminate methods with pathological properties. However, when defining this limit, managers and other stakeholders must be careful to define the performance space in terms of highly undesirable outcomes. In other words, the performance metrics should define the minimum biomass level that is considered too risky, which is often the biomass level where recruitment is considered to become impaired, and assign a relatively high risk threshold for avoiding this space.

Further performance metrics can be also defined to exclude methods that chronically fish well below F_{MSY}, or result in frequent closures of the fishery. In this way, the performance metrics are used to eliminate all methods with completely undesirable properties, and the remaining methods can be examined from trade-offs among the other management objectives. We demonstrate this approach using the same MSE results as discussed above. In this example, we defined a single minimum performance metric of at least 80% probability that the biomass in the last 10 years of the projection period is greater than $0.5B_{MSY}$. This has the consequence of eliminating 32 of the 80 management procedures included in the MSE (a). Figure 27b shows that these eliminated methods typically had low probability of the biomass being above B_{MSY}, and predominantly fell on the left side of the biomass-yield curve. However, the probability of being at or above the target biomass level of B_{MSY} is not being used to exclude methods.

The remaining methods in Figure 27b include several that have low expected long-term yields and high probabilities that the biomass is above B_{MSY}. These methods are likely to be consistently fishing at very low levels, and managers may wish to reject these methods as unsuitable for managing the fishery. In this example, we defined a minimum yield metric of 60% of the long-term optimum yield and eliminated any methods where the long-term yield was below this level (Figure 27c). It may be possible to define an upper limit on the biomass which would essentially have the same effect. However, defining upper bounds on biomass may be more difficult due to the lack of appropriate biological reference points. Furthermore, such an approach may be undesirable if managers and other stakeholders are more concerned with low yields rather than with biomass rebuilding to a level that is considered too high.

Applying the minimum yield threshold removed another 15 methods from the list of candidates, with the remaining 33 methods are shown in Figure 27d (note some points overlap in the plot). The trade-offs in other metrics of interest (e.g., average annual variation in yield) can then be examined for these 33 acceptable methods to identify those that best meet the management objectives for the stock. Likewise, projection plots can be displayed to examine the emergent properties of these acceptable methods.

The advantage of the bracketing approach to performance metrics is that it allows managers to selectively eliminate methods that have pathological or undesirable properties and thus simplify the remaining analysis to those methods that are most likely to achieve the management goals. Furthermore, this method avoids the problem of arbitrarily eliminating methods due to Monte Carlo error, or because they perform marginally worse than the ideal management goal. However, it is important that the performance brackets are defined carefully and are achievable given the fishery dynamics. It is possible that stakeholders and decision-makers define performance brackets that are not achievable, even with perfect fishery management (for example, yield must be 90% or greater of MSY and the stock must be above 90% of B_0 95% of the time). Therefore, we recommend that sufficient time is given to examining the properties of potential performance limits or brackets under conditions of perfect management. If it is not possible, or highly unlikely, to meet the management objectives with perfect management, it is likely that no management procedures will meet these conditions under more realistic simulations.

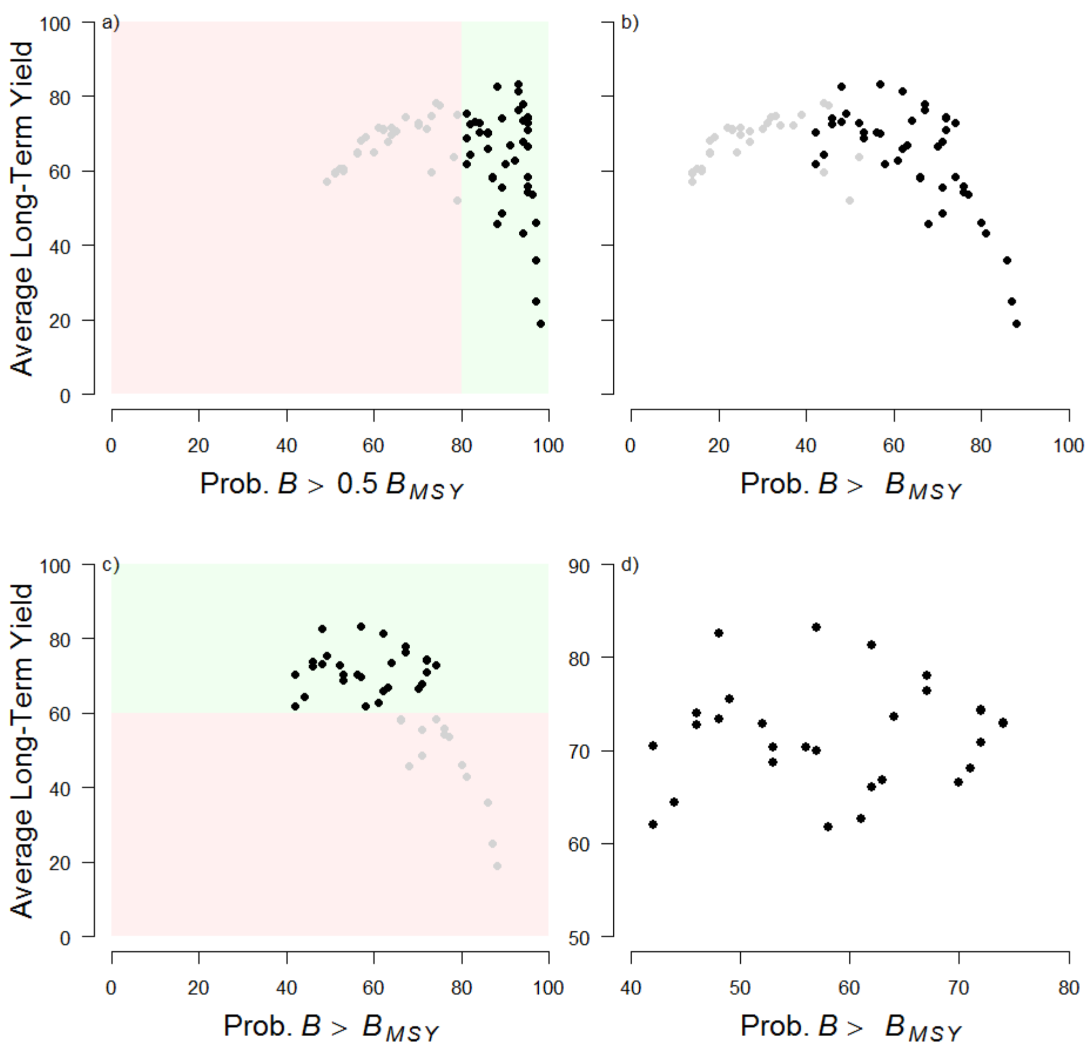

Figure 27: An example of the bracketing approach for eliminating methods with pathological or undesirable properties. First minimum performance criteria are defined, here defined as an 80% probability that the biomass is above $0.5B_{MSY}$, and all methods that fail to meet this threshold are excluded (a, b). Next, upper bounds are used to remove methods which result in low long-term yields and high levels of biomass (c). Finally, the remaining Acceptable methods which meet all minimum performance criteria are identified and the properties and trade-offs examined using additional plots.

Incorporating Performance Metrics Related to Rebuilding Overfished Fisheries

In addition to the biomass and yield performance metrics used in this study, managers may be interested in examining other aspects of the performance of management procedures, such as how quickly different methods would be likely to rebuild a stock from an overfished condition. In California, the MLMA stipulates that for overfished stocks, fishery management plans "shall contain measures to prevent, end, or otherwise appropriately address overfishing and to rebuild the fishery." CA FGC § 7086(b). Specifically, rebuilding plans for overfished stocks must specify a time period for rebuilding that is "as short as possible, and shall not exceed 10 years except in cases where the biology of the stock of fish or other environmental conditions dictate otherwise." CA FGC § 7086(c). Unlike the federal rebuilding requirement under the Magnuson-Stevens Act, the MLMA contains the broad caveat that policies and regulations must only adhere to the stated conservation requirements of the Act "to the extent practicable" CA FGC §§ 7055, 7058.

Such rebuilding targets can be used to evaluate the performance of management procedures, or eliminate methods from a list of candidate methods, using the results of the MSE. For this example, we took a subset of the MSE simulations for the California halibut, where the current depletion level was below $0.5B_{MSY}$, and calculated the probability that a management procedure would rebuild the stock with a given timeframe. For simplicity and ease of presentation, we subset the MSE to include only seven example management procedures (two input controls: *matlenlim* and *MLL675*, and five output controls: *DD*, *DD4010*, *MCD*, *DCAC4010*, *HDAAC*). The selection of these management procedures was primarily for demonstration purposes, and they were chosen as they represented a wide range of performance in rebuilding time. We also included four reference methods, *FMSYref*, *FMSYref75*, *FMSYref50*, and *NFref*, which represent fishing exactly at F_{MSY}, $0.75F_{MSY}$, $0.5F_{MSY}$, and no fishing respectively. Including these reference methods can be useful for providing context on the expected rebuilding time given the life history characteristics and environmental variability included in the operating model. For example, the *NFref* method allows the calculation of the minimum amount of time the stock takes to rebuild under no fishing (tmin).

We calculated the probability of an overfished stock being rebuilt to B_{MSY} for these seven management procedures within four different time periods: 10 years, tmin + mean generation time, two times tmin, and two times the mean generation time. These results demonstrate that there is a low probability of an overfished California halibut stock being rebuilt within ten years, with less than 50% chance that the stock is rebuilt within this time period even if no catches are taken (Figure 28a). The remaining plots show a similar pattern, and show the typical trade-off in the increased probability of rebuilding the stock against higher average long-term yields (Figure 28). These results also highlight the importance of accounting for life history characteristics when setting a minimum rebuilding time for an overfished stock.

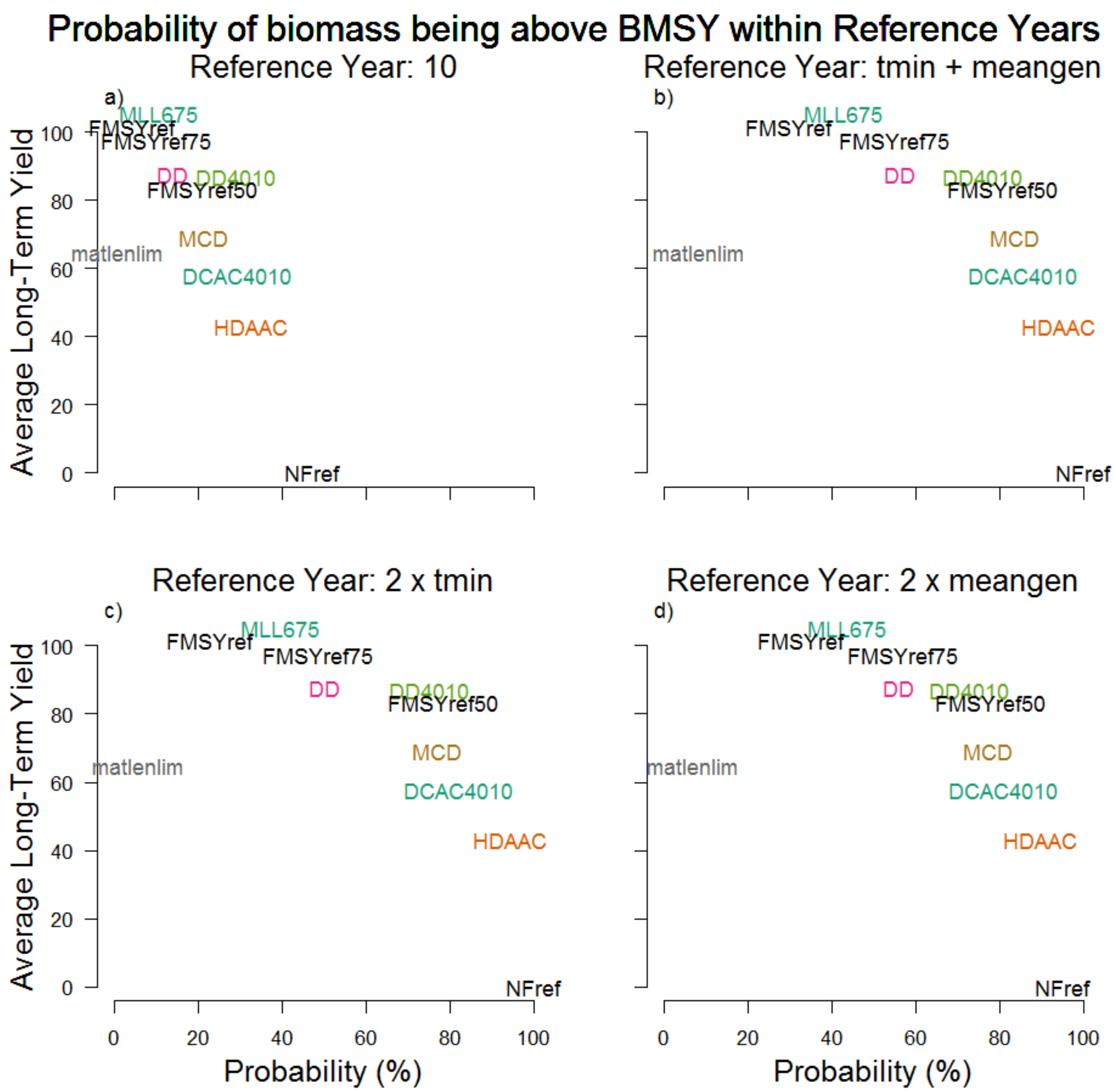

Figure 28: The probability of an overfished stock ($B<0.5B_{MSY}$) being rebuilt within a) 10 years, b) the rebuilding time under no fishing (tmin) plus a mean generation time, c) twice tmin, and d) twice the mean generation time, for seven example management procedures. The reference methods are shown in black text. The center of the text labels corresponds to the probability on the x-axis.

Considering Data Quality and Governance Realities When Choosing MPs

Once the subset of acceptable and available management procedures has been identified through the MSE, the management agency experts, in this case CDFW, must then evaluate various factors for selecting the final management procedure that will be applied to current data to obtain management recommendations. While it may appear straightforward to simply select the MP with the highest long-term yield (remember that all of the remaining methods have passed the biological performance limits and targets, or bracketing approach described above), it is incumbent upon the scientists most closely involved in the analysis to evaluate management procedures according to the quality of the data they rely on, the assumptions of the methods, and the applicability of particular management procedures within the current management regime.

It is important to consider the types of data that different management procedures make use of in calculating management recommendations like a catch limit or effort control, and to prioritize those management procedures that use the most reliable data available. For example, in examining possible management procedures for CA halibut, the Working Group noted the fact that the CPUE index is stable whereas the landings have dropped at the same time. One explanation for this was that the landings data are primarily commercial, while the CPUE index comes from the Commercial Passenger Fishing Vessel data, which is part of the recreational fishery. It was speculated that the stable CPUE index from the recreational fishery may not represent a stable abundance, but rather may reflect hyperstability in this index, as recreational anglers tend to adjust to declining abundance by fishing harder in areas of localized abundance, hence masking an overall decline in stock-wide abundance.

The lack of representative catch and effort data from the other fleets targeting halibut in Southern California meant that it was not possible to construct alternative indices of abundance for this stock (Maunder et al. 2011), and despite its limitations the CPFV data was considered the most reliable source of information. However, it is important to determine if hyperstability is occurring, possibly through robustness testing of the CPUE index, and identify whether that index is a reliable measure of stock abundance. This is especially important if management is considering relying on a management procedure that uses that index of abundance, such as the acceptable and available output control method identified for CA halibut in this study with the highest long-term yield, *Itarget1*. This example highlights the importance of understanding the quality and source of data being relied upon, as well as the relationships between data sources, before selecting a final management procedure to use in management.

It is also essential to consider whether a management procedure is prescribing a type of management control that is compatible with the current management system and is most likely to be complied with and enforceable in the real world. For example, the only method that was acceptable and available for warty sea cucumber in the MSE conducted for this project is an output control that relies on a TAC. However, as was discussed by the Working Group, a TAC would be particularly challenging to implement, monitor, and enforce for this fishery due to the expense and logistics of maintaining an effective system for a relatively small fishery. Alternative management controls, like a minimum size limit, were also identified as challenging due to difficulties in measuring animals that change shape and size significantly once they are cut and dried. This led the Working Group to discuss the possibility of controlling effort through hard seasonal closures, which appeared to offer the best opportunity for effective management. It was therefore recommended that new management procedures be developed that work similarly to the acceptable and available output control method, but instead of prescribing a TAC, would provide for similar changes in fishing effort. These newly developed MPs could be tested in the same MSE framework to identify the method that best meets the management objectives of the fishery.

Providing Scientific Peer Review & Triggers for Updating MSEs

Providing efficient and thorough scientific peer review of the DLMtool process is essential to ensuring that the resulting management recommendations are prudent and reliable. We recommend that any new MSE, whether conducted with DLMtool or not, should undergo an independent review akin to the kind of evaluation done for benchmark stock assessments. Once the results have been accepted and a management procedure selected for use in a fishery, routine updates of the fishery data used with the management procedure should occur on a predetermined, regular schedule (e.g., annually or biannually). This step – in which the CDFW scientist responsible for that stock updates and processes the most current fishery data, enters it into the DLMtool Data Table, and applies the management procedure with the updated data – should be reviewed through an internal mechanism in an expedited fashion.

Management strategy evaluations should be revisited periodically to ensure the resulting management recommendations are based on the best available scientific information. CFDW should develop specific criteria, or triggers, for determining when an MSE update is necessary. One trigger for a new MSE is when substantial new information on a stock's life-history, biology, productivity, or vulnerability becomes available such that the existing MSE operating model no longer represents the understanding of the fishery. A second trigger could involve performance indicators, such as the anticipated amount of variability in catch or effort under a particular management procedure, diverge from the actual experience in the fishery over a period of time. Another trigger could occur when new information on a stock becomes available, perhaps as a result of a new research program, and that new type of data unlocks a heretofore unavailable management procedure that previous MSEs have shown would improve performance in the fishery. Changes in the management system that make different classes management procedures possible (e.g., TAC instead of an effort control), or evidence that an existing management type is not being adequately complied with, monitored, or enforced, would also provide a basis for redoing an MSE. CDFW should also consider implementing a predetermined time limit for using an MSE before it must be updated (e.g., 5, 7, or 10 years).

Stakeholder Engagement

A management strategy evaluation can be a powerful tool for engaging stakeholders in the process of identifying and understanding management objectives and trade-offs in how specific fisheries may be managed over time. The process also provides opportunities for input on questions of governance, such as how to design a management system that can provide high levels of compliance, can be implemented and monitored efficiently by the state, and achieves the objectives of the fishery as articulated in a specific set of performance metrics. Engaging stakeholders early in the process, especially when a new scientific process is being used for the first time, is important for educating stakeholders on how the process works and how and when they can provide important feedback into the process. Successful stakeholder engagement will enhance the credibility of the management system with the public, set expectations appropriately, and improve compliance and enforcement.

We recommend that CDFW convene a public process for explaining how the MSE approach works, its benefits and limitations, and how stakeholders may participate. For fisheries where CDFW has decided to use the MSE, it is suggested that the Department solicit information from key stakeholders early in the process regarding the overall objectives of the fishery (e.g., what would represent a successful fishery?), details for how it operates, concerns about the current status of the stock and the fishery, information and data that may help inform the operating model or DLMtool data tables, and feedback on the most effective mechanisms for management (e.g., input vs. output controls). Various fora exist for stakeholder engagement among different fisheries, such as the task forces established for abalone and Dungeness crab, and the commission for sea urchin. These can serve as potential models for convening new stakeholder engagement mechanisms, along with more ad hoc stakeholder processes that have been used in the past for the sand bass and kelp bass fisheries and for Pacific halibut. Further public notice and comment, consistent with the state's administrative law requirements, should occur following all necessary internal scientific peer review of the MSE and method application results.

Collecting, Processing & Using Fishery Data in a Timely Manner

The Fishery Information Data Table is used for the application of management procedures, and thus the recommendation from a management procedure critically depends on the fishery data entered into the table. For example, output control methods often use estimates of total landings in recent years to scale the recommended total allowable catch limit. Accordingly, the accuracy and reliability of the catch records affect the performance of the management procedure. Moreover, many methods use an index of relative abundance, often catch-per-unit-effort (CPUE), to determine population trends and to provide management recommendations. There are often numerous ways to process and analyze CPUE data (called CPUE standardization methods), and it is not always clear which method is best or most appropriate for a fishery.

Furthermore, data often comes from disparate sources and needs to be combined or summarized in some way. Therefore, it is important that the researchers that are familiar with the history and dynamics of the fishery are involved in the processing of the fishery data, particularly with the time-series information. For example, the catch statistics for the California halibut stock, used as a case study in this project, came from several different commercial fleets and two recreational fleets, and was stored in numerous different databases. The processing and aggregating of these data was only possible by the CDFW staff who had familiarity with the different data sources, and the systems in which the data was stored.

In addition, the CPUE index for the California halibut was developed from data from the Commercial Passenger Fishing Vessel fleet, although some catch and effort data also exist for the trawl fleet. In situations like this, a decision needs to be made regarding the reliability of the various data streams, and which should be included in the CPUE standardization procedure. In the case of the California halibut, this process was relatively straightforward as information from the recent stock assessment could be used to make and justify these decisions. However, in the absence of this information, or CDFW scientists who were familiar with the history of the fishery and the characteristics of the different data sources, it would be difficult for an analyst to determine which method or data would be most useful for developing the CPUE index. Although an analyst with little first-hand experience with the fishery can run an MSE using the DLMtool, it is important that researchers with knowledge of the various aspects of the fishery are involved in analyzing the fishery data and populating the fishery data table. It is also very important for any scientist who is applying the DLMtool or similar MSE framework, and interpreting the results, are trained in population dynamics, modelling, and other fundamental aspects of fisheries science.

An advantage of the management procedure approach is that it is typically very straightforward to provide updated management advice when new data becomes available. However, it is important to be aware that DLMtool's management strategy evaluation operating model assumes that there is no lag in data collection and that data from one year is immediately available the following year. In reality, there is sometimes a lag between the collection of the data and the processing into a form that can be used by a management procedure. For example, although the information has been collected, the fishing effort data for the red sea urchin fishery was only available up to 2013 and therefore the CPUE index did not include the two most recent years. While it is possible to modify the DLMtool to incorporate this lag, most data-limited methods typically do not require large amounts of data processing. Therefore, an important aspect of the management procedure approach is maintaining an efficient data collection and processing system that ensures that there is little delay between collecting the fishery information and processing it in a form that can be entered into the Fishery Information Data Table.

Such data systems could involve processes for ensuring that data are entered quickly and efficiently, and standardized reporting systems for extracting and summarizing the information. With respect to the former, quality control checks and other diagnostics could be developed to flag possibly erroneous data records. Well documented and standardized data systems would ensure that the data processing process is consistent between years and not dependent on the knowledge or experience of a single person within the organization.

To best support the adaptive management process, we recommend that CDFW engage in a review of its fishery information databases to improve efficiency and throughput for use in DLMtool and the stock assessment process. This review should include a member of any future MSE team at CDFW, as well as a number of staff scientists involved in collecting and processing fishery data. We further recommend the development of a repository designed to house all processed fishery data in a single database, accessible by all authorized CDFW staff. The format of such a database could be made compatible with the DLMtool Fishery Information Data Tables, thereby saving time and redundancy in effort as the DLMtool is applied across multiple species. Automated quality control checks should be included as part of the data entry process.

Potential Additional Extensions to the DLMtool

A central aim of this project was to evaluate the utility of the DLMtool for managers to evaluate, select, and apply a suitable management procedure for data-limited fisheries in California. The CDFW Working Group identified a number of extensions to the DLMtool that would be valuable for use in California and beyond. Some of these were incorporated into the DLMtool as part of this project (see page 50), while others proved beyond the scope of this phase of the project. We recommend that CDFW consider the following extensions and DLMtool development work if the state decides to move forward with its use in management.

Implementation Error Model

The DLMtool currently assumes that all recommendations (e.g., catch limit, size limits, etc.) from the management procedures are perfectly implemented. An implementation error model is necessary to account for actual catch levels above or below the total allowable catch limit, to account for discard mortality that is associated with catch and size limits, and to account for fluctuations in effort above or below any prescribed effort control. It is important to model the potential failure of prescribed management procedures since this may alter the performance picture (for example favoring more conservative management procedures if the likelihood of overages is relatively high). Accounting for implementation error may be particularly important when comparing different classes of management procedures. For example, it may be easier to monitor and enforce input controls, such as fishing effort recommendations (e.g., days-at-sea) or marine reserves, than output controls that prescribe total catches. However, in a data-limited setting, determining credible scenarios for implementation error requires data on non-compliance, enforcement strategy, and the probability of detecting infringements, which are not currently available even for many data-rich stocks. Consequently, it was not possible to specify these in a credible way within the scope of this project and, therefore, further development work is required to incorporate this extension into the DLMtool. We recommend this as a high priority and are currently working on developing this for the a future release of the DLMtool.

Conditioning the Operating Model with Historical Fishery Data

The DLMtool was developed for conducting MSE on data-limited fisheries, where, by definition, little data exist on various aspects of the fishery. As such, it is possible to parameterize the DLMtool operating model for a fishery where no information exists on historical exploitation patterns, and very little data on the stock biology or fleet dynamics. Where sufficient information exists, the operating model in the DLMtool can be tuned using the historical pattern of exploitation, including broad patterns in the changes in the size-selectivity pattern and trends in fishing effort. Some of this was done in this project (see page 50). However, in some situations, additional fishery information may exist, such as a time-series of catches for the entire exploitation period, which could be used to further condition the operating model so that it more accurately reflects the history of the fishery and reduces the uncertainty in the MSE.

Management Procedures That Combine Output and Input Controls

The management procedures in the DLMtool are divided into two categories: output controls (catch limits) and input controls (size limits, spatial closures, and effort controls). The CDFW Working Group noted that in some cases there may be an interest in exploring management procedures that involve a combination of input and output controls. Management procedures which include adaptive input and output controls are not common, and it was determined to be difficult to incorporate this recommendation into the DLMtool without extensive reworking of the structure of the model.

This recommendation was identified as a low priority for this project and therefore was not explored in detail. However, for red sea urchin, we ran MSE's with a modified version of the DLMtool that included the presence of a closed spatial area in combination with the other management procedures (see page 70). This was used to compare the MSE results with and without accounting for the MPAs. This approach should be considered preliminary and further development of the DLMtool is necessary if output and input control methods are to be used simultaneously in this way.

Multiple Fleets in the Operating Model

The DLMtool assumes a single fishing fleet that aims to capture the exploitation pattern of the stock aggregated across the different fleets. Many the California fisheries are exploited by multiple fleets with different characteristics, and the Working Group suggested that it may be important to consider this in the application of the DLMtool. Adding additional fleets to the operating model may better represent reality, but this extension would introduce potential issues of different ways of combining data, as well as additional parameters that need to be specified. Furthermore, the data-limited management procedures included in the DLMtool assume that the stock is being managed in aggregate, not on a fleet-by-fleet basis, and return a single management recommendation (e.g., a total allowable catch). While it is possible to modify the DLMtool to include multiple fishing fleets, the required information to parameterize this model is unlikely to be available in many data-limited situations. It was decided that this potential extension was a low priority for the current project, and additional development work is required if this extension is to be included in the DLMtool in the future.

Economic Performance Indicators

A suggestion was made by the Working Group that it may be valuable to include economic indicators as performance metrics when evaluating alternative management procedures. It was agreed that this would be a valuable addition to the DLMtool, but noted that this addition was outside the scope of the current project, particularly due to the lack of information on costs of data-collection, assessment, and implementation of management recommendations.

Additional Spatial Controls

The DLMtool operating model is a spatial model, which, by default, includes two areas, although it is relatively straightforward to increase the number of spatial cells. Spatial management options are possible by selectively closing or opening one of the areas. However, incorporating the effects of existing spatial closures is more difficult in the DLMtool. In some respects, existing spatial closures can be incorporated into the operating model when specifying the bounds for the current level of depletion, which may be assumed to be higher if a sufficiently large area of habitat has been closed to fishing for an extended period of time. However, this does not explicitly incorporate the fact that a proportion of the stock has been, and will remain, inside an area that is closed to fishing.

A modified version of the DLMtool was used for the red sea urchin MSE, that included, in conjunction with other management procedures, a closed spatial area in all future projections (see page 70). These results demonstrated that including the MPA had an impact on the performance of the management procedures, and generally reduced the risk of stock declining to low levels. For technical reasons, it was not possible to include the existence of the MPA in the historical simulations, and the model essentially assumed that the MPA came into existence at the beginning of the projection period (although the effects of the MPA were considered when setting the depletion bounds for this stock). It is not clear if including the historical MPA would have had a significant impact on the relative performance of the alternative management procedures. Moreover, individual MPAs often come into existence during different time periods, and the total size of the no-take area may increase or decrease over time. Future development work on the DLMtool could include existing spatial closures into the operating model, which may be a valuable addition for regions which have an extensive network of areas closed to fishing like California state waters.

In some instances, more sedentary species (e.g. shellfish, echinoderms) may be managed using rotational closures (like harvest rotation in terrestrial farming). DLMtool currently assumes two spatial areas – one that can be closed to fishing in future projections. There was discussion by the Working Group of extending the model to incorporate additional spatial areas, especially for examining the effects of rotational spatial closures for the sea cucumber fishery. This feature would require the inclusion of additional management areas in the model and changes to the design of the spatial closure management procedures.

After discussion with the CDFW, it was decided not to pursue this extension at this stage due to the difficultly of incorporating these dynamics in the current framework and because rotational spatial closures were not considered a feasible management option for the California stocks at the present time due to the large data requirements. Time-closures are possible to simulate in the current framework by reductions in effort or by simulating a fully mixed stock over two areas and closing an area to fishing that is proportional to the seasonal closure. This was explored as an option in the barred sand bass MSE (see page 56).

Automatically Populating Unknown Operating Model Parameters

A final additional development for the DLMtool would be a series of functions that could be used to extract information from the fishery data to populate the operating model parameter tables. For example, numerous models have been developed to estimate the parameters of the von Bertalanffy growth model from size frequency data. While these methods may in some cases be crude, they could be used to derive broad ranges for the growth parameters that encompass reasonable bounds based on the data. In addition, numerous studies have demonstrated general correlations in life history parameters. Models could be developed in the DLMtool that take all existing life history information in the fishery data table, e.g., from biological studies, and use the results of these empirical relationships to derive reasonable bounds for the remaining life history parameters. Finally, catch-at-age, length structure, or catch and effort data may be used to determine likely bounds on the current depletion parameter, which is usually unknown but can be important for driving the dynamics of the MSE model. However, even if these models were included, analysts still must ensure that sufficient time is spent examining the parameters to ensure that they correspond to what is known about the fishery.

Developing New & Modified Management Procedures

The DLMtool includes a wide range of data-limited management procedures, many of which have been published and applied elsewhere, and some that have been developed specifically for this project. Many management procedures have "tuning parameters" that affect the performance of the method. For example, methods often have parameters that control the responsiveness of the harvest control rule to different signals in the data. Many of these alternative configurations have been included in the DLMtool (e.g., *Itarget1* and *Itarget4*). However, there are essentially an infinite number of alternative management procedures and it is not possible to explore the fine-scale tuning of the methods while simultaneously comparing vastly different management methods. One possible use of the DLMtool, which was not explored in this study but may be useful in the future, is to use the model to identify the best performing methods and then to develop and explore alternative parameterizations or combinations of these methods. This may include developing novel harvest control rules based on the specific characteristics of different fisheries.

Appendix A: California Fisheries DLMtool Working Group

Name	Organization	Title
Tom Carruthers	University of British Columbia	Research Associate Scientist
Todd Gedamke	MER Consultants	Senior Scientist
Adrian Hordyk	University of British Columbia	Postdoctoral Scientist
David Newman	Natural Resources Defense Council	Fisheries Policy Expert
Lisa Suatoni	Natural Resources Defense Council	Senior Scientist
Tom Barnes	CA Dept. of Fish & Wildlife	Program Manager, State Marine Finfish Fisheries
Kathryn Crane	CA Dept. of Fish & Wildlife	Environmental Scientist
Heather Gliniak	CA Dept. of Fish & Wildlife	Environmental Scientist
Carlos Mireles	CA Dept. of Fish & Wildlife	Environmental Scientist
Derek Stein	CA Dept. of Fish & Wildlife	Environmental Scientist
Chuck Valle	CA Dept. of Fish & Wildlife	Senior Environmental Scientist
E.J. Dick	National Marine Fisheries Service	Research Fisheries Biologist
Leila Sievanen	CA Oceans Science Trust	Associate Scientist
Bob Bertelli	CA Sea Urchin Commission	Vice Chairman
Ken Franke	Sportfishing Association of CA	President
Steve Crooke	Sportfishing Association of CA	Senior Advisor
Bruce Steele	Independent	Commercial Fisherman
Huff McGonigal	Fathom Consulting	Principal
Jono Wilson	Nature Conservancy	Senior Fishery Scientist
Mike Weber	Resources Legacy Fund	Program Officer

Appendix B: Operating Model Input Parameters

Each parameter is briefly described, with the "slot" name used in the DLMtool R code and spreadsheet in parentheses. The DLMtool is a stochastic model and most input parameters are required to be specified as a range (i.e., a minimum and maximum value). The model randomly draws parameter values from a uniform distribution with bounds specified by these input parameters for each simulation. Some derived parameters in the OM also vary by year. For example, mean natural mortality (M) is sampled for each simulation, together with a sampled of inter-annual variability in M (Msd), and (if used) a mean gradient in M (Mgrad). A vector of M by year is generated for each year in the simulation, where M is sampled from a log-normal distribution using the mean and standard deviation sampled for that simulation. This same process occurs for all parameters with inter-annual variability (i.e., those with parameters for standard deviation). The stochastic nature of the DMLtool is fundamental to transparently accounting for the inherent uncertainty in the input parameters of the simulation model. This is important for identifying the management procedures that perform the best in meeting the management objectives and are most robust under conditions of high uncertainty.

Stock Model

Slot Name	Type	Example	Description
Name	character	"Tile fish"	Name of the Stock object
maxage	integer	23	The maximum age of the individuals that are simulated (there is no "plus group" - individuals die-off beyond the maximum age so there is not a cost to simulating more older age classes).
R0	numeric	1000	The magnitude of unfished recruitment (a scalar and usually not important in MSE)
M	numeric vector	c(0.12,0.18)	Natural morality rate (bounds on) [positive real number]. The mean natural mortality rate of the stock. M is often assumed to be around 0.2 for many fish stocks, although it can be significantly greater for short lived species, and much lower for longer lived species.
Msd	numeric vector	c(0.02, 0.05)	Interannual variability in natural mortality rate (log-normal standard deviation) [positive real number]. Typical values may range from 0 to 0.1.
Mgrad	numeric vector	c(-0.5, 0.5)	Mean slope in natural mortality rate (% change in *M* per year) [real number]. Typical values may range from -0.5 to 0.5. Time-varying natural mortality rates are an active area of research (see for example Johnson *et al.*, 2014).
h	numeric vector	c(0.3, 0.8)	Recruitment compensation (steepness) [real number bounded between 0.2 and 1)
SRrel	integer	1	Type of stock-recruitment relationship: (1) Beverton Holt (2) Ricker
Linf	numeric vector	c(187, 199)	Maximum length of individuals (von Bertalanffy L_∞) [positive real number]
K	numeric vector	c(0.08, 0.14)	Maximum growth rate of individuals (von Bertalanffy κ) [positive real number]

t0	numeric vector	c(-0.5, -0.1)	Theoretical age at zero length (von Bertalanffy t_0) [real number]
Ksd	numeric vector	c(0.05, 0.15)	Interannual variability in K parameter (% per year) [positive real number]
Kgrad	numeric vector	c(-0.5, 0.5)	Mean slope in K parameter (% per year) [real number]
Linfsd	numeric vector	c(0.05, 0.15)	Interannual variability in Linf parameter (% per year) [positive real number]
Linfgrad	numeric vector	c(-0.5, 0.5)	Mean slope in Linf parameter (% per year) [real number]
recgrad	numeric vector	c(-0.5, 0.5)	Mean slope in recruitment deviations (% per year) [real number]
AC	numeric vector	c(0.5, 0.95)	Autocorrelation in recruitment deviations [real numer]
a	numeric	1.04E-06	a parameter of the length-weight relationship $W=aL^b$ [positive real number]
b	numeric	3.051	b parameter of the length-weight relationship $W=aL^b$ [positive real number]
L50	numeric vector	c(145,155)	Length at which individuals are 50% mature
L50_95	numeric vector	c(5,10)	Length increment from 50% to 95% maturity
D	numeric vector	c(0.05, 0.6)	Current level of stock depletion (biomass relative to unfished) [positive real number]
Perr	numeric vector	c(0.2, 0.4)	Process error, the standard deviation of log normal recruitment deviations [positive real number]
Size_area_1	numeric vector	c(0.1,0.1)	Relative size of area 1 [fraction]
Frac_area_1	numeric vector	c(0.05,0.2)	Fraction of the unfished biomass ('habitat') in area 1 [fraction]
Prob_staying	numeric vector	c(0.9, 0.99)	Probability that individuals in area 1 stay in area 1 between years [fraction]
Source	character	"www.url.org"	Primary source of the inputs listed above

Fleet Model

Slot Name	Type	Example	Description
Name	character	"Mostly seining"	Name of the Fleet object
nyears	integer	50	The number of years for the historical simulation. This should be set a close as possible to the length of time that the fishery has been exploited.
Spat_targ	numeric vector	c(1, 1.5)	Fishing in relation to vulnerable biomass (proportional to $vulnerablebiomass^{Spat\_targ}$) [positive real number]
LFS	numeric vector	c(0.75,1.1)	Length at full selectivity (expressed as a fraction of length at 50% maturity)
L5	numeric vector	c(1.5, 2)	Length at 5% selectivity (expressed as a fraction of length at 50% maturity)
Vmaxlen	numeric vector	c(0.5, 1)	The selectivity of the longest length class (controls extent of dome-shaped using a double normal selectivity function) [fraction]
Fsd	numeric vector	c(0.1, 0.2)	Interannual variability in historical fishing mortality rate (log normal standard deviation) [positive real number]
Fgrad	numeric vector	c(-5, 5)	Final historical slope (last five years) in historical fishing mortality rate (% per year) [real number]
qinc	numeric vector	c(-2, 2)	Mean percentage change in fishing efficiency ('catchability', forward projection and input controls) [real

			number]
qcv	numeric vector	c(0.1, 0.2)	Interannual variability in fishing efficiency ('catchability', forward projection and input controls) [positive real number]

Observation Model

Slot Name	Type	Example	Description
Name	character	"Imprecise"	Name of the observation object
LenMcv	numeric	0.2	Controls the range of biases for L50 (length at 50% maturity, lognormal standard deviation) [positive real number]
Cobs	numeric vector	c(0.2, 0.6)	Catch observation error (log normal standard deviation) [positive real number]
Cbiascv	numeric	0.3	Controls the range of biases for annual catch observations (lognormal standard deviation) [positive real number]
CAA_nsamp	integer vector	c(50, 100)	Total number of catch-at-age observations per year [positive integer]
CAA_ESS	integer vector	c(10, 20)	Effective sample size of annual catch-at-age observations (independent draws of multinomial observation model)
CAL_nsamp	integer vector	c(50, 100)	Total number of catch-at-length observations per year [positive integer]
CAL_ESS	integer vector	c(10, 20)	Effective sample size of annual catch-at-length observations (independent draws of multinomial observation model)
CAL_cv	numeric vector	c(0.1, 0.15)	The lognormal variability in length at age (lognormal standard deviation) [positive real number]
Iobs	numeric vector	c(0.2, 0.6)	Relative abundance index observation error (log normal standard deviation) [positive real number]
Mcv	numeric	0.4	Controls the range of biases sampled for natural mortality rate (lognormal standard deviation) [positive real number]
Kcv	numeric	0.1	'' for growth parameter K
t0cv	numeric	0.1	'' for growth parameter t0
Linfcv	numeric	0.1	'' for growth parameter Linf
LFCcv	numeric	0.1	'' for Length at First Capture (first observed length in fishery)
LFScv	numeric	0.1	'' for shortest Length at Full Selection
B0cv	numeric	4	'' for unfished stock size
FMSYcv	numeric	0.2	'' for Fishing mortality rate at Maximum Sustainable Yield
FMSY_Mcv	numeric	0.5	'' for ratio of FMSY to natural mortality rate M
BMSY_B0cv	numeric	0.2	'' for position of most productive stock size relative to unfished
rcv	numeric	0.5	'' for intrinsic rate of increase (surplus production parameter r)
Dbiascv	numeric	0.75	'' for stock depletion (biomass relative to unfished)
Dcv	numeric vector	c(0.5, 1)	Observation error in stock depletion (lognormal standard devation) [positive real number]
Btbias	numeric vector	c(0.2, 5)	Bounds on bias in observations of current absolute stock size (uniform on log) [positive real number]

Btcv	numeric vector	c(0.5, 1)	Observation error in current absolute stock size (lognormal standard deviation) [positive real number]
Fcurbiascv	numeric	0.75	" for current fishing mortality rate
Fcurcv	numeric vector	c(0.5, 1)	Observation error in current fishing mortality rate (lognormal standard deviation) [positive real number]
hcv	numeric	0.3	'' for recruitment compensation (steepness, h)
Icv	numeric	0.4	'' for relative abundance index
maxagecv	numeric	0.2	'' for maximum age
Reccv	numeric vector	c(0.1, 0.3)	Observation error for slope in recent recruitment (absolute recruitment over last 10 years, age 1 individuals)
Irefcv	numeric	0.3	'' for target (reference) relative abundance index (IMSY)
Crefcv	numeric	0.3	'' for target (reference) catch (MSY)
Brefcv	numeric	0.5	'' for target (reference) biomass level (BMSY)
beta	numeric vector	c(0.333, 3)	Bounds on hyperstability / hyper depletion parameter that controls relationship between relative abundance index and biomass (*index(t) = vulnerablebiomass(t)*^{beta}) (uniform on log) [positive real number]

Appendix C: Management Strategy Evaluation Output Object

This is the object that is created in R after the MSE is run. The list below contains the types of data that are created through the simulation.

Slot	Type	Description
General		
Name	character	Name of the MSE object
nyears	integer	Number of years of the historical simulation
proyears	integer	Number of projected years for closed-loop simulation
nMPs	integer	Number of MPs tested in closed-loop simulation
MPs	character vector	Names of the MPs that were tested
nsim	integer	Number of simulations (i.e., historical stock trends and projections)
Operating Model	**Data Frame**	**Sampled Parameters of the Operating Model (a table of nsim rows)**
RefY	numeric vector	Reference yield, the highest long-term yield (mean over last five years of projection) from a fixed F strategy. Used as a reference for framing performance of MPs because it standardizes for starting point and future productivity.
M	numeric vector	Instantaneous natural mortality rate
Depletion	numeric vector	Stock depletion (biomass / unfished biomass) in the final historical year (prior to projection)
A	numeric vector	Absolute abundance (biomass) updated in each management update of projection
BMSY_B0	numeric vector	Most productive stock size relative to unfished
FMSY_M	numeric vector	Fishing mortality rate at MSY divided by natural mortality rate
Mgrad	numeric vector	Mean percentage gradient in natural mortality rate (percentage per time step)
Msd	numeric vector	Interannual variability in natural mortality rate (lognormal standard deviation)
procsd	numeric vector	Process error - standard deviation in log-normal recruitment deviations
Esd	numeric vector	Interannual variability in historical effort (fishing mortality rate)
dFfinal	numeric vector	Gradient in fishing mortality rate over final five years of the historical simulation
MSY	numeric vector	Maximum Sustainable Yield
qinc	numeric vector	Mean percentage increase in fishing efficiency (catchability) in projected years (input controls only)
qcv	numeric vector	Interannual variability in future fishing efficiency (catchability) in projected years (input controls only)
CALcv	numeric vector	Variability in lengths at age around the growth curve (normal standard deviation)
FMSY	numeric	Fishing mortality rate at Maximum Sustainable Yield

	vector	
Linf	numeric vector	Maximum length (von Bertalanffy L_∞ parameter)
K	numeric vector	Maximum growth rate (von Bertalanffy κ parameter)
t0	numeric vector	Theoretical length at age zero (von Bertalanffy t_0 parameter)
hs	numeric vector	Steepness of the stock recruitment relationship (the fraction of unfished recruitment at a fifth of unfished stock levels)
Linfgrad	numeric vector	Mean gradient in maximum length (per cent per time step)
Kgrad	numeric vector	Mean gradient in maximum growth rate (per cent per time step)
Linfsd	numeric vector	Inter-annual variability in maximum length (log normal standard deviation)
recgrad	numeric vector	Gradient in recruitment strength (age 1 population numbers) over last 10 years of historical simulations
Ksd	numeric vector	Interannual variability in maximum growth rate (log normal standard deviation)
L50	numeric vector	Length at 50% maturity
LFS	numeric vector	Length at full selection (the shortest length class where fishery selectivity is 100 percent)
L5	numeric vector	Length at 5% selectivity (expressed as a fraction of length at 50% maturity)
Vmaxlen	numeric vector	Selectivity of the longest length class (controls dome shape of selectivity curve)
LFC	numeric vector	Length at first capture, the smallest length that can be caught by the gear
OFLreal	numeric vector	True simulated Over Fishing Limit (FMSY x biomass) updated in each management update of the projection
Spat_targ	numeric vector	Spatial targeting parameter, fishing mortality rate is proportional to vulnerable biomass raised to this power.
Frac_area_1	numeric vector	Fraction of unfished biomass inhabiting area 1 (can be seen as fraction of habitat in area 1 or relative size of area 1)
Prob_staying	numeric vector	Probability that individuals in area 1 remain there between time-steps
AC	numeric vector	Autocorrelation in recruitment
Observation	**Data Frame**	**Sampled Parameters of the Observation Model (a table of nsim rows)**
Cbias	numeric vector	Bias in observed catches
Csd	numeric vector	Observation error in observed catches (lognormal CV)
CAA_nsamp	integer vector	Number of catch-at-age observations per time step
CAA_ESS	integer vector	Effective sample size of multinomial catch-at-age observation model (number of independent draws)
CAL_nsamp	integer vector	Number of catch-at-length observations per time step
CAL_ESS	integer	Effective sample size of multinomial catch-at-length observation model

	vector	(number of independent draws)
Isd	numeric vector	Observation error in relative abundance index (lognormal CV)
Dbias	numeric vector	Bias in observed stock depletion (also applies to depletion Dt for DCAC)
Derr	numeric vector	Imprecision in observations of current stock depletion (log normal CV)
Mbias	numeric vector	Bias in observed natural mortality rate
FMSY_Mbias	numeric vector	Bias in ratio of FMSY to natural mortality rate
BMSY_B0bias	numeric vector	Bias in ratio of most productive stock size relative to unfished
LenMcv	numeric vector	Bias in length at 50 per cent maturity
LFCbias	numeric vector	Bias in length at first capture
LFSbias	numeric vector	Bias in length at full selection
Aerr	Numeric vector	Imprecision in observations of current absolute stock size (lognormal CV)
Abias	numeric vector	Bias in observed current absolute stock biomass
Kbias	numeric vector	Bias in maximum growth rate (von Bertalanffy K parameter)
t0bias	numeric vector	Bias in theoretical length at age zero (von Bertalanffy t0 parameter)
Linfbias	numeric vector	Bias in maximum length (von Bertalanffy Linf parameter)
hbias	numeric vector	Bias in observed steepness of the stock recruitment relationship
Irefbias	numeric vector	Bias in abundance index corresponding to BMSY stock levels
Crefbias	numeric vector	Bias in MSY prediction (target or reference catch)
Brefbias	numeric vector	Bias in BMSY stock levels (target or reference biomass levels)
Time-series	**Arrays**	**Stored Information from the MSE Model**
F_FMSY	numeric 3D array	Stored fishing mortality rate relative to FMSY over the projection (dimensions nsim, nMPs, proyears)
B	numeric 3D array	Stored stock biomass over the projection (dimensions nsim, nMPs, proyears)
FM	numeric 3D array	Stored fishing mortality rate over the projection (dimensions nsim, nMPs, proyears)
C	numeric 3D array	Stored catches (taken) over the projection (dimensions nsim, nMPs, proyears)
TAC	numeric 3D array	Stored Total Allowable Catch (prescribed) over the projection (dimensions nsim, nMPs, proyears)
SSB_hist	numeric 4D array	Stored historical spawning stock biomass (historical simulations - dimensions nsim, nages, nyears, nareas)

CB_hist	numeric 4D array	Stored historical catches in weight (historical simulations - dimensions nsim, nages, nyears, nareas)
FM_hist	numeric 4D array	Stored historical fishing mortality rate (historical simulations - dimensions nsim, nages, nyears, nareas
Effort	numeric 3D array	Stored relative fishing effort over the projection (dimensions nsim, nMPs, proyears)

Appendix D: Fishery Information Data Table Inputs

Slot	Description
Time Series Data	
Year	Years
Cat	Annual catches in weight (landings plus dead discards)
Ind	Relative abundance index (e.g. standardized Catch Per Unit Effort (CPUE), acoustic survey)
t	Duration of data used for DCAC - relevant only to AvC and Dt
AvC	Average catch over time t (for DCAC only)
Dt	Depletion over time t (for DCAC only)
Rec	Index of relative recruitment strength
CAA	Catch-at-age data (frequency of catches in each age class) a matrix years x age classes
CAL_bins	The definition (break points) of the length classes
CAL	Catch-at-length data (frequency of catches in each length class) a matrix years x age classes
Biological Parameters	
Mort	Instantaneous natural mortality rate
L50	Length at 50% maturity
L95	Length at 95% maturity
vbK	Von Bertalanffy κ parameter
vbLinf	Von Bertalanffy L_∞ parameter
vbt0	Von Bertalanffy t_0 parameter
wla	Length-weight parameter a ($W=aL^{b)}$
wlb	Length-weight parameter b ($W=aL^b$)
steep	Steepness of the stock-recruitment function (the fraction of unfished recruitment at 1/5 of unfished biomass)
MaxAge	Maximum age
Selectivity	
LFC	Length at first capture
LFS	Length at full selection
Reference Points	
FMSY_M	The ratio of FMSY to natural mortality rate (typically in the range 0.3 - 1.5)
BMSY_B0	The depletion level corresponding to the most productive stock size (BMSY)
Cref	Target catch level (e.g. a proxy of MSY)
Bref	Target biomass level (e.g. a proxy of BMSY)
Iref	Target relative abundance level (e.g. a proxy of a CPUE near BMSY)
Dep	Current stock depletion (biomass today relative to unfished levels)
Abun	Current stock abundance (absolute, for example in tonnes)
Uncertainties (CV is the coefficient of variation - the standard deviation divided by the mean)	
CV_Cat	Imprecision in historical annual catches
CV_Dt	Imprecision in value of depletion over time t (DCAC only)
CV_AvC	Average catch over time t (DCAC only)
CV_Ind	Imprecision in historical annual relative abundance
CV_Mort	Imprecision in instantaneous natural mortality rate
CV_Rec	Imprecision in historical recruitment strength
CV_FMSY_M	Imprecision in the ratio of FMSY to natural mortality rate
CV_BMSY_B0	Imprecision in the position of the most productive stock size relative to unfished

CV_Cref	Imprecision in the target catch level
CV_Bref	Imprecision in the target biomass level
CV_Iref	Imprecision in the target relative abundance index level
CV_Dep	Imprecision in the estimate of current stock depletion (biomass relative to unfished)
CV_Abun	Imprecision in the estimate of current stock abundance
CV_vbK	Imprecision in the von B. κ parameter
CV_vbLinf	Imprecision in the von B. L_∞ parameter
CV_vbt0	Imprecision in the von B. t_0 parameter
CV_L50	Imprecision in the Age at 50% maturity
CV_LFC	Imprecision in the Length at first capture
CV_LFS	Imprecision in the Length at full selection
CV_wla	Imprecision in the Length-weight parameter a
CV_wlb	Imprecision in the Length-weight parameter b
CV_steep	Imprecision in the Steepness
sigmaL	Imprecision in length composition data
General	
Name	Name of the dataset
Units	Units (e.g. tonnes)
Ref	Reference OFL (e.g. a previous catch recommendation)
Ref_type	Reference OFL type (input control, catch limit)
LHYear	Last historical year of the simulation (prior to projections)
MPrec	A previous recommendation of a management procedure (e.g. a catch limit in tonnes).

Appendix E: DLMtool Management Procedures

More details on the management procedures included in the DLMtool can be found at https://dlmtool.github.io/DLMtool/index.html

Code	Name	Description	Comment
Input Control Methods – Effort			
curE	Current effort	A reference input control that maintains current effort (subject to fishing efficiency changes)	
curE75	75% of Current effort	A reference input control that maintains 75% of current effort	
DDe	Delay-difference assessment with instant update	Sets fishing effort to that consistent with estimated FMSY instantly with no lag	
DDe75	Delay-difference assessment with instant update	Sets fishing effort to that consistent with 75% of estimated FMSY instantly with no lag	
DDes	Delay-difference assessment FMSY seeking	Sets fishing effort to that consistent with estimated FMSY up to a maximum change of +/-10%	Developed for CDFW project
DTe40	Depletion target of 40% B0 using effort control	Modifies effort to reach target depletion of 40% up to a maximum change of +/-10%	Developed for CDFW project
DTe50	Depletion target of 50% B0 using effort control	Modifies effort to reach target depletion of 50% up to a maximum change of +/-10%	Developed for CDFW project
ItargetE1	CPUE target MP	Effort is adjusted to achieve a target CPUE	
ItargetE4	CPUE target MP (more biologically precautionary)	Effort is adjusted to achieve a target CPUE	
ITe10	Index target seeking	Modifies effort to reach target index level (index at BMSY) up to a maximum change of +/- 10%	Developed for CDFW project
ITe5	Index target seeking	Modifies effort to reach target index level (index at BMSY) up to a maximum change of +/- 5%	Developed for CDFW project
LBSPR_ItEff	SPR target seeking MP	Iteratively adjusts Effort based on distance between estimated and target SPR (40%), and slope of recent SPR estimates	Exceeded time-limit and not used in MSE
LstepCE1	Mean length MP	Mean length relative to historical levels is used to alter fishing effort	
LstepCE2	Mean length MP (more biologically precautionary)	Mean length relative to historical levels is used to alter fishing effort	
LtargetE1	Length target MP	Effort is adjusted to reach a target mean length	
LtargetE4	Length target MP (more biologically precautionary)	Effort is adjusted to reach a target mean length	

Code	Name	Description	Comment
Input Control Methods – Size-Selectivity			
LBSPR_ItSel	SPR target seeking MP	Iteratively adjusts size selectivity based on SPR estimates	Exceeded time-limit and not used in MSE
matlenlim	Size selectivity matches the maturity curve	Fishing selectivity at length is the same as fraction mature at length	
matlenlim2	Size selectivity substantially higher than the maturity curve	Fishing selectivity at length is translated (longer lengths) than the fraction mature at length	
slotlim	Size selectivity follows a slot limit	Fishing selects individual between upper and lower bounds based on length at maturity and maximum length	
Input Control Methods – Spatial			
MRreal	Area 1 Marine Reserve with reallocation	Sets a marine reserve in Area 1 and reallocates fishing effort to area 2	
MRnoreal	Area 1 Marine Reserve with no reallocation	Sets a marine reserve in Area 1 with no reallocation of fishing effort to area 2	
Output Control Methods			
BK	Beddington and Kirkwood life-history	Sets a total allowable catch (TAC) according to current abundance and an approximation of FMSY based on length at first capture.	
BK_CC	BK linked to a catch curve	Catch-curve analysis is used to estimate current abundance that is linked to BK FMSY estimate to give the TAC	
BK_ML	BK linked to a mean length	Mean length estimate of current F (abundance) is linked to BK FMSY estimate to provide the TAC	Often returned NA and dropped out of MSE
CC1	Constant catch linked to average catches	TAC is an average of historical catches	
CC4	Constant catch linked to average catches	TAC is 70% of average historical catches	
CompSRA	Age Composition - Stock Reduction Analysis	What constant F creates the current composition, what is FMSY? TAC = FMSY x F / C	
CompSRA4010	CompSRA linked to a 40-10 rule	A 40-10 harvest control rule is added to the CompSRA MP	
DBSRA	Depletion-Based Stock Reduction Analysis	The TAC is M x (FMSY/M) x depletion x unfished biomass (the first three factors are user defined, the fourth is determined by historical catches and stock reduction analysis)	
DBSRA_40	DBSRA assuming current depletion is 40%	DBSRA where stock depletion is fixed at 40%	
DBSRA_ML	DBSRA using mean length to estimate depletion	Mean length estimate of depletion is used to inform DBSRA depletion	Often returned NA and dropped out of MSE
DBSRA4010	DBSRA linked to a 40-10 rule	A 40-10 harvest control rule is added	

Code	Name	Description	Comment
		to the DBSRA MP	
DCAC	Depletion-Corrected Average Catch	An MSY proxy that accounts for catches occurring whilst dropping to productive stock sizes	
DCAC_ML	DCAC using mean length to estimate depletion	Mean length estimate of depletion is used to inform DCAC depletion	Often returned NA and dropped out of MSE
DCAC40	DCAC assuming depletion is 40%	DCAC where stock depletion is fixed at 40%	
DCAC4010	DCAC linked to a 40-10 rule	A 40-10 harvest control rule is added to the DCAC MP	
EDCAC	Extra DCAC	DCAC * 2 * depletion * B0 / BMSY	
DD	Delay-Difference assessment	A delay difference model is fitted to historical abundance indices and catches. The model does not estimate process error.	
DD4010	DD linked to a 40-10 rule	A 40-10 harvest control rule is added to the DD MP	
DepF	Fratio linked to a production curve control rule	Below BMSY, the TAC is multiplied by a production curve i.e. dep x (1-dep) x 4	
DynF	Dynamic Fratio MP	Inferred derivative of surplus production with biomass is used to adjust F in relation to M	
Fadapt	Adaptive F MP	Inferred derivative of surplus production with biomass is used to adjust F between bounds FMSY/2 and 2 FMSY	
Fdem	Demographic FMSY method	FMSY is calculated as r/2 where r is calculated from a demographic approach (inc steepness). Coupled with an estimate of current abundance that gives you the TAC.	
Fdem_CC	Fdem linked to a catch curve	Current abundance estimates from a catch curve are linked to Fdem estimate of FMSY	
Fdem_ML	Fdem using mean length to estimate depletion	Mean length estimate of current abundance is lined to Fdem estimate of FMSY	Often returned NA and dropped out of MSE
FMSYref50	Half of FMSY ref	50% of true simulated TAC	Reference Method
FMSYref75	75% of FMSY ref	75% of true simulated TAC	Reference Method
Fratio	Fixed FMSY to M ratio	FMSY is a fixed fraction of natural mortality rate	
Fratio_CC	Fratio linked to a catch curve	Current abundance estimates from a catch curve are linked to the Fratio MP	
Fratio_ML	Fratio using mean length to estimate depletion	Mean length estimate of depletion is used to inform Fratio abundance	Often returned NA and dropped out of MSE
Fratio4010	Fratio linked to a 40-10 rule	A 40-10 harvest control rule is added to the Fratio MP	

Code	Name	Description	Comment
GB_CC	Geromont and Butterworth constant catch	MSY seeking rule that uses average historical catch as a proxy for MSY	
GB_slope	Geromont and Butterworth CPUE slope	TAC recommendations to stabilize CPUE	
GB_target	Geromont and Butterworth target CPUE and catch	TAC recommendations to achieve target CPUE and target catch	
Gcontrol	G-control MP	Inferred derivative of surplus production with biomass is used to alter the TAC	
Islope1	CPUE slope MP	TAC is adjusted to maintain constant CPUE	
Islope4	CPUE slope MP (more biologically precautionary)	TAC is adjusted to maintain constant CPUE	
Itarget1	CPUE target MP	TAC is adjusted to achieve a target CPUE	
Itarget4	CPUE target MP (more biologically precautionary)	TAC is adjusted to achieve a target CPUE	
LstepCC1	Mean length MP	Mean length relative to historical levels is used to alter the TAC	
LstepCC4	Mean length MP (more biologically precautionary)	Mean length relative to historical levels is used to alter the TAC	
Ltarget1	Length target MP	TAC is adjusted to reach a target mean length	
Ltarget4	Length target MP (more biologically precautionary)	TAC is adjusted to reach a target mean length	
MCD	Mean Catch Depletion MP	MP to demonstrate high information content of depletion TAC = mean catches x 2 x depletion	
MCD4010	MCD linked to a 40-10 rule	A 40-10 harvest control rule is added to the MCD MP	
NFref	No Fishing Reference MP	Catch is set to 0 for all years	Reference Method
Rcontrol	R-control MP	A demographic prior for intrinsic rate of increase is used to firm up surplus production calculation of G-control	
Rcontrol2	Rcontrol with quadratic SP-B relationship	As Rcontrol but fits a quadratic relationship to the derivative of SP with stock biomass	
SBT1	Southern Bluefin Tuna 1	An MP that adjusts TACs according to apparent trend in CPUE	
SBT2	Southern Bluefin Tuna 2	An MP that adjusts TACs according to achieve target CPUE and catch	
SCA	Statistical Catch at Age using SS3	A data-rich stock assessment model using estimates of catch composition, catch, an index, M and growth parameters.	
SPmod	Surplus production based TAC modifier	Inferred derivative of surplus production with biomass is used to adjust the TAC	
SPMSY	Catch-trend MSY MP	Catch trends reflect depletion and combined with catches can be used to	

Code	Name	Description	Comment
		find viable r-K pairs. The TAC is dep x (1-dep) x 2 x r x K	
SPslope	Slope in surplus production MP	Inferred derivative of surplus production with biomass is used to adjust the TAC	
SPSRA	Surplus Production Stock Reduction Analysis	Like DBSRA but uses a surplus production model and a prior for intrinsic rate of increase	
SPSRA_ML	SPSRA using mean length to estimate depletion	mean length estimate of depletion is used to inform SPSRA depletion	Often returned NA and dropped out of MSE
VPA	Virtual population analysis	Data-rich assessment using complete catch-at age data, a relative abundance index and an estimate of natural mortality	Currently not working and not included in CDFW MSE
YPR	Yield Per Recruit	Yield Per Recruit estimate of F0.1 (FMSY proxy) multiplied by estimate of current stock biomass	
YPR_CC	YPR linked to a catch-curve	Current abundance estimates of a catch curve analysis is linked to the YPR MP	
YPR_ML	YPR using mean length to estimate current abundance	Mean length estimate of current abundance is used to inform YPR abundance	Often returned NA and dropped out of MSE
FMSYref	Perfect TAC MP	True simulated FMSY is multiplied by a current estimate of abundance to derive true TAC	Reference Method
Custom MPs for Barred Sand Bass			
BSB_Scls	Summer month fishing closure	Annual fishing effort reduced to 55% of current level to reflect a closed fishing season during the summer months	An approximation, which assumes a linear relationship between fishing effort and season length that may not be realistic for this fishery.
curE50	50% of Current effort	A reference input control that maintains 50% of current effort	
ItargetE1ML	ItargetE1 with a minimum legal length	ItargetE1 method with a minimum legal length of 360 mm	
ItargetE1SL	ItargetE1 with a harvest slot limit	ItargetE1 with a slot limit between 360 and 383 mm	
ItargetE4ML	ItargetE4 with a minimum legal length	ItargetE4 method with a minimum legal length of 360 mm	
ItargetE4SL	ItargetE4 with a harvest slot limit	ItargetE4 with a slot limit between 360 and 383 mm	
LtargetE1ML	LtargetE1 with a minimum legal length	LtargetE1 method with a minimum legal length of 360 mm	
LtargetE1SL	LtargetE1 with a harvest slot limit	LtargetE1 with a slot limit between 360 and 383 mm	

Code	Name	Description	Comment
LtargetE4ML	LtargetE4 with a minimum legal length	LtargetE4 method with a minimum legal length of 360 mm	
LtargetE4SL	LtargetE4 with a harvest slot limit	LtargetE4 with a slot limit between 360 and 383 mm	
MLL350	Minimum legal length method	Minimum legal length of 350 mm	
MLL360	Minimum legal length method	Minimum legal length of 360 mm	
MLL365	Minimum legal length method	Minimum legal length of 365 mm	
SL350_382	Harvest slot limit method	Harvest slot limit between 350 and 382 mm	
SL355_382	Harvest slot limit method	Harvest slot limit between 355 and 382 mm	
SL360_382	Harvest slot limit method	Harvest slot limit between 360 and 382 mm	
Custom MPs for California Halibut			
LogSel600	Arbitrary logistic selectivity curve	Selectivity curve shifted to the right of existing selectivity. Length of first capture = 500 and length at full selection = 600 mm	
LogSel650	Arbitrary logistic selectivity curve	Selectivity curve shifted to the right of existing selectivity. Length of first capture = 550 and length at full selection = 650 mm	
LogSel750	Arbitrary logistic selectivity curve	Selectivity curve shifted to the right of existing selectivity. Length of first capture = 600 and length at full selection = 750 mm	
MLL555	Minimum legal length method	Minimum legal length of 555 mm	
MLL585	Minimum legal length method	Minimum legal length of 585 mm	
MLL615	Minimum legal length method	Minimum legal length of 615 mm	
MLL645	Minimum legal length method	Minimum legal length of 645 mm	
MLL675	Minimum legal length method	Minimum legal length of 675 mm	
MLL705	Minimum legal length method	Minimum legal length of 705 mm	
MLL735	Minimum legal length method	Minimum legal length of 735 mm	
Custom MPs for Red Sea Urchin			
ItargSL1	Itarget1 method that adjusts slot limit	Minimum legal length switches between 86 and 89 mm based on trends in CPUE, and upper limit of 139.7 mm	
ItargSL4	Itarget4 method that adjusts slot limit	Minimum legal length switches between 86 and 89 mm based on trends in CPUE, and upper limit of 139.7 mm	
LtargSL1	Ltarget1 method that adjusts slot limit	Minimum legal length switches between 86 and 89 mm based on trends in mean length, and upper limit of 139.7 mm	
LtargSL4	Ltarget4 method that adjust slot limit	Minimum legal length switches between 86 and 89 mm based on trends in mean length, and upper limit of 139.7 mm	

Code	Name	Description	Comment
MLL3.375	Minimum legal length method	Minimum legal length of 86 mm (3.375 inch)	
MLL3.375_5.5	Harvest slot limit method	Harvest slot limit between 86 and 139.7 mm	
MLL3.5	Minimum legal length method	Minimum legal length of 88 mm (3.5 inch)	
MLL3.5_5.5	Harvest slot limit method	Harvest slot limit between 88 and 139.7 mm	
Custom MPs for Warty Sea Cucumber			
curE50	50% of Current effort	A reference input control that maintains 50% of current effort	
MLL100	Minimum legal length method	Minimum legal length of 100 mm	
MLL120	Minimum legal length method	Minimum legal length of 120 mm	

Appendix F: Management Procedure Data Requirements

Name	Catch (Cat)	Index of Abundance (Ind)	Recruitment (Rec)	Average Catch (AvC)	Relative depletion (Dt)	Natural mortality (M)	FMSY/M (FMSY_M)	BMSY/B0 (BMSY_B0)	Reference Catch (Cref)	Reference Index (Iref)	Length at 50% maturity (L50)	Length at 95% maturity (L95)	Length at first capture	Length at full selection	Catch-at-age (CAA)	Catch-at-length (CAL)	Depletion (Dep)	Abundance (Abun)	Growth (Linf, K, t0)	Stock-recruit (steepness)
Input Controls																				
curE																				
curE75																				
DDe	+	+				+					+								+	
DDe75	+	+				+					+								+	
DDes	+	+				+					+								+	
DTe40																	+			
DTe50																	+			
ItargetE1		+																		
ItargetE4		+																		
ITe10		+								+										
ITe5		+								+										
LBSPR_ItEff						+										+			+	
LBSPR_ItSel						+					+					+			+	
LstepCE1																				
LstepCE2																				
LtargetE1																				
LtargetE4																				
matlenlim											+									
matlenlim2											+									
MRnoreal																				
MRreal																				
slotlim											+									
Output Controls																				
AvC	+																			
BK													+					+	+	
BK_CC	+					+							+		+				+	
BK_ML	+					+							+						+	
CC1	+																			
CC4	+																			

Name	Catch (Cat)	Index of Abundance (Ind)	Recruitment (Rec)	Average Catch (AvC)	Relative depletion (Dt)	Natural mortality (M)	FMSY/M (FMSY_M)	BMSY/B0 (BMSY_B0)	Reference Catch (Cref)	Reference Index (Iref)	Length at 50% maturity (L50)	Length at 95% maturity (L95)	Length at first capture	Length at full selection	Catch-at-age (CAA)	Catch-at-length (CAL)	Depletion (Dep)	Abundance (Abun)	Growth (Linf, K, t0)	Stock-recruit (steepness)
CompSRA	+					+					+		+	+	+				+	+
CompSRA4010	+					+					+		+	+	+				+	+
DAAC				+	+	+	+	+												
DBSRA	+					+	+	+			+						+		+	
DBSRA_40	+					+	+	+			+						+		+	
DBSRA_ML	+					+	+	+			+						+		+	
DBSRA4010	+					+	+	+			+						+		+	
DCAC				+	+	+	+	+												
DCAC_40				+		+	+	+												
DCAC_ML	+			+		+	+	+											+	
DCAC4010				+	+	+	+	+												
DD	+	+				+					+								+	
DD4010	+	+				+					+								+	
DepF						+	+	+									+	+		
DynF	+	+				+	+											+		
Fadapt	+	+				+	+											+		
Fdem						+												+	+	+
Fdem_CC	+					+									+				+	+
Fdem_ML	+					+													+	+
FMSYref																				
FMSYref50																				
FMSYref75																				
Fratio						+	+											+		
Fratio_CC	+					+	+								+					
Fratio_ML	+					+	+												+	
Fratio4010					+	+	+										+	+		
GB_CC	+								+											
GB_slope	+	+																		
GB_target	+	+							+	+										
Gcontrol	+	+																+		
HDAAC				+	+	+	+	+												
Islope1	+	+																		
Islope4	+	+																		

Name	Catch (Cat)	Index of Abundance (Ind)	Recruitment (Rec)	Average Catch (AvC)	Relative depletion (Dt)	Natural mortality (M)	FMSY/M (FMSY_M)	BMSY/B0 (BMSY_B0)	Reference Catch (Cref)	Reference Index (Iref)	Length at 50% maturity (L50)	Length at 95% maturity (L95)	Length at first capture	Length at full selection	Catch-at-age (CAA)	Catch-at-length (CAL)	Depletion (Dep)	Abundance (Abun)	Growth (Linf, K, t0)	Stock-recruit (steepness)
IT10	+	+								+										
IT5	+	+								+										
Itarget1	+	+																		
Itarget4	+	+																		
ITM	+	+				+				+										
LBSPR_ItTAC						+					+	+				+			+	
LstepCC1	+																			
LstepCC4	+																			
Ltarget1	+																			
Ltarget4	+																			
MCD	+																+			
MCD4010	+																+			
Rcontrol	+	+				+											+	+	+	+
Rcontrol2	+	+				+											+	+	+	+
SBT1	+	+																		
SBT2	+		+						+											
SPmod	+	+																+		
SPMSY	+										+								+	
SPslope	+	+																+		
SPSRA	+					+											+		+	+
SPSRA_ML	+					+													+	+
YPR						+								+				+	+	
YPR_CC	+					+								+	+				+	
YPR_ML	+					+								+					+	

Appendix G: DLMtool Functions

Function	Arguments	Description
DLM Data Objects		
Can	DLM_data (a DLM_data object)	What MPs can be applied to a DLM_data object? *Can(Canary_Rockfish)*
Cant	DLM_data (a DLM_data object)	What MPs can't be applied to a DLM_data object? *Cant(Canary_Rockfish)*
Needed	DLM_data (a DLM_data object)	What data are needed to make MPs work with DLM_data object *Needed(Canary_Rockfish)*
Required	MPs (a character vector of MPs, optional)	What are the data requirements of the various MPs? *Required()*
replic8	DLM_data (a DLM_data object), nrep (number of replicate positions)	Extend DLM_data object to nrep positions *replic8(Canary_Rockfish, 10)*
DLM_output	x (position in data object), reps (number of TAC samples),	Calculate TAC *sapply(1,DLM_output, DLM_data, nreps=50)*
summary	DLM_data (a DLM_data object)	Data summary *plot(DLM_data)*
TAC	DLM_data (a DLM_data object), MPs (character vector of MPs to apply, optional), reps (number of TAC samples), maxlines (maximum number of lines per plot), perc (a percentile line to draw through TACs), xlims (custom graph width)	Calculates the TAC for all applicable MPs (or those specified by MPs) *TAC(DLM_data, MPs=NA, reps=100, maxlines=6, perc=NA, xlims=NA)*
plot	DLM_data (a DLM_data object that has had TAC run on it)	Plots TACs *plot(DLM_data)*
DLM Operating Model Objects		
runMSE	OM (operating model object), MPs (character vector of MP names), nsim (number of simulations), reps (number of TAC samples), proyears (number of projected years), interval (number of years between management updates), custompars (a table nsim by npars providing custom samples of parameters)	Runs a closed-loop simulation *runMSE(OM,MPs,nsim=20,reps=1,proyears=30,interval=5,custompars=0)*
MSE Objects		
Tplot	MSEobj (an MSE object), nam (the title of the plot optional)	Plots the tradeoff among several performance metrics including relative yield (yield in last 5 years of projection compared with the best fixed-F strategy), probability of overfishing, P10, P50 and P100 (probability of dropping below 10, 50 and 100% of BMSY over entire projection). *Tplot(MSE)*

Tplot2	MSEobj (an MSE object), nam (the title of the plot optional)	An alternative to Tplot that plots short-term yield (fraction of simulations achieving over half FMSY yield over the first 10 years of the projection), long term yield (fraction of simulations achieving over 50% FMSY yield over the final ten years of the projection), variability in yield (fraction of simulations achieving less than 10% average annual variability in yield) and biomass (fraction of simulations that remain above 10% BMSY).
Kplot	MSEobj (an MSE object), maxsim (maximum number of simulations to plot), nam (the title of the plot optional)	Kobe plot showing progression of time series over the projection in relation to FMSY and BMSY. *Kplot(MSE)*
Pplot	MSEobj (an MSE object), nam (the title of the plot optional)	Projection plot showing trend in biomass and fishing mortality rate relative to MSY levels. *Pplot(MSE)*
VOI	MSEobj (an MSE object), ncomp (maximum number of variable to examine), nbins (number of equally spaced percentile bins over which to evaluate utility), maxrow (maximum number of rows, MPs, in each plot), Ut (a custom utility matrix of nsim rows and nMP columns, optional), Utnam (custom utiltiy name for plotting)	Value of information plot that detects relevant operating model and observation model parameters that are most correlated with utility. The top ncomp parameters are plotted in descending order of importance in determining utility (left to right). *VOI(MSEobj, ncomp=6, nbins=10, maxrow=8, Ut=NA, Utnam="Utility")*
plot	MSEobj (an MSE object)	Runs Tplot, Kplot and Pplot *plot(MSE)*
summary	MSEobj (an MSE object)	Summarizes performance trade-offs in terms of relative yield, probability of overfishing, P10, P50 and P100 *summary(MSE)*
CheckConverg	MSEobj (an MsE object), thresh (numeric: percentage convergence criterion), plot (logical: produce a plot)	Evaluates convergence of the MSE - have performance metrics stabilized or are more simulations needed?
General		
avail	classy (class of object e.g.' Stock')	Lists all objects in the current workspace of class classy *avail('Stock')*
DLMDataDir	none	Provides the location of example DLM_data .csv files on your machine *DLMDataDir()*
Fease	Class of object DLM_fease	What MPs are feasible given certain data inputs?

Appendix H: DLMtool Data Availability Questionnaire

There are two main components to the DLMtool that require inputs: 1) the management strategy evaluation operating model (MSE model), and 2) the application of management procedures data identified as most suitable from the management strategy evaluation.

The MSE model requires around 70 different parameters to be specified to run (see Appendix B). The model is completely stochastic, which means that there is uncertainty attributed to all parameter values and processes, and almost all the parameters require two values: a minimum and maximum value that capture the range of possible values for the parameter. Some of these parameters may be quite well known, for example growth, and the range may be quite narrow. In other cases, and especially for data-limited stocks, no information may exist for specific parameters. In these cases, expert judgement and meta-analysis studies may be used to set wide ranges that reflect this uncertainty. This uncertainty is propagated through the MSE; the relative performance of the different management procedures and the impact of this uncertainty is one of the key outputs of the model.

A key objective of the MSE using the DLMtool is to identify the data-limited management procedures that are most likely to meet the chosen management objectives. The next step involves applying these selected management procedures to the fisheries in question. A comprehensive understanding of fishery characteristics and available data is required to determine which of the management procedures can be applied to the fisheries. This questionnaire is intended to provide a guide for the collection and aggregation of existing information and data. The accompanying Fishery Information Data Input Table is used for entering the available data into a form that can be inputted to the DLMtool (see Appendix D). The format of this document follows the structure of the DLM data object in the DLMtool. There is some overlap in the inputs for both tables, for example, estimates of the growth and mortality parameters (although the format is slightly different).

It is important to note that the aim here is to identify and aggregate the relevant meta-data and existing data for the fisheries. The MSE Input Table, Fishery Information Data Input Table, and the questionnaire below details all the data inputs that the DLMtool can accommodate. Particularly in data-limited fisheries, there may be many data types that do not exist. Identifying the absence of such data is also important, as it can be used in the "value of information" analysis.

The questions and bullet points below are intended to guide the process of documenting the available data. Some data may be entered into the Tables as numeric values (e.g., growth and mortality), or some questions may be answered with a simple yes or no. Other data sources may be more complex and may require extra details to explain the data characteristics and availability. A short narrative or description of the data source is useful in these situations. This information will enable expert fisheries scientists trained in DLMtool to determine what type of further analyses may be required for use as inputs to the MSE and/or Fishery Information Data Tables.

Description of Fishery

- Species Range/Spatial Extent of Fisheries:
    - Does the species range extend beyond the boundaries of these data collection efforts?
    - Is the species migratory or does it have limited movements (i.e. reef fish vs. tuna)?
    - Does fishing occur on the complete depth and spatial extent of the species or are there de facto reserves (i.e. no fishing at deepest range of species or location too far from nearest port)?
- Does fishing occur consistently year round? If not, when does season start and end and/or what are most heavily fished months (Some idea of landings/species/month/area necessary for sampling design)?
- What are approximate total landings (if not known, ballpark order of magnitude; 1000's of lbs., 1000's of tons, etc.). How many landings sites? Are landings distributed evenly at each landing site or do one or a few sites comprise most landings? A list, and if possible a map, of landings sites with approximate contributions to fishery is extremely informative for the development of a sampling design.
- Are fishing licenses required and if so, is it by boat, owner, or individuals? Any requirement to report how many days or landings at renewal? If annual renewal, for how many years do you have records?
- How many boats make up the fishery? If vessels are of different sizes/capacities, what percentage of each type/size is used in the fishery? For each vessel type/size, what are average landings/trip and/or average landings/year?
- What is the 'normal' trip length (hrs /days) by vessel type? Does fishing occur all days of week or does the market drive fishing for particular days?
- Have fishing behaviors or practices changed over time? For example, has the fishery moved from a purse seine to longline gear or have larger vessels become more common?
- Are FAD's utilized? If so, do logbook forms indicate the use of a FAD - yes/no? If yes, are design, size, length of deployment, depth, and/or other specific details of the FAD collected?
- Is any at-sea processing done or are fish landed whole?
- Are multiple gear types used to harvest the species complex or does a single gear type dominate the fishery/habitat being fished?
- If multiple gear types are used, provide a list of the gears used and approximately what percentage each gear type contributes to removals.

Historical Management Measures

Is there a record of management measures? If any of the below apply, when were they implemented, are they still in place (i.e. need timeline of management measures), and are they well enforced?

- Are there any marine reserves? Do they include representatives of the major types of habitats used by priority species throughout their life cycles?
- Have there been effort restrictions on the fishery (e.g. crew size, trip length, maximum allowable catch per trip, maximum number of traps, etc.)?
- Have there been changes in allowable gear (e.g. minimum hook size, minimum mesh size changes, etc.)?
- Have minimum and/or maximum size restriction been placed on catch?
- Are there any written or unwritten self-imposed (e.g. fishing community decisions, cultural taboo practices) practices that we should be aware of? For example, in Chile, one fishing community I worked with stopped fishing on Tuesdays because they noted declining catch rates.
- Any other existing management in place?

Constraints on Potential Management Procedures

Are there likely constraints or restrictions on potential management options? For example, size limits, catch limits, spatial closures.

Data Availability

- Aggregate Time-Series:
    - Catch time series – do landing records exists?
    - Years – over how many years?
    - How close are reported landings to actual landings of the stock (e.g. reporting rate of 50% fishers, or from 50% of landing sites)?
    - Average catch – an estimate of average catch. This can be calculated from catch time series and number of years.
    - Discards
    - Index of abundance – does an index of abundance exist? Over how many years? How is the index calculated? Fishery dependent (e.g., CPUE) or fishery independent (e.g., scientific survey)
- Estimate of depletion – is there an estimate of current depletion?
- Recruitment time-series – are there records of historical recruitment trends?
- Catch-at-age data – Does catch-at-age data exist? If yes, for how many years and what are approximate sample sizes? These can be tabulated as a matrix with counts of catch-at-age in columns and years in rows.

- Catch-at-length data - Length frequency of the catch? If yes, for how many years and what are approximate sample sizes? These can be tabulated as a matrix with counts of catch-at-length in columns and years in rows.

Species Biology

- Natural mortality – is there an estimate of natural mortality for the stock?
- Maturity – does information exist on the age and/or length at maturity?
- Fecundity – is there information on fecundity and age, weight or length?
- von Bertalanffy growth parameters – length at age data or known age/growth relationship (i.e. von Bertalanffy parameters)?
- Length-weight parameters – Weight at Length data or known relationship?
- Recruitment –Are there any estimates of the stock-recruitment relationship? Steepness of stock-recruitment relationship? Inter-annual variability in recruitment – e.g., highly variable or relatively stable between years? Do you see really good years and/or really bad years (indicative of recruitment driven fishery)?
- Maximum age – what is the maximum observed age?
- What is the maximum size of the species?
- Do they live in the same habitat their whole lives or do you find them at different sizes in different places (e.g. small fish/juveniles live in mangrove habitats and the larger adults live on reefs; or larger fish are found in deeper water)?

Selectivity and Catchability

- Length at first capture – what is the length at first capture for the species?
- Length at full selection – what is the length at full selection for the species?
- Any other information on the selectivity pattern of the fishery (e.g., large fish are avoided/targeted because of …)
- Is fishing better, worse, or the same as in the past (specify time frame; e.g. 5, 10, 25, or 50 years ago)? If not the same, how much longer/shorter does it take to catch the same amount as before?
- What is the minimum, maximum and most common size of the fish caught by the gear (indicate gear type; for nets include mesh size; for hook/line/longline include hook size)?
- What gear types are used in the fishery (e.g. 90% caught in longlines, 10% caught on handline hook and line)?
- Are all sizes retained or, for example, are small fish returned to sea? If some are returned, what percentage would you expect to survive (e.g. 50% of fish survive)?
- Has the gear used changed over time (e.g. types of hooks used, bait type, mesh size)? If so, what years did they change?

Reference Points

- FMSY/M – do estimates or proxies exist for the ratio of fishing mortality to natural mortality that results in maximum sustainable yield (MSY)?
- BMSY/B0 – do estimates or proxies exist for the ratio of stock biomass at maximum sustainable yield to unfished biomass?
- MSY – is there an estimate of maximum sustainable yield?
- BMSY – is there an estimate of stock biomass at MSY?
- Current stock depletion – is there an estimate of current stock depletion (ratio to unfished conditions)?
- Current stock abundance – is there an estimate of current stock abundance?

Uncertainties

Please provide an estimate of the level of uncertainty for each of the provided sources of data. For example, a CV of the catch time-series, or CV of the von Bertalanffy L_∞, K and t_0 parameters. See the MSE and Fishery Information Data Input Tables (Appendices B and D, respectively) for the specific parameters that DLMtool can accommodate.

Miscellaneous Information

Units of the catch and biomass time-series (e.g., tonnes).

Other information on the stock or fishery.

Appendix I: Fishery Information Summary – Barred Sand Bass

Description of Fishery

The barred sand bass is an important target species for the Commercial Passenger Fishing Vessel (CPFV) and private recreational fishers in southern California. The species range extends down to Magdalena Bay in Baja California in the south, and to Santa Cruz in the north. Buying and selling of bass species has been banned in southern California since 1953, and since this time the fishery has been exclusively recreational (Love et al 1996; Jarvis et al 2014). The stock has been managed with bag limits since 1939, and a minimum size limit was implemented in 1956. The bag limit and size limit has been modified several times, most recently in 2013, when the bag limit was reduced to 5 bass species in aggregate and a minimum size of 355 mm (Jarvis et al 2014). The barred sand bass form spawning aggregations during the summer months, and it is during this time that the stock is most heavily targeted.

Both the total catch and catch rates of the CPFV fleet increased from 1980 (when reliable records starts) until 2000 (**Error! Reference source not found.**). Data for both catch and catch rates was taken from log-book records from the CPFV fleet in southern California. Both catch and catch rates sharply declined in the early 2000s, and total catches now are lower than in 1980. Reports from CPFV industry suggest that spawning aggregations are sparser and more difficult to find in recent years (H. Gliniak pers. comms 2016). The CDFW is concerned about the decline in catch rates, and the recent management changes implemented in 2013 were an effort to address this issue. No estimate of depletion exists for this stock, but there appears to be general agreement (at least in the CDFW) that stock abundance is lower than in the past.

Recruitment is known to be highly dependent on environmental conditions. Low recruitment occurs during cold water periods, and high water temperature is associated with increased production (Jarvis et al 2014).

The issue of stock delineation is an important issue for the management of many marine species in southern California. The barred sand bass is no exception, with a species range that extends well past the artificial boundary separating US and Mexico waters, down to Magdalena Bay in Baja California. Jarvis et al. (2012) found evidence of high spawning fidelity in barred sand bass, and most migrations of a distance up to tens of kilometers. There is very little information on the catch or other fishery characteristics of the barred sand bass in Mexico waters. Barred sand bass are known to move with changing environmental conditions, and there is undoubtedly some movement of stock across the US-Mexico boundary. The high spawning site fidelity and the targeting of the spawning aggregations may suggest that the US fishery is predominantly exploiting a distinct portion of the stock. The CDFW consider it appropriate to manage the California barred sand bass as a separate stock.

The stock is currently managed by a combination of minimum size and bag limits. The bag limits apply to all bass species in aggregate. Total catch limits are difficult to implement in a recreational fishery, due to the high cost of data collection and aggregation, and difficulty in enforcement.

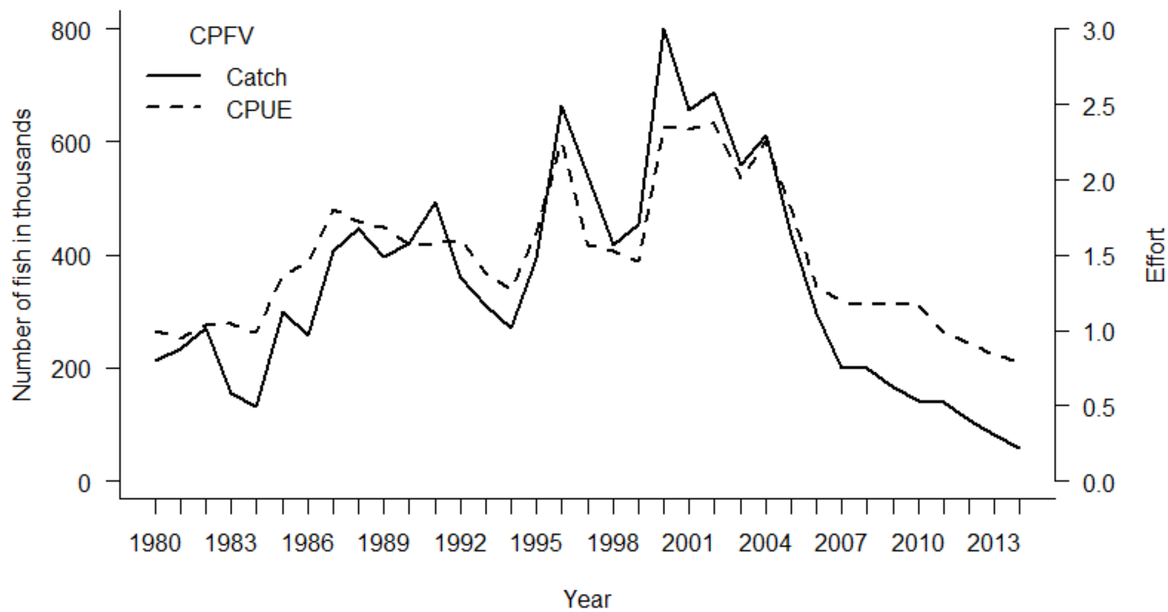

Figure 29: Barred sand bass total catch (solid line) and CPUE (dashed line) from CPFV logbook data from 1980 to 2014 for all blocks and seasons in southern California.

Potential management actions that could be considered and will be tested in the MSE:

- Fixed increase in size limit
- Regular adjustment of size limit by harvest control rule (e.g., mean length method)
- Fixed decrease in total effort – e.g., a seasonal closure during some months of the spawning period to reduce total effort
- Regular adjustment of fishing effort by harvest control rule
- Modify bag limit – either fixed reduction in effort or responsive HCR

The interval of management changes is an important consideration for this fishery. Modifications of regulated bag or minimum size limits is likely to be expensive to implement in a recreational-based fishery, and it is likely that these changes would occur less frequently than a total catch limit on a commercial fishery.

MSE Operating Model Parameters

Stock Inputs

The Stock Table contains all information relating to the fish stock that is simulated in the DLMtool. The sections below provide a description of the parameter bounds determined for the Stock parameters for each case study, together with a brief summary of the information and reasoning on which these values are based. The relevant variable names used in the DLMtool table and operating model are included in parentheses behind each sub-heading. Refer to the MSE Operating Model Input Parameter Table (Appendix B) for a description of each variable, and Appendix M for the values used in the MSE.

Natural Mortality (M)

Jarvis et al. (2014) estimated natural mortality to be 0.218 using Pauly (1980) method. This corresponds to an approximate maximum age of about 21 years which appears to be too low given that individuals above this age have been observed. The upper bound for *M* was set to 0.21, and the lower bound at 0.15, which corresponds to maximum age of approximately 30 years. The oldest observed age in recent years is 24, but the species has a long history of exploitation and this is unlikely to represent the longevity of the species. The maximum age parameter was set to 35, which corresponds to an upper limit for longevity that corresponds to the lower bound on *M*.

Growth (Linf, K, t0, a, b)

Love et al. (1996) provide the only available estimates of the von Bertalanffy growth parameters for the barred sand bass. The ranges for the growth parameters were set at the mean values reported by Love et al. (1996) ± 2 standard deviations: L_∞ = 560.4 – 763.6 mm; *K* = 0.052 – 0.108; t_0 = -3.89 – -1.37. The length-weight parameters were sourced from Miller et al. (2008).

Recruitment (h, Perr, AC)

No information exists on steepness of stock-recruitment relationship for this species, and a range of 0.6 - 0.9 was used, based on the meta-analysis of Myers et al.(2002). Inter-annual variability in recruitment appears to be low, but recruitment error appears auto-correlated and driven by environmental conditions (Jarvis et al. 2014). The recruitment process error (*Perr*) was set at 0.2 – 0.5, and auto-correlation parameter (*AC*) at 0.5 – 0.9.

Maturity (L50, L50_95)

Love et al. (1996) estimated maturity-at-length for both male and females. The range used in this study represents the range of estimates for females and males: *L50* = 219 – 239 mm.

There appears to be a rapid transition from immature to mature state (Love et al. 1996) and the *L50_95* parameter was set to 10 – 15 mm (*L95* is 10 – 15 mm greater than *L50*).

Depletion (D)

No reliable information exists for current depletion for the barred sand bass in southern California. Recent declines in catch rates suggests that stock may be at lower levels. A recent publication suggests that hyper-stability in the CPUE index may have masked a decline in abundance in recent years (Erisman et al. 2011), however scientists at CDFW dispute this interpretation based on the use of inappropriate catch data (Jarvis et al. 2014). The fishery has been managed as a recreational only fishery since the early 1900s, with a minimum legal length at or above the size of maturity since 1956. Furthermore, the size limit was increased in 2013 as a management response to the perceived decline in the stock. The bounds for the depletion parameter were set to 0.20 - 0.60 which capture the uncertainty of a stock at low levels (around half of B_{MSY}), to one that has been exploited but is still above B_{MSY}.

Spatial Information (Frac_area_1, Prob_staying)

The species forms large spawning aggregations that are targeted by recreational fishers, both on private boats and commercial passenger fishing vessels. MPAs are not believed to offer protection to this species because of high movement, and the probability of staying in Area 1 between years (*Prob_staying*) set at 0.095 – 0.105.

General Parameters

The remaining *Stock* parameters had common values across all four case studies. The MSE model is not conditioned on fishery data, and the number of initial recruits (*R0*) is set at an arbitrary 100,000 individuals. There was assumed to be no long-term gradient in the life history parameters (*Mgrad*, *Linfgrad*, *Kgrad* all set to 0). Little information exists on inter-annual variability in natural mortality and growth parameters for the case study stocks, and a common set of values was used for all four species (*Msd* = 0 - 0.05, *Linfsd* = 0 - 0.025, *Ksd* = 0 - 0.025). The maximum age parameter (*maxage*) defines the number of age classes in the simulation model. This parameter is fixed for each case study, and the model is not sensitive to this value, provided it is high enough to account for all values of natural mortality that are included.

Fleet Inputs

The Fleet Table contains all information relating to the historical and future exploitation patterns of the stock. The information in the Fleet Table can be divided into three categories: *exploitation history*, *selectivity*, and *targeting and catchability.* The exploitation history and selectivity pattern varies between the four stocks, and information exists to specify these values. Little specific information is available for the catchability and targeting for these stocks, and common values were used for the four case studies.

Exploitation History (nyears, EffYears, EffLower, EffUpper)

The fishery for barred sand bass in southern California began in the early 1900s, and a historical period of 117 years (1900 – 2016) was used in the model (*nyears*). Hill and Schneider (1999) present the trends in fishing effort from the commercial passenger fishing vessel (CPFV) fleet from 1936 - 1996. Barred sand bass did not contribute a significant amount to the CPFV catch until the mid-1900s. It was assumed that fishing mortality was low from 1900 to 1950, then generally increased from 1950 - 1980. Fishing effort in recent decades appears to have been slightly decreasing since the early 1960s, and declined more steeply in recent years (Erisman et al. 2011).

Selectivity (LFS, L5, Vmaxlen)

A minimum legal length of 266 mm was regulated in 1956. The size limit was increased by 13 mm each year until 1959, when it was set to 304 mm. In 2013 the size limit was increased to 355 mm. The size at selection has been above the size at maturity for most of the history of the fishery. Barred sand bass are targeted by hook and line fishery on spawning aggregations, and selectivity-at-length is assumed to be asymptotic.

Targeting and Catchability (Spat-targ, Fsd, qinc, qcv)

Spatial targeting (*Spat_targ*) was set to 1 for all case studies. This represents a stock that is actively targeted by the fishers. Default values from the DLMtool were used to represent the inter-annual variability in fishing mortality (*Fsd*; 0.1 - 0.4), and annual increase in catchability (*qinc*; 0 - 2; catchability increases by up to 2% per year), and the annual variability in catchability (*qcv*; 0.1 - 0.3).

Observation Inputs

The Observation Table contains the parameters that are used to generate the simulated fishery data within the MSE model. The parameters used for the observation model were based on the values presented in Carruthers et al. (2014) and are found in the 'Generic_obs' observation object in the DLMtool. Common values were used for the observation table for the four case studies, except where information was found to suggest alternative values (see below).

The fishery for the barred sand bass predominantly targets spawning aggregations, and it is possible that the CPUE index is affected by hyper-stability. The range for the beta parameter in the Observation Table to was set to 0.45 – 1.00. Catch-at-length effect sample size (*CAL_ESS*) was increased to 150 – 300 to reflect availability of length data for this species.

Information for Tuning the MSE Operating Model

- Estimates of annual trends in CPFV effort in southern California exist since 1936 (Hill & Schneider 1999). These can be used to tune the general trend in historical effort for the MSE, although it must be noted that sand bass are not the primary target of the entire fleet.
- No estimate of depletion exists, but the recent sharp decline in catch rates, together with the long history of exploitation of spawning aggregations suggest that the stock may be at relatively low levels.
- Long history of management by size limit, above the size of maturity, suggests that the stock has been protected from recruitment overfishing.
- The fishery predominantly targets spawning aggregations, and the CPUE index is likely to exhibit hyper-stability. This can be reflected in the MSE.
- Fishery-independent indices of abundance show similar declining trend in abundance since 2000.

Fishery Information Data Inputs

Two main sources of fishery data were available for the barred sand bass case study: catch-per-unit effort (CPUE) information from the commercial passenger fishing vessel (CPFV) fleet, and size composition data from the recreational fishing surveys.

Catch-Per-Unit-Effort from Commercial Passenger Fishing Vessels

The Commercial Passenger Fishing Vessel (CPFV) logbook data from 1980 to 2016 appears to the most reliable record of catch and effort for the barred sand bass fishery. An onboard observer sampling program for the CPFV fleet has been running since 1999, but we were not provided with this data for this study. Estimates of catch and effort do exist from before 1980 (back to 1936), but these records are not as reliable and are not accessible in compatible digital databases. Prior to 1980 the three species of bass that are commonly caught in southern California were grouped together in a 'bass' category. Some records do exist on the species composition of the catch prior to 1980, and it may be possible to estimate the proportion that each species contributes to the total catch.

A catch-per-Unit-Effort (CPUE) index was generated from the CPFV logbook data. Catch was calculated as the sum of the number kept, number released and number lost to sea lions on each trip. Effort was calculated as the number of fishers for each trip.

Some estimates of catch per trip appear unrealistically high, and may be the result of error in data entry or recording. For example, while the mean catch in 1987 was 52 fish per trip, some records report catches of over 1,000 individuals. The dataset was filtered by removing all records with reported catches greater than two standard deviations from the mean annual catch. The effort data was filtered in a similar way, by removing all reported number of fishers greater than two standard deviations from the annual mean. Records which reported zero fishers were removed from the data set.

Spatial blocks were used as a covariate in the GLM for CPUE standardization (in addition to year and month). It was first necessary to reduce the number of unique spatial blocks. The dataset included records from 207 spatial blocks in southern California. Ten nearshore spatial blocks (701, 702, 718, 719, 738, 739, 740, 756, 801, and 878) contributed to over 70% of the total records. All data from the remaining zones were aggregated into a single spatial block. As it was incomplete, the 2016 data was not included in the CPUE standardization. Figure 30 shows the CPUE index for barred sand bass from 1980 to 2015. Some information of catch data from the private recreational vessels is available. However, due to changes in methodology over time it is not possible to construct a time-series of total catch estimates for this fishery.

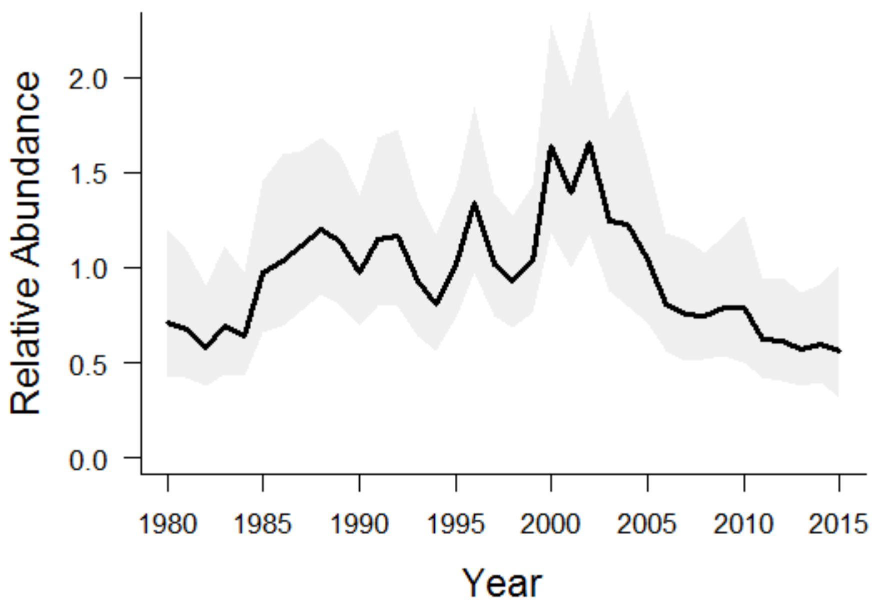

Figure 30: Index of relative abundance (catch-per-unit-effort (CPUE)) from 1980 – 2015 for the barred sand bass fishery in Southern California (mean and 95% confidence intervals).

Length Data from Recreational Database

The RecFin database contains records of sampled length composition from the surveyed recreational fishers from 1980 – 2014 (no data in 1990, 1991 and 1992). The size limit for barred sand bass was increase from 304 mm (total length) to 355 mm in 2013.

Lengths in the RecFin database before 1990 were measured as total length, and have been converted to fork length. All records since 1990 are recorded as fork length. However, all regulations and analyses for this species use total length, therefore the length records were converted to total length using the following equation (H. Gliniak, pers. comms 2016): $\mathrm{TL} = 2.8144 + 1.0076\mathrm{FL}$. The dataset was filtered to only contain records from the Nearshore and Offshore areas (areas 1 & 2) in southern California.

Figure 31 shows the relative size frequency distribution of barred sand bass in southern California from 1980 – 2016. A small proportion of the retained catch appeared to be below the minimum legal length (MLL; vertical dashed lines), particularly in the earlier years.

The proportion of records below the size limit may vary over years due to differences in enforcement and reporting. To compare the trends in the size distribution, the length data was filtered to only include records greater or equal to the minimum legal length of 304 mm (Figure 32). Note that the size limit was increased to 355 mm in 2013.

The increase in size limit to 355 mm means that future size distributions of the catch will not be directly comparable to the pre-2013 data. Figure 33 shows the trend in mean length for all years (1980 – 2016) and all observations above the recent size limit of 355 mm. This analysis suggests that mean length (above 355 mm) decreased from 1980 to the early 2000s, and has been increasing since. The mean length of individuals above 355 mm was used as the index of mean length for the data object.

Finally, a lagged recruitment index was constructed by calculating the proportion of the catch in each year, above the 355mm size limit, that was in the smallest size class. A *loess* smoother was applied to smooth the time-series using the *ggplot2* package in R (Wickham 2009). This index suggests that recruitment has been stable from 1980 to 2000, and generally declining since (Figure 34). However, there are alternative explanations for this trend, including a shift in fishing behavior towards larger sized individuals. Higher resolution spatial data would be required to address this question in more detail. The recruitment index has been included for demonstration purposes in the Data Object. This analysis should be revisited if more data becomes available, or if a management procedure is selected that uses the recruitment index to provide management recommendations.

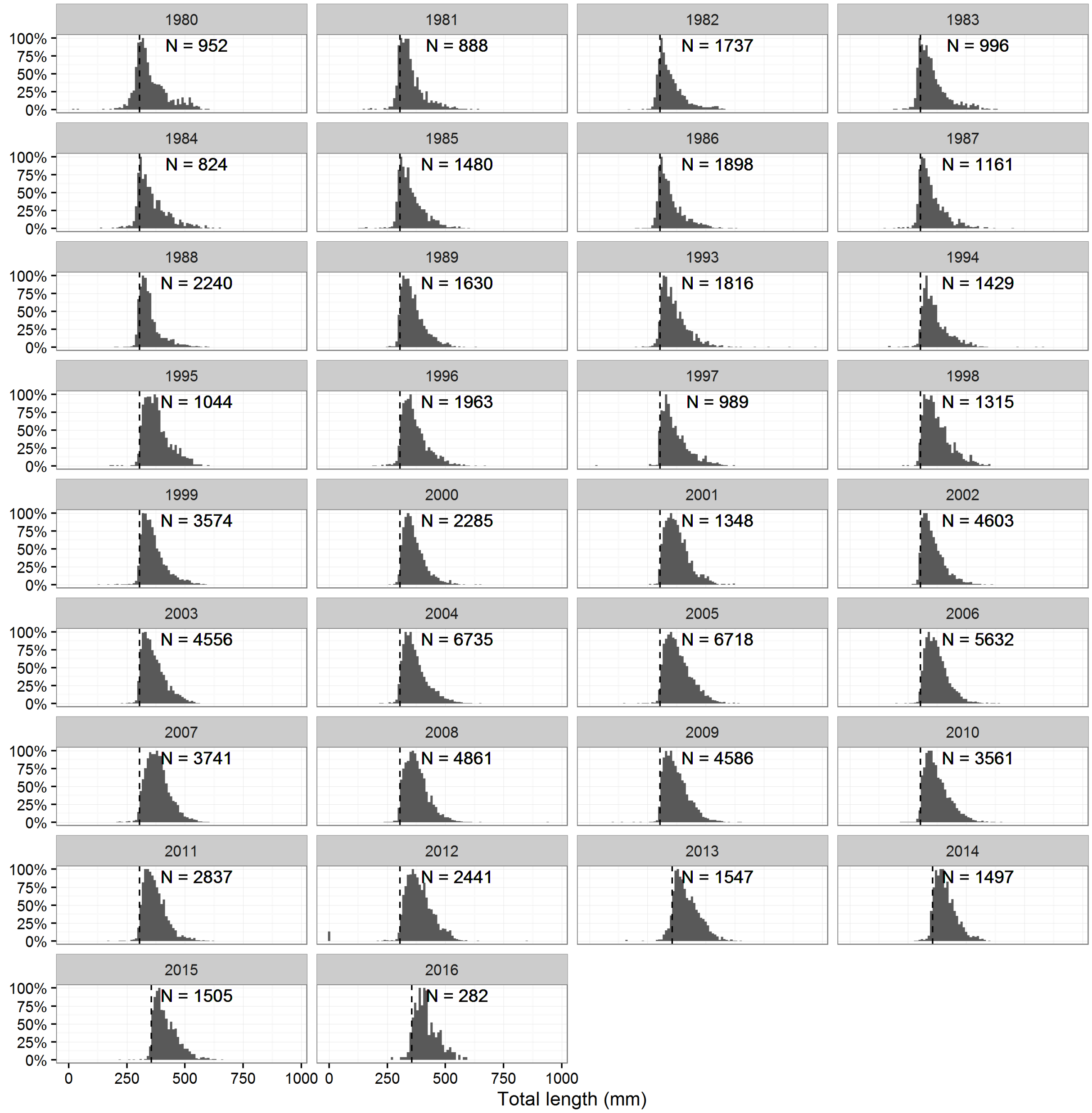

Figure 31: The relative size frequency distribution of barred sand bass in Southern California from 1980 – 2016. The vertical dash line shows the minimum legal length, which was increased to from 304 mm to 355 mm in 2013.

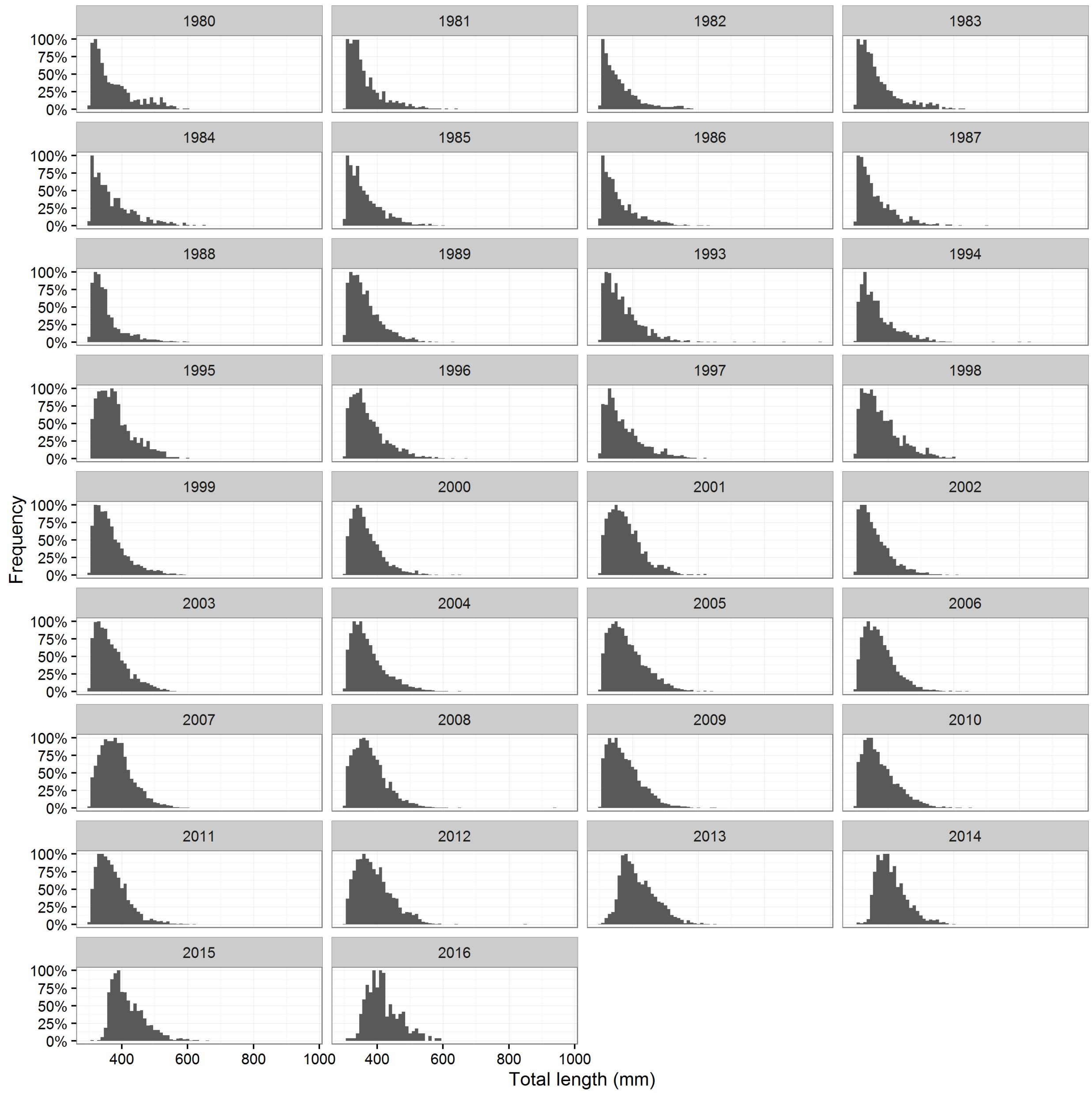

Figure 32: The relative size frequency distribution of barred sand bass in Southern California above the 305 mm minimum size limit, from 1980 – 2016. Note that the size limit was increased to 355 mm in 2013.

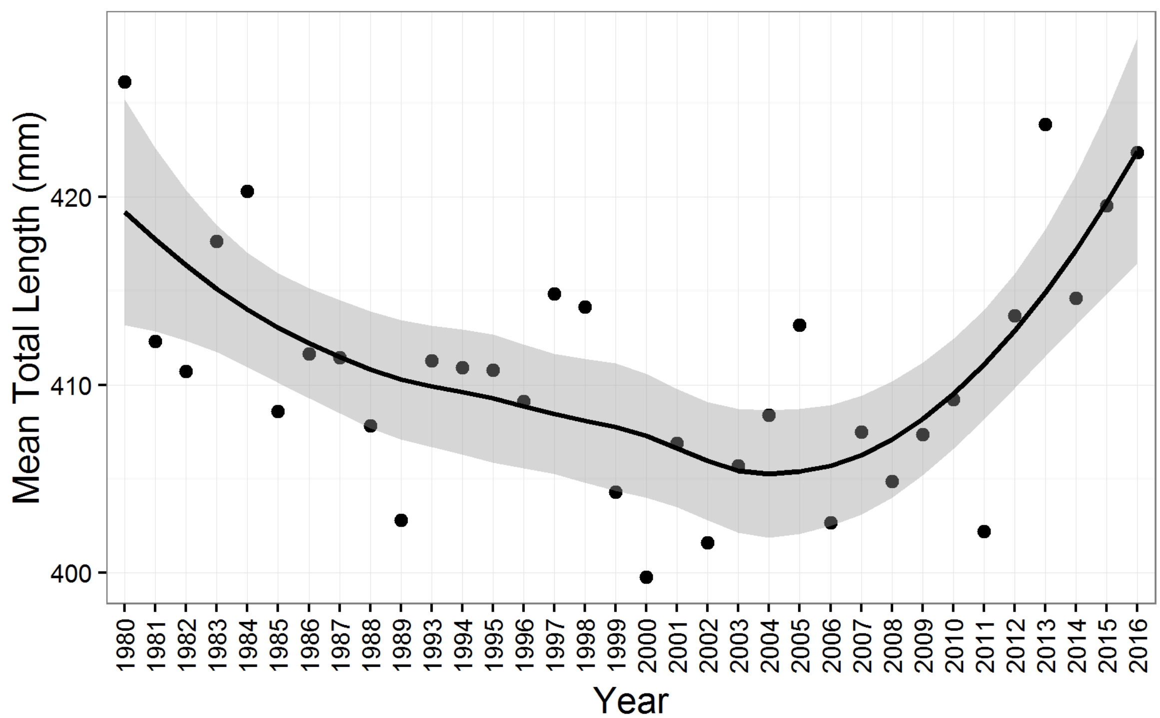

Figure 33: Mean length of the barred sand bass catch for all individuals above 355 mm from 1980 to 2016. A *loess* smoother was applied to estimate a time-series of mean length.

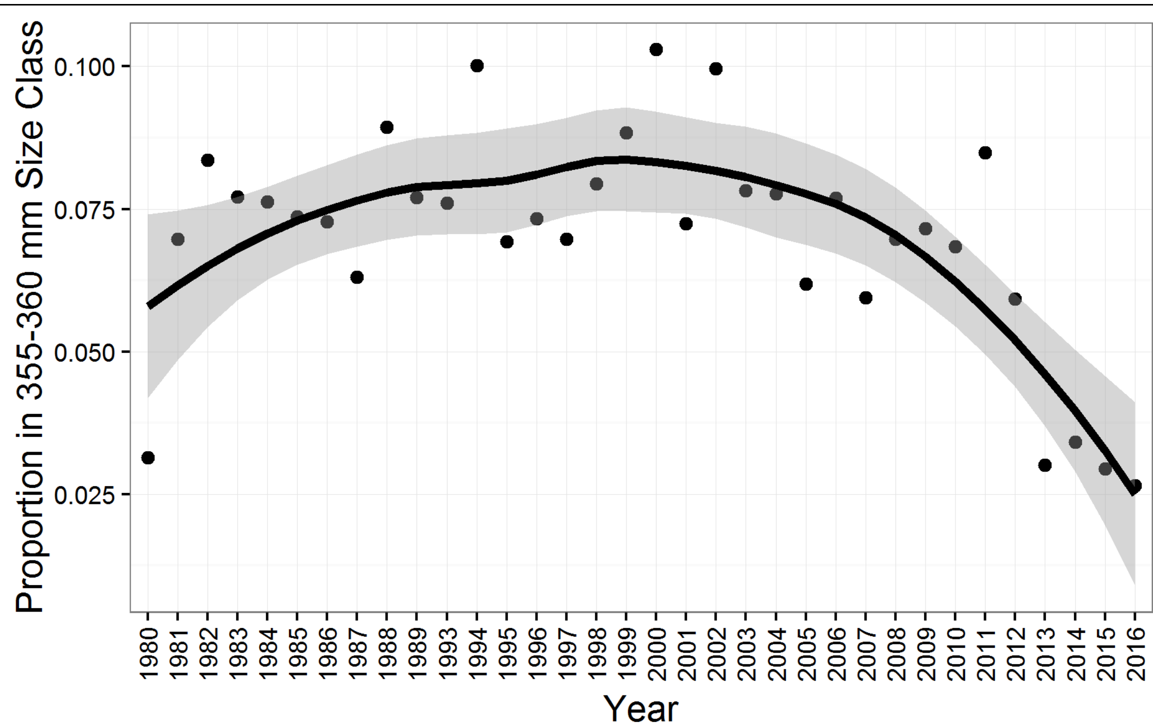

Figure 34: An index of lagged recruitment for the barred sand bass, constructed by calculating the proportion of individuals in the 355- 360 mm size class in each year. A *loess* smoother was applied.

Additional Data Sources

Underwater visual censuses of adult barred sand bass have been conducted at two sites in southern California near Los Angeles (King Harbor and Palos Verdes Point) from 1974 to 2014, and may provide source of fishery-independent trends in abundance. However, this dataset is very localized and it is not clear if the trends in this data are representative of the entire stock. A second source of fishery-independent data is available from samples of fish trapped in cooling water intake in electricity generating plants in southern California. Data is available from 1980 – 2009 for three plants in southern California. These data suffer from the same issue of non-representativeness of the entire stock. Furthermore, due to changes in the operation of the plants these surveys will no longer be continued in the future, so this data will not be useful for future management of the stock.

Appendix J: Fishery Information Summary – California Halibut

Description of the Fishery

The California halibut is native to the Pacific Coast of North America, with a range extending from Magdalena Bay, Baja California, Mexico, in the south, to Washington, USA and British Columbia, Canada, in the north (Allen, 1990). The highest (historic) population density is at least anecdotally in Baja California, MX and in southern California. The species has a long history of exploitation in California, with the earliest landing records extending back to 1916 (Maunder et al. 2011).

Although there is insufficient evidence for separate stocks in Californian waters, for assessment and management purposes the stock is split into two regions, Southern and Central, separated at Point Conception. This distinction is based mainly on an observed difference in growth rates and different exploitation histories of the two regions.

Similar to the barred sand bass and many other marine species in the region, the issue of stock delineation between southern California and Mexico is an important consideration. The halibut fishery in Mexico is apparently effectively unmanaged, and there is little information on the exploitation pattern or total landing. The two regions likely share a common recruitment pool, and it is likely that there is some movement of adults up and down the coast. The extent of this overlap is not known, and the California halibut fishery in southern California is managed separately by the CDFW.

The first stock assessments were conducted for California halibut in both the Southern and Central zones in 2010 (Maunder et al. 2011). Although a lot of information exists on the biology of the species and the characteristics of the fishery, there remains a lot of uncertainty in the stock assessment. California halibut show strong sexual dimorphism, with females growing considerably larger than males, and a lack of sex-specific sampling of age and size compositions was identified as a problem for the assessment (Maunder et al. 2011). However, under of wide range of different scenarios, the assessment for the Southern region gave very similar results and suggested that the final depletion (in 2010) was low. Although the Central stock assessment suffered similar shortcomings, the conclusion that the Central stock is considerably healthier was generally supported by the assessment team and the review panel. In this study, we focus on the southern California fishery.

The recent stock assessment estimated that current depletion (in 2010) was around 14%, and the stock abundance had not markedly changed in the last 3 decades. There is a lot of uncertainty surrounding the stock assessment, particularly to a lack of catch-at-age and other sex-specific data (Maunder et al. 2011). Following Maunder et al. (2011), the CPUE index from the CPFV fleet was used as the main data source for the assessment. The assessment estimated a depletion level of 16% at the beginning of the modelling period (1971) based on available length composition data, and because the CPUE index is relatively flat and contains little information, the final level of depletion is also low. The assessment assumed, essentially arbitrarily as little data exists, that recruitment is independent of spawning stock size. This results in very low estimates of B_{MSY} relative to B_0, and the conclusion that even at <15% B_0 the stock is above MSY. The southern California halibut assessment states, "Despite the resilience of flatfish and the fact that California halibut have sustained high exploitation rates for several decades, the uncertainty in the biological and fishing processes and the recent series of low recruitments indicate that management action may be needed to reduce the risk of fishery collapse," which suggests that the stock should be managed to higher levels of abundance than the assumed B_{MSY} (Maunder et al. 2011).

California halibut are subject to fishing pressure offshore by trawl and gillnet, and inshore by hook and line methods (from either a boat of from shore during the summer). There are distinct fishing seasons that result from a combination of factors including onshore/offshore migration of adult halibut, regulations prohibiting trawling and gillnetting in state waters (except a small area known as the California halibut trawl grounds, closed 15 March – 15 June), weather, and participation in other fisheries (e.g. sea cucumber).

The California halibut is exploited by several fleets, including commercial operators with a range of gear types and recreational fishers. A 22-inch size limit and a bag limit of 5 fish (south of Point Sur) were regulated in 1971 for the recreational fishery. A series of regulations have also been imposed on the commercial fleets over the years. Some of the most significant changes include a 22-inch minimum size limit for all commercially landed fish (1979), a minimum mesh size of 7.5 inches for trawl nets in State waters (1972), a minimum mesh size of 4.5 inches for trawl nets in federal waters (1975), and an 8.5 inch minimum mesh size for the gillnet fishery in the 1980s.

Potential management options include:

- Modifying the existing size limit – need to consider implementation error on gill net and trawl fleets, and post-release mortality. Gear modifications that adjust selectivity may also need to be considered to minimize an associated increase in discard mortality.
- TAC is theoretically possible, although allocation issues between commercial and recreational sectors may pose a potential implementation challenge. Increased administrative and staff time/costs may also be difficult to justify.
- Seasonal closure – this could be modelled as a reduction in total fishing effort.
- Reducing daily bag limit – this would only apply to the recreational sector.

MSE Operating Model Parameters

Stock Inputs

The Stock Table contains all information relating to the fish stock that is simulated in the DLMtool. The sections below provide a description of the parameter bounds determined for the Stock parameters for each case study, together with a brief summary of the information and reasoning on which these values are based. The relevant variable names used in the DLMtool table and operating model are included in parentheses behind each sub-heading. Refer to the MSE Operating Model Input Parameter Table (Appendix B) fort a description of each variable, and Appendix M for the values used in the MSE.

Natural Mortality (M)

Natural mortality for the California halibut is not well understood, and is estimated to be within the range of 0.1 – 0.3. Reed and MacCall (1988) estimated *M* as 0.3 using the method of Pauly (1980) and 0.15 is based on Hoenig's (1983) method using age of oldest individual. A range of 0.1 – 0.2 was considered most appropriate by Reed and MacCall (1988) and was used in this study. Maximum age is believed to be about 30 years old, although individuals of this age are rarely seen today. The maximum age in the model was set to 40 to account for the scenarios with lower *M*.

Growth (Linf, K, t0, a, b)

Growth has been well studied, but appears to vary between regions (Southern and Central) and perhaps also over time (MacNair et al. 2001, Barnes et al. 2015). Females grow considerably larger than males, and all parameters reported below are for female fish. The sexual dimorphism in growth must be accounted for when evaluating the practical application of models that rely on length data.

The von Bertalanffy growth parameters for southern California halibut have been estimated at L_∞ = 925.3 mm (standard error (SE) 121.4), K = 0.08 (0.02) and t_0 = -2.2 (0.41) for males, and L_∞ = 1367.7 mm (273.4), K = 0.08 (0.02) and t_0 = -1.2 (0.48) for females (MacNair et al. 2001). The DLMtool is a single-sex model, and parameters from the female growth curve were used to set the parameter range. The ranges for the growth parameters were set at the reported mean +/- two times the reported standard deviation. Length-weight parameters from Reed and MacCall (1988).

Recruitment (h, Perr, AC)

There does not appear to be a relationship between spawning stock abundance and the magnitude of recruitment for the range of stock sizes that have been observed (Maunder et al., 2011). The recent stock assessment assumed a steepness (*h*) of 1, which means that recruitment is completely independent of spawning stock and results in a very low biomass at MSY. However, it is believed that strong autocorrelation in recruitment due to favorable environmental conditions may affect the estimation of the stock-recruit curve.

The spawning stock appears to have been at low levels for the last three decades, and there may be insufficient contrast in the data to estimate steepness reliably. However, there is evidence that steepness is high for productive flatfish (van der Veer et al. 2015). The range for steepness was set at 0.7 – 0.9. Recruitment is known to be relatively variable, with clear large recruitment years, and high auto-correlation. Recruitment process error (*Perr*) was set at 0.3 – 0.6 and auto-correlation (AC) at 0.5 – 0.9.

Maturity (L50, L50_95)

Love and Brooks (1990) estimated the size at maturity for the California halibut. They estimated *L50* of 471 mm and *L95* of about 600 mm for female fish. The range for *L50* was set at the reported value for females (471) ± a CV of 10% (424 – 515 mm) and *L50_95* at 80 – 100 mm.

Depletion (D)

The 2011 stock assessment estimated that southern stock of California halibut is at 14% of virgin stock size. The range for depletion in the operating model was set to 0.10 – 0.25 to reflect the low but uncertain estimate of current stock size.

Spatial Information (Frac_area_1, Prob_staying)

California halibut are highly mobile. The probability of staying in Area 1 (*Prob_staying*) in a given year was set to the same values as those for the barred sand bass (0.095 – 0.105).

General Parameters

The remaining *Stock* parameters had common values across all four case studies. The MSE model is not conditioned on fishery data, and the number of initial recruits (*R0*) is set at an arbitrary 100,000 individuals. There was assumed to be no long-term gradient in the life history parameters (*Mgrad*, *Linfgrad*, *Kgrad* all set to 0). Little information exists on inter-annual variability in natural mortality and growth parameters for the case study stocks, and a common set of values was used for all four species (*Msd* = 0 - 0.05, *Linfsd* = 0 - 0.025, *Ksd* = 0 - 0.025). The maximum age parameter (*maxage*) defines the number of age classes in the simulation model. This parameter is fixed for each case study, and the model is not sensitive to this value, provided it is high enough to account for all values of natural mortality that are included.

Fleet Inputs

The Fleet Table contains all information relating to the historical and future exploitation patterns of the stock. The information in the Fleet Table can be divided into three categories: *exploitation history*, *selectivity*, and *targeting and catchability.* The exploitation history and selectivity pattern varies between the four stocks, and information exists to specify these values. Little specific information is available for the catchability and targeting for these stocks, and common values were used for the four case studies.

Exploitation History (nyears, EffYears, EffLower, EffUpper)

The fishery for California halibut began in the late 1800s, and the number of historical years (*nyears*) was set to 117 years (1900 – 2016). Data from the CPFV fleet logbooks, using only records where California halibut were caught, fishing effort in recent decades appears to have been relatively constant. The broad trends in historical fishing effort were based on those used for the barred sand bass, except that for the halibut there has does not appear to have been a decline in effort in recent years. The CPFV data may be problematic because the fleet targets multiple species and effort records may not accurately reflect the fishing effort on the halibut stock alone. We recommend that single-species historical effort trends are developed for the halibut fishery and used to parameterize the MSE model in the future.

Selectivity (LFS, L5, Vmaxlen)

The California halibut stock is targeted by several fleets and different gear types. The fishery also has a long history of regulations, including closed areas and size limits. A minimum legal length of 559 mm was implemented in 1971 for all recreationally landed fish and then in 1979 for all commercially landed fish (Maunder et al. 2011). There is some amount of catch below this limit, which varies by fleet. The potential for dome-shaped selectivity exists among these fleets, and *Vmaxlen* was set to 0.5 – 1.0 for the historical period.

Targeting and Catchability (Spat-targ, Fsd, qinc, qcv)

Spatial targeting (*Spat_targ*) was set to 1 for all case studies. This represents a stock that is actively targeted by the fishers. Default values from the DLMtool were used to represent the inter-annual variability in fishing mortality (*Fsd*; 0.1 - 0.4), and annual increase in catchability (*qinc*; 0 - 2; catchability increases by up to 2% per year), and the annual variability in catchability (*qcv*; 0.1 - 0.3).

Observation Inputs

The Observation Table contains the parameters that are used to generate the simulated fishery data within the MSE model. The parameters used for the observation model were based on the values presented in Carruthers et al. (2014) and are found in the "Generic_obs" observation object in the DLMtool. Common values were used for the observation table for the four case studies, except where information was found to suggest alternative values (see below).

The CV for natural mortality was increased to 30% to reflect high uncertainty in this parameter. The range for the beta parameter was set to 0.8 – 1.2 to reflect the perceived increased reliability of CPUE data for this stock compared to the "Generic_obs" default values.

Information for Tuning the MSE Operating Model

The assessment suggests that depletion is very low, and this information can be directly input into the MSE. The historical fishing effort is reasonably well documented, and this information can be used to tune the historical period of the MSE.

The is marked sexual dimorphism in the growth of California halibut, with females growing considerably larger than the males. Until recently, size and other data were not sex-specific, and this limitation was highlighted in the assessment.

Fishery Information Data Inputs

Commercial Passenger Fishing Vessel Catch and Effort

A catch-per-unit-effort (CPUE) index was constructed for the southern California halibut fishery using the reported catch and effort records from the commercial passenger fishing vessel (CPFV) fleet. The CPFV log book data extends from 1980 to 2015 and appears to be the most reliable data source for the southern California halibut.

The CPUE index was generated following the same process described for the barred sand bass (see above), with month and area effects. The CPUE is assumed to reflect the relative trend in the Southern California halibut stock. The CPUE suggests that stock was relatively stable from 1980 until the early 1990s, then increased over the next decade. Since the early 2000s the stock appears to have declined in abundance, although the CPUE in recent years is higher than that from the 1980s (Figure 35).

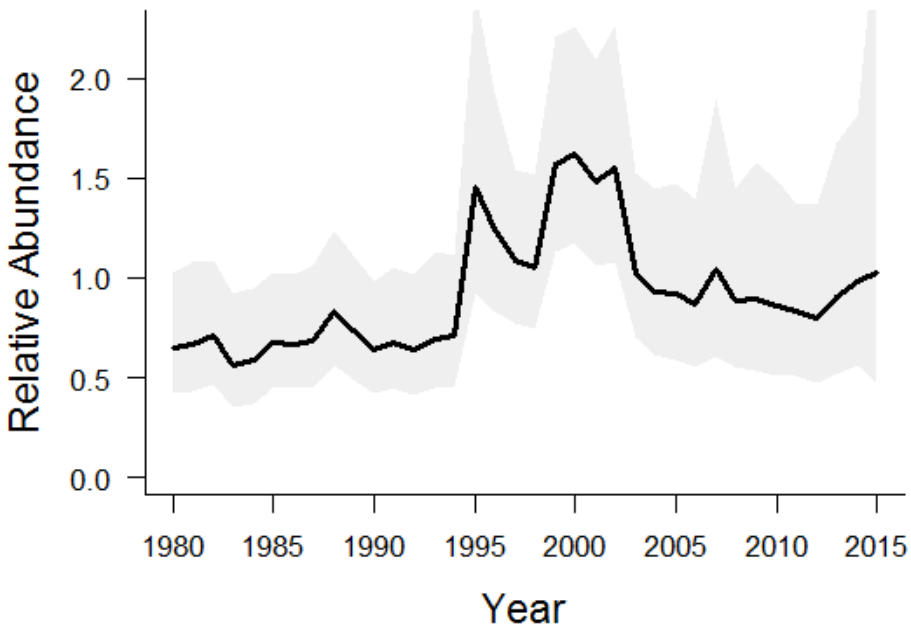

Figure 35: Index of relative abundance (catch-per-unit-effort (CPUE)) from 1980 – 2015 for the Southern California Halibut Commercial Passenger Fishing Vessels (mean and 95% confidence intervals).

This CPFV data was used to create the CPUE index in the recent stock assessment (Maunder et al. 2011). The assessment review panel suggested several alternative analyses that could be used to construct this index. These suggestions include using the Stephens-MacCall filter (Stephens and MacCall, 2004) which uses information on the species composition of the catch to subset the catch and effort data. The alternative analyses have not been conducted at this stage, although the CDFW staff are actively working on this in preparation for the updated stock assessment. The alternative or additional analyses of the CPUE data should be explored if this data is going to be used in a management procedure to provide management advice.

Commercial Landing Receipts

Commercial landing receipts are available from 1971 – 2015, and some data has been published on total removals back to 1916. There is no effort data accompanying this landing information, and it is unlikely that this can be used to develop an index of abundance.

Time-Series of Total Landings

Estimates of total landings from the commercial fleets in Southern California are available from 1971 to 2015 (Figure 36). Estimates of recreational landings are available beginning in 1980 from two different survey methodologies. However, the data were only processed from the most recent survey method, from 2004 to 2015, since it is the most reliable and only the most recent years of catch were needed (Figure 36). The lack of data on recreational catches prior to 2004 may not be an issue for the application of the DLMtool, as most the output control methods use information on the catches in recent years (5 – 10 years) to calculate recommended TACs. However, we were not able to generate a time-series of total catch or effort from the beginning of the fishery, which resulted in some output control methods not able to be applied to the data. The time-series of total landings used in the Data Object was the sum of commercial and recreational catches from 2004 – 2015, which showed a general declining trend in catch over the last 10 years (Figure 36).

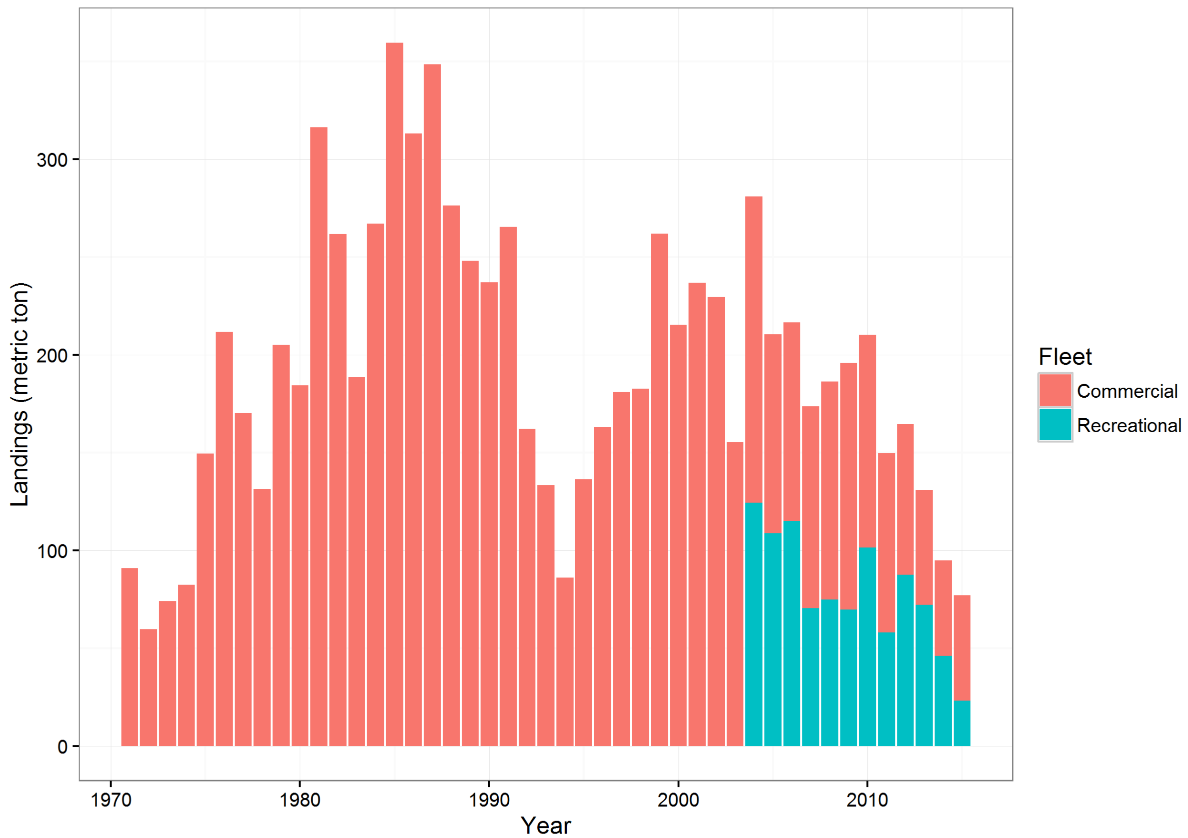

Figure 36: Estimated total landings of California halibut from the commercial (1971 – 2015) and recreational (2004 – 2015) fleets in Southern California. Estimates of recreational catch before 2004 were not used.

Trawl Log Books

Logs from the trawl fleet are available from 1981 to present at the individual tow level. Although these data represent all trawl fishing, those trips targeting halibut can be isolated within a reasonable level of certainty by the average tow depth recorded. This effort is primarily concentrated within the California halibut trawl grounds, a strip of ocean between 2 and 3 nautical miles from shore along the Santa Barbara coast. However, this area is very small, and may not reflect the trends in the overall stock.

Commercial Port Sampling

Market sampling has been conducted in central and southern California from 1981 – 2006, with length samples taken from all gear types. A similar survey has been conducted since 2007, which records age, length and sex information of sampled halibut. However, the sample size of these data are relatively small, and it is unclear how useful this data will be in the future for monitoring trends in population abundance.

Gillnet Observer Data

A data set exists from observers who intercepted and sampled gillnet vessels in the 1980s. This data contains information on the catch and size structure from this fleet during this time period. The methodology of this survey is unclear, and this is unlikely to be useful for our current purposes.

RecFin Database

The RecFin database contains records of size structure of the recreational fleet, from 1980 to present. These samples were not sex-specific until 2012. Given the marked sexual dimorphism in halibut growth, and the lack of sex-specific size data, it is unclear how useful the historical length data will be for our purposes. The sex-specific size data currently being collected may provide a useful data stream for monitoring trends in the population. However, the selectivity of the recreational fishery will need to be studied to ensure that this data meets the assumptions of most length-based methods.

San Francisco Trawl Survey

A trawl survey in conducted in San Francisco Bay which captures young-of-the-year and may provide a useful index of recruitment. However, the location of this site is in Central California, and this is unlikely to provide a reflection of the recruitment trends in southern California. The recruitment index does however appear to show that recruitment is strongly affected by environmental conditions, e.g., the El Niño–Southern Oscillation.

Appendix K: Fishery Information Summary – Red Sea Urchin

Description of Fishery

The red sea urchin (*Strongylocentrotus franciscanus*) is one of the largest sea urchins in the world, with a test diameter reaching 18 cm, and is among the most well-known and best studied urchin species in the world (Rogers-Bennett 2007). The red sea urchin fishery in southern California began in the early 1960s, with a small number of urchins caught to supply domestic markets and home consummation (Kato and Schroeter 1985). The first processing plant for sea urchin was opened in California in 1972, and an export market was developed shipping fresh product to Japan. Catches in southern California peaked at 11,000 t in 1981, followed by a number of years of declining catch. This decline in catch was coincident with changing oceanographic conditions linked to an El Nino event.

There has been little change in the method of harvesting red sea urchin since the fishery began in the 1970s, with divers using hookah or SCUBA and using small rakes to hand-pick the urchins. Sea urchins are usually closely associated with reef structure, and divers are not allowed to move rocks or use mechanical devices to destroy habitat. The urchins are found from low intertidal to 125 meters in depth, although normally fishing will not occur deeper than 30 meters due to diver constraints and sufficient sea urchin to harvest in shallower waters (Kato and Schroeder, 1985).

Fishing occurs year-round, but fishing patterns can vary. Fishing for sea urchin primarily depends on demand for the product and suitable weather conditions for diving. Most fishers also fish for other species, such as the warty sea cucumber, and fishers may choose to target another species if weather and market conditions are favorable (CDFW, pers. comms). The commercial fishery is open 7 days a week from November to May, but is restricted to Monday-Thursday from June to October each year. The recreational component of the red sea urchin fishery is minimal, and illegal and unreported harvesting is considered to be negligible or non-existent (CDFW, pers. comms).

Fishing licenses are required for both sport and commercial harvest. For sport, anyone with a license can harvest. For commercial, a sea urchin permit is required and it is limited entry (300 nontransferable permits). There is no effort or landings requirements to keep an urchin dive permit, therefore, there is an abundance of latent capacity. Typically, 150 of the 300 divers will harvest 98% of the annual sea urchin catch. CDFW has required a permit since 1986 (Figure 37). Divers are required to fill out a logbook each day they fish and must return it to CDFW each month. Currently the fishery is proposing to reduce permit capacity below 300 via a 10:1 lottery and add one day to the June – October fishing season in the south.

It is unlikely that new harvest control rules (e.g. size limits, catch limits, or spatial closures) will be implemented in the upcoming years until a fishery management plan (FMP) for red sea urchin is adopted. The Department is currently prioritizing fisheries to determine the timeline for new FMPs.

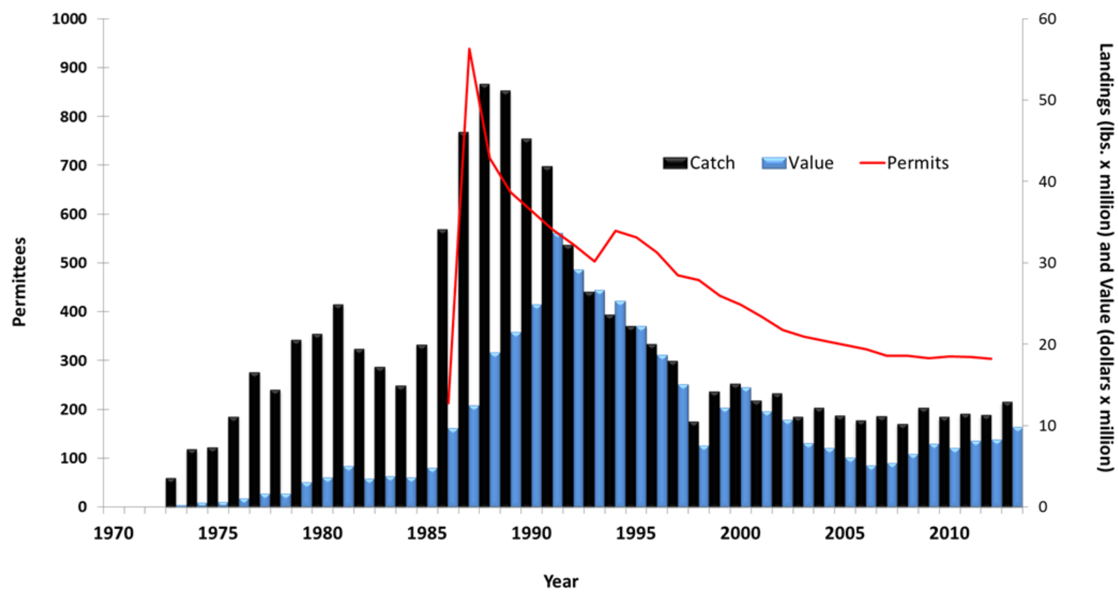

Figure 37: Total catch, estimated value and number of permits from 1973 to 2013 for the red sea urchin fishery in California (CA DFW data). Note that this includes both north and south California.

A minimum legal size for red sea urchin was regulated in 1988, and current regulations restrict harvest to sea urchins with a test diameter over 3.25 inches and 3.5 inches in southern and northern California respectively. Many fishermen believe in only harvesting A or B grade sea urchin, which fetches a higher price. However, there are some processors that encourage the take of low quality sea urchin for less desirable "uni" products. Many new divers must learn how to find high quality sea urchins and often it takes many years of experience to bring in a consistently high quality product. Some urchin divers also try to harvest larger sea urchins than the minimum because it results in a higher gonad yield, thus making more money for the effort.

The sea urchin fisheries in northern and southern California are two distinct regions, separated by a large distance and experiencing different exploitation histories and environmental and ecological conditions (**Error! Reference source not found.**). Landings in southern California have typically been higher than those from the north, and the bulk of the southern catch comes from the Channel Islands region (**Error! Reference source not found.**).

The red sea urchin fishery is currently considered a single management unit, and permit holders can fish anywhere in the state. For the purposes of this project, we are focusing the MSE on the southern portion of the stock.

There appears to be a general perception among the sea urchin industry in southern California that "pickable" urchin are becoming harder to find. Pickable, in this context, means sea urchin that have high quality gonads, and are likely to command a high price. The quality of sea urchin gonad appears to be primarily determined by the amount kelp in the urchin diet. Feeding rates on kelp depend on a number of factors, including amount of kelp cover, which is likely impacted by water temperature, the density of sea urchin, and presence of other predators. When diving a new location, urchin divers often crack open several individuals and examine the quality of the gonad underwater. If the quality of the gonad is considered sufficient, the diver will harvest the site, or otherwise may move to a new location with better quality gonad.

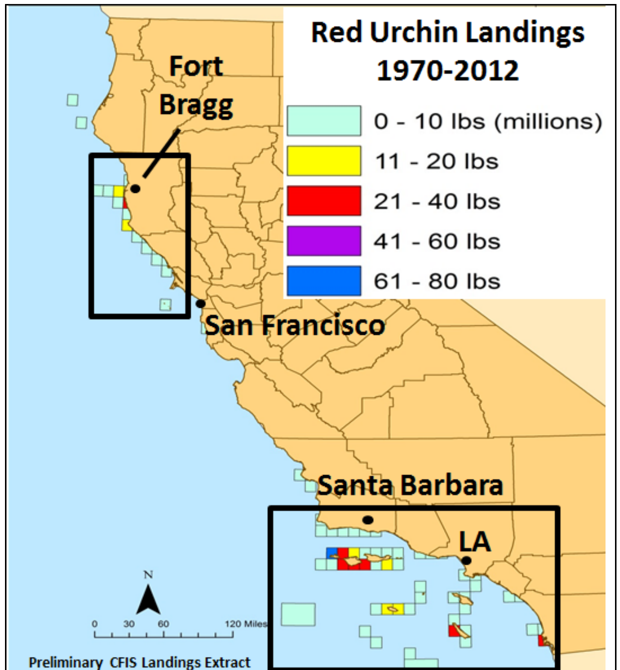

Figure 38: Red sea urchin landings from 1970 – 2012 for north and south California.

The discrepancy between "pickable" and "non-pickable" is an important consideration when interpreting statistics from the fishery, and parameterizing the MSE model. The current perception in the south California sea urchin industry, and among the CDFW researchers, appears to be that catch rates are falling in recent years, and pickable sea urchin are harder to obtain. Catch rates may reflect the abundance of pickable sea urchin, and may not be a fair representation of the sea urchin population as a whole. The kelp beds are known to be highly affected by environmental factors, e.g., El Nino conditions, especially in south California. It may be possible that the quality of the sea urchin will decline dramatically in these periods, while the abundance of sea urchin population is not so severely affected. Thus, adverse environmental conditions may result in low catch rates but not significantly impact the abundance of the stock. This issue is particularly important when considering fishery-dependent data as an indicator of trends in stock abundance. This dynamic is difficult to capture in the current MSE modelling framework, and there is little information on the proportion of all sea urchin that are pickable in any given year, nor a clear understanding of how this proportion is affected by kelp availability, and the density of the sea urchin population itself.

The fishery is currently managed with a minimum size limit, limited entry, and a fishing season (open 7 days per week November to May, and open Monday through Thursday from June to October). Efforts are being made to halve the number of permits in the fishery, but it may take many years before this effort reduction is achieved.

Potential management options may be:

- Effort controls by modifying season length or days per week
- Total allowable catch – not currently used but has been considered in the past.
- Modifying size limit – either fixed change or regular adjustments based on estimate in stock trends (unlikely to be useful in the sea urchin fishery which already has a high size limit)

MSE Operating Model Parameters

Stock Inputs

The Stock Table contains all information relating to the fish stock that is simulated in the DLMtool. The sections below provide a description of the parameter bounds determined for the Stock parameters for each case study, together with a brief summary of the information and reasoning on which these values are based. The relevant variable names used in the DLMtool table and operating model are included in parentheses behind each sub-heading. Refer to the MSE Operating Model Input Parameter Table (Appendix B) for a description of each variable, and Appendix M for the values used in the MSE.

Natural Mortality (M)

In the early days of the fishery, the life span of red sea urchin was suggested to be 7 – 10 years. However, more recent work using tetracycline and calcein tagging has demonstrated that the longevity of the species if much greater, exceeding 100 years in British Columbia and Washington (Ebert and Southon 2003, Ebert 2008). The lifespan of red sea urchin in southern California appears to be much shorter, with few individuals reaching ages of 50 years (Ebert and Southon 2003).

Both growth and natural mortality have been found to vary spatially in northern California (Morgan et al. 2000). Natural mortality (*M*) has been estimated from 0.05 – 0.204 in northern California, and 0.088 – 0.4 in southern California (Ebert and Russell 1992, Ebert et al. 1999, Morgan et al. 2000). These fine-scale variations in *M* are thought to be related to greater abundance of sea urchin predators in southern California (Morgan et al. 2000). Sea urchin are believed to be slow-growing, and reach large sizes. This implies that maximum age must be quite high.

Ebert et al. (1999) estimated a mean annual survival probability of 0.77 yr^{-1} in southern California, which corresponds to a value of *M* of 0.26. This value was selected as the best estimate of *M* for red sea urchin in southern California, and given the high uncertainty in this parameter, a CV of 25% was assumed and the range for *M* defined as 0.195 – 0.32. Maximum age was set at 50 years, which is high enough that only a small proportion of the original cohort remains alive at maximum age for the full range of *M* values examined in the MSE.

Growth (Linf, K, t0, a, b)

The von Bertalanffy equation may not the best model for describing growth (Ebert et al. 1999, Rogers-Bennett et al. 2003), and in particular does not describe the growth of the small individuals very well. However, given the existing size limit, the focus of the MSE model is on the larger size classes, which are usually better described by the von Bertalanffy model. Currently, the DLMtool only includes the von Bertalanffy growth model, and parameters must be specified which most closely represent the growth of the species. Additionally, all the management procedures which use growth information assume a von Bertalanffy growth curve. It may be possible to add alternatives growth curves to the MSE model in the DLMtool, and develop alternative management procedures. However, given the uncertainty in growth and mortality parameters, it is unlikely that methods which rely on growth will be used for this species.

Roger-Bennett et al. (2003) fitted six different growth curves to data from northern California, and found that the logistic dose-response model provided the best fit to the data. The growth of red sea urchin is highly variable, and the estimates of the von Bertalanffy parameters from Roger-Bennett et al. (2003) and Ebert et al. (1999) were used to determine the range used in this study: L_{∞} = 109 – 145 mm, K = 0.13 – 0.30. No information exists on appropriate values for t_0, and this was set to 0 for the study. No estimates for the length-weight parameters exist for California. The MSE model is not sensitive to these parameters, and values from a Canadian study were used (Campbell 1998).

Recruitment (h, Perr, AC)

Recruitment appears to be episodic in northern California, Oregon, Washington, and British Columbia, but more stable in southern California (Kalvass and Hendrix 1997). Many researchers suggest that red sea urchin are particularly vulnerable to recruitment overfishing, this suggests that the steepness of the stock recruitment relationship is low. However, little data exists to estimate this parameter. The range for steepness (*h*) was set to 0.4 – 0.6. Recruitment variability is believed to be moderately high, and driven by environmental conditions. The ranges for annual recruitment variability (*Perr*) and autocorrelation in recruitment (*AC*) were set to 0.3 – 0.6 and 0.5 – 0.9 respectively.

Maturity (L50, L50_95)

Most studies cite Bernard and Miller (1973) for information on the size-at-maturity (sexually mature at 40 – 50 mm test diameter). However, this study was conducted around Vancouver Island in Canada. There does not appear to be any information on size-at-maturity from the southern California region. Given the paucity of available data, the range for length at 50% maturity (*L50*) was assumed to be 45 mm test diameter +/- a 30% CV. Similarly, the difference between the length at 95% maturity and 50% maturity (*L50_95*) was assumed to be 10 – 30 mm.

Depletion (D)

No information exists on current level of depletion for the stock in southern California. A minimum legal length above the size of maturity has been in place since 1988, and 100% of the catch is mature. There does not appear to be any evidence of a decline in recruitment attributable to the fishery. Furthermore, it is estimated that 15-25% of the red sea urchin stock in California is in marine protected areas (MPAs) that are closed to all fishing activities. Therefore, it is believed that the red sea urchin stock in southern California is not heavily depleted. The bounds for the depletion level were set at 0.3 - 0.6. Although the stock is not believed to be overfished, the lower bound was set to determine the performance of the MPs at lower stock levels, and to find a management procedure that was robust to a stock that was at a lower level of biomass.

Spatial Information (Frac_area_1, Prob_staying)

Sea urchin are relatively sedentary, and the probability of staying in a spatial area (*Prob_staying*) was set to a high value of 0.95 - 0.99 (same values were used for the warty sea cucumber). It is believed that 15 - 25% of the red sea urchin stock is within the MPA network in southern California, and the fraction of the stock in area 1 (*Frac_area_1*) was set to 0.15 - 0.25. This range was used for all the case study species, although the probability of staying in an area was modified for the finfish species.

General Parameters

The remaining *Stock* parameters had common values across all four case studies. The MSE model is not conditioned on fishery data, and the number of initial recruits (*R0*) is set at an arbitrary 100,000 individuals. There was assumed to be no long-term gradient in the life history parameters (*Mgrad*, *Linfgrad*, *Kgrad* all set to 0). Little information exists on inter-annual variability in natural mortality and growth parameters for the case study stocks, and a common set of values was used for all four species (*Msd* = 0 - 0.05, *Linfsd* = 0 - 0.025, *Ksd* = 0 - 0.025). The maximum age parameter (*maxage*) defines the number of age classes in the simulation model. This parameter is fixed for each case study, and the model is not sensitive to this value, provided it is high enough to account for all values of natural mortality that are included.

Fleet Inputs

The Fleet Table contains all information relating to the historical and future exploitation patterns of the stock. The information in the Fleet Table can be divided into three categories: *exploitation history*, *selectivity*, and *targeting and catchability.* The exploitation history and selectivity pattern varies between the four stocks, and information exists to specify these values. Little specific information is available for the catchability and targeting for these stocks, and common values were used for the four case studies.

Exploitation History (nyears, EffYears, EffLower, EffUpper)

The fishery for red sea urchin in southern California began in the early 1970s, and 47-year (1970 – 2016) fishing history was assumed (*nyears*). The number of active permitees in the fishery was used as a proxy for historical fishing effort. The permits were introduced in the mid-1980s, and the number of active divers decreased during the next two decades, and appears to have been relatively stable since 2005. Fishing mortality generally increased from 1970 to the mid-1980s, then gradually decreased until 2005 and has been relatively stable since (*EffYears*, *EffLower*, *EffUpper*).

Selectivity (LFS, L5, Vmaxlen)

A minimum legal length of 82.5 mm was regulated in 1988 for sea urchin in southern California. The model is less sensitive to the selectivity pattern in historical years than the more recent time period. Selectivity (*LFS*) was assumed to be at the size of maturity for initial years of fishery, and then increased to 82.5 mm from 1988. Selectivity is assumed to be asymptotic (non-dome shaped; *Vmaxlen* = 1).

Targeting and Catchability (Spat-targ, Fsd, qinc, qcv)

Spatial targeting (*Spat_targ*) was set to 1 for all case studies. This represents a stock that is actively targeted by the fishers. Default values from the DLMtool were used to represent the inter-annual variability in fishing mortality (*Fsd*; 0.1 - 0.4), and annual increase in catchability (*qinc*; 0 - 2; catchability increases by up to 2% per year), and the annual variability in catchability (*qcv*; 0.1 - 0.3).

Observation Inputs

The Observation Table contains the parameters that are used to generate the simulated fishery data within the MSE model. The parameters used for the observation model were based on the values presented in Carruthers et al. (2014) and are found in the ‘Generic_obs’ observation object in the DLMtool. Common values were used for the observation table for the four case studies, except where information was found to suggest alternative values (see below).

The effective sample size for catch-at-age (*CAA_ESS*) was reduced to 10 – 20 to reflect the paucity of this type of data. The CV for natural mortality was increased to 30% to reflect the uncertainty in this parameter. The CV for the growth (*Linf* and *K*) parameters was increased to 10% and 20% respectively to reflect high uncertainty in these parameters. The range for the beta parameter was set to 0.8 – 1.2 to reflect the perceived increased reliability of CPUE data for this stock compared to the 'Generic_obs' default values.

Information for Tuning the MSE Operating Model

Data exists on historical fishing effort for most of the exploitation history, and this information can be used to tune the MSE to a trend in historical fishing mortality. The stock has been heavily exploited, and is thought to be at relatively low levels, but no information on current depletion exists. Given the declining catch rates, and long history of exploitation, it may be reasonable to assume that the stock is relatively depleted. Some biological information exists for the red sea urchin in southern California, but many of the estimates of highly variable. Growth of sea urchin is often better described by alternatives to the usual von Bertalanffy growth model. Typically, alternative growth curves describe different shapes to the juvenile portion of the growth curve, and this is often not significant when focusing exploitation on the adult portion of the stock. The MSE model will need to be modified to account for different growth curves, and the significance of including this information could be evaluated.

Fishery Information Data Inputs

Processor Landing Receipts

Records of total landings of red sea urchin were available from the processor landing receipts database (1973 - 2016), and were filtered to only include landings from southern California (Figure 39).

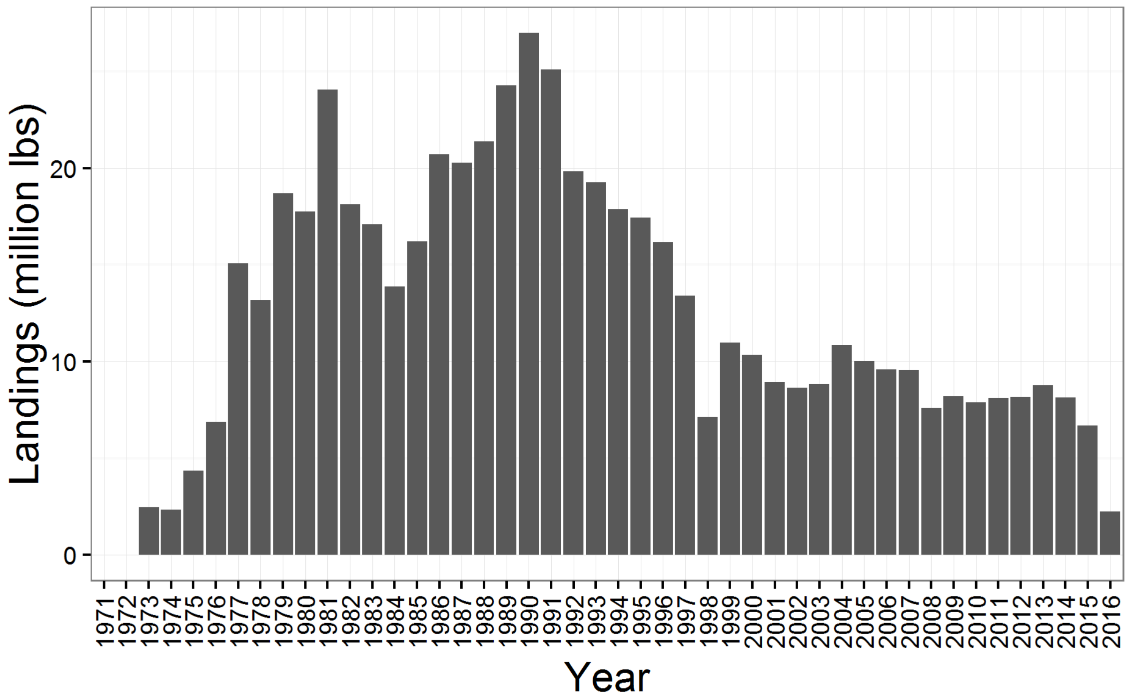

Figure 39: Annual landings of red sea urchin in Southern California from the processor landing receipts. The 2016 data goes up to July, and does not represent a full year of catch.

Diver Log Books

The effort data for the red sea urchin fishery was available from the dive logs books of the fishing fleet. This database was filtered to only include records from southern California, and included information from 1977 through to 2014. However, the effort data before 1998 appears incomplete, with very few records from 1977 - 1997 (Figure 40). The effort data from 2014 also appears incomplete and there is currently no effort data is available for 2015.

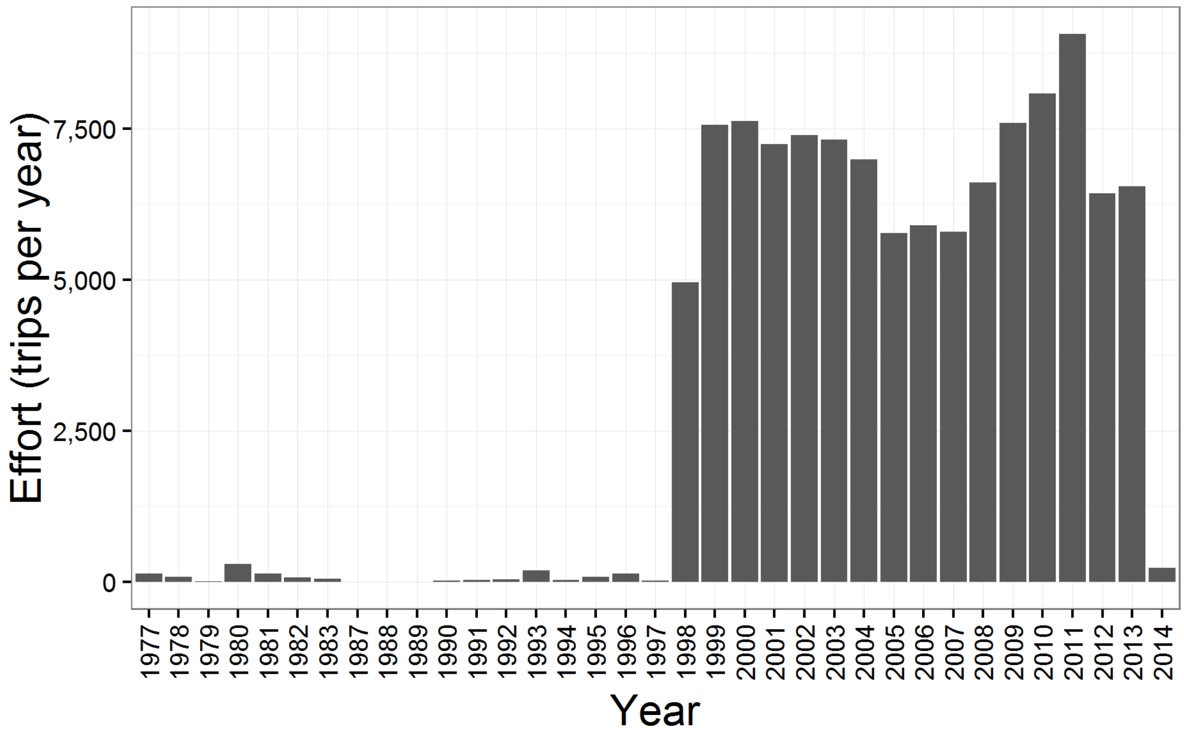

Figure 40: Reported effort (number of trips) for red sea urchin in Southern California from the dive log books.

Catch-Per-Unit-Effort Analysis

The reported annual catch from the dive log books was consistently lower than that recorded in the processor landing receipts (Figure 41). A possible explanation for this is that the dive logs record the estimated catch, while the processor landing receipts report the actual weighed catch.

The CPUE analysis was conducted following the same method described for the warty sea cucumber. A GLM model was used to standardize the CPUE data, using Year and Area interaction and Month covariates (Figure 42**Figure 42**). It is important to note, however, that the CPUE index was only calculated up to 2013, as the effort data in recent years is not available. This index was included in the DLM_data object for this stock as a demonstration, but it should be updated with current information before it is used for management of this stock.

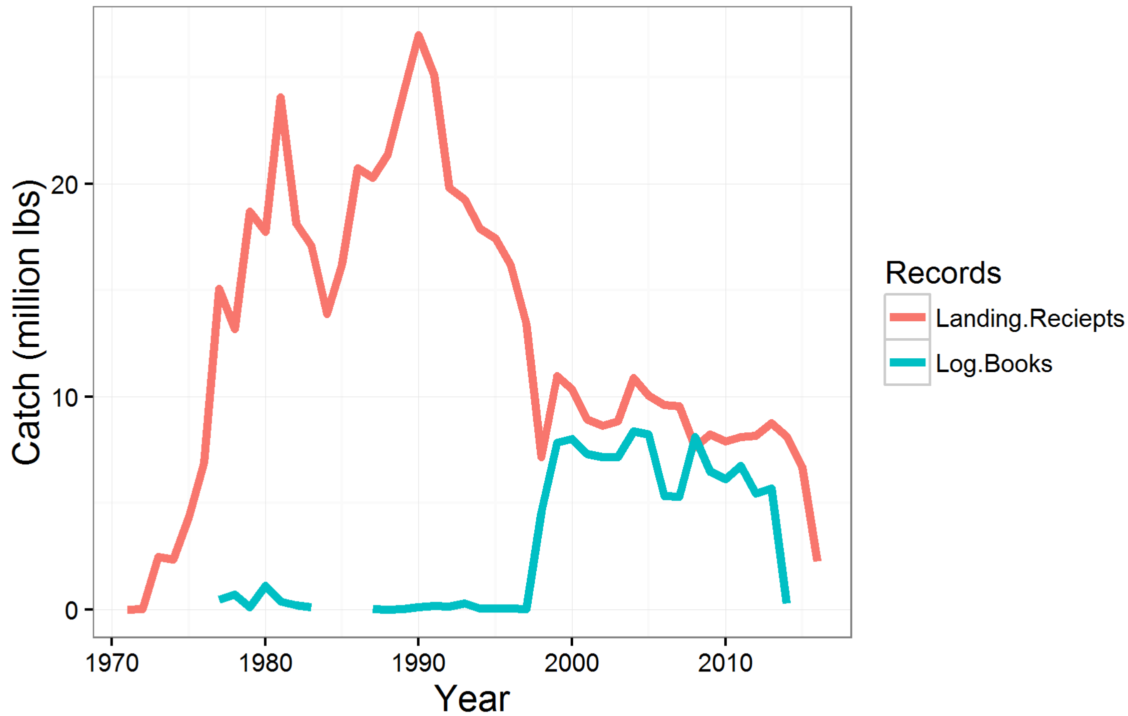

Figure 41: Reported annual landing of red sea urchin in Southern California from the dive log books and the processor landing receipts.

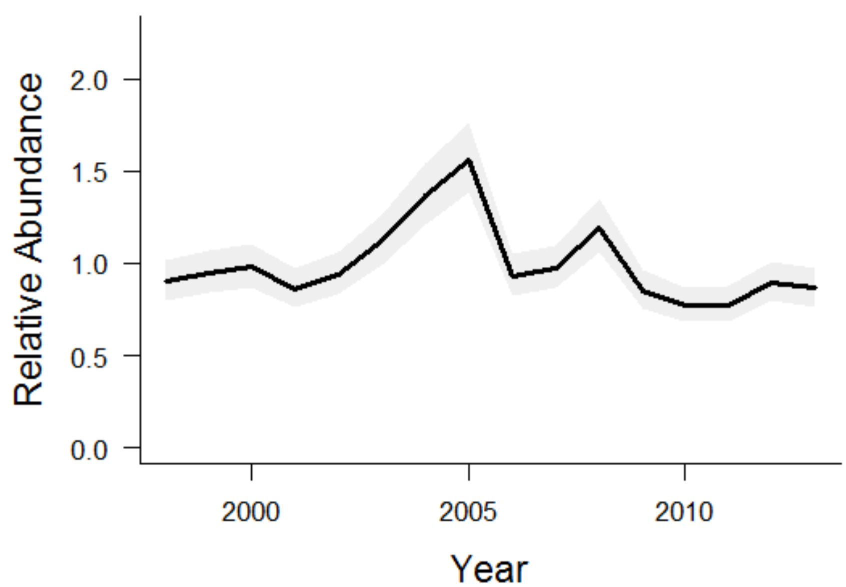

Figure 42: Index of relative abundance (catch-per-unit-effort (CPUE)) from 1998 – 2013 for the red sea urchin fishery in Southern California (mean and 95% confidence intervals).

Length Composition Data

The CINPS Kelp Forest Monitoring program has been monitoring sites in southern California since 1985, and length measurements of red sea urchin in southern California are from 37 sites, mainly around the Channel Islands. The 37 sites include a number of MPAs, where no fishing of red sea urchin occurs. The length data was processed by filtering out all records from within the MPA sites, and all individuals under the 82 mm minimum legal length. A time-series of the mean length of exploitable sea urchin, and the size composition of exploitable sea urchin was produced for each year and included in the DLM_data object. There may be alternative ways to analyze this length data, particularly if there is additional information on representativeness of the different sites. This analysis should be re-visited in more detail if a management procedure is selected that will use the length information.

Density Surveys

The Kelp Forest Monitoring surveys conducted by the National Parks Service also contains records of sea urchin abundance and density for 32 sites around the Channel Islands (15 inside and 17 outside MPAs). This dataset extends from the early 1980s until 2015, and also contains data on the size structure of the red sea urchin observed on the transects. The MPAs came into effect at different times, and the analysis would need to consider the amount of time an area has been protected from fishing. This data may be useful for estimating the density ratio of sea urchin in and outside MPAs, which could provide a potential indicator of depletion. However, the density information of red sea urchin is complicated by the complex interactions between sea urchin abundance and kelp cover. Kelp cover is affected by water temperature, wave action, and urchin predation. Density ratio methods assume that the two sites being compared (MPA and non-MPA) are representative and comparable in all aspects other the fishing activity. This assumption may not hold for the sea urchin density data, and it is unclear at the present time how this density information can be used in a management procedure and incorporated into the DLMtool.

Recruitment Index from Brush Studies

A sea urchin settlement study commenced in 1990 and has continued to present. This study uses brush collectors that are sampled every 1 to 2 weeks to track sea urchin settlement. The CDFW has access to this data, but at this stage it is unclear how it could be used as a data stream for a management procedure for the fishery. However, a key finding from this study is that the settlement of the red sea urchin appears highly correlated with the settlement of the lightly exploited purple urchin, which suggests that fishing is not affecting the recruitment of the red sea urchin in southern California. This information was used to determine the bounds for the recruitment parameters in the Operating Model.

Appendix L: Fishery Information Summary – Warty Sea Cucumber

Description of Fishery

The first recorded commercial catches of sea cucumber in southern California were made in 1978 in the Los Angeles region (Rogers-Bennet and Ono, 2001). Catches of the warty sea cucumber (*Parastichopus parvimensis*) increased significantly in the early 1990s, and there has been an increase in fishing effort in recent years due to a considerable spike in price (Rogers-Bennet and Ono, 2001; CDFW, pers. comms 2016).

The fishery for warty sea cucumber is entirely a commercial dive fishery, with no sport fishery. The fishery is managed with a limited entry system, with 80 transferable dive permits. Currently there are about 50-65 active fishers, although this number could increase if prices continue to increase (CDFW, pers. comms 2016). Many sea cucumber license holders also hold permits for the sea urchin fishery, and switch between the two species depending on price. Landings are very seasonal, and are typically zero over the winters months, then increase to a peak in May – June before declining again towards the end of the year (CDFW data).

Similar to most sea cucumber species around the world, there is very little known about the biology of the warty sea cucumber in California (Rogers-Bennet and Ono, 2001). Some estimates of the weight-at-maturity and timing of spawning do exist, but essentially no knowledge currently exists on the lifespan or natural mortality of the species. However, it is believed that, like many marine invertebrates, sea cucumber reproduction is likely impacted by the Allee effect, and a minimum density is required for successful spawning (Anderson et al. 2011).

Sea cucumber fisheries around the world typically have a lifespan of about 10 years, and a generally considered the posterchild for 'boom and bust' fisheries (Anderson et al. 2011). The warty sea cucumber industry in southern California has been expressing some concerns about decreasing catch rates in recent years (CDFW, pers. comms. 2016). The CPUE index, generated from diver log book data on catch and effort, appears to show a general decline in recent years, and there is evidence to suggest that divers are shifting to deeper waters in search of viable product (CDFW, pers. comms. 2016). The CDFW is concerned about the declining catch rates of warty sea cucumber, and the apparent harvest of immature individuals.

The following management options may be considered for the southern California warty sea cucumber fishery, and will be evaluated in the MSE:

- Minimum size limit – some fishers are reportedly landing very small individuals. The protection of immature individuals is important for the sustainable exploitation of a stock. Sea cucumber are very difficult and time-consuming to measure, especially underwater, and it is unclear how a minimum size limit would be determined and enforced. However, an incentive for divers to target larger size individuals is likely be an important benefit to this fishery.

- Total allowable effort – the total fishing effort could be controlled, either through number of days per week, or seasonal closures. The fishery appears to be most intense over a four- to five-month period (Feb-July) which appears to coincide with the spawning season for the sea cucumber.
- Total allowable catch (TAC) – a TAC could theoretically be implemented for the sea cucumber fishery. Recently, Florida and Hawaii have implemented daily trip limits for their sea cucumber fisheries.
- Rotational closures – this involves opening and closing different areas of fishing grounds in response to surveys of sea cucumber density. This requires a high level of dive effort before the season opens, and may be difficult to implement in California. The MSE model will need to be modified to account for this type of MP.

MSE Operating Model Parameters

Stock Inputs

The Stock Table contains all information relating to the fish stock that is simulated in the DLMtool. The sections below provide a description of the parameter bounds determined for the Stock parameters for each case study, together with a brief summary of the information and reasoning on which these values are based. The relevant variable names used in the DLMtool table and operating model are included in parentheses behind each sub-heading. Refer to the MSE Operating Model Input Parameter Table (Appendix B) for a description of each variable, and Appendix M for the values used in the MSE.

Natural Mortality (M)

Some research suggests that the natural mortality rates for the California sea cucumber species is relatively high, with a maximum age of 8 – 12 years (Bruckner 2006). However, studies of other holothurian species indicate longevity of at least several decades. The slow recovery rates of over-exploited sea cucumber stocks suggest that adult natural mortality is relatively low. Bounds for natural mortality (*M*) were set at 0.2 – 0.6, which relate to a maximum age between 8 and 23 years. Maximum age is unknown and was set to 30 years, which is allows for sufficient ages classes for all values of natural mortality (see note on maximum age at end of this section).

Growth (Linf, K, t0, a, b)

The lack of age data and the difficulty in measuring the length of sea cucumber, make estimates of growth problematic. Chavez et al. (2011) report an estimate of L_∞ of 50 mm using the ELEFAN technique, which is an order of magnitude smaller than other estimates, and perhaps a typographical error in the units. Bruckner (2006) reports a maximum length of 30 – 40 cm for the warty sea cucumber. The measurement of sea cucumber length is problematic, and depends on the method of measurement. The CDFW measures contracted length of the sea cucumber on the sea floor using diver surveys, and all length measurements reported here for the California WSC are in units of underwater contracted length. Length frequency data from the CDFW shows a modal length of 100 mm and a maximum length around 220 mm. Based on this information, it was determined that a suitable range for the $L\infty$ parameter was 190 – 220 mm.

Chavez et al. (2011) estimated a *K* value of 0.6 using the ELEFAN method. No other information appears to exist on the growth curve for the species. There are few details of the ELEFAN analysis in Chavez et al. (2011) and estimates of *K* can be highly variable using this method. It is difficult to define an appropriate range for this parameter without more detailed studies. Most literature suggests that growth rates for sea cucumber are relatively slow (Bruckner 2006), whereas a value of *K*=0.6 would typically be considered relatively fast growth. Based on the knowledge that sea cucumber growth is relatively slow, it was determined that a *K* of 0.6 is unrealistically high, and the range for this parameter was set at 0.1 – 0.4. No information exists for estimates of t_0, and it was fixed at zero. Length-weight parameters were estimated from survey data provided by the CDFW.

Recruitment (h, Perr, AC)

Little data exists on recruitment trends. Recruitment is believed to be sporadic (Rogers-Bennett and Ono 2007). In the absence of any additional information, the recruitment parameters for the warty sea cucumber were set to the same values as those used for the red sea urchin (see section below).

Maturity (L50, L50_95)

Based on the presence or absence of gonads, the CDFW found females to reach sexual maturity at a total contracted length of 64 mm and at a 53 gram cut body weight (internal viscera and water removed). Males were found to reach sexual maturity at a contracted length of 55 mm and at a 47 gram cut body weight. Given the uncertainty associated with these parameters, the range for the length at 50% maturity (*L50*) was set to 50 – 70 mm, and difference between the length at 95% and 50% maturity (*L50_95*) to 10 – 20 mm.

Depletion (D)

Declines in catches and divers moving to deeper waters provide some evidence that the abundance of warty sea cucumber may be somewhat lower than in the past. Dive log analysis also suggests that CPUE has decreased from 2005 – 2012. However, there is no estimate of current depletion, and the range for this parameter was set to 0.05 – 0.40, which allows for the possibility of a stock at very low size (5% of unfished biomass) as well a stock at much higher levels (40% of unfished biomass).

Spatial Information (Frac_area_1, Prob_staying)

Sea cucumber are mobile and able to move. However, movement rates are not well understood, and the probability of staying in a spatial area was set equal to that used for the red sea urchin (see next section).

General Parameters

The remaining *Stock* parameters had common values across all four case studies. The MSE model is not conditioned on fishery data, and the number of initial recruits (*R0*) is set at an arbitrary 100,000 individuals. There was assumed to be no long-term gradient in the life history parameters (*Mgrad*, *Linfgrad*, *Kgrad* all set to 0). Little information exists on inter-annual variability in natural mortality and growth parameters for the case study stocks, and a common set of values was used for all four species (*Msd* = 0 - 0.05, *Linfsd* = 0 - 0.025, *Ksd* = 0 - 0.025). The maximum age parameter (*maxage*) defines the number of age classes in the simulation model. This parameter is fixed for each case study, and the model is not sensitive to this value, provided it is high enough to account for all values of natural mortality that are included.

Fleet Inputs

The Fleet Table contains all information relating to the historical and future exploitation patterns of the stock. The information in the Fleet Table can be divided into three categories: *exploitation history*, *selectivity*, and *targeting and catchability.* The exploitation history and selectivity pattern varies between the four stocks, and information exists to specify these values. Little specific information is available for the catchability and targeting for these stocks, and common values were used for the four case studies.

Exploitation History (nyears, EffYears, EffLower, EffUpper)

The first catches of sea cucumber in southern California were landed in 1978, and a 39-year historical fishing period (1978 – 2016) was assumed (*nyears*). Fishing mortality appears to have been increasing since the beginning of the fishery 40 years ago. A generally increasing trend in fishing mortality over time, with reasonably larger variability between years, was assumed for the historical fishing mortality (*EffYears*, *EffLower*, *EffUpper*).

Selectivity (LFS, L5, Vmaxlen)

The smallest capture sea cucumbers appear to be about 40 mm contracted length, and the mode of the size distribution is around 90 mm. This information was used to set the bounds for length at 5% selection (*L5*) at 35 - 45 mm length, and smallest length at full selection (*LFS*) at 85 - 95 mm. There appears to be no evidence or reason to expect dome-shaped selectivity pattern, and the vulnerability at maximum length (*Vmaxlen*) was set to 1.

Targeting and Catchability (Spat-targ, Fsd, qinc, qcv)

Spatial targeting (*Spat_targ*) was set to 1 for all case studies. This represents a stock that is actively targeted by the fishers. Default values from the DLMtool were used to represent the inter-annual variability in fishing mortality (*Fsd*; 0.1 - 0.4), and annual increase in catchability (*qinc*; 0 - 2; catchability increases by up to 2% per year), and the annual variability in catchability (*qcv*; 0.1 - 0.3).

Observation Inputs

The Observation Table contains the parameters that are used to generate the simulated fishery data within the MSE model. The parameters used for the observation model were based on the values presented in Carruthers et al. (2014) and are found in the "Generic_obs" observation object in the DLMtool. Common values were used for the observation table for the four case studies, except where information was found to suggest alternative values.

For warty sea cucumber, CV of length at maturity was increased to 20%, and the effective sample size for catch-at-age (*CAA_ESS*) was reduced to 10 – 20 to reflect the paucity of this type of data. The CV for natural mortality was increased to 40% to reflect high uncertainty in this parameter. The CV for the growth (*Linf* and *K*) parameters was increased to 10% and 30% respectively to reflect high uncertainty in these parameters. The range for the beta parameter was set to 0.8 – 1.2 to reflect the perceived increased reliability of CPUE data for this stock compared to the "Generic_obs" default values.

Information for Tuning the MSE Operating Model

Some information exists on the total fishing effort since the beginning of the fishery in the 1970s. This can be used to tune the MSE model to trends in historical fishing mortality. Some size data also exists, which may be useful for determining historical selectivity patterns. Very little information exists on the biology of the warty sea cucumber. Research programs are ongoing to address the deficiency in biological information, but it is unlikely that this data will be available in time for this study.

Fishery Information Data Inputs

Processor Landing Receipts

Total landings (landed catch in pounds) of warty sea cucumber were obtained from the processors landing receipts for southern California, and were available from 1978 to 2015. The dataset was filtered to include only records from southern California; CDFW spatial blocks between 632 and 904 inclusive.

Prior to 2003 the processors landings were not recorded by individual species, and records only indicate 'unspecified sea cucumber', and from 2003 the landings were recorded as either 'giant red', 'warty' or 'unspecified' sea cucumber. Since 2003, the majority of the catch has been warty sea cucumber, and based on information from the CDFW (pers comm. C. Mireles), it was assumed that all 'unspecified' records were warty sea cucumber.

Divers and processors originally reported all catch in terms of whole weight. However, divers switched to cutting the product and draining of the internal fluids, which reduces overall weight by about 50%. Divers began 'cutting' at different times, however the landings receipts do not indicate if the landings were measured as whole or cut weight. It is important to account for this fact when examining historical records of catch.

CDFW conducted a mail survey with the warty sea cucumber divers, and asked, among other things, when the license holder started cutting the catch. Twenty-seven license holders responded to this survey, and indicated a range of years when they started cutting the sea cucumber product, and reducing the total recorded weight by 50% (Table 9). This information was used to estimate the proportion of the landings that were recorded as cut and whole weight in each year. A correction factor was applied to the historical landings, so that all landings are presented in terms of total cut weight (Figure 43).

Table 9: Responses to the CDFW mail survey to gauge when divers began cutting the sea cucumber product, and reducing the weight by 50%.

Year Began Cutting Catch	# respondents	Cumulative Proportion	
		Cutting	Not Cutting
1985 – 1999	7	0.26	0.74
2000 – 2004	0	0.26	0.74
2005 – 2007	3	0.37	0.63
2008 – 2010	11	0.78	0.22
2011 – 2013	5	0.96	0.04
Never cut product	1	0.96	0.04
Total	27		

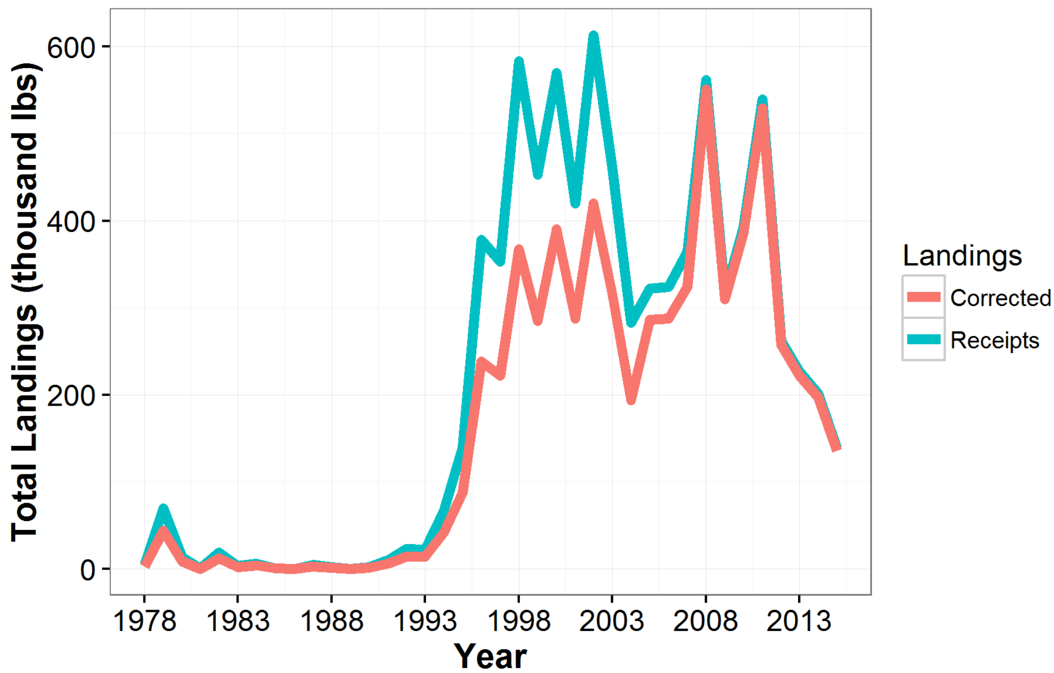

Figure 43: Warty sea cucumber landings data from the processors receipts, and after the correction factor was applied to account for the change in handling of the sea cucumber product.

Diver Log Books

Similar to the landings data, the dive logbooks were filtered to only include records from southern California and for catches of 'unspecified' or 'warty' sea cucumber. The dive logbooks record total effort in terms of dive hours and total number of dives or trips. Effort was believed to be under-reported or under-recorded in 2004 (CDFW pers. comms.) (Figure 44), and the effort (annual number of trips) for 2004 was calculated as the mean of the effort in 2003 and 2005.

The dive log books also report the weight of the sea cucumber catch for each trip, which divers estimate on board the vessels. The cutting correction factor was applied to this dataset in the same manner as that described for the processor landing receipts. The annual landings reported in the dive logs appeared to match reasonably well with the processor landing receipts (Figure 45).

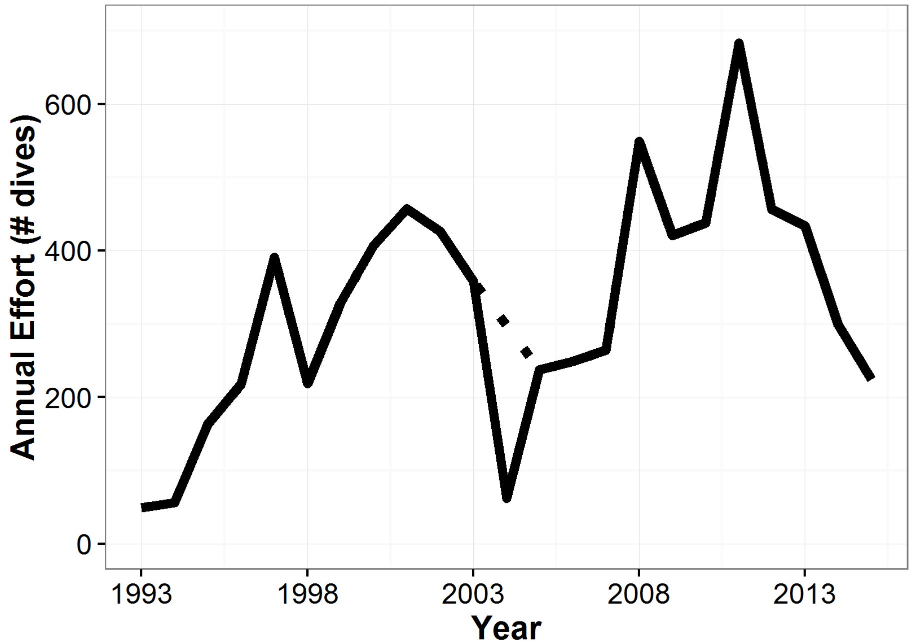

Figure 44: Total number of annual dives (1993 – 2015) calculated from the number of records in the warty sea urchin dive log books in Southern California. Effort was believed to be under-reported or miss-recorded in 2004, and this data point was replaced with the mean effort from 2003 and 2005.

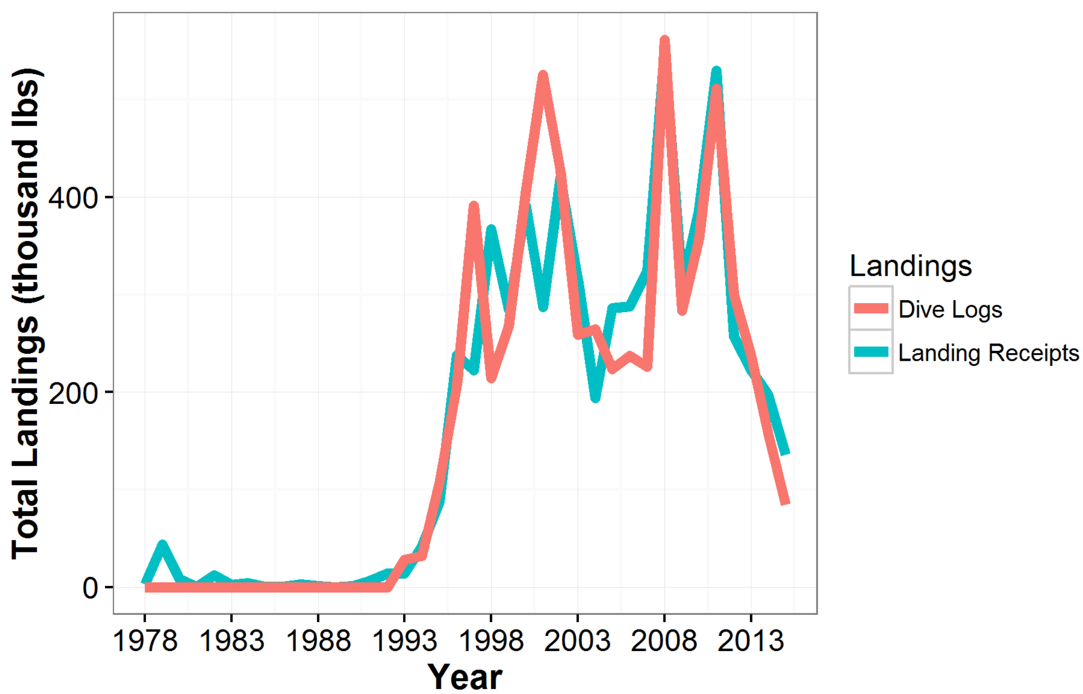

Figure 45: Reported annual landing of warty sea cucumber in Southern California from the dive log books and the processor landing receipts. A correction factor has been applied to both datasets to deal with the change in handling of the product over time (see main text).

Catch-Per-Unit-Effort

Both the landing receipts and logbooks contained records of the CDFW spatial block relating to the catch and effort respectively. However, it was not possible to match the two datasets by spatial block in each year or month, due to the large mismatch in records in the two databases. For example, many of the landing were recorded to come from a particular spatial block in a particular year, however there was no corresponding effort data for that same block and year.

A similar issue existed with the license IDs in the two databases (modified to prevent individual identification). It was not possible to match the license IDs in the landing receipts to the diver logbooks due to some large discrepancies between the two databases. For example, some license IDs were recorded with landings in some years with no matching records of dive effort.

The processor landing receipts were used to estimate the annual landings of warty sea cucumber for the DLM_data object. To calculate the CPUE index, however, catch and effort data (1993 – 2015) from the dive log books was used. The advantage of this approach is that any spatial and seasonal effects can be incorporated into the model to standardize the CPUE index. The CPUE standardization was carried out following Carruthers et al. (2011) and Walters (2003), using data imputation to fill missing Year – Area strata. A Gaussian generalized linear model (GLM) was used to carry out the CPUE standardization with a Year × Area interaction and Month as a covariate. CPUE initially increased until the early 2000s, appeared to be relatively stable from 2001 to 2010, and has been declining since 2011 (Figure 46).

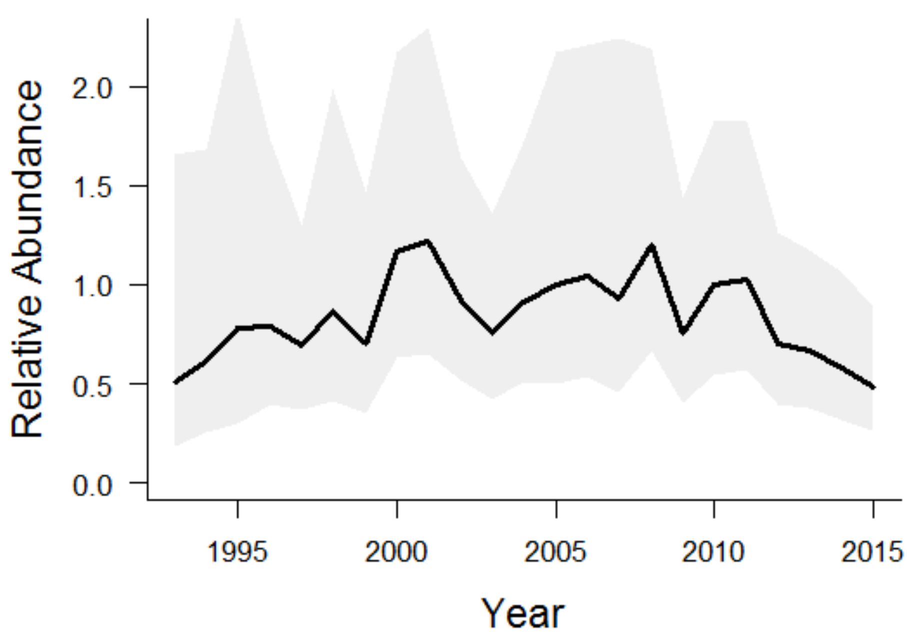

Figure 46: Index of relative abundance (catch-per-unit-effort (CPUE)) from 1993 – 2015 for the warty sea cucumber fishery in Southern California (mean and 95% confidence intervals).

Density Surveys

The CDFW has been conducting dive surveys of 13 sites in the sea cucumber fishing grounds, and recording the density and size distribution of sea cucumber observed on a 100 meter transect. The dive surveys begin in mid-2013 and were conducted at regular intervals (intended to be conducted seasonally, but not always possible). The surveys are conducted both within marine protected areas (MPAs) and in nearby regions open to fishing. Many of these MPAs have been established for up to 30 years, and this data may provide a useful indicator of relative density and abundance in fished grounds versus unfished portions of the stock in comparable environmental conditions.

The surveys often find very low densities of sea cucumber in the fished areas. However, the timing of the survey also needs to be considered. CDFW researchers do not know when, or if, a particular site is fished by a commercial diver, and it is likely that density is markedly reduced after a diver has fished an area.

The National Parks Service has been conducting Kelp Forest Monitoring (KFM) surveys in southern California since 1982. Similar to the CDFW surveys, the transects are located both within and outside of MPAs. The sites of the KFM surveys were not specifically selected for the purpose of monitoring sea cucumber abundance, but were chosen to reflect a wide range of environmental conditions and habitat types. Schroeter et al. (2001) used the KFM data, together with some data from the USGS from five sites of San Nicolas Island, to examine the long-term changes in abundance of warty sea cucumber around the Channel Islands. They found that the abundance of sea cucumber declined within 3 – 6 years of the commencement of fishing, and fished sites had considerably lower densities compared to the unfished sites. In contrast, the CPUE index from this same period did not show any decline.

CDFW intends to continue the density surveys of sea cucumber around the Channel Islands. These surveys are designed to estimate sea cucumber density and employ a methodology that can be used to directly compare CDFW density data to density estimates of other independent survey programs (i.e. KFM, PISCO, LTER).

Appendix M: Management Strategy Evaluation Operating Model Inputs

Note: light gray shading indicates parameters that are common for the four cases studies. Dark gray shading indicates parameters that are not currently used in the DLMtool.

Stock Parameters

Parameter	Barred Sand Bass		California Halibut		Red Sea Urchin		Warty Sea Cucumber		Description
	Min	Max	Min	Max	Min	Max	Min	Max	
Name	BSB		HAL		RSU		WSC		Name of the stock object
maxage[5]	35		40		50		30		Maximum age class in model.
R0	10,000								Number of initial recruits
M	0.15	0.21	0.10	0.20	0.195	0.32	0.20	0.60	Natural mortality rate (bounds on)
Msd	0	0.05	0	0.05	0	0.05	0	0.05	Interannual variability in natural mortality rate
Mgrad	0								Not included in this study
h	0.4	0.9	0.6	0.9	0.4	0.6	0.4	0.6	Recruitment compensation (steepness)
SRrel	1								Beverton-Holt SRR assumed for all species
Linf[6]	560	763	821	1914	109	145	190	220	Asymptotic length of vB growth curve
Linfsd	0	0.025	0	0.025	0	0.025	0	0.025	Interannual variability in Linf parameter (% per year)
Linfgrad	0								Not included in this study
K	0.052	0.108	0.04	0.12	0.13	0.30	0.1	0.4	Maximum growth rate of individuals (von Bertalanffy K)
Ksd	0	0.025	0	0.025	0	0.025	0	0.025	Interannual variability in K parameter (% per year)
Kgrad	0								Not included in this study
t0	-3.89	-1.37	-2.16	-0.24	0	0	0	0	Theoretical age at age length
recgrad	0								Not used in MSE Model
AC	0.5	0.9	0.5	0.9	0.5	0.9	0.5	0.9	Autocorrelation in recruitment deviations
a	3.5E-05		7.8E-6		0.0012659		0.0132		a parameter of the length-weight relationship W=aL^b

[5] Maximum age (maxage) defines the maximum age of the population dynamics model in the operating model (there is no plus group), and model results are invariant to this parameter provided it is set high enough for numbers at age to reduce to essentially zero (or small fraction of R0) under natural conditions (no fishing).

[6] Length-at-age is assumed to be normally distributed with mean length-at-age given by the von Bertalanffy growth equation, and variability assumed to be constant CV of 0.1 for all age classes.

b	2.98		3.05		2.71		1.90		b parameter of the length-weight relationship W=aL^b
L50	219	239	424	515	31.5	58.5	50	70	Length at 50% maturity.
L50_95	10	15	80	100	10	30	10	20	Difference between L95 and L50
D	0.2	0.6	0.1	0.25	0.3	0.6	0.05	0.4	Current level of stock depletion (biomass relative to unfished)
Perr	0.2	0.5	0.3	0.6	0.3	0.6	0.3	0.6	Process error, the standard deviation of log normal recruitment deviations
Size_area_1	0								Not used in MSE Model
Frac_area_1	0.15	0.25	0.15	0.25	0.15	0.25	0.15	0.25	Fraction of the unfished biomass ('habitat') in area 1
Prob_staying	0.095	0.105	0.095	0.105	0.95	0.99	0.95	0.99	Probability that individuals in area 1 stay in area 1 between years

Fleet Parameters

Parameter	Barred Sand Bass		California Halibut		Red Sea Urchin		Warty Sea Cucumber		Description
	Min	Max	Min	Max	Min	Max	Min	Max	
Name	BSBFleet		HALFleet		RSUFleet		WSCFleet		Name of the fleet object
nyears	117		117		47		39		Number of years of historical exploitation
Spat_targ	1	1	1	1	1	1	1	1	Fishing in relation to vulnerable biomass. Default is 1.
SelYears	1, 57, 58, 59, 61, 114		1, 80		1, 18				Year index where MLL was changed
AbsSelYears	1900, 1956, 1957, 1958, 1959, 2013		1900, 1979		1970, 1988		-		Years when MLL was changed
LFSLower	248, 264, 277, 292, 302, 353		445, 540		45, 80		-		Lower bound of LFS for each year
LFSUpper	252, 268, 281, 296, 306, 357		450, 560		50, 84		-		Upper bound of LFS for each year
L5Lower	243, 259, 272, 288, 298, 348		211, 400		40, 70		-		Lower bound of L5 for each year
L5Upper	247, 263, 276, 291, 301, 352		328, 500		42, 75		-		Upper bound of L5 for each year
VmaxLower	0.85, 0.85, 0.85, 0.85, 0.85, 0.85		0.5, 0.5		1, 1		-		Lower bound for vulnerability of largest size class for each year
VmaxUpper	1, 1, 1, 1, 1, 1		1,1		1, 1		-		Upper bound for vulnerability of largest size class for each year
LFS	0	0	0	0	0	0	85	95	Smallest length at full selection relative to size at maturity (0 if parameters above used)
L5	0	0	0	0	0	0	35	45	Length at 5% selection relative to size at maturity (0 if parameters above used)

Vmaxlen	0	0	0	0	0	0	1	1	Vulnerability of largest size individuals (0 if parameters above used)
Fsd	0.1	0.4	0.1	0.4	0.1	0.4	0.1	0.4	Interannual variability in historical fishing mortality rate
qinc	0	2	0	2	0	2	0	2	Mean percentage change in fishing efficiency.
qcv	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	Interannual variability in fishing efficiency
EffYears	1, 11, 35, 40, 47, 50, 65, 66, 87, 90, 101, 117		1, 11, 35, 40, 47, 50, 65, 66, 87, 90, 101, 117		1, 3, 15, 39, 47		1, 13, 31, 39		Year index for fishing effort vertices
EffLower	0, 0.1, 0.1, 0, 0, 0.35, 0.65, 0.65, 0.65, 0.85, 0.5, 0.3		0, 0.1, 0.1, 0, 0, 0.35, 0.65, 0.65, 0.65, 0.85, 0.85, 0.85		0, 0.05, 0.85, 0.25, 0.25		0, 0.3, 0.6, 0.6		Minimum relative fishing effort
EffUpper	0, 0.2, 0.2, 0, 0, 0.65, 0.95, 0.95, 0.75, 1.00, 1.00, 0.4		0, 0.2, 0.2, 0, 0, 0.65, 0.95, 0.95, 0.75, 1.00, 1.00, 1.00		0, 0.15, 1.0, 0.45, 0.45		0, 0.7, 1.0, 1.0		Maximum relative fishing effort

Observation Error Parameters

Parameter	Barred Sand Bass		California Halibut		Red Sea Urchin		Warty Sea Cucumber		Description
	Min	Max	Min	Max	Min	Max	Min	Max	
Name	BSBObs		HALObs		RSUObs		WSCObs		Name of the observation object
LenMcv	0.1		0.1		0.1		0.2		Controls the range of biases for L50 (length at 50% maturity, lognormal standard deviation) [positive real number]
Cobs	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	Catch observation error (log normal standard deviation) [positive real number]
Cbiascv	0.1		0.1		0.1		0.1		Controls the range of biases for annual catch observations (lognormal standard deviation) [positive real number]
CAA_nsamp	100	200	100	200	100	200	100	200	Total number of catch-at-age observations per year [positive integer]
CAA_ESS	25	50	25	50	10	20	10	20	Effective sample size of annual catch-at-age observations (independent draws of multinomial observation model)
CAL_nsamp	400	600	100	200	100	200	100	200	Total number of catch-at-length observations per year [positive integer]
CAL_ESS	150	300	25	50	25	50	25	50	Effective sample size of annual catch-at-length observations (independent draws of multinomial observation model)
CALcv	0.05	0.15	0.05	0.15	0.05	0.15	0.05	0.15	The lognormal variability in length at age (lognormal standard deviation) [positive real number] Not currently used

Iobs	0.1	0.4	0.1	0.4	0.1	0.4	0.1	0.4	Relative abundance index observation error (log normal standard deviation) [positive real number]
Mcv	0.2		0.3		0.3		0.4		Controls the range of biases sampled for natural mortality rate (lognormal standard deviation) [positive real number]
Kcv	0.1		0.1		0.2		0.3		'' for growth parameter K
t0cv	0.1		0.1		0.1		0.1		'' for growth parameter t0
Linfcv	0.05		0.05		0.1		0.1		'' for growth parameter Linf
LFCcv	0.05		0.05		0.05		0.05		'' for Length at First Capture (first observed length in fishery)
LFScv	0.05		0.05		0.05		0.05		'' for shortest Length at Full Selection
B0cv	3		3		3		3		'' for unfished stock size
FMSYcv	0.2		0.2		0.2		0.2		'' for Fishing mortality rate at Maximum Sustainable Yield
FMSY_Mcv	0.2		0.2		0.2		0.2		'' for ratio of FMSY to natural mortality rate M
BMSY_B0cv	0.2		0.2		0.2		0.2		'' for position of most productive stock size relative to unfished
rcv	0.5		0.5		0.5		0.5		'' for intrinsic rate of increase (surplus production parameter r)
Dbiascv	0.5		0.5		0.5		0.5		'' for stock depletion (biomass relative to unfished)
Dcv	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10	observation error in stock depletion (lognormal standard deviation) [positive real number]
Btbias	0.333	3	0.333	3	0.333	3	0.333	3	Bounds on bias in observations of current absolute stock size (uniform on log) [positive real number]
Btcv	0.2	0.5	0.2	0.5	0.2	0.5	0.2	0.5	Observation error in current absolute stock size (lognormal standard deviation) [positive real number]
Fcurbiascv	0.5		0.5		0.5		0.5		" for current fishing mortality rate
Fcurcv	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	Observation error in current fishing mortality rate (lognormal standard deviation) [positive real number]
hcv	0.2		0.2		0.2		0.2		'' for recruitment compensation (steepness, h)
Icv	0.2		0.2		0.2		0.2		'' for relative abundance index
maxagecv	0.1		0.1		0.1		0.1		'' for maximum age
Reccv	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	Observation error for slope in recent recruitment (absolute recruitment over last 10 years, age 1 individuals)
Irefcv	0.2		0.2		0.2		0.2		'' for target (reference) relative abundance index (IMSY)
Crefcv	0.2		0.2		0.2		0.2		'' for target (reference) catch (MSY)
Brefcv	0.5		0.5		0.5		0.5		'' for target (reference) biomass level (BMSY)
beta	0.45	1.00	0.80	1.2	0.80	1.2	0.80	1.2	Bounds on hyperstability / hyper depletion parameter that controls relationship between relative abundance index and biomass ($index(t) = vulnerablebiomass(t)^{beta}$) (uniform on log) [positive real number]

Appendix N: MSE Results Table for Barred Sand Bass

The numerical results for the performance limits and target, reference, and average annual variability in yield and effort represent the proportion of simulated runs in the MSE where the stated performance metric was met. The yield metric represents the projected yield for each method in the MSE relative to the yield at F_{MSY}.

Key: Regular Text = Acceptable/Available — *Italic Text = Acceptable/Not Available*
Shaded Regular Text = Not Acceptable/Available — *Shaded Italic Text = Not Acceptable/Not Available*
* = Not Acceptable/Not Available (due to the lack of implementation error regarding sub-legal size fishing mortality)

Management Procedure	Performance Limits: Prob. $B > 0.2\ B_0$ Yrs 41-50	Yrs 11-50	Performance Target: Prob. $B > 0.4\ B_0$ Yrs 41-50	Reference: Prob. $B > B_{MSY}$	Long-Term Yield vs. F_{MSY}	Avg Annual Var. Yield (AAVY)	Avg Annual Var. Effort (AAVE)	Management Type
ITe5	0.94	0.96	0.55	0.66	98	22	1	Effort
curE	0.96	0.97	0.69	0.77	86	22	0	Effort
LstepCE1	0.96	0.97	0.71	0.79	80	22	1	Effort
curE75	0.98	0.98	0.77	0.84	79	22	0	Effort
ItargetE1	0.95	0.97	0.72	0.79	76	22	3	Effort
LstepCE2	0.96	0.97	0.73	0.80	74	22	1	Effort
BSB_Scls	0.99	0.99	0.84	0.89	70	22	0	Effort/Seasonal
curE50	0.99	0.99	0.86	0.90	67	22	0	Effort
LtargetE1	0.98	0.99	0.86	0.90	51	22	3	Effort
ItargetE4	0.99	0.99	0.91	0.94	37	22	4	Effort
LtargetE4	1.00	1.00	0.97	0.97	20	22	5	Effort
DDes	*0.96*	*0.97*	*0.57*	*0.70*	*95*	*23*	*2*	*Effort*
DTe40	*0.96*	*0.97*	*0.63*	*0.73*	*88*	*22*	*2*	*Effort*
AvC	*0.91*	*0.93*	*0.64*	*0.71*	*86*	*7*	*18*	*TAC*
IT10	*0.93*	*0.96*	*0.68*	*0.75*	*86*	*3*	*13*	*TAC*
DAAC	*0.90*	*0.93*	*0.54*	*0.64*	*85*	*8*	*17*	*TAC*

ITM	*0.94*	*0.96*	*0.69*	*0.77*	*85*	*3*	*13*	*TAC*
SPSRA	*0.88*	*0.91*	*0.52*	*0.62*	*85*	*10*	*21*	*TAC*
DCAC	*0.95*	*0.96*	*0.71*	*0.78*	*81*	*2*	*14*	*TAC*
YPR	*0.87*	*0.88*	*0.57*	*0.66*	*81*	*14*	*23*	*TAC*
DCAC_40	*0.95*	*0.95*	*0.72*	*0.78*	*80*	*2*	*14*	*TAC*
SPMSY	*0.83*	*0.86*	*0.57*	*0.63*	*80*	*15*	*27*	*TAC*
DTe50	*0.98*	*0.98*	*0.72*	*0.79*	*79*	*22*	*2*	*Effort*
Fdem	*0.92*	*0.93*	*0.63*	*0.72*	*78*	*14*	*22*	*TAC*
BK	*0.88*	*0.88*	*0.59*	*0.67*	*77*	*14*	*23*	*TAC*
MCD	*0.96*	*0.97*	*0.72*	*0.79*	*77*	*5*	*14*	*TAC*
MCD4010	*0.97*	*0.98*	*0.75*	*0.81*	*74*	*6*	*15*	*TAC*
DCAC4010	*0.99*	*0.99*	*0.83*	*0.87*	*71*	*3*	*13*	*TAC*
IT5	*0.97*	*0.98*	*0.83*	*0.88*	*66*	*1*	*12*	*TAC*
Itarget1	*0.99*	*0.99*	*0.89*	*0.93*	*62*	*3*	*12*	*TAC*
HDAAC	*1.00*	*1.00*	*0.93*	*0.94*	*54*	*3*	*12*	*TAC*
Islope1	*0.99*	*0.99*	*0.91*	*0.94*	*47*	*1*	*11*	*TAC*
Islope4	*0.99*	*0.99*	*0.91*	*0.94*	*46*	*1*	*11*	*TAC*
Ltarget1	*0.99*	*0.99*	*0.93*	*0.95*	*45*	*3*	*13*	*TAC*
Rcontrol2	*0.84*	*0.87*	*0.70*	*0.72*	*43*	*16*	*32*	*TAC*
LstepCC1	*0.99*	*0.99*	*0.92*	*0.94*	*41*	*1*	*11*	*TAC*
LstepCC4	*0.99*	*0.99*	*0.92*	*0.94*	*41*	*1*	*11*	*TAC*
Itarget4	*1.00*	*1.00*	*0.97*	*0.98*	*34*	*2*	*10*	*TAC*
Ltarget4	*1.00*	*1.00*	*0.97*	*0.98*	*31*	*2*	*11*	*TAC*
CC4	*0.99*	*0.99*	*0.94*	*0.95*	*19*	*4*	*14*	*TAC*
ITe10	0.89	0.94	0.39	0.52	104	23	2	Effort
DD	*0.86*	*0.90*	*0.42*	*0.53*	*93*	*8*	*20*	*TAC*
CC1	*0.63*	*0.77*	*0.28*	*0.34*	*92*	*14*	*33*	*TAC*
DepF	*0.89*	*0.90*	*0.43*	*0.56*	*91*	*19*	*27*	*TAC*

GB_CC	*0.62*	*0.74*	*0.25*	*0.32*	*91*	*13*	*30*	*TAC*
DBSRA	*0.76*	*0.81*	*0.32*	*0.41*	*90*	*16*	*34*	*TAC*
DD4010	*0.92*	*0.94*	*0.48*	*0.61*	*90*	*9*	*21*	*TAC*
DynF	*0.81*	*0.81*	*0.34*	*0.45*	*89*	*26*	*35*	*TAC*
Fadapt	*0.75*	*0.78*	*0.29*	*0.40*	*89*	*19*	*28*	*TAC*
Fratio4010	*0.94*	*0.95*	*0.49*	*0.63*	*89*	*20*	*28*	*TAC*
DBSRA_40	*0.62*	*0.70*	*0.24*	*0.30*	*88*	*17*	*44*	*TAC*
DBSRA4010	*0.87*	*0.89*	*0.40*	*0.52*	*88*	*18*	*34*	*TAC*
Fratio	*0.83*	*0.84*	*0.39*	*0.50*	*88*	*18*	*27*	*TAC*
GB_slope	*0.66*	*0.79*	*0.33*	*0.40*	*88*	*14*	*31*	*TAC*
GB_target	*0.57*	*0.70*	*0.19*	*0.27*	*88*	*15*	*32*	*TAC*
SBT1	*0.67*	*0.79*	*0.35*	*0.41*	*87*	*13*	*31*	*TAC*
*MLL350**	*0.96*	*0.97*	*0.68*	*0.76*	*86*	*22*	*0*	*Size*
SBT2	*0.59*	*0.68*	*0.22*	*0.29*	*86*	*13*	*30*	*TAC*
*MLL360**	*0.97*	*0.98*	*0.71*	*0.79*	*85*	*22*	*0*	*Size*
*MLL365**	*0.97*	*0.98*	*0.72*	*0.81*	*85*	*22*	*0*	*Size*
*MLL370**	*0.98*	*0.98*	*0.74*	*0.82*	*84*	*22*	*0*	*Size*
SPmod	*0.54*	*0.63*	*0.19*	*0.26*	*83*	*22*	*39*	*TAC*
DDe	*0.74*	*0.83*	*0.32*	*0.40*	*82*	*25*	*10*	*Effort*
Gcontrol	*0.67*	*0.77*	*0.35*	*0.42*	*82*	*17*	*37*	*TAC*
Fdem_CC	*0.48*	*0.52*	*0.14*	*0.20*	*77*	*31*	*108*	*TAC*
BK_CC	*0.48*	*0.51*	*0.14*	*0.20*	*76*	*31*	*110*	*TAC*
CompSRA	*0.47*	*0.50*	*0.13*	*0.19*	*76*	*30*	*111*	*TAC*
CompSRA4010	*0.47*	*0.50*	*0.13*	*0.19*	*76*	*30*	*111*	*TAC*
Fratio_CC	*0.47*	*0.50*	*0.13*	*0.19*	*76*	*30*	*121*	*TAC*
YPR_CC	*0.47*	*0.51*	*0.14*	*0.20*	*76*	*31*	*112*	*TAC*
slotlim	*0.71*	*0.77*	*0.35*	*0.43*	*73*	*22*	*0*	*Size*
matlenlim2	*0.65*	*0.72*	*0.30*	*0.38*	*72*	*22*	*0*	*Size*

matlenlim	*0.60*	*0.67*	*0.26*	*0.33*	*67*	*22*	*0*	*Size*
SPslope	*0.75*	*0.83*	*0.52*	*0.57*	*62*	*19*	*32*	*TAC*
DDe75	*0.58*	*0.63*	*0.36*	*0.39*	*50*	*29*	*20*	*Effort*
*ItargetE1ML**	*1.00*	*1.00*	*0.96*	*0.97*	*30*	*22*	*4*	*Size/Effort*
*LtargetE1ML**	*1.00*	*1.00*	*0.96*	*0.97*	*30*	*22*	*4*	*Size/Effort*
*SL350_382**	*0.95*	*0.97*	*0.90*	*0.92*	*29*	*29*	*0*	*Size*
*SL355_382**	*0.90*	*0.93*	*0.87*	*0.87*	*26*	*31*	*0*	*Size*
*SL360_382**	*0.80*	*0.85*	*0.78*	*0.78*	*23*	*34*	*0*	*Size*
*ItargetE4ML**	*1.00*	*1.00*	*0.97*	*0.98*	*18*	*23*	*5*	*Size/Effort*
*LtargetE4ML**	*1.00*	*1.00*	*0.97*	*0.98*	*18*	*23*	*5*	*Size/Effort*
*ItargetE1SL**	*0.80*	*0.85*	*0.79*	*0.80*	*5*	*35*	*3*	*Size/Effort*
*LtargetE1SL**	*0.80*	*0.85*	*0.79*	*0.80*	*5*	*35*	*4*	*Size/Effort*
*ItargetE4SL**	*0.80*	*0.85*	*0.80*	*0.80*	*2*	*35*	*5*	*Size/Effort*
*LtargetE4SL**	*0.80*	*0.85*	*0.80*	*0.80*	*2*	*35*	*5*	*Size/Effort*

Appendix O: MSE Results Table for California Halibut

The numerical results for the performance limits and target, reference, and average annual variability in yield and effort represent the proportion of simulated runs in the MSE where the stated performance metric was met. The yield metric represents the projected yield for each method in the MSE relative to the yield at F_{MSY}.

Key: Regular Text = Acceptable/Available *Italic Text = Acceptable/Not Available*
Shaded Regular Text = Not Acceptable/Available *Shaded Italic Text = Not Acceptable/Not Available*
* = Not Acceptable/Not Available (due to the lack of implementation error regarding sub-legal size fishing mortality)

Management Procedure	Performance Limits: Prob. $B > 0.125\ B_0$ Yrs 41-50	Performance Limits: Prob. $B > 0.125\ B_0$ Yrs 11-50	Performance Target: Prob. $B > 0.25\ B_0$ Yrs 41-50	Reference: Prob. $B > B_{MSY}$	Long-Term Yield vs. F_{MSY}	Avg Annual Var. Yield (AAVY)	Avg Annual Var. Effort (AAVE)	Management Type
Itarget1	0.93	0.93	0.65	0.47	95	5	11	TAC
ItargetE1	0.89	0.89	0.55	0.39	92	22	3	Effort
DepF	0.91	0.90	0.62	0.49	87	14	19	TAC
DTe40	0.90	0.86	0.54	0.37	87	22	2	Effort
DAAC	0.90	0.91	0.68	0.57	85	4	10	TAC
Fratio4010	0.96	0.96	0.72	0.58	85	15	21	TAC
DTe50	0.93	0.88	0.62	0.44	84	21	2	Effort
MCD	0.98	0.98	0.88	0.79	75	4	9	TAC
MCD4010	0.99	0.99	0.89	0.82	71	6	11	TAC
DCAC	0.81	0.83	0.68	0.60	70	1	14	TAC
Itarget4	0.99	0.99	0.94	0.89	68	3	9	TAC
DCAC4010	0.99	0.99	0.91	0.86	67	3	10	TAC
ItargetE4	0.99	0.97	0.90	0.80	67	22	4	Effort
HDAAC	1.00	1.00	0.98	0.94	51	3	9	TAC
CC4	0.83	0.85	0.80	0.77	22	5	13	TAC
DD	*0.89*	*0.91*	*0.64*	*0.49*	*92*	*3*	*10*	*TAC*

DD4010	*0.99*	*0.99*	*0.84*	*0.69*	*91*	*5*	*11*	*TAC*
DBSRA4010	*0.89*	*0.90*	*0.62*	*0.48*	*86*	*12*	*18*	*TAC*
SPSRA	*0.92*	*0.93*	*0.73*	*0.61*	*85*	*5*	*10*	*TAC*
Ltarget4	*0.92*	*0.93*	*0.86*	*0.81*	*55*	*5*	*13*	*TAC*
LtargetE4	*0.96*	*0.93*	*0.86*	*0.78*	*53*	*22*	*4*	*Effort*
curE75	0.68	0.76	0.25	0.15	95	21	0	Effort
DDe	0.49	0.65	0.18	0.10	87	22	2	Effort
curE	0.47	0.57	0.12	0.07	84	22	0	Effort
YPR	0.78	0.77	0.54	0.45	81	13	19	TAC
Fratio	0.73	0.74	0.49	0.40	80	13	19	TAC
Fdem	0.75	0.74	0.54	0.43	79	13	19	TAC
DynF	0.65	0.65	0.41	0.32	78	21	28	TAC
BK	0.78	0.79	0.59	0.49	77	12	18	TAC
Fadapt	0.57	0.57	0.34	0.25	73	12	18	TAC
DCAC_40	0.77	0.80	0.65	0.58	68	2	16	TAC
AvC	0.52	0.59	0.41	0.35	61	7	28	TAC
DDe75	0.13	0.25	0.03	0.02	52	23	3	Effort
Islope1	0.64	0.62	0.53	0.47	51	3	13	TAC
SPMSY	0.54	0.59	0.46	0.42	51	14	36	TAC
Islope4	0.63	0.62	0.53	0.48	50	3	13	TAC
Rcontrol	0.35	0.45	0.24	0.19	50	12	20	TAC
Gcontrol	0.23	0.31	0.16	0.15	37	17	30	TAC
SPslope	0.33	0.41	0.27	0.25	36	22	28	TAC
GB_slope	0.16	0.23	0.11	0.09	33	14	27	TAC
SBT1	0.16	0.23	0.12	0.10	32	14	27	TAC
CC1	0.10	0.18	0.06	0.05	28	14	34	TAC
Rcontrol2	0.45	0.47	0.42	0.41	23	18	32	TAC
SPmod	0.05	0.09	0.01	0.01	22	24	31	TAC

*LogSel750**	*0.84*	*0.88*	*0.51*	*0.38*	*109*	*22*	*0*	*Size*
*MLL675**	*0.85*	*0.88*	*0.52*	*0.40*	*109*	*23*	*0*	*Size*
*MLL705**	*0.88*	*0.91*	*0.59*	*0.45*	*109*	*23*	*0*	*Size*
*MLL735**	*0.90*	*0.92*	*0.64*	*0.50*	*109*	*24*	*0*	*Size*
MLL645	*0.81*	*0.85*	*0.47*	*0.34*	*108*	*23*	*0*	*Size*
MLL615	*0.77*	*0.82*	*0.40*	*0.28*	*105*	*23*	*0*	*Size*
LogSel650	*0.74*	*0.79*	*0.35*	*0.24*	*103*	*22*	*0*	*Size*
MLL585	*0.71*	*0.77*	*0.32*	*0.22*	*102*	*22*	*0*	*Size*
MLL555	*0.64*	*0.71*	*0.25*	*0.16*	*96*	*22*	*0*	*Size*
LogSel600	*0.61*	*0.70*	*0.22*	*0.15*	*95*	*22*	*0*	*Size*
DDes	*0.80*	*0.80*	*0.32*	*0.17*	*94*	*22*	*2*	*Effort*
ITe10	*0.80*	*0.79*	*0.34*	*0.18*	*93*	*22*	*2*	*Effort*
ITe5	*0.67*	*0.70*	*0.20*	*0.10*	*91*	*21*	*1*	*Effort*
Slotlim	*0.56*	*0.64*	*0.20*	*0.12*	*86*	*22*	*0*	*Size*
DBSRA	*0.72*	*0.76*	*0.46*	*0.34*	*85*	*7*	*13*	*TAC*
LstepCE1	*0.60*	*0.64*	*0.21*	*0.13*	*85*	*22*	*1*	*Effort*
matlenlim2	*0.48*	*0.58*	*0.16*	*0.10*	*84*	*22*	*0*	*Size*
LstepCE2	*0.66*	*0.69*	*0.36*	*0.25*	*79*	*22*	*2*	*Effort*
LtargetE1	*0.71*	*0.72*	*0.42*	*0.31*	*78*	*22*	*3*	*Effort*
matlenlim	*0.37*	*0.47*	*0.10*	*0.05*	*74*	*22*	*0*	*Size*
IT10	*0.74*	*0.72*	*0.60*	*0.52*	*66*	*4*	*12*	*TAC*
ITM	*0.73*	*0.71*	*0.59*	*0.52*	*64*	*4*	*12*	*TAC*
IT5	*0.69*	*0.67*	*0.57*	*0.50*	*58*	*3*	*12*	*TAC*
Ltarget1	*0.64*	*0.67*	*0.55*	*0.49*	*57*	*9*	*26*	*TAC*
LstepCC1	*0.65*	*0.63*	*0.57*	*0.52*	*43*	*4*	*13*	*TAC*
LstepCC4	*0.65*	*0.63*	*0.57*	*0.52*	*43*	*4*	*13*	*TAC*
GB_target	*0.14*	*0.23*	*0.07*	*0.05*	*36*	*12*	*26*	*TAC*
GB_CC	*0.12*	*0.19*	*0.07*	*0.06*	*31*	*13*	*28*	*TAC*

SBT2	*0.12*	*0.18*	*0.07*	*0.06*	*29*	*12*	*43*	*TAC*
DBSRA_40	*0.09*	*0.13*	*0.05*	*0.04*	*25*	*14*	*65*	*TAC*
CompSRA4010	*0.08*	*0.10*	*0.06*	*0.05*	*17*	*36*	*103*	*TAC*
CompSRA	*0.07*	*0.08*	*0.06*	*0.05*	*16*	*33*	*102*	*TAC*
BK_CC	*0.02*	*0.02*	*0.00*	*0.00*	*13*	*36*	*84*	*TAC*
Fdem_CC	*0.02*	*0.02*	*0.00*	*0.00*	*13*	*37*	*86*	*TAC*
Fratio_CC	*0.01*	*0.02*	*0.00*	*0.00*	*13*	*37*	*86*	*TAC*
YPR_CC	*0.01*	*0.02*	*0.00*	*0.00*	*13*	*37*	*84*	*TAC*

Appendix P: MSE Results Table for Red Sea Urchin

The numerical results for the performance limits and target, reference, and average annual variability in yield and effort represent the proportion of simulated runs in the MSE where the stated performance metric was met. The yield metric represents the projected yield for each method in the MSE relative to the yield at F_{MSY}.

Key: Regular Text = Acceptable/Available *Italic Text = Acceptable/Not Available*
Shaded Regular Text = Not Acceptable/Available *Shaded Italic Text = Not Acceptable/Not Available*

Management Procedure	Performance Limits: Prob. $B > 0.25\ B_0$ Yrs 41-50	Yrs 11-50	Performance Target: Prob. $B > 0.5\ B_0$ Yrs 41-50	Reference: Prob. $B > B_{MSY}$	Long-Term Yield vs. F_{MSY}	Avg Annual Var. Yield (AAVY)	Avg Annual Var. Effort (AAVE)	Management Type
ItargSL1	0.89	0.92	0.51	0.72	74	23	0	Size
ItargSL4	0.89	0.92	0.51	0.72	74	23	0	Size
LtargSL1	0.89	0.91	0.51	0.72	74	23	0	Size
LtargSL4	0.89	0.91	0.51	0.72	74	23	0	Size
MLL3.375	0.89	0.91	0.50	0.72	74	23	0	Size
MLL3.375_5.5	0.89	0.91	0.50	0.72	74	23	0	Size
MLL3.5	0.90	0.92	0.54	0.74	73	23	0	Size
MLL3.5_5.5	0.90	0.92	0.54	0.74	73	23	0	Size
curE75	0.89	0.92	0.51	0.72	71	22	0	Effort
Islope1	0.80	0.82	0.51	0.66	58	2	11	TAC
Islope4	0.80	0.82	0.52	0.66	58	2	11	TAC
LstepCE2	0.90	0.91	0.54	0.74	58	22	2	Effort
Itarget1	0.91	0.92	0.58	0.76	56	5	12	TAC
Ltarget1	0.83	0.87	0.57	0.71	56	5	15	TAC
ItargetE1	0.91	0.93	0.57	0.77	54	22	3	Effort
LstepCC1	0.84	0.84	0.57	0.71	49	2	11	TAC
LstepCC4	0.84	0.84	0.57	0.71	49	2	11	TAC

CC4	0.81	0.86	0.55	0.68	46	5	16	TAC
LtargetE1	0.93	0.93	0.63	0.80	46	22	3	Effort
Ltarget4	0.91	0.93	0.67	0.81	43	4	12	TAC
Itarget4	0.95	0.96	0.71	0.86	36	3	10	TAC
ItargetE4	0.95	0.95	0.73	0.87	25	23	5	Effort
LtargetE4	0.96	0.96	0.75	0.88	19	23	5	Effort
HDAAC	*0.91*	*0.93*	*0.57*	*0.76*	*54*	*4*	*11*	*TAC*
ITe10	0.83	0.87	0.32	0.57	83	23	2	Effort
ITe5	0.85	0.88	0.37	0.62	81	22	1	Effort
DCAC_40	0.64	0.72	0.29	0.45	78	5	20	TAC
curE	0.86	0.89	0.44	0.67	76	22	0	Effort
AvC	0.53	0.63	0.18	0.32	74	10	29	TAC
CC1	0.44	0.57	0.10	0.22	72	15	41	TAC
GB_slope	0.45	0.57	0.11	0.23	71	15	36	TAC
SBT1	0.45	0.57	0.11	0.23	71	15	36	TAC
IT10	0.77	0.80	0.39	0.57	70	4	12	TAC
ITM	0.77	0.80	0.37	0.56	70	4	12	TAC
GB_CC	0.40	0.52	0.08	0.19	69	15	35	TAC
GB_target	0.40	0.51	0.08	0.18	68	16	34	TAC
LstepCE1	0.88	0.91	0.49	0.71	68	22	1	Effort
IT5	0.78	0.81	0.45	0.62	66	3	11	TAC
L95target	0.69	0.74	0.38	0.52	64	5	20	TAC
matlenlim2	0.68	0.75	0.25	0.44	64	22	0	Size
matlenlim	0.67	0.73	0.23	0.42	62	22	0	Size
DDe	*0.75*	*0.82*	*0.26*	*0.48*	*83*	*24*	*4*	*Effort*
DCAC	*0.62*	*0.72*	*0.27*	*0.44*	*78*	*5*	*20*	*TAC*
DDes	*0.88*	*0.90*	*0.42*	*0.67*	*78*	*23*	*2*	*Effort*
DD	*0.70*	*0.76*	*0.31*	*0.49*	*76*	*7*	*19*	*TAC*

DBSRA	*0.57*	*0.64*	*0.18*	*0.33*	*75*	*14*	*34*	*TAC*
DepF	*0.65*	*0.67*	*0.21*	*0.39*	*75*	*17*	*25*	*TAC*
DTe40	*0.87*	*0.90*	*0.41*	*0.64*	*74*	*23*	*2*	*Effort*
EtargetLopt	*0.88*	*0.91*	*0.47*	*0.69*	*74*	*22*	*1*	*Effort*
Fratio4010	*0.76*	*0.77*	*0.25*	*0.46*	*74*	*18*	*26*	*TAC*
DAAC	*0.68*	*0.74*	*0.27*	*0.46*	*73*	*9*	*19*	*TAC*
DD4010	*0.73*	*0.77*	*0.33*	*0.52*	*73*	*11*	*24*	*TAC*
DynF	*0.55*	*0.59*	*0.16*	*0.31*	*73*	*22*	*35*	*TAC*
SPSRA	*0.71*	*0.76*	*0.29*	*0.48*	*73*	*10*	*23*	*TAC*
DBSRA_40	*0.47*	*0.57*	*0.12*	*0.25*	*72*	*13*	*47*	*TAC*
Fratio	*0.56*	*0.60*	*0.18*	*0.34*	*72*	*16*	*29*	*TAC*
minlenLopt1	*0.77*	*0.82*	*0.33*	*0.54*	*72*	*22*	*0*	*Effort*
SPMSY	*0.57*	*0.65*	*0.22*	*0.37*	*72*	*16*	*34*	*TAC*
DDe75	*0.56*	*0.66*	*0.15*	*0.30*	*71*	*26*	*9*	*Effort*
Gcontrol	*0.49*	*0.60*	*0.14*	*0.27*	*71*	*16*	*41*	*TAC*
DBSRA4010	*0.70*	*0.74*	*0.23*	*0.42*	*70*	*16*	*33*	*TAC*
Fadapt	*0.48*	*0.54*	*0.12*	*0.25*	*70*	*17*	*31*	*TAC*
MCD	*0.75*	*0.79*	*0.33*	*0.53*	*70*	*7*	*15*	*TAC*
Fdem	*0.72*	*0.75*	*0.35*	*0.53*	*69*	*13*	*20*	*TAC*
YPR	*0.49*	*0.53*	*0.14*	*0.27*	*68*	*17*	*32*	*TAC*
DCAC4010	*0.83*	*0.86*	*0.41*	*0.63*	*67*	*5*	*13*	*TAC*
DTe50	*0.90*	*0.92*	*0.47*	*0.70*	*67*	*23*	*2*	*Effort*
BK	*0.44*	*0.49*	*0.12*	*0.24*	*65*	*19*	*38*	*TAC*
SBT2	*0.39*	*0.46*	*0.08*	*0.18*	*65*	*14*	*36*	*TAC*
SPmod	*0.39*	*0.47*	*0.07*	*0.18*	*65*	*21*	*48*	*TAC*
MCD4010	*0.82*	*0.85*	*0.38*	*0.61*	*63*	*9*	*17*	*TAC*
slotlim	*0.80*	*0.85*	*0.37*	*0.58*	*62*	*23*	*0*	*Size*
CompSRA	*0.36*	*0.40*	*0.07*	*0.16*	*60*	*28*	*118*	*TAC*

CompSRA4010	*0.36*	*0.40*	*0.06*	*0.16*	*60*	*29*	*119*	*TAC*
Fdem_CC	*0.35*	*0.40*	*0.06*	*0.15*	*60*	*27*	*124*	*TAC*
Fratio_CC	*0.34*	*0.38*	*0.05*	*0.14*	*60*	*28*	*135*	*TAC*
Rcontrol2	*0.61*	*0.69*	*0.32*	*0.44*	*60*	*16*	*43*	*TAC*
BK_CC	*0.34*	*0.37*	*0.05*	*0.14*	*59*	*27*	*141*	*TAC*
YPR_CC	*0.34*	*0.38*	*0.05*	*0.14*	*59*	*27*	*137*	*TAC*
DBSRA_ML	*0.33*	*0.36*	*0.05*	*0.14*	*58*	*28*	*136*	*TAC*
SPslope	*0.67*	*0.72*	*0.37*	*0.50*	*52*	*22*	*36*	*TAC*

Appendix Q: MSE Results Table for Warty Sea Cucumber

The numerical results for the performance limits and target, reference, and average annual variability in yield and effort represent the proportion of simulated runs in the MSE where the stated performance metric was met. The yield metric represents the projected yield for each method in the MSE relative to the yield at F_{MSY}.

Key: Regular Text = Acceptable/Available | *Italic Text = Acceptable/Not Available*
Shaded Regular Text = Not Acceptable/Available | *Shaded Italic Text = Not Acceptable/Not Available*

Management Procedure	Performance Limits: Prob. B > 0.125 B_0 Yrs 41-50	Yrs 11-50	Performance Target: Prob. B > 0.25 B_0 Yrs 41-50	Reference: Prob. B > B_{MSY}	Long-Term Yield vs. F_{MSY}	Avg Annual Var. Yield (AAVY)	Avg Annual Var. Effort (AAVE)	Management Type
Itarget4	0.83	0.83	0.53	0.67	70	5	12	TAC
HDAAC	*0.85*	*0.85*	*0.53*	*0.67*	*61*	*6*	*11*	*TAC*
curE50	0.55	0.61	0.18	0.31	95	22	0	Effort
Itarget1	0.61	0.62	0.27	0.41	86	9	17	TAC
ITe10	0.38	0.40	0.08	0.17	86	22	2	Effort
curE75	0.36	0.42	0.09	0.17	85	22	0	Effort
ITe5	0.29	0.34	0.06	0.13	81	22	1	Effort
ItargetE1	0.57	0.55	0.21	0.36	79	22	3	Effort
MRnoreal	0.54	0.57	0.12	0.26	78	23	0	Spatial
curE	0.23	0.29	0.05	0.10	71	22	0	Effort
ItargetE4	0.77	0.71	0.43	0.58	64	22	4	Effort
MRreal	0.28	0.33	0.05	0.10	50	22	0	Spatial
IT10	0.50	0.49	0.29	0.39	49	6	15	TAC
IT5	0.49	0.48	0.30	0.39	47	5	16	TAC
Islope1	0.48	0.46	0.29	0.38	44	5	16	TAC
Islope4	0.49	0.47	0.30	0.39	43	5	16	TAC
CC4	0.27	0.33	0.18	0.23	27	10	29	TAC

AvC	0.06	0.11	0.03	0.04	17	14	83	TAC
GB_slope	0.03	0.06	0.01	0.01	12	19	35	TAC
SBT1	0.03	0.06	0.01	0.02	12	19	35	TAC
GB_CC	0.02	0.05	0.01	0.01	11	18	38	TAC
GB_target	0.02	0.05	0.01	0.01	11	17	36	TAC
CC1	0.02	0.05	0.01	0.02	10	18	47	TAC
MLL120	0.69	0.73	0.33	0.48	117	24	0	Size
MLL100	0.53	0.58	0.19	0.32	110	23	0	Size
slotlim	0.43	0.48	0.13	0.23	91	23	0	Size
DTe40	0.52	0.49	0.16	0.29	84	22	2	Effort
DTe50	0.57	0.52	0.20	0.34	84	22	2	Effort
DepF	0.60	0.61	0.25	0.39	83	17	23	TAC
DD4010	0.62	0.64	0.29	0.43	82	14	23	TAC
DDes	0.35	0.39	0.08	0.17	82	23	2	Effort
Fratio4010	0.69	0.71	0.29	0.45	80	20	27	TAC
DBSRA4010	0.56	0.61	0.20	0.33	78	21	27	TAC
DAAC	0.55	0.59	0.25	0.36	77	9	13	TAC
LtargetE1	0.49	0.49	0.19	0.30	77	22	3	Effort
MCD	0.62	0.64	0.30	0.42	77	7	13	TAC
DCAC4010	0.74	0.76	0.39	0.53	74	8	14	TAC
LstepCE1	0.29	0.34	0.08	0.14	74	22	1	Effort
matlenlim2	0.27	0.32	0.06	0.12	74	23	0	Size
LstepCE2	0.36	0.39	0.12	0.20	72	22	2	Effort
MCD4010	0.74	0.76	0.36	0.51	72	12	18	TAC
SPSRA	0.46	0.53	0.20	0.30	72	12	16	TAC
Fdem	0.49	0.50	0.23	0.34	71	15	21	TAC
DBSRA	0.38	0.45	0.15	0.23	69	13	19	TAC
Fratio	0.47	0.48	0.22	0.31	68	15	21	TAC

DynF	*0.43*	*0.43*	*0.20*	*0.29*	*66*	*22*	*29*	*TAC*
matlenlim	*0.22*	*0.27*	*0.05*	*0.10*	*66*	*23*	*0*	*Size*
DD	*0.37*	*0.44*	*0.18*	*0.26*	*59*	*10*	*19*	*TAC*
Fadapt	*0.31*	*0.32*	*0.13*	*0.20*	*58*	*16*	*23*	*TAC*
LtargetE4	*0.83*	*0.74*	*0.51*	*0.66*	*56*	*22*	*4*	*Effort*
ITM	*0.51*	*0.50*	*0.29*	*0.39*	*52*	*6*	*15*	*TAC*
BK	*0.28*	*0.28*	*0.11*	*0.18*	*50*	*19*	*24*	*TAC*
Ltarget4	*0.66*	*0.68*	*0.46*	*0.56*	*45*	*6*	*27*	*TAC*
DDe	*0.15*	*0.21*	*0.06*	*0.09*	*40*	*26*	*12*	*Effort*
YPR	*0.16*	*0.17*	*0.05*	*0.10*	*40*	*20*	*25*	*TAC*
LstepCC1	*0.53*	*0.50*	*0.34*	*0.43*	*39*	*5*	*16*	*TAC*
LstepCC4	*0.53*	*0.50*	*0.34*	*0.43*	*39*	*5*	*16*	*TAC*
Ltarget1	*0.42*	*0.46*	*0.28*	*0.35*	*39*	*10*	*47*	*TAC*
DCAC	*0.22*	*0.30*	*0.11*	*0.15*	*36*	*8*	*58*	*TAC*
DCAC_40	*0.20*	*0.28*	*0.11*	*0.15*	*33*	*9*	*62*	*TAC*
Rcontrol	*0.08*	*0.13*	*0.03*	*0.05*	*22*	*17*	*24*	*TAC*
Rcontrol2	*0.19*	*0.25*	*0.14*	*0.16*	*22*	*20*	*39*	*TAC*
SPMSY	*0.08*	*0.13*	*0.04*	*0.05*	*19*	*20*	*83*	*TAC*
DBSRA_40	*0.08*	*0.13*	*0.04*	*0.05*	*18*	*13*	*83*	*TAC*
DDe75	*0.09*	*0.09*	*0.05*	*0.07*	*18*	*28*	*15*	*Effort*
Gcontrol	*0.06*	*0.12*	*0.03*	*0.04*	*18*	*19*	*38*	*TAC*
SPslope	*0.14*	*0.19*	*0.09*	*0.12*	*18*	*23*	*34*	*TAC*
CompSRA	*0.05*	*0.06*	*0.03*	*0.04*	*10*	*30*	*127*	*TAC*
SBT2	*0.02*	*0.04*	*0.01*	*0.01*	*10*	*17*	*71*	*TAC*
SPmod	*0.01*	*0.02*	*0.00*	*0.00*	*9*	*24*	*36*	*TAC*
CompSRA4010	*0.02*	*0.03*	*0.01*	*0.01*	*8*	*39*	*130*	*TAC*
Fdem_CC	*0.01*	*0.03*	*0.01*	*0.01*	*7*	*33*	*87*	*TAC*
Fratio_CC	*0.03*	*0.04*	*0.02*	*0.02*	*7*	*32*	*86*	*TAC*

BK_CC	*0.01*	*0.01*	*0.00*	*0.00*	*6*	*31*	*97*	*TAC*
YPR_CC	*0.01*	*0.01*	*0.00*	*0.00*	*6*	*31*	*100*	*TAC*
DBSRA_ML	*0.01*	*0.02*	*0.00*	*0.01*	*5*	*35*	*102*	*TAC*

Appendix R: MSE Results Table for Warty Sea Cucumber (w/ Increased Selectivity)

Key: Regular Text = Acceptable/Available *Italic Text = Acceptable/Not Available*
Shaded Regular Text = Not Acceptable/Available *Shaded Italic Text = Not Available/Not Acceptable*

Management Procedure	Performance Limits: Prob. **B** > 0.125 **B_0** Yrs 41-50	Yrs 11-50	Performance Target: Prob. **B** > 0.25 **B_0** Yrs 41-50	Reference: Prob. **B** > **B_{MSY}**	Long-Term Yield vs. **F_{MSY}**	Avg Annual Var. Yield (AAVY)	Avg Annual Var. Effort (AAVE)	Management Type
ItargetE4	0.82	0.80	0.51	0.65	63	23	4	Effort
Itarget4	0.89	0.86	0.59	0.73	61	5	14	TAC
HDAAC	*0.89*	*0.87*	*0.57*	*0.72*	*57*	*6*	*14*	*TAC*
Ltarget4	*0.84*	*0.80*	*0.59*	*0.70*	*46*	*6*	*19*	*TAC*
LtargetE4	*0.90*	*0.83*	*0.61*	*0.75*	*43*	*23*	*4*	*Effort*
ITe5	0.63	0.66	0.21	0.36	93	23	1	Effort
ITe10	0.64	0.67	0.22	0.36	92	23	2	Effort
curE75	0.70	0.72	0.28	0.45	91	23	0	Effort
curE	0.61	0.64	0.21	0.37	90	23	0	Effort
curE50	0.79	0.80	0.40	0.57	86	23	0	Effort
ItargetE1	0.70	0.71	0.30	0.46	86	23	3	Effort
Itarget1	0.74	0.73	0.35	0.51	85	9	17	TAC
MRnoreal	0.76	0.76	0.32	0.51	82	24	0	Spatial
MRreal	0.65	0.66	0.23	0.39	77	23	0	Spatial
AvC	0.43	0.44	0.17	0.26	68	13	39	TAC
CC1	0.37	0.38	0.12	0.21	67	18	41	TAC
CC4	0.58	0.60	0.30	0.41	67	11	26	TAC
GB_slope	0.38	0.39	0.13	0.21	67	18	36	TAC
GB_target	0.37	0.38	0.13	0.21	67	17	34	TAC
SBT1	0.39	0.40	0.13	0.22	67	17	36	TAC

GB_CC	0.37	0.38	0.13	0.21	66	17	35	TAC
IT10	0.75	0.71	0.44	0.57	64	5	15	TAC
IT5	0.75	0.70	0.46	0.59	60	4	15	TAC
Islope1	0.74	0.69	0.47	0.59	56	4	15	TAC
Islope4	0.74	0.69	0.48	0.59	55	3	15	TAC
MLL120	*0.68*	*0.70*	*0.28*	*0.44*	*92*	*24*	*0*	*Size*
DDes	*0.67*	*0.69*	*0.24*	*0.40*	*91*	*24*	*2*	*Effort*
DepF	*0.72*	*0.70*	*0.29*	*0.45*	*87*	*18*	*26*	*TAC*
DBSRA	*0.57*	*0.59*	*0.19*	*0.33*	*86*	*16*	*32*	*TAC*
DTe40	*0.73*	*0.72*	*0.29*	*0.46*	*86*	*23*	*2*	*Effort*
DBSRA4010	*0.70*	*0.71*	*0.25*	*0.42*	*85*	*21*	*36*	*TAC*
LstepCE1	*0.65*	*0.66*	*0.27*	*0.43*	*85*	*23*	*1*	*Effort*
MLL100	*0.50*	*0.54*	*0.15*	*0.26*	*85*	*23*	*0*	*Size*
Fratio4010	*0.79*	*0.77*	*0.32*	*0.50*	*84*	*20*	*28*	*TAC*
SPSRA	*0.68*	*0.70*	*0.29*	*0.45*	*84*	*13*	*25*	*TAC*
DAAC	*0.70*	*0.70*	*0.30*	*0.46*	*83*	*10*	*18*	*TAC*
DD	*0.63*	*0.66*	*0.28*	*0.42*	*83*	*11*	*25*	*TAC*
DTe50	*0.78*	*0.75*	*0.34*	*0.52*	*82*	*23*	*2*	*Effort*
DynF	*0.61*	*0.59*	*0.25*	*0.38*	*82*	*23*	*31*	*TAC*
Fratio	*0.64*	*0.62*	*0.26*	*0.40*	*82*	*17*	*25*	*TAC*
Fadapt	*0.55*	*0.54*	*0.21*	*0.34*	*81*	*18*	*27*	*TAC*
MCD	*0.76*	*0.75*	*0.36*	*0.53*	*79*	*9*	*16*	*TAC*
DD4010	*0.74*	*0.75*	*0.39*	*0.54*	*78*	*14*	*26*	*TAC*
YPR	*0.56*	*0.55*	*0.23*	*0.35*	*78*	*18*	*26*	*TAC*
DCAC	*0.51*	*0.54*	*0.22*	*0.33*	*75*	*10*	*31*	*TAC*
LstepCE2	*0.68*	*0.68*	*0.34*	*0.48*	*75*	*23*	*2*	*Effort*
DCAC_40	*0.50*	*0.53*	*0.22*	*0.33*	*74*	*10*	*32*	*TAC*
DCAC4010	*0.81*	*0.81*	*0.44*	*0.60*	*74*	*8*	*17*	*TAC*

LtargetE1	*0.71*	*0.70*	*0.37*	*0.51*	*74*	*23*	*3*	*Effort*
Fdem	*0.76*	*0.74*	*0.42*	*0.57*	*73*	*14*	*22*	*TAC*
Rcontrol	*0.44*	*0.47*	*0.16*	*0.26*	*73*	*16*	*28*	*TAC*
Gcontrol	*0.43*	*0.45*	*0.16*	*0.25*	*72*	*17*	*36*	*TAC*
MCD4010	*0.83*	*0.82*	*0.43*	*0.60*	*71*	*12*	*20*	*TAC*
slotlim	*0.40*	*0.44*	*0.09*	*0.18*	*70*	*23*	*0*	*Size*
SPMSY	*0.43*	*0.45*	*0.18*	*0.27*	*70*	*18*	*44*	*TAC*
BK	*0.57*	*0.56*	*0.28*	*0.40*	*69*	*17*	*24*	*TAC*
DBSRA_40	*0.39*	*0.41*	*0.14*	*0.22*	*69*	*18*	*52*	*TAC*
Rcontrol2	*0.48*	*0.51*	*0.23*	*0.32*	*66*	*20*	*48*	*TAC*
SPmod	*0.36*	*0.37*	*0.12*	*0.20*	*66*	*20*	*39*	*TAC*
ITM	*0.74*	*0.71*	*0.42*	*0.56*	*65*	*5*	*15*	*TAC*
SBT2	*0.37*	*0.37*	*0.13*	*0.21*	*65*	*16*	*39*	*TAC*
CompSRA4010	*0.33*	*0.33*	*0.10*	*0.17*	*62*	*38*	*111*	*TAC*
DDe	*0.60*	*0.62*	*0.32*	*0.41*	*62*	*27*	*15*	*Effort*
Fdem_CC	*0.33*	*0.33*	*0.10*	*0.18*	*62*	*29*	*92*	*TAC*
CompSRA	*0.34*	*0.34*	*0.11*	*0.18*	*61*	*34*	*108*	*TAC*
Fratio_CC	*0.32*	*0.31*	*0.09*	*0.16*	*61*	*32*	*100*	*TAC*
BK_CC	*0.32*	*0.31*	*0.10*	*0.17*	*60*	*30*	*101*	*TAC*
YPR_CC	*0.32*	*0.31*	*0.09*	*0.16*	*60*	*32*	*103*	*TAC*
SPslope	*0.50*	*0.50*	*0.26*	*0.34*	*59*	*20*	*35*	*TAC*
Ltarget1	*0.71*	*0.68*	*0.46*	*0.56*	*55*	*9*	*25*	*TAC*
matlenlim2	*0.22*	*0.27*	*0.05*	*0.09*	*55*	*23*	*0*	*Size*
matlenlim	*0.18*	*0.23*	*0.04*	*0.07*	*49*	*23*	*0*	*Size*
LstepCC1	*0.77*	*0.71*	*0.52*	*0.63*	*46*	*4*	*15*	*TAC*
LstepCC4	*0.77*	*0.71*	*0.52*	*0.63*	*46*	*4*	*15*	*TAC*
DDe75	*0.53*	*0.50*	*0.33*	*0.40*	*44*	*29*	*22*	*Effort*

Appendix S: Feasibility Tables

Barred Sand Bass (1=high confidence, 0.5=low confidence, 0=no confidence or lacking)

Data type	Score	Comment
Catch	1	Catch recorded in number of fish
Index	1	CPUE index available from 1980
Natural_mortality_rate	1	Range of estimates from a number of empirical techniques - 0.15 - 0.21 appears reasonable
Maturity_at_length	1	Catches are typically 100% mature
Growth	1	Lack of small fish in sample suggests that estimate of K may be biased
Length_weight_conversion	1	
Fleet_selectivity	1	Single fleet with size-limit
Catch_at_length	1	Believe that extensive database exists, but may need to be compiled
Catch_at_age	0	
Recruitment_index	0	
Stock_recruitment_relationship	0	
Target_catch	0	
Target_biomass	0	
Target_index	0	
Abundance	0	

California Halibut (1=high confidence, 0.5=low confidence, 0=no confidence or lacking)

Data Type	Score	Comment
Catch	1	Time-series from early 1900s. Log-books and surveys
Index	1	CPUE-based index of abundance developed by Maunder (2011) in assessment
Natural_mortality_rate	1	Estimated range using a number of different methods. 0.1 - 0.2 considered most appropriate
Maturity_at_length	1	Study from 1990 - may vary over regions but estimates are available
Growth	1	Varies between regions and sexes. Well-studied but variable.
Length_weight_conversion	1	
Fleet_selectivity	1	Estimates do exist. Multiple fleets.
Catch_at_length	1	Does exist but need to be compiled
Catch_at_age	1	Data from at least 2007 to recent, and some earlier years
Recruitment_index	1	Abundance index of age 0, 1 & 2, from SF Bay.
Stock_recruitment_relationship	1	Previous assessment assumed h=1, unrealistically high but stock appears productive at low spawning biomass. Data does exist.
Target_catch	1	estimate of MSY from recent assessment
Target_biomass	1	From recent assessment.
Target_index	0	Unsure
Abundance	1	An estimate of depletion exists for Southern stock.

Red Sea Urchin (1=high confidence, 0.5=low confidence, 0=no confidence or lacking)

Data Type	Score	Comment
Catch	1	Time-series of total catch exists from early 1970s to 2015, CDFW landings receipts,
	0.5	Time-series total catch from dive logbooks, fishermen recorded poundage, unreliable estimates compared to landing receipt, but linkage not streamlined
Index	0.5	Possible to construct CPUE from logbooks; divers required to record diver hours to nearest 1/2 hour, each day fished, block fished, each location; logbooks
		Nor CA logs 1988-2015; So CA logs 1977-2014
Natural_mortality_rate	1	But very uncertain. Estimates range from 0.05 to 0.15
Maturity_at_length	1	Some estimates exist. Although maybe uncertain for CA
Growth	1	Varies between regions, von Bertalannfy growth curve not considered most appropriate, work needs to be done to determine best parameters
Length_weight_conversion	0	Not currently known, but should be straightfoward to estimate
Fleet_selectivity	1	Size limit, and single fleet (divers) so should be able to estimate
Catch_at_length	1	Record do exist from late 80s early 90s. Unsure of more recent records. 2002-2006 17,000 test diameter and block number from Pkalvass CDFW. No discard in diver logs
Catch_at_age	0	
Recruitment_index	0	CINPS artificial recruitment modules record urchin size each year, long-term monitoring; recruitment brush studies Schroeter et. al and CSUC; CDFW abalone recruitment modules 2010-2015
Stock_recruitment_relationship	0	
Target_catch	0	
Target_biomass	0	DCAC method applied in 2012 P Kalvass CDFW using MacCall 2009
Target_index	0	
Abundance	0.5	Long-term monitoring density CINPS (KFM) 1982-2015 Channel Islands, CDFW 1999-2015 nor CA density 8 index sites, Reef Check 2006-2014 statewide, PISCO (years?)
	0.5	CDFW ROV surveys 2000, 2009, 2012, 2014-2015; 102 sites including 16 SMRs and 15 SMCAs; 270 km of video. Depth distributions 15-20m to 80-100m (density, size possible)

Warty Sea Cucumber (1=high confidence, 0.5=low confidence, 0=no confidence or lacking)

Data type	Score	Comment
Catch	1	Catch time-series since 1975
Index	0	May be able to construct CPUE index
Natural_mortality_rate	0	Some estimates exist, but not very well known at all
Maturity_at_length	0	Few data exist. DFW has some data with may be able to be used to estimate this
Growth	0	Difficult to measure and age
Length_weight_conversion	1	Length x Width ~ Weight appears to be best metric

Fleet_selectivity	1	Should be able to be estimated
Catch_at_length	1	DFW has data, but further work needed to determine most appropriate way of processing
Catch_at_age	0	
Recruitment_index	0	
Stock_recruitment_relationship	0	
Target_catch	0	
Target_biomass	0	
Target_index	0	
Abundance	0	

Appendix T: Value of Information Analysis

Post-Hoc Value of Information Analysis

The MSEs quantified the performance of management procedures subject to varying degrees of bias and imprecision in a range of observations (e.g., catch data, relative abundance index, etc.). A post-hoc analysis can reveal which observation processes were driving the performance of the various management procedures. For example, a management procedure that requires catch data may perform poorly when there are small biases in reported catches (consistent over-reporting or under-reporting of catches), but may be relatively unaffected by imprecision (error or "noise") in catch observations. This type of value of information analysis can not only reveal priorities for data collection and improvement, but also asymmetries in the risks in observation processes (e.g., perhaps catch over-reporting is less critical than the same degree of catch under-reporting). In these analyses, we use long-term yield as a metric of value which is often well correlated with other management objective such as maintaining productive stock sizes (as chronic under- and over-fishing typically lead to low yields over the long-term). For each stock, 600 MSE simulations (sufficiently numerous for simulation results to be stable and visualize trends in performance) were used to evaluate the yield performance of the top four MPs with respect to their respective data.

Barred Sand Bass

The top performing acceptable and available management procedure for barred sand bass *ITe5* is an index target management procedure that aims for a level of relative abundance corresponding with a productive biomass, but only allows for up to +/-5% changes in fishing effort. The two principal inputs to the *ITe5* are a current relative abundance index and the target level for the index (i.e., how far our target index level is from the best-case index level that corresponds to B_{MSY}). Error in the index and hyperstability are both simulated. The error is the inter-annual observation error in the index ("Index Abundance error") where higher coefficients of variation (CVs) are indicative of higher levels of error (or noise) around the true simulated level. In this case, only varying degrees of hyperstability are simulated in which the index is less responsive to changes in abundance (Index proportional to $\text{Biomass}^{\text{beta}}$, where beta is the hyperstability/hyperdepletion parameter).

The value of information analysis for *ITe5* (Figure 47) reveals that the yield performance of the management procedure is relatively invariant to these observation phenomena, relative to the general degree of uncertainty in yield. The level of error in the abundance index had the largest impact but this was weak and tended to reward noisy data indicating that any mean relationship is spurious. The robustness of the *ITe5* approach is primarily due to using an input control. The management procedure's fishing rate stays approximately near F_{MSY} levels and cannot respond rapidly to new data. This, however, does not prevent the approach from responding rapidly to stock size changes since the catch taken is a reasonably stable fraction of the current biomass.

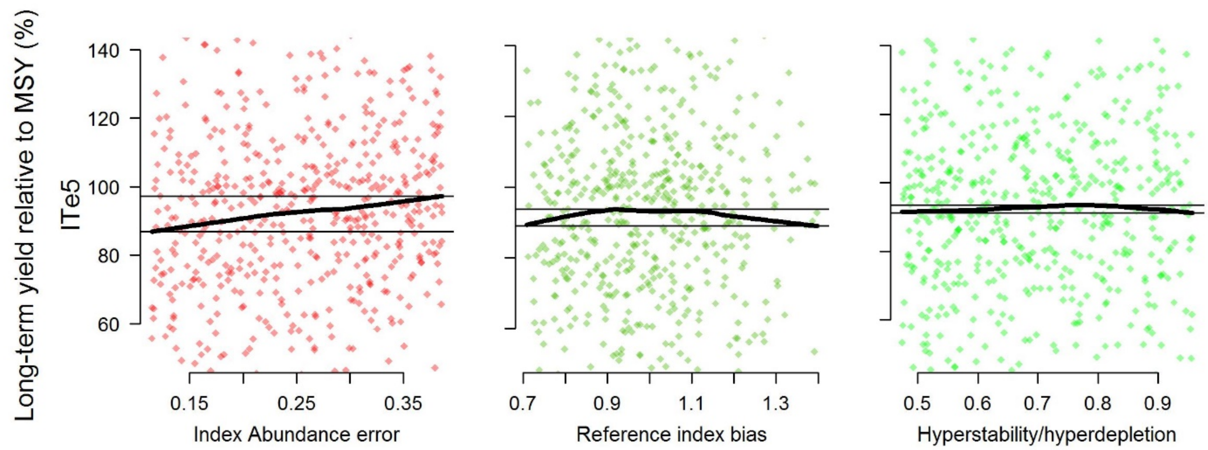

Figure 47: The post-hoc value of information analysis for barred sand bass. Only the *ITe5* method required data and relied on just inter-annual variability in the observed, relative abundance index ('Index Abundance error'), bias in the target index level (Reference index bias) and hyperstability of the relative abundance index (for values less than 1 this is an index that responds slower to changes in real simulated abundance).

California Halibut

The top peforming acceptable and available management procedures for California halibut was *Itarget1*, an output control method which makes incremental changes to the TAC to reach an index target. Similarly to *ITe5* above, *Itarget1* is invariant to the associated observation processes (Figure 48). This includes some potential bias in catches (between 85% and 115% of true catches) moderate hyperstability/hyper depletion in the index (beta between 0.8 and 1.2) and error in annual catches (CVs between 0.1 and 0.3).

The *DepF* was another high performing output control method, which uses estimates of current abundance and a fixed fishing mortality rate based on natural mortality (M) to provide a TAC recommendation that throttles the fishing mortality rate per depletion. The principal behind this method is that an MP that uses imprecise and biased information about current stock size and current depletion may be more advantageous than just using one or the other (note that in the context of California halibut, the initial values of these are set up using a stock assessment, and then updated into the future by an index or length composition data).

The yield performance of the *DepF* method was only reduced when abundance estimates were negatively biased. This is the result of the depletion-based control rule (which is like a 40-10 control rule). When abundance is overestimated, the management procedure calculates an overly high estimate of F_{MSY}. Without a depletion control rule, this leads to overexploitation and stock declines. However, positively biased estimates of current abundance are not penalized in terms of long-term yield with *DepF* because catches are further throttled by the depletion control rule (which is why the yield performance remains high above biases of 1). However, there is no control rule to increase fishing rates when depletion is above B_{MSY}, which often occurs in these simulations by negative bias in the abundance data. The management procedure perceives the stock to be smaller than it actually is so underfishes, obtaining 20% lower yields on average at an abundance bias level of 0.5. Note that not only is the risk of over/underestimating abundance asymmetrical (the shape of the mean line in the figure), the yield loss due to underestimation of abundance is not proportional (a 20% yield loss from a -50% bias in abundance).

An important caveat of this result is that it relies on the assumption that is possible to estimate current stock size and depletion independently (*e.g.*, depletion from length composition, current abundance from an index linked to a previous stock assessment, or depletion from catch rates and current abundance from a fishery independent survey).

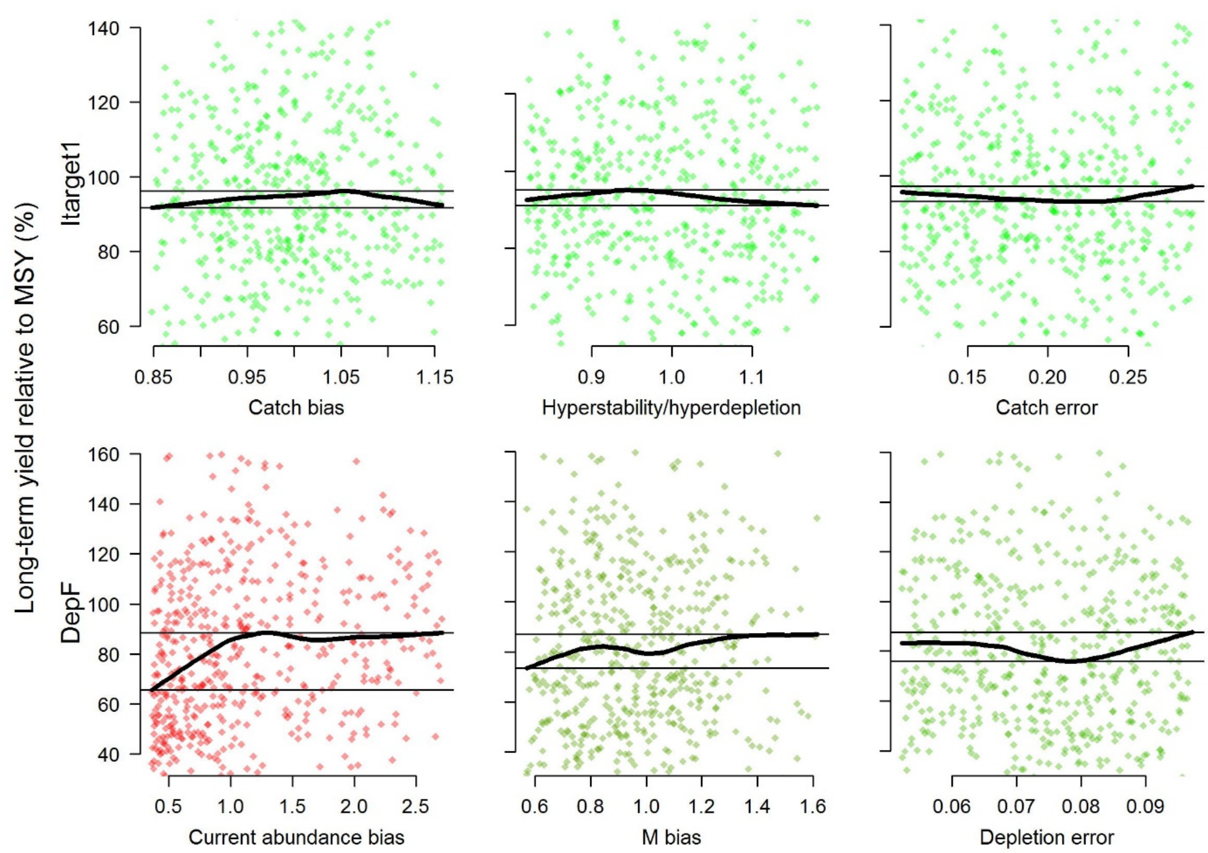

Figure 48: The post-hoc value of information analysis for California halibut.

Red Sea Urchin

The top performing management procedures that required data for red sea urchin include *Islope1* and *Islope4*. Both of *Islope* methods are largely invariant to the quality of data (Figure 49). Since these approaches tend towards a stable index level (are not responding to changes in the index), they do not assume that the index is proportional to abundance, and are therefore not affected strongly by hyperstability in the index. Historical catches are used to initialize the algorithm, so biases and imprecision in catches do not strongly affect the management procedure through the rest of the projection.

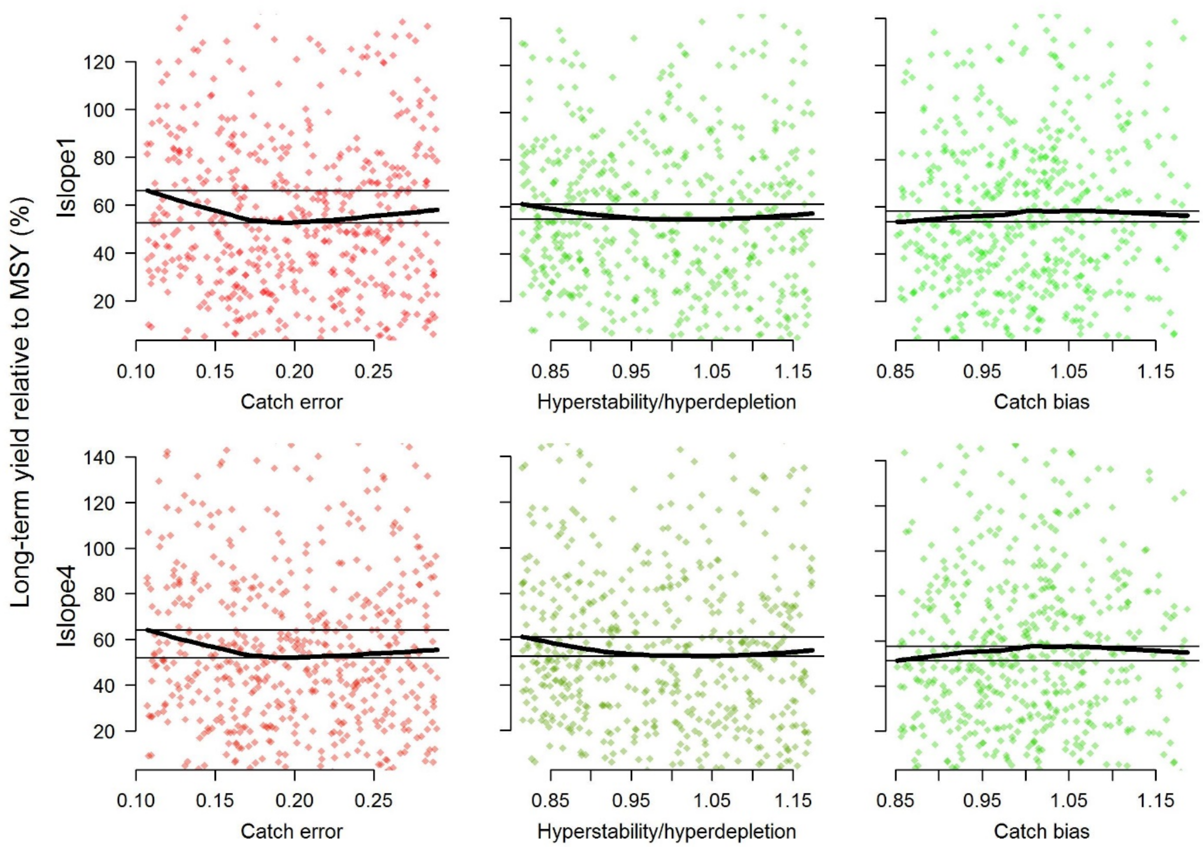

Figure 49: The post-hoc value of information analysis for red sea urchin.

Warty Sea Cucumber

The top four performing management procedures for warty sea cucumber all have data requirements, but only *HDAAC* has yield performance that is strongly determined by a data input (Figure 50). In this case, negative bias in depletion (values less than 1, inferring the stock is more depleted than it really is) leads to the throttling of TAC. This is a similar phenomenon to that seen in the *DepF* method for California halibut. Low depletion levels invoke a control rule in *HDAAC* that leads to linear throttling of TAC from 100% TAC at 50% depletion to 0% TAC at 0% depletion.

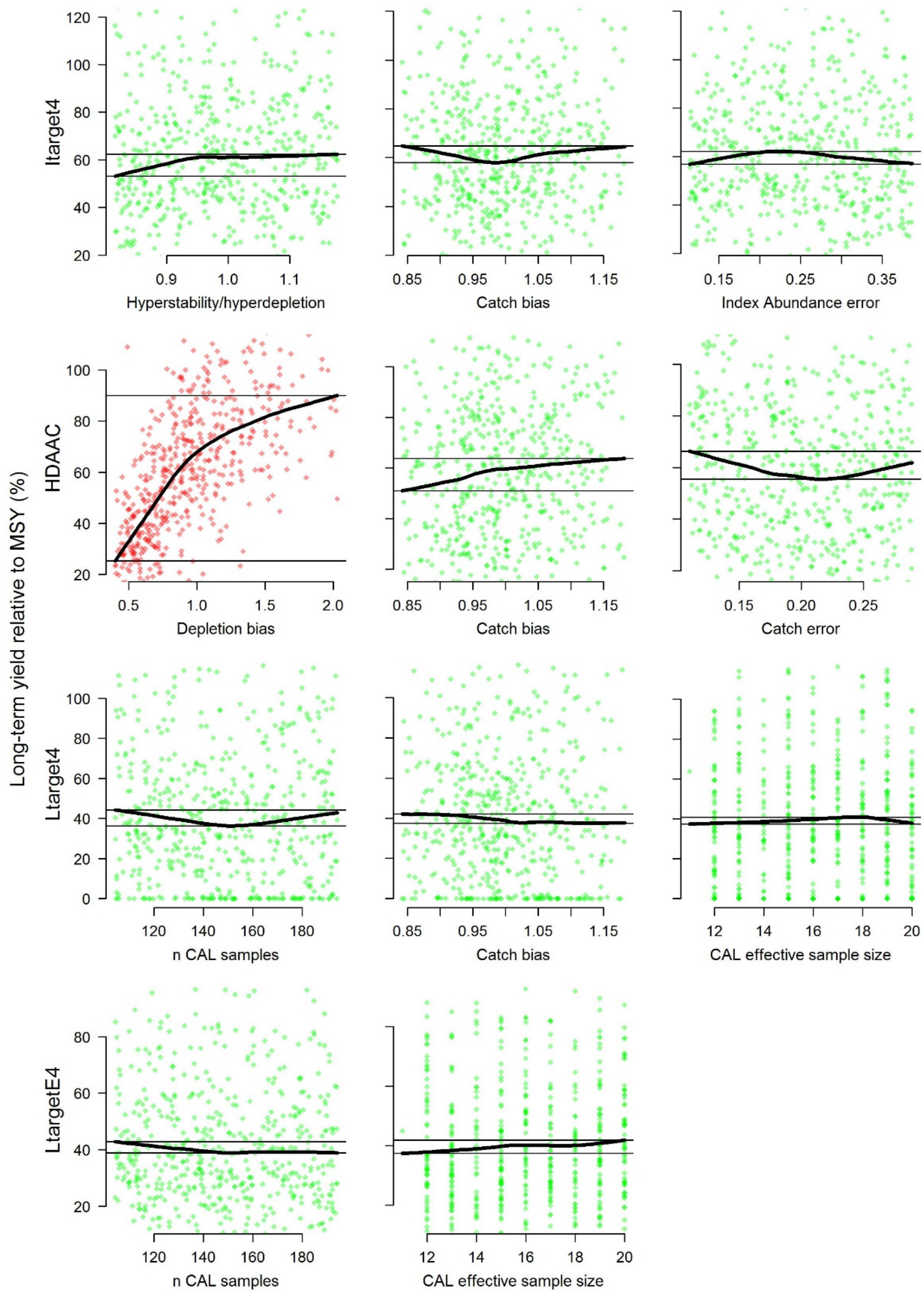

Figure 50: The post-hoc value of information analysis for warty sea cucumber.

Cost of Current Uncertainties

Barred Sand Bass

The yield performance of the *ITe5* MP was largely invariant to simulated conditions such as maximum length (von Bert. Linf) and average annual percentage change in catchability (fishing efficiency) (Figure 51). The input controls (*MLL350*, *MLL360*, *curE*) were somewhat more sensitive to simulated conditions particularly increases in fishing efficiency where these approaches could achieve higher yields relative to MSY when catchability increases were strongest. These management procedures were also robust to depletion and obtained higher relative yields on average when stocks were more depleted. In general, the cost of current uncertainties is potentially less than for the other stocks where more pronounced correlations among yield performance and simulation parameters are observed.

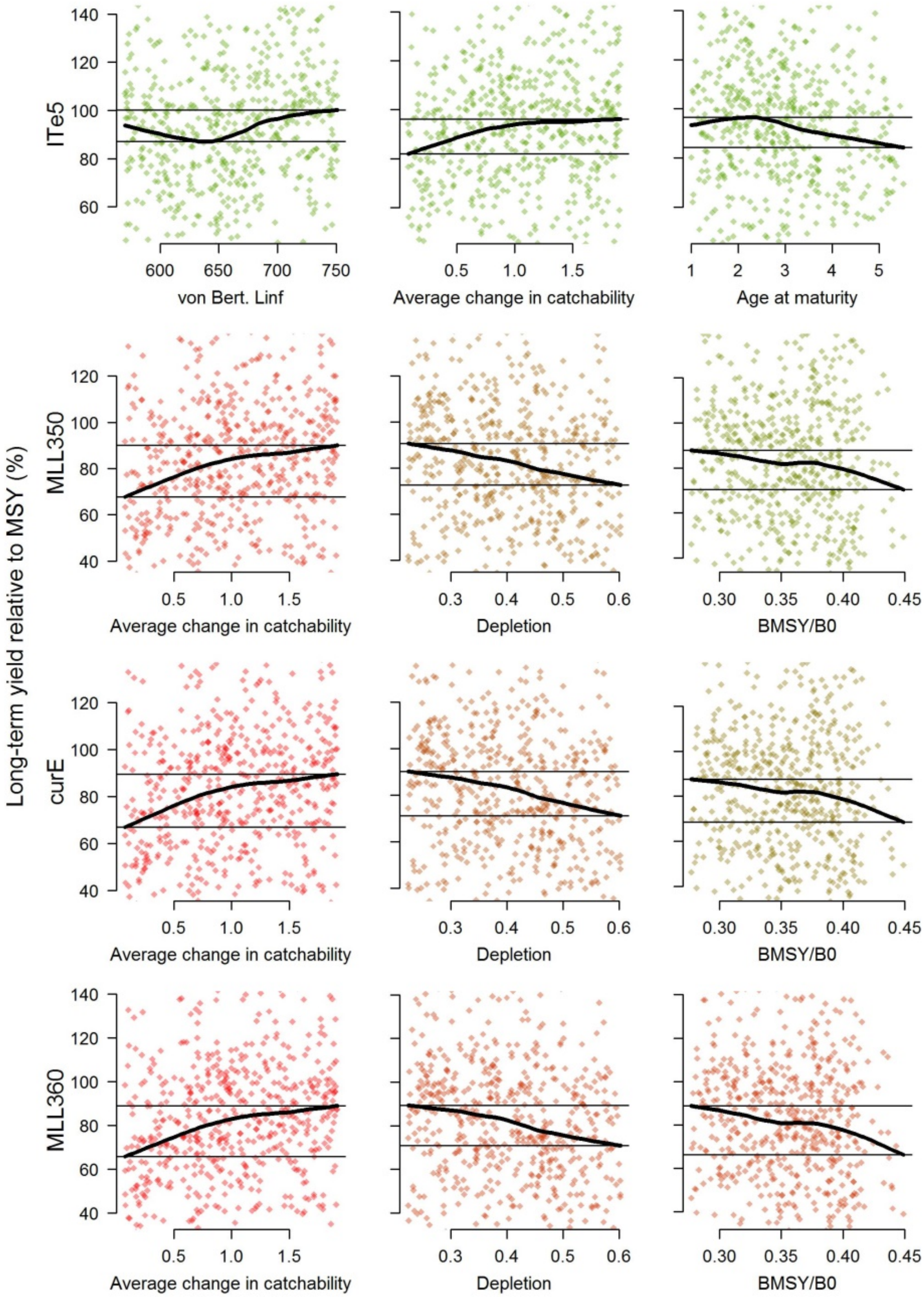

Figure 51: The cost of current uncertainties analysis for barred sand bass.

California Halibut

The performance of the two input controls *IncSel3* and *MLL5* were most strongly correlated with age-at-maturity (a key driver of the ratio of FMSY/M that is also affected by uncertainty in growth) (Figure 52). At ages-at-maturity above and below around age 4-5, the yield performance drops substantially by up to 30% for these management procedures. If age at maturity is in fact closer to one of these extremes, alternative management procedures may perform better pointing to potential value in better characterizing maturity for halibut. The *Itarget1* and *DepF* methods were relatively robust to uncertainty in operating model parameters, obtaining similarly high expected yield over all simulated parameter ranges.

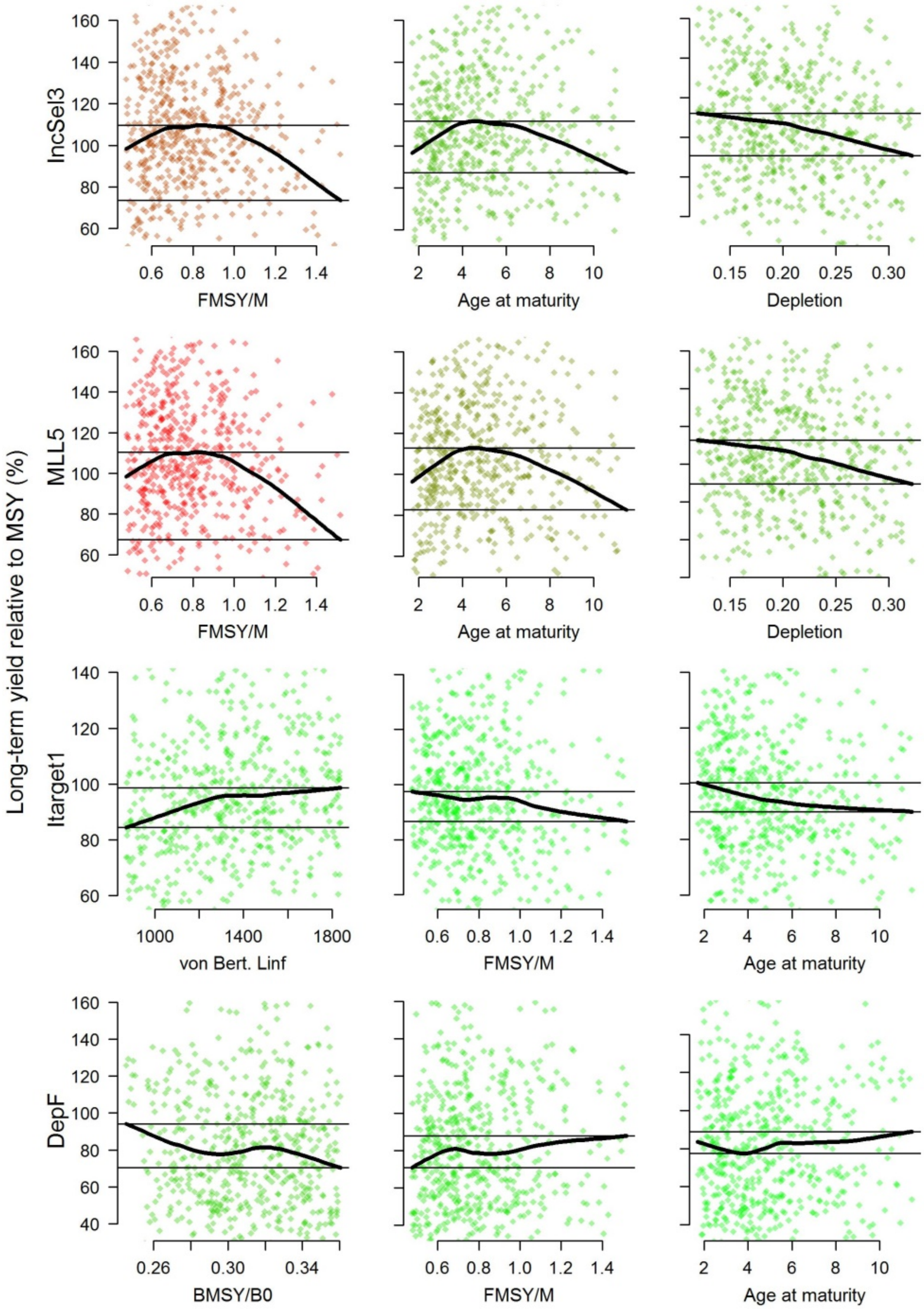

Figure 52: The cost of current uncertainties analysis for California halibut.

Red Sea Urchin

A principal driver of yield performance in the top-ranking management procedures for red sea urchin was uncertainty in the current level of stock depletion ('Depletion', current spawning biomass relative to unfished) (Figure 53). Management procedures such as Islope1 and Islope4 provide substantially worse yield relative to MSY management at initial stock levels below around 45% of unfished levels pointing to potential value in narrowing the range of possible depletion for the purposes of optimal management procedure selection. An emergent property of the simulations, the ratio of FMSY to natural mortality rate (FMSY/M) appears to strongly drive yield performance for the *MLL3.5* MP however this is mostly at the upper tail of the distribution (at ratios higher than 1) where there are few simulations. On average the *MLL3.5* and *MLL3.375* length limit management procedures performed better relative to MSY management when expected catchabilities (fishing efficiency) is assumed to be increasing above 0.5% per year.

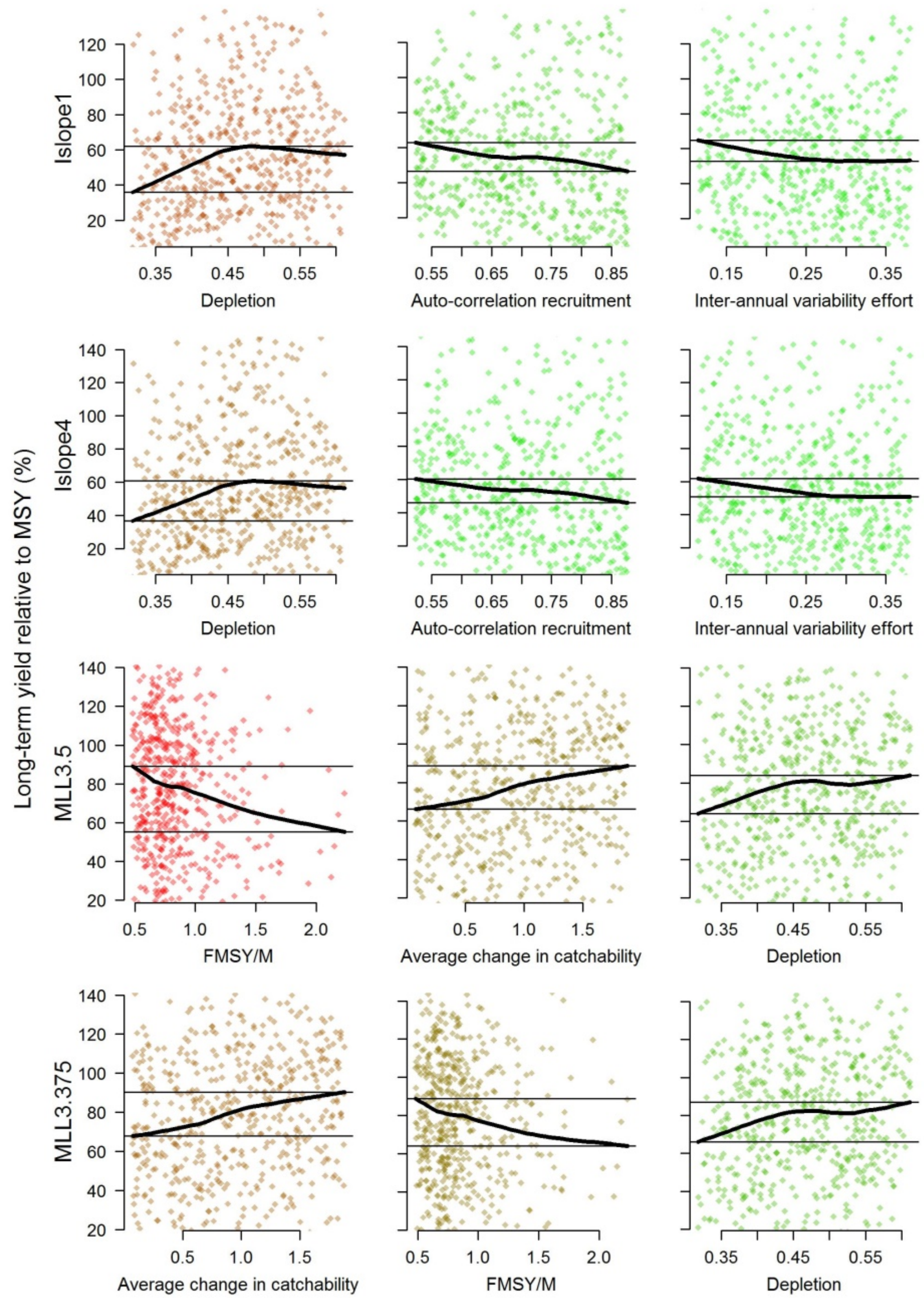

Figure 53: The cost of current uncertainties analysis for red sea urchin.

Warty Sea Cucumber

Among the four case study stocks, warty sea cucumber showed the highest variability in management procedure performance relative to simulated conditions, which may be expected as the level of simulated uncertainty was generally high for this species. While *Itarget4* was relatively unaffected by simulated uncertainties, the yield performance of *HDAAC* and *Ltarget4* were driven strongly by initial stock depletion (Figure 54). *LargetE4* also provided almost double the relative yield performance in simulations where fishing efficiency increased by 2% per year.

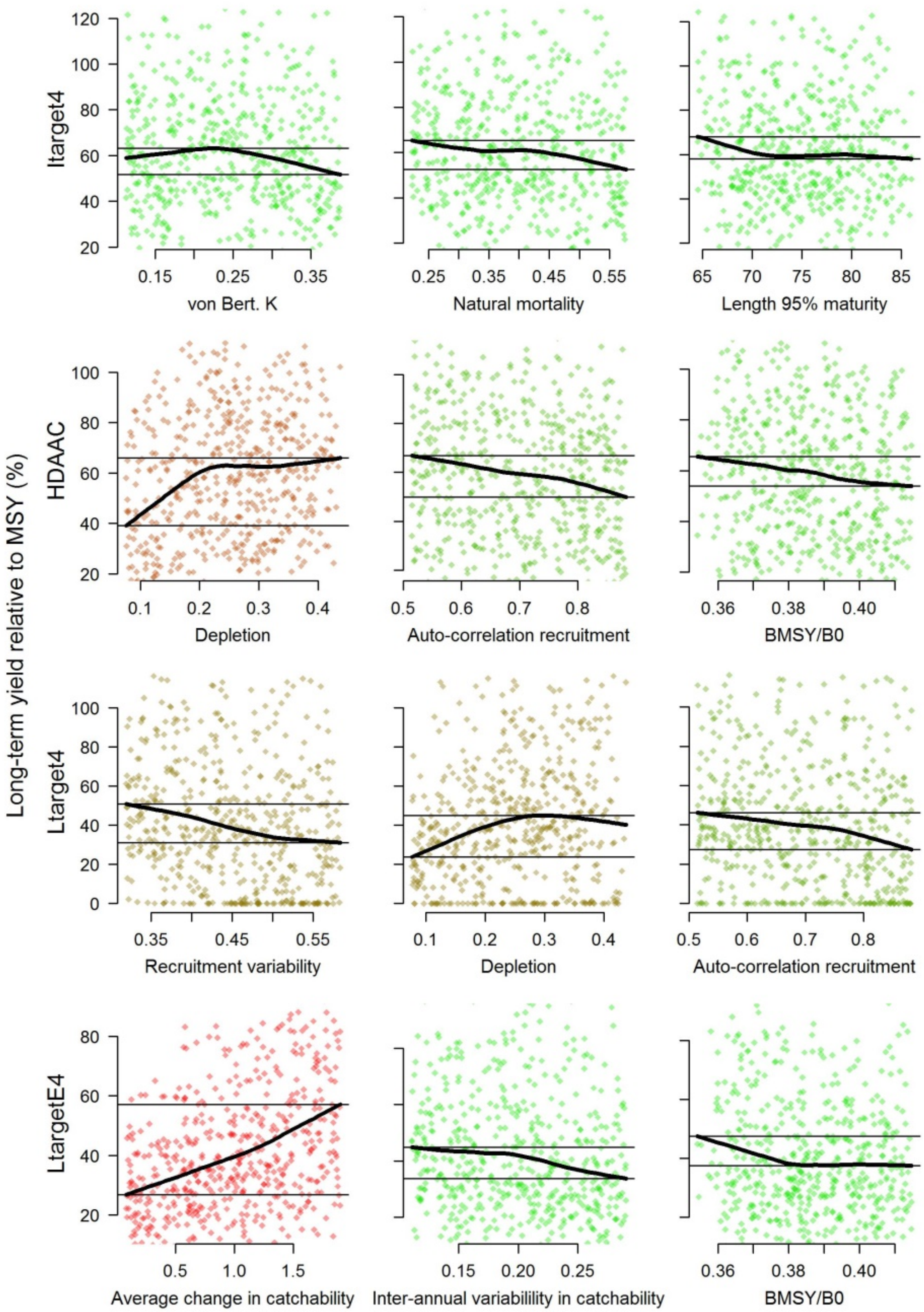

Figure 54: The cost of current uncertainties analysis for warty sea cucumber.

Value of New Data

For each stock, the management procedures that passed the performance requirements were separated into those that can and cannot be applied given the data that are currently available. MSE performance was determined for all management procedures, so it is possible to compare performance of methods that currently can and cannot be used. This provides the ability to analyze the value of collecting new data that would make available for use better performing management procedures. Where higher yields could be obtained from a management procedure that is not currently available due to one or more missing data types, the potential gain in yield was recorded along with the new data required to use that management procedure.

Across all four stocks, there was only one instance of a management procedure providing more yield than was not currently available due to lack of data: the *DDes* (Delay Difference effort control) for barred sand bass, which provided only a 1.5% increase in expected yield over the best performing index target management procedure, *ITe5*. This is a very small potential gain considering that the *DDes* management procedure requires many new data types, including: annual catches, an estimate of natural mortality rate, a maturity at age schedule and a fitted growth model.

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