Report on the California Data-Limited Fisheries Project:

Integrating MSE into the Management of California State Fisheries

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Introduction

Over the past six years, the California Department of Fish and Wildlife (Department) has made a substantial investment of resources in integrating management strategy evaluation (MSE) into the science and management of California state fisheries. The initial phase of the project, beginning in July 2015, used a stakeholder process to demonstrate how MSE could be used to manage data-limited fisheries in the state through the application of the Data-Limited Methods Toolkit (DLMtool). Four fisheries were analyzed as case studies for that phase of the project: barred sand bass, California halibut, red sea urchin, and warty sea cucumber. This led to the incorporation of MSE into the revised 2018 Master Plan for Fisheries (Master Plan) and laid the groundwork for continued collaboration with the Department to build the scientific capacity of its staff and to apply MSE to additional fisheries.

The current phase of the project, beginning in February 2018, included a series of webinars and workshops with a group of six Department biologists and managers to train them in basic fishery population dynamics modeling and the fundamentals of MSE using the DLMtool. The second component of the project involved developing new or updated MSEs for eight fisheries, including the four from the initial phase of the project and the following additional fisheries: kelp bass, rock crab, spiny lobster, and redtail surfperch. The eight fisheries were chosen because they represent a range of life histories and data availability. The outputs of these MSEs will be used to understand the tradeoffs and levels of uncertainty with the current management frameworks for each fishery and how they perform in both the short- and long-term. The results of the MSEs will be incorporated as appendices in the Enhanced Status Reports (ESR) for each fishery.

This report summarizes the more recent collaboration and provides recommendations for continued integration of MSE into the California fisheries management program. In addition to the MSE work under the original scope of work for the project, NRDC was able to use unspent funds with the permission of the grantors on the development of a new web-based version of DLMtool called Method Evaluation and Risk Assessment (MERA), which is also described below, as well as the production of video tutorials in the coming months.

Background

Fisheries Policy in California

Conservation, rebuilding, and sustainability are the overriding policies of fisheries management in California under the Marine Life Management Act (MLMA) (CA FGC §7050(b)). Sustainability is defined as managing at or below optimum yield in order to "secur[e] the fullest possible range of present and long-term economic, social, and ecological benefits, [while] maintaining biological diversity…" (CA FGC §99.5). Optimum yield means fishing at "the highest average yield over time that does not result in a continuing reduction in stock abundance, taking into account fluctuations in abundance and environmental variability" and as "reduced by relevant economic, social, or ecological factors…" (CA FGC §96.5, 97). In the case of a fishery that is overfished, optimum yield must provide "for rebuilding to a level consistent with producing maximum sustainable yield." (CA FGC §97).

To achieve sustainable fisheries, the MLMA prescribes the development and use of fishery management plans and fishery status reports that are based on the best available scientific information and stakeholder input. The statutorily mandated Master Plan for Fisheries is intended to prioritize management actions and define necessary tools and procedures (CA FGC § 7073). As stated in the Master Plan, "the sustainable management of fisheries requires information on the status of a population relative to management targets." (2018 Master Plan for Fisheries, p 25). Determining stock status needed for setting quantitative targets and limits is often based on complex statistical models that require extensive data that are often unavailable or cost prohibitive to collect. While many California fisheries lack this type of information and analysis, the Master Plan describes the use of alternative data-limited methods (DLMs) that require fewer data and adjust exploitation rates or levels based on the limited data that are available.

DLMs generally do not seek to provide a quantitative measure of current stock status, but rather use available data to inform future management changes that are most likely to meet the sustainability requirements of the law. The use of DLMs allows for the adoption of predetermined and cohesive management procedures (MPs) that adjust management measures based on informative signals in the available data. The selection of MPs is a process that requires objective and transparent evaluation of the likely performance of potential MPs for each fishery. MSE is a tool described in the Master Plan for analyzing and identifying MPs that are most likely to meet the Department's sustainability requirements and management objectives. Using a stochastic model parameterized with the best available information, each fishery is simulated and projected into the future to quantify the performance of candidate MPs under a range of plausible uncertainty scenarios. The simulation results are then evaluated using a stepwise decision framework designed first to eliminate those MPs that do not meet MLMA mandated sustainability limits or that are currently infeasible due to data or governance capacity limitations, and then to highlight the remaining MPs that are most likely to maximize management objectives. The MSE approach is also useful for understanding potential avenues for fishery improvement through additional data collection or better implementation of fishery regulations.

MSE Design and Analysis

MSE relies on the construction of simulation models (called operating models) that are designed to imitate the dynamics of a fish stock, the fishery exploiting it, and the monitoring, assessment, and management framework that is used to manage the fishery. A key aspect of the MSE approach is that the simulation includes the full management cycle: data collection, analysis of that data, and application of an MP, which is then fed back into the system and used to update the stock and fleet dynamics in the next time-step (Walters and Martell 2004). Simulation models with this type of feedback loop, allow us to model an adaptive management system that can respond to changing conditions (Walters and Martell 2004).

The primary aim of MSE is to identify the emergent behavior of alternative management strategies and to describe the various trade-offs that are likely to arise among conflicting management objectives (Punt et al. 2016). This is done by constructing models based on the best available information for a given fishery, and then conducting simulation experiments to understand how each MP tested is likely to perform. MSE aims to provide decision-makers with the information they require to make rational and defensible decisions on the management of the fishery that balance their own management objectives and acceptable levels of risk (Smith 1994). Additionally, MSE can be used to develop and test new management strategies, either for specific fisheries or for more general applications, as well as to identify classes of management methods that are unlikely to perform well under most circumstances and thus can be rejected as candidates for management (Butterworth 2007).

Department Capacity Building

In order to build capacity and support the goal of training Department scientists to conduct MSEs, we developed a training curriculum covering four discreet areas: fisheries science, with an emphasis on population dynamics and statistical modelling; data processing and standardization; R software training; and immersive trainings on how to set up and run MSEs using the DLMtool. This training took place over the first year of the project. Two-hour webinars were held every two weeks. Prior to the beginning of the webinar series we held a one-day intensive in-person training in R to provide participants with limited experience in coding the basic skills necessary to participate in the webinars. Each webinar included a 45-minute lecture on the topic to explain the theory, provide examples, and explain how the topic covered pertains to MSE and the DLMtool package, followed by an exercise in which code and data were provided so that participants could follow along. Whenever possible examples were taken from one of the eight case study stocks.

The first six webinars introduced modeling and population dynamics, primarily key biological concepts such as growth, reproduction, and natural mortality, and covered fitting basic biological models to estimate these life history parameters. The next seven webinars covered simple techniques to analyze commonly available fishery data and to infer stock status. These skills will likely be necessary for Department staff tasked with operating model development for data-limited fisheries lacking published estimates of key parameters. The remaining webinars focused on how to use the DLMtool to conduct MSEs. These were split into the different building blocks of an MSE analysis – how to set up the required input files and read them into the DLMtool program, how to model data collection and implementation error, how to explore built in MPs as well as set up custom MPs, how to test MPs and visualize results, and how to structure an analysis to alter parameters for robustness testing. Each of these webinars included homework assignments for the Department participants to set up their own MSE components while the topic was fresh in their minds.

We hope that these webinars will be a resource to future Department staff to learn how to estimate the inputs to describe the species and fishery they are interested in modeling using the DLMtool. Additional Department staff beyond those who are directly participating in the DLMtool training and development project have attended the webinars. At times there were as many as 20 additional staff participating in the live webinars, and to date, 188 other staff both inside and outside of the Marine Region have registered with the Department’s training system to view the recorded webinars. Staff have provided feedback on the webinars, saying they find them helpful and asking additional questions about analyses related to their own fisheries. This suggests that the webinars are generally helpful to the Department beyond those staff that are actively developing MSE models.

In April 2019, the Department hired one of the key participants in this project, Julia Coates, to fill a new position assisting fisheries with in-depth data analysis, including aiding Department biologists in running MSEs and interpreting the results. Working with Julia, the project team identified a common goal that, by the end of the project, she would be able to assist another Department biologist through parameterizing an operating model, running an MSE, and interpreting the results. To facilitate this, we identified three key areas of development, which included: 1) developing a deeper understanding of the theory of MSE and risk-based decision-making, as well as best practices, 2) gaining increased familiarity with the functionality and underlying population model of DLMtool, and 3) enhancing her understanding of fisheries modeling and populations dynamics generally. To achieve this, we worked with Julia to develop a guided study approach involving fisheries modeling books and course work. In addition, she participated in an online class offered by the University of Washington. In order to facilitate her ability to take over the role of guiding the Department through the development of their operating model and the application of the analytical process, Julia participated in one-on-one meetings between Sarah Valencia of the DLMtool team and the Department biologists so that she could gain a deeper understanding of both the details of each fishery, as well as the overall process. Within a year, Julia has emerged as a strong leader at the Department, both on the technical side of running MSEs and working with the DLMtool, as well as at a broader level of how the MSE outputs could be used effectively to continue to improve management decision making and outcomes.

We anticipate that, with Julia’s current skill set, she is now capable of working with Department staff to review the available data and information for a fishery, develop operating models to describe what is known about stock dynamics, identify the major uncertainties, and develop custom MPs for testing. The amount of time required to develop MSE inputs depends on the type of data available (and how much QA/QC is required), the biology of the stock, and the complexity of the fishery and management system, as well as each staff member’s other ongoing responsibilities. However, for a fishery with the standard data streams available for most California stocks (catch, minimal information on historical fishing effort, size frequency info), we believe that preliminary MSE results could be obtained within one to two months. For fisheries with additional data, including CPUE data that needs to be standardized, fishery-independent survey data, and additional biological data, MSE development would take longer. Data analysis can be time consuming but is a crucial part of both developing model parameters as well as assessing key uncertainties. For more complex stocks with multiple stocks or fleets, spatial dynamics or other unusual life history characteristics that require creative approaches to modeling, additional historical data, or complex management systems, MSE development can take more than a year. For stocks with these types of complexities we recommend that the Department obtain outside assistance to aid in MSE development.

Department Performance Metrics and MSE Decision Making Framework

One of the goals of this project was to develop a standardized, reproducible approach to analyzing and ultimately selecting MPs for use in management (see Appendix A: Procedure for Evaluating Performance of Candidate MPs for a full description of the decision making framework used for this project). The approach we developed is designed to reflect the management mandates and objectives as outlined in the MLMA, and one of the major areas of focus of our third workshop was obtaining feedback on what types of thresholds and risk tolerance levels to use.

Performance metrics are necessary to ensure that all candidate MPs are being evaluated against the same standard, and that standard reflects the Department's mandates and objectives for sustainable management. The MLMA provides a mandate for sustainable management but does not define performance metrics in terms of biomass targets or limits, nor does it define a risk tolerance for achieving targets or avoiding limits, and no quantitative reference points or risk tolerance thresholds have been formally adopted by the California Fish and Game Commission or the Department. In the absence of mandated performance metrics, the DLMtool project team worked with Department staff to define management requirements and objectives, and to develop quantitative performance metrics around those.

Performance metrics can be grouped into two categories. The first, Performance Limits, specify the minimum requirements that must be reached to ensure that the sustainability of the resource is maintained with high probability. These represent hard limits, and any MPs that cannot meet these limits are not considered further. The second, Performance Objectives, specify goals for the fishery. They may include diverse objectives that fishery managers and stakeholders would like to maximize in aggregate, such as stock size, catch or fishery participation, or other ecological or economic targets.

Based on feedback from Department staff, the following Performance Limits were used, and are described in more detail below:

1. 80% probability of SSB > 50% SSBMSY (years 11 – 50, or one mean generation time through year 50)

2. 80% probability of SSB > 50% SSBMSY (years 41 – 50)

To satisfy the first performance limit, the spawning stock biomass (SSB) for the simulated stock must be greater than 50% of the target SSB that would produce maximum sustainable yield (MSY) for at least 80% of the simulation runs for years 11 through 50 of the MSE projection period.[1] Stocks that are at sizes below 50% of SSBMSY are considered to be "overfished" and in need of rebuilding, and this performance limit is designed to eliminate any MPs that result in the stock being overfished more than 20% of times across all simulations. The SSB of the stock in the first 10 years (or longer, for stocks with mean generation times (MGTs) greater than 10) are not considered for this first limit to account for the possibility that the stock may still be rebuilding from a depleted condition while the MP is first implemented. For long-lived stocks with an MGT of greater than 10 years, the period analyzed for this limit is adjusted to range from the simulation year equal to one MGT through year 50. Note that while the threshold of 50% of SSBMSY is an appropriate overfished limit for most fisheries, there are some

[1] Even though these are data-limited stocks for which status targets are generally unknown, the simulated fishery data generated as part of the MSE provides stock status information.

species that exhibit high variability in stock size from year to year and may be below this threshold more than 20% of the time even without fishing.

The second performance limit requires that the SSB for the simulated stock must be greater than 50% of SSBMSY for at least 80% of the simulation runs for years 41 through 50 of the MSE projection period. This is to prevent a situation in which an MP could theoretically pass Limit 1 by keeping the stock above the limit for the first 40 years of the simulation, but then overfish the stock in the last 10 years.

These overfished limits are the minimum criteria that each MP must meet to be considered for use in managing a Department fishery. Managers and stakeholders may ultimately prefer an MP that meets more stringent sustainability criteria than these, but any MPs that do not meet both overfished limits for both the base model, as well as those robustness scenarios are that deemed to be plausible, are eliminated from consideration.

After eliminating MPs that do not meet the overfished limits, managers must then evaluate which MPs are likely to maximize management objectives. Traditionally fisheries management objectives have involved trade-offs between short- and long-term economic and biological goals. MSE is particularly suited to help decisionmakers, and their constituents weigh such trade-offs in an open and transparent manner by analyzing MP performance through a series of predefined management objectives. Such performance objectives generally reflect common fisheries management goals, including maximizing yield, stabilizing catch or effort, avoiding overfishing and maintaining healthy biomass levels. The management objectives used for this analysis include:

1. The probability that the long-term biomass (years 41-50) is above 80% of SSBMSY, which reflects the MP's ability to maintain a long-term healthy biomass.

2. The long-term yield (years 41-50) relative to the theoretical yield one would obtain under the best possible fixed fishing mortality strategy, which reflects the long-term economic productivity of the stock.

3. The short-term yield (years 1-10) relative to the theoretical yield one would obtain under the best possible fixed fishing mortality strategy, which reflects the short- term costs of implementing the MP.

4. The probability that the percent coefficient of variation in catch is less than 20. MPs that result in more stable catches from year to year will have a higher probability of achieving this metric.

5. The probability that the percent coefficient of variation in effort is less than 20. MPs that result in more stable effort from year to year will have a higher probability of achieving this metric.

While these management objectives were developed to capture a wide range of common fishery management objectives, additional performance metrics could be used. It is anticipated that fishery-specific management objectives may be developed in consultation with stakeholders in the future, but the performance metrics used in this analysis demonstrate how tradeoffs between competing objectives are considered within the MSE decision-making framework. One of the benefits of the DLMtool platform is that, once simulations are run and saved, new customized performance metrics can be coded up and applied to simulation results to aid managers and stakeholders in viewing the results in a way that is meaningful to them, without having to re-run the simulations.

MSE Results

The following summaries describe the results for each of the eight case study fisheries. These summaries are available on the Department website as appendices to each fishery's ESR and the full reports are available upon request. These fisheries were chosen because they reflect a range of different life history strategies, data availabilities, gear types, and governance constraints. The most data poor fishery is rock crab, in which there is spotty biological information and landings data that aggregates the three species for many years. This fishery, along with spiny lobster, provided an opportunity to learn about the challenges of modeling crustacean growth and commercial trap fisheries using the DLMtool. The spiny lobster case study also allowed us to test out our ability to create custom MPs to simulate the assessment plan laid out in the Spiny Lobster Fishery Management Plan (FMP). The warty sea cucumber fishery was the most limited in terms of biological data because there is currently no way to age individuals and their life span is unknown. However, recent data collection efforts by Department staff as well as a long time-series of fishery-independent abundance data helped us feel confident about our recommendations for the management of this stock. Red sea urchin provided an opportunity to explore the DLMtool's ability to model environmental stressors on a fishery, while Redtail Surfperch has the unusual feature of bearing live young. The barred sand bass and kelp bass represented some of California's most popular recreational fisheries, and the approaches developed to analyze fishery data for those stocks will be helpful for other recreational fisheries. California halibut was our most data-rich fishery, and that case study enabled us to use DLMtool functions to create an operating model directly from the stock assessment outputs.

For the purpose of this project, we defined "governance limitations" as situations where it would be impractical to implement a specific type of MP because it would require a protracted and costly political process, would require substantial regulatory changes across a number of fisheries, or is at odds with other marine management goals. It is important to note that Department staff involved in this project have attempted to consider enforcement feasibility in the construction of custom MPs and MP recommendations. However, this work has not yet been vetted by enforcement staff and therefore some results may need to be reconsidered based on enforcement input. Because this phase of the project began in 2018, the most recent year of data in each case study is either 2017 or 2018. We used DLMtool version 5.4.3. The DLMtool package has since undergone updates and has been integrated into a new package called openMSE. These updates do not change the DLMtool core functions but may impact precise repeatability of results.

Barred Sand Bass

Barred sand bass (*Paralabrax nebulifer*) form large, predictable spawning aggregations over nearshore sand or mud flats, making them a popular target for recreational fishers in southern California. Since the mid-1900s they have been managed as part of the saltwater bass complex, along with kelp bass (*P. clathratus*) and spotted sand bass (*P. maculatofasciatus*), with a size limit and aggregate bag limit. Due to concerns about the status of the stock the bag limit was reduced to 5 fish in aggregate and the minimum size limit was increased to 14 inches in 2013. Fishery-dependent data indicate continued declines in the catch and Catch Per Unit Effort for barred sand bass, and spawning aggregations have not been seen for the last few years, suggesting additional management measures may be necessary to ensure that the stock is sustainably managed.

We conducted a Management Strategy Evaluation (MSE) using the DLMtool to understand how likely the current management strategy (defined as the current size limit and fishing effort) is to meet management objectives. An initial risk assessment showed that, given the best available information about the stock, current management is unable to meet the minimum performance limits. This suggests that the current management approach will not promote recovery. We tested Management Procedures (MPs) simulating changes in size limits, slot limits, effort limits, and bag limits in order to determine which MPs are most likely to improve stock conditions. Based on this analysis we identified a suite of MPs that were able to achieve performance limits and are feasible given current governance limitations for the fishery. However, many of these MPs would be difficult to implement for various reasons. While slot limits with 0.5 to 1-inch slots were robust to uncertainty, the very small size range would make them very difficult to enforce. Additionally, there was concern that the size limits that were robust would create intense fishing pressure on the largest and oldest fish in the stock, which may contribute to the sustainability of the stock by producing large amounts of recruits. Consequently, the bag limit MPs identified were the most promising.

Bag limit reductions were robust to a number of key uncertainties and were able to promote stock recovery over medium-term time periods (10-20 years), which is a priority for this fishery. However, bag limits were sensitive to assumptions about effort, both the amount of fishing effort currently applied to barred sand bass as well as how bag limit changes impact future fishing effort. This is a key uncertainty, and additional information about current fishing effort as well as bag limit impacts would improve model outputs. MP performance was also sensitive to assumptions about the discard mortality rate of the fishery, which may be higher than reported. Bag limits are difficult to model within the DLMtool because they require information about how a change in bag limit impacts both the catch and fishing effort, which is likely to vary depending on both the limit and the stock size. We approximated the impacts of bag limits using bag distribution data from California Recreational Fisheries Survey sampling, which is the best information available. However, we recommend additional research to develop quantitative predictions of how changes in bag limits alter fishing effort, as well as further development of the DLMtool to better model this important management tool for recreational fisheries.

California Halibut

California halibut (*Paralichthys californicus*) has long been an important resource in the state, with commercial exploitation records existing since the late 1800s and subsistence fishing occurring long before then. Consequently, it is a relatively data rich fishery that has undergone a full stock assessment as well as an update. The analyses presented here illustrate the ability for relatively seamless transition from a stock assessment performed in Stock Synthesis into management strategy evaluation (MSE) using the Data-Limited Methods Toolkit (DLMtool). At the time of MSE development, the draft stock assessment update indicated that the southern California halibut stock was in a depleted state. Subsequent revision suggested the stock is not depleted below limits used to describe flatfish sustainability. However, confidence intervals around the depletion estimate span the limit and biomass is considerably reduced from historic levels. This motivates a desire for improved management, which currently consists of a size limit, area closures, seasonal closure within the California Halibut Trawl Grounds, and limits on the numbers of commercial trawl and gill net permits. While the stock assessment can estimate the stock's current status relative to an unfished condition, MSE is needed to evaluate the relative future performance of alternative management options and their robustness to uncertainty. In this analysis we use the DLMtool to model the stock using the parameters estimated in the draft stock assessment update and test a suite of alternative management procedures (MPs) under various uncertainty scenarios. While the results presented here are preliminary, and additional modeling work is needed, they highlight two important features of the southern California halibut fishery (discussed below) that add complexity to any management strategy considered.

First, management statewide is complicated by multiple stocks and fleets. The halibut fishery is managed as two stocks occurring in southern and northern California. Dimorphic sexes are also modeled in the DLMtool as separate stocks. Multiple fleets utilize different gear types to target halibut therefore selecting different sizes of halibut and resulting in different rates of discard mortality. At the time of this effort, the DLMtool did not have the capability to model multiple stocks and fleets in a single MSE and therefore the probabilities of selection associated with the gear used in each fleet were aggregated in this analysis to model a single fleet. Our results show a pattern of increasing loss to discard mortality with MPs implementing increasing size limits, as expected. Given the complexity of the halibut fishery, we recommend that an additional fleet-specific MSE be performed to optimize management using multiple fleet-specific MPs and highlight that this effort will need to quantify losses due to discard mortality, given uncertainty, and balance this against improvements in yield.

Second, halibut biomass is subject to high and low regimes due to environmental influences on recruitment. Halibut recruitment has historically been variable due to strong linkage to environmental conditions. Our recommended MPs allow the fleet to take advantage of high biomass periods to maximize yield while safeguarding against unsustainable take during low biomass conditions. This may be achievable under the current size limit which meets sustainability limits in the long term both under the assumption that future recruitment looks like the past and under more pessimistic recruitment scenarios. It may also be accomplished using MPs that iteratively adjust the catch limit based on biomass conditions. Additional uncertainty in halibut recruitment and resulting biomass due to historic nursery habitat destruction and climate change means that we cannot assume future halibut recruitment will be like the past. Therefore, we stress that MPs should be robust to pessimistic but plausible future scenarios to ensure sustainability of this fishery.

Results suggest that achieving historical catch levels is dependent on favorable environmental conditions for recruitment and cannot be achieved through management changes alone. Regardless of the MPs chosen, they should not exceed a total catch target of 40% of MSY to be robust to plausible recruitment uncertainties. While current management under a size limit performs well in this fleet-aggregated MSE, it may be possible to more equitably allocate the recommended overall catch among the fleets using fleet-specific MPs optimized to their unique characteristics and to adequately safeguard against excessive discard mortality. Future fleet-specific MSE will also need to enumerate real-world effort metrics such as trawl net tows or recreational angler trips to more fully explore the use of effort limit MPs.

Kelp Bass

Kelp bass (Paralabrax clathratus) are an important recreational species in southern California. Though no formal stock assessment has been conducted for kelp bass, fishery-dependent and fishery-independent datasets indicated abundance had declined, likely due to increased exploitation over several decades and poor environmental conditions. In response to those concerning trends, the minimum size limit was increased to 14 inches and the bag limit was decreased to five fish in 2013. Since the regulation change, kelp bass landings have varied for commercial passenger fishing vessels and remained relatively stable for private/rental boats, while catch per unit effort (kept and released fish per angler) has been on an upward trajectory for both boat modes.

Management Strategy Evaluation (MSE) using the DLMtool was used to test whether current management is likely to meet long-term goals by avoiding overfished limits and maximizing management objectives, or if additional changes are required. Prior management recommendations for the size limit were based on deterministic yield per recruit and spawning potential ratio (SPR) models. MSE provided an opportunity to assess the size limit and current level of fishing effort, along with other candidate management procedures (MPs), using a stochastic framework under several uncertainty scenarios, including some hypothesized climate change effects. Our analysis suggests the kelp bass fishery is currently at low risk of becoming overfished under the existing management approach given the conditions assumed in the base model, which reflect the best available information for this stock. In addition, the current management approach was robust to all uncertainty scenarios that were considered plausible. Based on these results we recommend maintaining the current size limit and bag limit.

The DLMtool provides a way to understand how climate change may impact the fishery. In addition to the uncertainty scenarios modeled, we also tested MP performance under two exploratory climate change scenarios. In recognition that our understanding of climate change impacts is nascent and continually evolving, these scenarios were not used to eliminate candidate MPs. Instead, they were used to understand how the fishery is likely to respond to extreme conditions. The current management strategy was not robust to the climate change scenarios modeled. However, we identified an MP that meets our defined performance objectives, is feasible given current governance and enforcement limitations, uses available data and was robust to all uncertainty scenarios tested, including exploratory severe climate change effects. Unlike the current management approach, which relies on a static size limit, this MP uses length frequency data available through the California Recreational Fisheries Sampling (CRFS) program to identify when the SPR of the stock falls below a certain threshold. Note that this MP, if adopted, does not require a change to the size limit or bag limit at this time. However, it would provide an opportunity to adaptively manage the kelp bass fishery by allowing the Department to be responsive in the event of declining stock conditions due to unforeseen conditions resulting from climate change. This MP would require length frequency sampling to continue at the current rate.

Effort reduction MPs also performed well across several management objectives, but due to the size and recreational nature of the kelp bass fishery it is currently not feasible to precisely implement a specified reduction in effort. The Department currently uses bag limits to reduce catch and effort, but it is difficult to model this within the DLMtool. The barred sand bass MSE attempts to model bag limit MPs and this may be done for kelp bass in the future. In the meantime, this analysis demonstrates how MSE can be used to guide management decisions for the kelp bass fishery and represents the first attempt to quantitatively incorporate climate change conditions into management of the kelp bass fishery. As our understanding of climate change evolves and additional information becomes available the MSE should be updated. We also recommend running the risk assessment every two to three years with updated data to confirm current catch and effort under the existing management approach continue to pass the minimum sustainability limits.

Red Sea Urchin

Southern California's red sea urchin (*Mesocentrotus franciscanus*) fishery, in which divers collect urchin by hand to target their roe, has historically been very stable, but in recent years has experienced a severe decline in landings. The fishery has been managed via a minimum size limit that has been in place since 1988 to protect immature individuals and ensure they can spawn multiple times before entering the fishery, as well as effort restrictions based on days of the week. A previous MSE of the fishery found that the current size limit was likely to be sustainable. Monitoring studies have also shown a decrease in density and availability of commercial-sized red sea urchin in both fished and protected sites at the Channel Islands. As a result, this decline is thought to be caused by changing environmental conditions, which in recent years have led to reduced Giant Kelp availability, which red sea urchin feed on. These food limitations are thought to have reduced gonad quality, and thus the number of harvestable urchins in the roe fishery. These conditions, in which the primary threats to the fishery are due to environmental factors, present a serious obstacle for management of the fishery.

We conducted MSE using the DLMtool to explore how the numerous uncertainties facing red sea urchin are likely to impact the current management approach, as well as to identify any additional MPs that are feasible given governance constraints and data availability, robust to uncertainties, and maximize performance objectives. One of the primary challenges we faced was how to link recent environmental changes to their potential impacts on urchin biology. The scenarios modeled explore a range of hypotheses that include reduced reproductive capacity, increased mortality due to starvation or disease events (which have been observed in recent years), and reduced or variable growth. We also looked at scenarios in which these conditions re-occur periodically in response to oceanic variation.

While no single MP was robust to all of the uncertainty scenarios modeled, there are a number of MPs that are robust to the majority of the scenarios, including effort limits and the current size limit. We also identify a suite of iterative MPs that maximize the probability of maintaining a sustainable stock under some of the most severe scenarios modeled. These MPs set annual catch limits in response to changes in an index of abundance. While no MP can shield the fishery from reduced availability of healthy urchin when environmental conditions are poor, the benefit of these types of MPs is that they allow the Department to respond to declines in stock abundance when they occur by reducing catches, while also increasing catch limits during times when urchin are abundant. This analysis highlights the importance of adaptive management approaches in the face of climate change. We used fishery-independent survey data collected by the Channel Islands National Park Kelp Forest Monitoring Project as an index of abundance because, unlike a fishery-dependent index such as CPUE, it tracks declines in abundance rather than declines in roe quality and thus is a more immediate indicator of stock health. Under poor environmental conditions, both these more proximate and ultimate indicators would be beneficial to fishery guidance.

This analysis represents a demonstration of how MSE can be used to quantitatively incorporate climate readiness into management strategy development, which to our knowledge has not yet been done via simulation testing on a wide scale by any management agency to date. Due to the nature of the uncertainties examined in this case study, in which it is assumed that the future will be unlike the past and so there is no historical experience to draw on, it is difficult to determine how much weight should be given to each scenario when considering MP performance. Department staff will need to determine which scenarios seem most plausible, likely with input from the fleet, in order to determine how MPs should be filtered. As climate science continues to evolve and more information becomes available this analysis should be updated to reflect that new information.

Redtail Surfperch

Redtail surfperch (*Amphistichus rhodoterus)* are a nearshore species that inhabit the sandy surf zone between central California and southern British Columbia. The species has been exploited for many decades, first by indigenous communities, and then commercially beginning in the late 1800s, though the largest take has occurred in the recreational sector over the last decade in part due to declines in commercial fishing effort. Redtail surfperch give birth to fully developed juveniles during the summer months in nearshore aggregations. This unusual life history characteristic means fecundity is low and may make surfperch vulnerable to overfishing and localized depletion. Given the recent increased catch trends in the recreational sector we conducted an MSE using the DLM Toolkit to assess whether the current management strategy used in the recreational fishery, which is composed of a size limit of 10.5 inches and a bag limit of 10 fish, is likely to meet management objectives given uncertainties. We also assessed alternative MPs, including size limits, slot limits, and some iterative MPs that adjust the size limit in response to changes in the length structure of the catch.

The primary uncertainty identified for this stock is that a recent study conducted by Department biologists estimated a size at maturity larger than previously published estimates, meaning that the current size limit may allow for some take of individuals before they have a chance to spawn. Other uncertainties modeled included the retention of undersized fish, the level of protection provided by MPAs, the potential for reduced sampling effort for length frequency data in shore-based fisheries such as redtail surfperch, and the potential for increased fishing effort over the next few decades as the population of California increases.

We found that given the high amount of habitat protected in de-facto reserves and relatively low levels of fishing effort, the current management approach is robust to the uncertainties modeled, even when the larger size at maturity was modeled in combination with other uncertainties. It also resulted in high long-term yield and high probability of maintaining a healthy biomass in the long term. However, should fishing effort increase substantially in the future the population may experience an increased risk in being overfished.

We identified a suite of adaptive MPs that respond to changes in the size structure of the stock that were robust to large increases in fishing effort. It is unknown whether large increases in fishing effort will occur, and the data used to monitor fishing effort reflects the total effort in the beach and bank fishing mode, not effort targeting redtail surfperch specifically. Department staff may consider retaining the current management approach while tracking the size structure in order to identify when stock conditions decline and a management change is needed. However, this method requires that length frequency sampling occur at least every five years and potential changes in data collection priorities may limit its availability. Given this uncertainty, the Department may consider increasing the size limit, which was also found to be robust to large increases in fishing effort.

Rock Crab

California's rock crab fishery is comprised of three species, which are managed as a complex: red (*Cancer productus*), yellow (*Metacarcinus anthonyi*) and brown (*Romaleon antennarium*) rock crab.

Because the fishery is severely data-limited both in terms of fishery-dependent and life history data, this analysis represents a demonstration of the DLMtool as a tool to assess the relative risks and benefits of different management options for data-limited fisheries. Based on this analysis we identified several management procedure (MP) options that meet our defined performance objectives, are feasible given current governance and enforcement limitations, minimize data collection requirements, and are robust to uncertainty. Two options that maximize yield include an effort limit and a size limit. Additional options include a series of catch limits that sacrifice some yield but provide benefits to sustainability and stability in yield. Trade-offs among these options should be shared with stakeholders for their input.

Our analysis suggests that future risk of overfishing and unsustainable biomass is low for this fishery given the life histories of the species and the existing size limit. However, other research and communications with the fleet have indicated that the vulnerable biomass of the stock (i.e. sizes visible to the fleet) has declined leading to reduced profit and satisfaction among fishermen. Therefore, we recommend focused consideration of effort limit MPs as options best suited for maintaining yield while reducing economic costs of fishing. Because the rock crab fishery is truly data-limited, effort limit management options cannot be immediately implemented because the true amount of effort expended in this fishery is unknown. Therefore, additional research and/or monitoring is needed to establish an effort baseline before limits could be developed.

The DLMtool does not currently have the capability to model multiple stocks in one MSE. Therefore, we focused our analysis on only female red rock crab. However, we did run separate MSEs on female yellow and brown rock crab in order to compare some key indicators of vulnerability. Because of limitations in our understanding of life history differences among the species, we are not confident in our assessment of which species may be most vulnerable under management as a complex. This limitation further recommends implementation of an effort limit as an additional measure of protection to these species. The DLMtool may soon have the required multi-stock capabilities but basic biological research will be required to refine species specific life history parameters. With further research, the DLMtool should be reapplied to address this question and ensure that management is appropriately benefiting each species and preventing serial depletion. This extension of DLMtool capabilities could also allow testing of additional management options, such as male only fishing. We also recommend a survey of the fleet to collect information on the economic costs of fishing. This would allow quantification of economic trade-offs among MPs allowing for justification and comparison of MPs that are resonant with the fleet.

Spiny Lobster

California's spiny lobster (*Panulirus interruptus*) fishery is managed with a Fishery Management Plan (FMP) that provides an adaptive framework to adjust management as threats to the sustainability of the fishery are identified. Should the adopted reference points (Catch, Catch Per Unit Effort (CPUE), and Spawning Potential Ratio (SPR)) pass predetermined thresholds, the FMP specifies a number of different management options that may be applied to the fishery, but currently provides little guidance on which option is most likely to achieve management and fishery objectives. This analysis provides a demonstration of the DLMtool to conduct Management Strategy Evaluation (MSE) to test the performance of the management options in the FMP to identify those that are feasible under the current management system, robust to uncertainties and meet sustainability and economic goals for the fishery. While there is no evidence currently indicating that the spiny lobster stock is overfished or that overfishing is occurring, these analyses represent an opportunity to proactively identify viable options should conditions change in the future.

Based on this analysis, which examined female lobster stock and commercial fleet parameters, we identified several management procedure (MP) options that meet defined performance objectives, are feasible given current governance and enforcement limitations, minimize data collection requirements, and are robust to uncertainty. A reduction in effort best maximizes both long-term biomass and long-term yield, but a Total Allowable Catch (TAC) limit can trade off long-term yield for lower variability in annual yield. A TAC limit also reduces the probability of multiple management actions needed to recover the fishery, relative to effort reduction approaches. Trade-offs among these options should be shared with stakeholders for their input.

Our analysis suggests that future risk of overfishing and unsustainable biomass is low for this fishery given the life history of spiny lobster and the existing size limit. Furthermore, it suggests that the fishery can be managed sustainably even with existing data gaps and areas of uncertainty identified in the FMP. This exercise also elucidated the importance of and the uncertainty surrounding the size distribution (CL and weight) of landed lobster and size-at-age. MSE results would be improved with sampling programs that regularly collect CL and weight of landed lobster. Given the performance of the effort reduction MPs, improving the collection and accuracy of effort data reported by the fleet would also be beneficial.

The DLMtool does not currently have the capacity to model multiple stocks and multiple fleets in one MSE. Therefore, we focused our analysis only on female spiny lobster and the commercial fishery. The spiny lobster MSE would benefit greatly from a multi-stock/multi-fleet model given the different biological parameters for male and female spiny lobsters, the regional variation in spiny lobster size and growth, and the size and impact of the recreational fishery. Additionally, planned updates to the DLMtool will eliminate many of the issues we had to address regarding size structure of the stock and the MSE should be re-run once those updates are available.

Warty Sea Cucumber

Warty sea cucumber (*Apostichopus parvimensis*) is an economically important echinoderm that is targeted by the commercial dive fishery in southern California. This resource has recently exhibited concerning declines in catch despite increasing ex-vessel prices, which mirrors trends observed in other sea cucumber fisheries around the world that have experienced serial depletion because of increasing foreign demand. In addition, fishery-independent monitoring of warty sea cucumber around the northern Channel Islands further indicate declines in abundance, suggesting that management intervention is likely needed. Development of management measures to address conservation issues for sea cucumber fisheries have proven to be extremely difficult, as traditional management measures have been found to be largely ineffective and/or difficult to implement based on sea cucumbers generally complex and poorly understood life history. Considering these challenges, the DLM Toolkit was used to perform MSE to assess the feasibility and tradeoffs associated with potential management options that could improve the management of this data-limited fishery.

Based on MSE results, management procedures (MPs) related to size limits and effort reductions were found to maximize both long-term yield and biomass, while meeting our thresholds established for performance limits, feasibility of governance & enforcement, and uncertainties related to various biological and fishery parameters. Findings suggest that a minimum size limit based on a cut body weight (internal viscera removed) that ranges from 130 to 150 grams (estimated weights at 90 to 95% sexual maturity) will best meet long term conservation objectives. As an alternative, effort reductions to 30-40% of current fishing effort perform well, but are less effective in meeting long-term conservation objectives when compared to size limits. Furthermore, effort was recently reduced with the implementation of a seasonal closure in 2018 to protect spawning aggregations and any further effort reductions could limit fishing opportunity. Harvest control rules that iteratively adjust catch limits (ex. Total Allowable Catch) based on an index of abundance using annual dive density survey data like the KFMP monitoring data, could be used to adaptively manage the fishery. Considering that this species appears to be negatively impacted by changing environmental conditions, particularly extended warm water periods, an adaptive approach that closely tracks the status of the stock will likely benefit the long-term sustainability of this resource by helping to build resiliency into this stock against future climate change. In addition, catch limits provide an element of protection against potential future surges in demand, like those experienced in 2011, which likely contributed the current low stock status of the fishery. Findings suggest that a combination of a size limit and iterative TAC may allow for the fishery to recover faster, while optimizing short-term and long-term sustainable levels of catch.

These findings demonstrate the value of the DLM Toolkit in performing MSE for the data-limited warty sea cucumber dive fishery. A key feature of this model is its’ ability to account for uncertainties related to critical life history parameters like age and growth, which was accomplished by modelling three different life history strategies related to short, moderate, and long-lived life spans. This provided us with greater confidence that the final MPs recommended by the analysis were robust to the range of possibilities associated with these life history parameters. This analysis would be improved by the addition of a seasonal or monthly time step to the DLM Toolkit, which would allow us to incorporate the seasonal behavior of this species and to further explore MPs related to seasonal closures. In addition, developing an accurate catch history for this fishery that accounts for landing condition (cut vs whole) is a potential data improvement that could be used to improve future MSE analysis and recommendations for MPs related to catch limits. The DLM Toolkit provides a valuable tool for conducting MSE in a transparent way that is both repeatable and adaptable. In the future, we aim to use the DLM Toolkit to work closely with the fishery to further identify potential MPs and to discuss the tradeoffs (cost vs benefits) associated with MP implementation.

Method Evaluation and Risk Assessment Tool (MERA)

MERA enables rapid quantitative risk assessment and MSE through a user-friendly graphical interface that relies on the DLMtool operating engine in the background. The tool is being developed in conjunction with the Marine Stewardship Council for use in data-limited fisheries around the world. Like DLMtool, MERA is an open-access tool that can be customized to fit the performance objectives of any fishery management system. In addition to removing the need for R programming, one of the other key advantages to MERA is that it allows the construction of generalized operating models through a questionnaire (operating models developed in the DLMtool can be imported as well, allowing for all of the functions of MERA to be applied to fisheries that have already used the DLMtool). MERA also streamlines and automates the production of diagnostic analytical tools and reports, enabling the user to focus on the results and not on navigating through the many options for outputting results that are available in DLMtool. The final benefit is the ability to quickly run a small set of risk assessment management procedures to gauge the efficacy of current management with clear quantitative outputs and transparently justified assumptions and inputs. This is particularly relevant given criticism that has been raised about the utility of more qualitative risk assessment tools like Productivity Susceptibility Analysis (PSA) (Hordyk and Carruthers, 2018). MERA can also be used to run full-fledged MSEs, including conditioning operating models with current fishery data, applying management procedures to get actual management advice, and conducting retrospective comparisons between predicted trends and actual data from the fishery (referred to as Ancillary Indicators).

With additional testing and evaluation, MERA could provide a real breakthrough for the Department to rapidly expand the risk assessment and MSE benefits of DLMtool to many more fisheries with fewer technical barriers and easier adoption by staff. Due to an underspend within our contract with RLF, we requested to redeploy unspent funds toward completing and launching a public version of the MERA tool. We are pleased to report that the tool is now available at www.merafish.org. The website also includes a fishery library of operating models and reports for fisheries to which MERA has been applied and user support materials. Work continues on MERA with the MSC, FAO, and other interested partners. We also continue to discuss ways to use the new tool within the Department as a complement and extension to the current work with DLMtool.

Recommendations

The following recommendations are focused on how the Department could further integrate MSE into its management system. In addition, Appendix B includes a discussion of the current modeling capabilities and limitations of the DLMtool, as well as recommendations for further development.

A Roadmap for Adaptive Management in a Changing World

MSE provides a roadmap for adaptive management, including quantitative support for specific management changes and data collection priorities. MSE is not intended to inform current stock status, which can be estimated via stock assessment, data-limited approaches, or expert judgment. Rather, MSE takes what we know about the current state of a fishery and analyzes the expected impacts of different management actions in a transparent way, allowing managers and stakeholders to objectively evaluate which management actions have the highest likelihood of meeting the mandates of the fisheries management system and stakeholders' objectives for the fishery. MSE uses the best available information to provide advice on what magnitude of management change is likely to produce the desired result.

The results from an MSE analysis are not necessarily groundbreaking or unexpected, and often support managers' intuition about what types of management changes are needed for a fishery. However, the benefits of MSE are: 1) that it provides a transparent way to document all of the information and assumptions that have produced each recommendation; 2) it can weed out candidate MPs that are unlikely to meet management objectives, guarding against approaches that are most likely to degrade the resource; 3) it provides an objective decision-making framework that allows all MPs adopted by the Department to be measured against the same standard; and 4) it provides evidence-based support when Department staff make a management recommendation to the Commission.

MSE is a useful tool because it can help to both design adaptive MPs and to identify when they are failing. It is possible that an MP that performs well during MSE testing, and is later implemented, still results in unintended stock declines. This may occur for a number of reasons, including misspecification of either biological or fleet dynamics due to a lack of information, or because future dynamics differ fundamentally than those observed in the past. MSE is well suited to testing the robustness of different prospective management actions in the face of ecological changes resulting from climate change and other ecosystem changes, but we cannot anticipate every possible variation. The best guard against this, however, is adaptive MPs that provide regular feedback. These allow managers to detect declines early, especially those that deviate from expected data based on simulation results and take action by revisiting the assumptions in the original model and update based on new information.

Using Operating Models to Conduct Rapid Risk Assessment and to Prioritize Fisheries

Once an operating model is created using the DLMtool or MERA application, current management can be projected forward in time to determine whether status quo approaches are likely to be sustainable. The results could be used to quantitatively and objectively support the Master Plan prioritization process. We recommend developing simple operating models using available information in ESRs to perform risk assessments. This work could complement the existing prioritization process, which relies on many of the same inputs as those required by MERA to create simple operating models for carrying out risk assessments. This streamlined process could help to flag fisheries for which current catch or effort levels are unlikely to meet performance limits, and to identify those fisheries that may require immediate management attention. The added advantage of this approach is that the same operating models used for the rapid risk assessment can then be further developed to run full MSEs that allow the Department to identify what specific management actions should be considered.

Applying a Standard Procedure for Evaluating and Filtering MPs

The development of a predetermined procedure for evaluating the performance of candidate MPs and filtering the results to identify acceptable and feasible methods is key to understanding the results of an MSE. The use of a consistent approach to interpreting results and documenting the decision-making process, including through standardized plots and tables, will help Department staff, decision-makers, and stakeholders become familiar with and conversant in MSE results over time. We recommend continuing to use and further refining the procedure developed in this project as new MSEs are created and updated in California. The Department should further develop a clear policy that outlines the minimum performance limits that MPs must meet to be considered for management. In addition to the performance limits used for this project, the Department should also consider the development of other medium-term performance limits or objectives. These could be useful for obtaining stakeholder buy-in, especially those interested in making economic decisions on shorter time horizon while maintaining long-term biological sustainability.

Scaled Peer Review & Integrating MSEs into ESRs and FMPs

We recommend scaling the peer review process depending on whether a baseline MSE is being done for the first time for a fishery or whether an existing MSE is being updated with new information. For the former, we recommend an external peer review process, whereas we believe an expedited internal process could be used for MSE updates. Once an MP is selected for use in management, future management outputs from re-running an MP with updated data should also be reviewed internally.

In addition, peer review could be scaled based on the management needs of a fishery and the magnitude of the changes to management indicated by the MSE. For high priority fisheries or those where MSEs will be used to support a regulatory change, we recommend an external peer review process. For lower priority fisheries or those where no immediate management change is recommended, an internal Department review process could be used prior to appending the results to an ESR. We also recommend integrating MSE results into the management framework by appending them to ESRs or FMPs.

Triggers for Updating MSEs

The Department should define specific criteria for when MSEs should be updated. These could include: time (e.g., every 5 years), when new information changes OM assumptions or significantly reduces data uncertainties, if documented performance from the fishery diverges from projected performance from the MSE, if significant and unanticipated changes in the fishery are occurring (e.g., new sectors/gear or unexpected changes in participation), or other indications that current management is not working. Specific rules can be established to flag when MSEs should be updated based on predetermined indicators, such as CPUE indices or significant price changes.

Using MSE as a Tool for Stakeholder Engagement

The MSE framework is well-suited to communicating with and engaging stakeholders in the management process. We recommend developing materials to aid staff in discussing results with stakeholders and decision-makers to increase understanding of results and prospective management approaches. Virtual or live presentations could provide general background on the MSE framework before stakeholders participate in a management process related to a fishery they are engaged in. Once stakeholders are sufficiently familiar with the vocabulary and general concepts underlying the MSE framework, meetings can be used to solicit input on operating model development, the availability of fishery data, and discussions focused on the various stakeholder objectives.

MSE is Well-Suited to Evaluate Climate-Resilient Management Approaches

This project allowed us to begin integrating climate-ready management approaches into California's fishery management by modeling environmental changes and their anticipated impacts on fisheries management. This is an important area for further development, especially as our understanding of the impacts of climate change on coastal habitats and fishery biology continues to evolve. We recommend reviewing the available research describing the anticipated biological effects of different climate change scenarios on various California species, as well as supporting future research into this area.

Learning from other Management Agencies

Throughout this process we have been asked by multiple people how other agencies have approached the process of using MSE to select MPs, and how those MPs have performed after implementation. While we have been able to share our anecdotal experiences, we are unaware of any comprehensive synthesis describing the experiences of fisheries that have implemented MPs that were selected via MSE. The Department could benefit from a research project summarizing the lessons learned after MP implementation, what criteria were used to choose an MP, how well the MP performed after implementation, how frequently MSEs have been updated, and what approach has been taken if data streams deviated from expected. While the scientific literature on MSEs has focused more on the simulation model and management recommendations, this information could be found in agency reports or via interviews with managers. There could be valuable insights from other agencies that are further down the path of using MSE to choose MPs that might be helpful for California moving forward.

Given the investment that the National Marine Fisheries Service (NMFS) is currently making in MSE, outreach to west coast science center staff would likely be fruitful.

Computing Needs for Running MSEs

One of the innovations of the DLMtool is that simulations can be run very fast. This is achieved in part by an option to take advantage of parallel processing, in which simulations are farmed out to different processing cores within a computer and then stitched back together to create a single set of results. However, larger simulations can be very memory intensive, and reaching the memory bounds of a computer can cause simulations to either slow down drastically or fail completely. We found that exploratory MSE runs with ~100 to 150 simulations could be easily run using laptops with 2 to 4 cores and 8 gigabytes of RAM. However, some of our fisheries either tested a very large number of MPs (> 200), had a large number of robustness scenarios to test, or required very large numbers of simulation runs to ensure convergence (usually 300 simulations for final results). We used cloud computing to complete these very large simulations. There are a range of potential cloud computing services, each with tradeoffs in terms of speed and costs. It may also be possible to run simulations on existing Department servers. These complex MSEs also produced outputs that required a lot of storage. An individual simulation test produced a file that can range from 0.5 to 5 gigabytes per simulation test for the largest analyses run, and for each fishery multiple simulation tests were run to test all robustness and fishery improvement scenarios. We recommend that the Department consider how best to handle the computing needs associated with MSE.

There are also approaches that can be taken to reduce the amount of memory needed to run simulations. These include testing fewer numbers of MPs at a single time. Because we tested all of the MPs included with the DLMtool, as well as those we customized, we had a large number of MPs. It is important when customizing MPs to test a range of possible parameterizations to understand how they work, but this could be done in multiple steps to allow each MSE iteration to be run on a standard laptop or desktop.

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References

Butterworth DS. 2007. Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science: Journal du Conseil 64: 613–617.

Hordyk A, Carruthers T. 2018. A quantitative evaluation of a qualitative risk assessment framework: Examining the assumptions and predictions of the Productivity Susceptibility Analysis (PSA). PLOS ONE 13(10): e0206575. https://doi.org/10.1371/journal.pone.0206575

Punt AE, Butterworth DS, de Moor CL, De Oliveira JAA, Haddon M. 2016. Management strategy evaluation: best practices. Fish and Fisheries. 17(2): 303-334.

Smith A. 1994. Management strategy evaluation: the light on the hill. In Population dynamics for fisheries management. Edited by D.A. Hancock. Australian Society for Fish Biology Workshop Proceedings, Perth, 24-25 August 1993, Perth. pp. 249–253.

Walters C, Martel SJD. 2004. Fisheries Ecology and Management. Princeton, New Jersey: Princeton University Press. 381 p.

Appendix A - Procedure for Evaluating Performance of Candidate MPs

Performance Limit Diagnostic

The first step in evaluating MP performance is to determine whether the standard minimum sustainability reference point (50% of SSBMSY) is biologically appropriate. In this analysis, a set of simulations with no fishing for the next 50 years is run to understand how likely the stock is to meet the baseline sustainability performance limits under normal biological variability alone. Some stocks that exhibit high natural variability may drop below this reference point more than 20% of time the even without fishing pressure. Using a reference point that is not biologically attainable penalizes all candidate MPs. If this is the case, a lower reference point should be used. This analysis determines what is the largest reference point that is biologically attainable and uses that for all future components of the analysis.

Risk Assessment of Current Management

We then evaluate catch and effort under the current management approach to determine whether current management meets the minimum sustainability criteria above. This analysis provides information on how much risk current management poses to the stock. Should either current catch or current effort fail to meet one or both of the minimum sustainability criteria, this suggests that this stock may be a higher priority for management changes in the near term to ensure continued sustainability of the stock.

Sustainability/Feasibility Filter (Base Model)

The next step is to run simulations that test all candidate MPs under the base operating model assumptions and determine whether each MP meets the minimum sustainability criteria as defined by the Performance Limits described above. Passing MPs are then filtered further to remove any that are not currently feasible due to data or governance limitations. Those MPs that pass both the sustainability and feasibility filters are considered in the robustness analysis and examined for tradeoffs.

Assessing Model Convergence

After MPs are tested via simulation on the base model, model convergence in checked. The model has convergence when running additional simulations does not change the performance of each MP. This happens when the performance metrics, which are calculated by taking the mean of a certain statistic (biomass relative to a threshold) have stabilized around a single value, rather than changing each time a new simulation (which has different randomly drawn parameters) is added. Convergence suggests that running additional simulations will not change the outcome and is used to determine how many simulations to run, because large numbers of simulations become computationally intensive.

Two criteria are used to ensure that the model converged. The first looks at whether the ranked performance of the MPs has changed over the last 20 simulations for each performance objective. If the order has changed, that means the model has not converged and more simulations should be run. The second criterion looks at whether the root mean square deviation is greater than a threshold value of 0.5. If this is the case, the MP performance still varies more than the desired amount and is considered unstable. Note that the model can converge based on the first criterion while some MPs are still unstable, especially in fisheries with high variability. Given the computational difficulties of running very large numbers of simulations (<400), we present results where a low number of MPs remain unstable.

Robustness Testing (Uncertainty Scenarios)

Simulations are run to determine whether those MPs that are feasible and meet the overfished limits under the base model assumptions are robust to uncertainties in OM assumptions. In these robustness scenarios, new parameter combinations are used to build alternative models of the fishery. For example, these scenarios may reflect an estimate of natural mortality from another source, an alternate plausible selectivity curve, or a different recruitment scenario. The structure of these tests is similar to those above, in that simulations are run to test MPs and the probability of each MP meeting the overfished limits is evaluated. Any MP that cannot meet the minimum performance limits under all plausible uncertainty scenarios is not robust to that source of uncertainty and will not be considered for adoption.

Note that there are some scenarios that represent hypothetical situations that may occur in the future but currently do not have scientific evidence to support them, either because they have not occurred in the past or because they have not been well studied. This lack of evidence makes it difficult to determine how plausible they are, but managers might still want to understand how MPs are likely to perform under that scenario. MPs that do not meet the overfished limits for these scenarios may be considered for use in management. When choosing between MPs, robustness to these reference scenarios may provide support amongst a set of similar performing MPs.

Rebuilding Test

For some fisheries, there may be concern that the resource is currently at depleted levels that require rebuilding. For many data poor stocks, while there is no concrete information on the current biomass relative to BMSY, there may be other signs that the stock needs rebuilding, such as low catch rates relative to historic levels or severely truncated size distributions. If this is the case, a rebuilding test can determine which MPs would be able to meet the MLMA requirement for rebuilding. In this test the underlying assumptions match those found in the base model, with the exception that the current depletion estimate is replaced with a depletion level equal to 50% of BMSY. Then, each candidate MP is tested on its ability to rebuild the stock to a healthy level, defined as 80% of BMSY within a specific timeframe. This level was chosen to reflect the fact that stocks often fluctuate at or around BMSY due to natural variability and are rarely found exactly at BMSY. The timeframe for rebuilding is based on the MLMA, which states that if a fishery is found to be overfished or in a depressed state, it is necessary to rebuild in the shortest time period possible, allowing for biological productivity. We calculated the minimum time it would take a stock to rebuild to 80% BMSY with 80% probability under no fishing and then added a mean generation time on to that to reflect biological differences between stocks.

Management & Fishery Objectives Analysis

After MPs that fail overfished and feasibility filters are removed from consideration, the remaining MPs are then evaluated based on their ability to meet multiple management objectives. This process, known as ‘trading-off,’ acknowledges that different stakeholders will value some management objectives more than others, and that decision-makers should attempt to find management strategies that achieve the best balance among competing objectives. This analysis is primarily carried out as a dialogue between biologists, managers, and stakeholders in order to make decisions about what MP to select, but here we illustrate the process using the general performance objectives described above. To facilitate this analysis, we present the results in terms of tables listing probabilities for all performance metrics, tradeoff plots (in which two desirable variables are plotted against each other for direct comparison) and projection plots to understand the long-term performance of each MP.

Trading off usually involves considerable discussion among managers and stakeholders to decide which MP is most preferable. However, there are some MPs that perform worse across all performance metrics. These are considered 'dominated' MPs, as other options are always preferable. If a large number of MPs have passed the overfished limits it is possible to determine which MPs are dominated and eliminate those from consideration. In addition, there may be management reasons why some MPs are preferable to others, and these are discussed in the results section. We then examine the tradeoffs between the remaining MPs and make recommendations for steps towards adoption and implementation of a preferred MP.

Fishery Improvement

MSE provides an opportunity to determine which management improvements would be most likely to provide increased performance, and thus might be worth the investment in additional data collection or enforcement processes. Fishery improvements can include a wide range of actions, such as improving current data collection activities to expand sample size or otherwise increase precision, initiating additional data collection procedures to collect new types of data, conducting new analyses of existing data, or better implementing current regulations.

We conducted two different types of analyses to determine avenues for potential fishery improvement. First, we examined the impact of improving current data collection or enforcement of existing regulations for those MPs that are feasible and meet the overfished limits. This analysis is similar to the robustness tests in Step 5 above, but the base model is used to describe the stock and fishery dynamics, while assumptions about improved data collection and management implementation are altered. MSEs are then run to understand the potential increase in long-term average yield for each MP under these alternative assumptions.

The second improvement analysis looked at the potential increases in yield available in sustainable MPs that are currently infeasible due to data or governance limitations. Long-term average yield for unfeasible MPs is compared to the highest yielding feasible MPs to determine when it might be worth the cost to initiate new data collection procedures in terms of potential improved yields.

Appendix B: Understanding the DLMtool's Modeling Capabilities

As part of the first phase of this project, which began in 2015, a number of components were added to the DLMtool in order to allow the package to better model issues that are of primary importance to California's fisheries, including retention curves that differ from selection curves in order to model size limits, as well as the potential for discard mortality from the release of sublegal fish, areas that were closed to fishing historically to better model California's MPA network, and cyclical changes in productivity of the stock to better model the environmental variation due to oceanographic regimes.

Additional functionalities were added during this second phase of the project in response to challenges identified as the case study models were being developed. These included the ability to import size-at-age data, to automatically estimate growth and weight-length parameters, changes to make custom MPs more flexible through the addition of more types of recommendations that can be specified, and the ability to track sampled data from each year, simulation, and MP, as well as others that are discussed in more detail below. There are also planned updates that have been developed based on findings and feedback from this project that will be included soon. These include more realistic simulation of fishing with targeting based on size rather than age, as well as spatial data collection to allow MPs to use comparisons of fished and MPA areas to inform MPs. These various updates to the DLMtool, which have vastly improved our ability to model important fishery details, highlights one of the major benefits of the DLMtool: that it is constantly evolving and being improved over time as issues are identified via application of the tool to real world case studies. And, due to its open-source nature, these improvements are available to all users.

The inclusion of eight case studies that covered a wide range of life history characteristics, fishery gear types, data availability, and implementation constraints provided an opportunity to learn about what features currently cannot be modeled easily in the current version of the DLMtool (version 5.4.5). Below we comment on various fishery characteristics or information gaps that present a challenge to modeling using the DLMtool but can be accomplished or cannot currently be modeled using the DLMtool but may soon be included given planned updates. We summarize the approaches we took to overcome these challenges when modeling the case study stocks, as well as lessons learned. We also highlight recent or planned improvements to the DLMtool as a result of these lessons. We hope this summary will assist with prioritization of future modeling and data collection efforts by describing which life history characteristics or information gaps currently present a challenge to obtaining informative MSE results.

Maximum Age

Data-poor fisheries rarely have precise information on the maximum age. For the case study fisheries, we used maximum observed ages in stocks where the information was available, as well as estimated based on natural mortality parameters to estimate the lifespan of the stock, and then added ~5-10 years to this estimate. This is because the current version of the DLMtool model does not include a plus group (an age class where the small number of individuals surviving to advanced age can accumulate) as a default setting, though it can be modeled using a custom parameter. As a result, any individuals that, based on the natural and fishing mortality rates applied, do survive to the maximum age are automatically removed from the population in the following year. Having a higher than necessary maximum age does not cause fish to live longer because life span is determined by the amount of natural and fishing mortality experienced by the stock, but it does ensure that enough space is allocated for all possible age classes.

Growth

The default growth assumption in the DLMtool is that the mean length at age follows the von Bertalanffy growth curve. This is generally a reasonable assumption for mature finfish, which are the age class of primary concern in fisheries modeling, because these fish make up the spawning biomass of the stock and are usually targeted by the fishery. The assumptions about growth percolate through the entire model to almost every parameter. This is because many of the DLMtool's parameters have length-based inputs, which are more likely to be available for data-poor fisheries, but the underlying calculations of the DLMtool are age-based, so the growth model is used to convert back and forth.

The DLMtool can be customized to model other growth relationships. If an alternative growth model better describes your stock, or if you have collected length at age data directly, it is possible to pass the DLMtool a matrix of the mean lengths at each age. This was done in the Spiny Lobster case study to understand how an alternative growth model, which better fits the available data, affected MP performance. For species whose growth likely deviates from von Bertalanffy growth (such as crustaceans and echinoderms) we recommend a research project to collect length at age or tagging data in order to parameterize alternative models.

There is almost no growth information available for warty sea cucumbers, so it is unknown whether the von Bertalanffy growth equation is an accurate description of growth for this species. For this reason, we modeled three different age-length relationships that spanned a wide range of possible parameters and maximum ages, and required MPs under consideration to be robust to all three. One of the reasons we were confident in our approach was that the primary data by which to assess stock status were abundance-based, rather than size-based. While it is absolutely possible to determine robust MPs for species where the von Bertalanffy growth curve is not the best description of growth, we recommend caution when attempting to simulate and assess size-based data for any stock where growth deviates strongly from von Bertalanffy growth.

Recruitment

Recruitment is rarely known for most stocks unless a stock assessment has been completed. The approach we have taken for the stocks we have modeled was to use life history information or recruitment studies from similar types of species to determine whether the stock is likely to be low, medium, or highly productive (which is specified by the steepness parameter). For example, crabs, lobsters and flatfish are all known to have high reproductive rates, and so we assumed high steepness values in our models. We assumed the basses had moderate to high productivity but used robustness tests to explore uncertainty surrounding this assumption. Urchin and Sea Cucumber were assumed to have low to moderate reproduction, as was surfperch, which bear live young and thus likely have low reproductive rates (but higher juvenile survival due to parental investment).

Larval time series from CalCOFI sampling can be used to estimate recruitment variability levels (Perr) and autocorrelation (AC). This was the approach taken for Spiny Lobster and the bass species, which had this data available. For the other species we modeled wide ranges in assumed parameter values to choose MPs that were robust to this uncertainty.

Currently, the two stock recruitment curves that can be modeled in the DLMtool assume that as long as there are adults left in the population recruitment will occur. There is concern that, for stocks that may display density dependent effects that reduce recruitment at low stock sizes (e.g., the Allee effect), this results in an overestimation of the productivity at low stock sizes. Density dependent dynamics, either in the number of recruits produced or in the survival of recruits to the next age class could be added to the DLMtool in a future iteration. However, this requires data to estimate the threshold at which recruitment becomes reduced and density dependence kicks in, which is currently not available for most stocks. In our case studies there was concern that Barred Sand Bass, which normally form dense spawning aggregations over sand flats in the summer months, may be experiencing reduced reproductive success if they are unable to aggregate. We modeled a robustness scenario in which we reduced the steepness of the stock in order to attempt to capture this loss in productivity, but this approach assumes that the productivity remains low for the entire 50-year projection period even after the stock recovers to higher densities, which may be an overly pessimistic approach. To account for this, we used a shorter-term performance metric (10-20 years) to eliminate MPs that were not able to achieve performance limits in the near term rather than penalize MPs.

Another limitation of the DLMtool was illustrated by the Halibut case study. We tried to model a scenario with reduced future recruitment, perhaps due to environmental regime change or loss of nursery habitat. Under this hypothesis, recruitment would be limited not by the size of the adult population, but by an external factor. This would be a major deviation from the way that fish populations are usually modeled because one of the fundamental assumptions in fisheries science is that the recruitment is related to the number of eggs produced each year. For this reason, there is no way to specify externally-estimated recruitment values in the DLMtool, only recruitment deviations, which can be used to produce below average recruitment numbers. This was the approach we used for this case study but this means that, as the stock size grows, recruitment increases. In the situation of habitat limitation, recruitment may be limited by something other than the adult stock size. The addition of density dependence to the model may be useful in addressing this situation.

Maturity

The size at selection relative to the size at maturity is arguably the most important determining factor of a stock's sustainability. If management is in place to prevent the mortality of immature fish the population is likely to be sustainable. Without this information, it would likely not be worth developing an MSE. In this case we recommend sampling to determine the size at maturity. The DLMtool has a number of options for specifying the probability that a species is mature by either weight or age, and it is also possible to model time-varying maturity. For the case study fisheries, we had estimates of maturity at size, though for redtail surfperch and spiny lobster one of the central uncertainties was how a change in the size at maturity (either due to estimates sampled from a different location, or because of changes that have occurred over time) impact the performance of MPs. Warty sea cucumber had the least biological information, but due to recent Department sampling there was data available to estimate the size at maturity.

Spatial Dynamics

The DLMtool allows users to model two areas of different sizes, each with different histories of MPA implementation. Areas are connected by specified probabilities of movement. More specific spatial models can be parameterized using the MSEtool, which can model any number of areas, as well as customized movement and recruitment dispersal between those areas. As a result, it is possible to develop highly detailed spatial models using the DLMtool/MSEtool architecture. Usually, the primary obstacle to developing a spatial MSE is that it would require spatially-specific data to estimate the amount of biomass in each area, the connectivity between areas, and differences in fishing histories for each area, which is rarely available on the scale required. Additionally, unless one is attempting to test out different MPs for each area such spatial specificity is unlikely to be necessary to make management recommendations.

Historical Effort

Because many of the MPs modeled adjust future fishing effort relative to that in the last historical year, performance may be sensitive to estimates of historical fishing effort. We found that for fisheries with logbook data the information collected was unreliable or needed considerable QA/QC to be useable. For this reason, in some of our fisheries we modeled historical effort trends based on catch data, which is well documented in California's commercial fisheries. This allowed us to better match catch trends in recent years. However, for recreational fisheries, where historical data on total catch is less reliable, we estimated historical effort using a number of different approaches, including using total number of shore-based trips estimated from CRFS sampling for the Redtail Surfperch fishery, trips that caught at least one barred sand bass, and an associated species model as a proxy for habitat in the Kelp Bass MSE. This approach was also used to define effort in the Halibut stock assessment, and we used the relative fishing mortality rate estimate within the stock assessment for that model.

Selection and Retention

Understanding the size and/or age of fish selected by the gear type and retained by fishermen is a crucial component to MSE modeling, because when a fishery routinely catches immature individuals a much more restrictive MP is necessary to meet sustainability goals. If this information is lacking, it can be obtained through port sampling or conversations with fishermen about what they are catching, though they may not be representative of the entire fleet.

Selection and retention are both highly customizable in the DLMtool. Users can specify either knife-edged or domed-shaped relationships, and these can be based on either simple parameter inputs requiring three pieces of information, or can be based on probabilities at age/length estimated from each year of data, as was done for our more data-rich case study species, including the Bass species and Halibut. Note that the DLMtool is an age-based model, so when selection/retention parameters are specified in relation to size they are converted to ages to simulate the removal of fish from the population. Those fish in the catch are then assigned sizes based on the growth parameters and LenCV parameter, which specify the variation in mean length at age. This can, in some cases, result in catch-at-length information that is skewed towards larger individuals than what is observed at that level of depletion in the real world (known as Lee's phenomenon). We found this to be a problem in the spiny lobster MSE, and the implications of it are discussed more in that report. The next version of the DLMtool will include an option to model fishing based on size rather than age, though due to the higher computational needs the model is much slower and so may make more sense for stocks where this issue is heavily skewing catch-at-length data.

Depletion

Very few stocks have an estimate of depletion unless they have undergone some kind of stock assessment. However, it is possible to either assume wide depletion ranges or robustness scenarios that assume a lower depletion level than was in the base model to ensure that any selected MPs are robust to uncertainty around the current depletion level. Over the course of the case studies modeled, we found that model initialization was difficult when there was a large difference between the size at maturity and the size at retention (i.e., a size limit that is much higher than the size at maturity). This was true in the crustacean stocks modeled. When the DLMtool initializes the model, it draws parameter values for each simulated population, and then uses the information provided to project the population from an unfished state in year one to the specified depletion level in the last historical year. In stocks with a size limit that was much larger than the size at maturity, we were attempting to specify high depletion levels to reflect the perceived information about the stock. However, this information was entirely from fishery dependent data, which reflects the available vulnerable biomass (VB) rather than the available spawning stock biomass (SSB), which was much larger due to the size limit. We added an option to model the current depletion level in terms of VB rather than SSB, and immediately saw improvements in model initialization and stability.

Seasonal Dynamics and Short-Lived Species

The current version of the DLMtool models populations in yearly time steps and during every time step the population undergoes growth, movement, recruitment, natural mortality, and fishing mortality. This means that there is currently no way to model the types of dynamics described below. However, this capability would be a major asset to the DLMtool and should be prioritized as an addition.

• Seasonal growth: Some species exhibit strong seasonal patterns in growth and may even decline in size slightly during the rest of the year. It is possible to average total changes in size across an entire year, but seasonal growth pulses cannot be modeled.

• Seasonal aggregations: There is currently no way to model increases in catchability that result from seasonal aggregations.

• Seasonal management: There is currently no way to model MPs that are designed to reduce catch or fishing effort by closing the fishery for part of the year. Should variable timesteps be added to the DLMtool in the future this would be possible. For now, note that it is possible to model fisheries that already have a closed season (such as we did with Spiny Lobster), but not to model a change in the length of the closed season as a potential MP.

• Short-lived species: The DLMtool is not currently suitable for modeling species with life spans that are less than ~5 years. This is because the annual values of natural mortality are so high that the model becomes unstable, as we found in early versions of the rock crab MSE. An update to the model that would allow the specification of shorter time steps, as well as flexibility in determining which time steps recruitment and movement occur in, would be a valuable extension and allow the tool to be applied to these type of stocks.

Sex-Specific Dynamics

Many marine species demonstrate dimorphic growth patterns, and these can influence how much protection each sex receives from a given MP. Historically, fishery models have focused on modeling the female portion of the stock to understand how SSB changes in response to different MPs. This is the approach we took for rock crab, spiny lobster and California halibut, both of which display differences between males and females in growth rates and size/age at maturity. Other species we modeled either do not display strongly dimorphic growth or do not have enough growth information to know if it differs between the sexes (sea cucumbers and urchins), so we assumed that the variation we modeled covered the ranges observed for males and females.

An extension to the DLMtool/MSEtool package (called Multi-MSE) has been developed to allow for the modeling of males and females with separate biological parameters. They are treated as separate stocks, with only females contributing recruits in each time step, and both males and females receiving recruits. This extension was further developed following completion of these case studies and is being tested on California halibut. This capability will also allow the testing of MPs or fleets that target either males or females only.

Stock Complexes and Multiple Fleets

As with sex specific modeling, the ability to model multiple stocks will allow for the modelling of fisheries that target stock complexes, and help managers identify which stocks are likely to be the most vulnerable, or if species-specific management approaches are needed. Similarly, the ability to model multiple fleets with different selection/retention probabilities and discard mortality rates allows for more accuracy in assessing MP performance, as well as the ability to test fleet specific MPs, which may provide a more optimal management approach. Again, this capability is being tested through analysis of the five separate fleets targeting California halibut.

Bioeconomic Modeling

The DLMtool was originally designed to model fishing effort changes in response to MPs that set either catch or effort. For MPs that do not cap catch or effort, such as size limit MPs, we currently assume that effort remains at the level in the last historical year unless a change in effort or catchability is specified. This is an unrealistic assumption, and in reality fishing effort fluctuates in response to changes in catch rates and profits as well as to external drivers. We attempted to model this dynamic for Halibut by creating an MP in which effort varies in response to catch rates, but this was a preliminary effort because the relationship between effort and catch rates in this fishery has not been well studied. In addition, a recent update to the DLMtool includes a bioeconomic model that takes information on revenues, costs, and latent effort. However, the primary limitation in applying this functionality within an MSE is the whether there is data (or assumptions) on how fishing effort responds to changes in profits.