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Using Length-Based Spawning Potential Ratio (LBSPR) for Assessment and Minimum Size Limit Evaluation in California Recreational Fisheries

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Using Length-Based Spawning Potential Ratio (LBSPR) for Assessment and Minimum Size Limit Evaluation in California Recreational Fisheries

A Thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Marine Biology

by

Connor L. Coscino

Committee in charge:

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The Thesis of Connor L. Coscino is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

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LIST OF ABBREVIATIONS

LBSPR	Length-Based Spawning Potential Ratio
TAC	Total Allowable Catch
SPR	Spawning Potential Ratio
MSL	Minimum Size Limit
L_{inf}	von Bertalanffy asymptotic length
M	Natural mortality
K	von Bertalanffy growth coefficient
M/K	Ratio of natural mortality to von Bertalanffy growth coefficient
TL	Total Length
FL	Fork Length
L_{50}	Length at 50% maturity
L_{95}	Length at 95% maturity
SL_{50}	Length at 50% selectivity
SL_{95}	Length at 95% selectivity
CRFS	California Recreational Fisheries Survey
RecFIN	Recreational Fisheries Information Network
CV	Coefficient of Variation
CCFRP	California Collaborative Fisheries Research Program
F/M	Relative fishing mortality
CPUE	Catch-per-unit effort

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ABSTRACT OF THE THESIS

Using Length-Based Spawning Potential Ratio (LBSPR) for Assessment and Minimum Size Limit Evaluation in California Recreational Fisheries

by

Connor L. Coscino

Master of Science in Marine Biology

University of California San Diego, 2023

Professor Brice X. Semmens, Chair

Fisheries size limits are a fundamental harvest control rule intended to support sustainability, usually by allowing fish to reach maturity and reproduce before harvest. California relies on size limits for the management of some, but not all, recreational fisheries. For those with size limits, it is unclear whether existing control rules are sufficient to achieve sustainable levels of spawning potential. For those without size limits, the potential benefits of instituting length-based control rules for improving harvest efficiency have not been assessed. In this study, we used Length-Based Spawning Potential Ratio (LBSPR) to conduct a data-limited assessment of equilibrium stock status for a subset of high value recreational fishes and make inferences about the cumulative performance of existing management regulations. Using these model products, we then simulated stock status under alternative size limit scenarios in order to estimate the benefit of new or alternative minimum size limits on a species-by-species basis. To validate our methodology for assessing alternative size limit regulations, we leveraged data on two species of *Paralabrax* from before and after a recent increase in the recreational minimum size limit regulations. Our findings provide valuable insight on the status of five recreationally important yet unassessed fisheries stocks in California and identify situations where LBSPR may be successfully applied and where it may fail. Furthermore, we developed and validated a procedure for evaluating alternative minimum size limit scenarios that can easily be applied to other fisheries worldwide.

1. Introduction

The loss of marine biodiversity and depletion of fish stocks are widely reported globally and have profound effects on ecosystem services (Murawski 2010; Worm et al. 2006; Worm et al. 2009). Overfishing, combined with a changing climate, puts the future of many fish stocks in jeopardy (Brander 2007; Lam et al. 2016; Pauly et al. 2003). One way to prevent stock collapse is through fishery management. Fisheries that are managed tend to perform better than those that are not managed (Hilborn and Ovando 2014; Hilborn et al. 2020). Fisheries management objectives are generally to balance the maintenance of ecosystem functions while supporting sustainable harvest for the benefit of those who rely on fisheries for a diverse range of socioeconomic activities (Arlinghaus and Cooke 2009; Hilborn 2007). Although commercial fishing receives greater attention due to market-driven economic impacts, recreational fisheries also have massive socioeconomic impacts, and economic values extend well beyond the market price of a fish and the direct price an angler pays for a trip (Abbott et al. 2022; Arlinghaus and Cooke 2009; Arlinghaus et al. 2002; Cowx 2002; Lovell et al. 2020). California's recreational fisheries alone generate an estimated $1.15 billion in sales impacts annually (National Marine Fisheries Service 2022). As recreational angling grows, so too does its effect on fish populations (Ihde et al. 2011).

A common misconception is that commercial fishing drastically impacts marine populations while recreational fishing has little or no impact. In reality, commercial and recreational fishing can impact marine environments and fish populations in similar ways through truncations of size and age structures, reductions in biomass, and alterations of community compositions (Coleman et al. 2004; Cooke and Cowx 2006; Font and Lloret 2014; McPhee et al. 2002; Post et al. 2002; Schroeder and Love 2002). In some cases, recreational fishing can be the main source of mortality, surpassing both natural mortality and mortality due to commercial fishing (Cooke and Cowx 2004; Schroeder and Love 2002). The impact of recreational fishing is evident by the disproportionate association with depleted fisheries (Coleman et al. 2004; Schroeder and Love 2002). Given the importance and impact of recreational fisheries, it is imperative that existing management approaches be scrutinized and optimized, where possible.

Fishery management often involves evaluation of fish stock status to quantify anthropogenic impacts and gauge sustainability. Age-based assessments are the most rigorous and typically the best practice, as they are population specific and incorporate complicated trends in catch, fishing effort, and abundance. However, they are also complex, data-intensive, and expensive (Prince 2021a). Data-limited fisheries can be defined as lacking formal assessment or the ability to manage with Total Allowable Catches (TAC) (Jardim et al. 2015; Prince and Hordyk 2019). While it is possible to manage recreational fisheries with TACs, it requires strong catch accounting. In practice, most are not managed with traditional TACs or direct regulation of fishing effort (McPhee et al. 2002; Pereira and Hansen 2003). Recreational fisheries are notoriously difficult to manage due to the challenge of obtaining catch and effort data, as well as the diverse motivations behind recreational fishing (Abbott et al. 2022; Radomski et al. 2001). These data deficiencies often preclude traditional and complex assessment methods, and overfishing goes undetected until communities are extensively impacted. Management actions, in response, are typically reactive, lagging well behind impacts and resulting in ‘too little too late’ scenarios evident by the ubiquitous shifting baseline syndrome (Bellquist et al. 2017; McPhee et al. 2002; Pauly 1995; Pereira and Hansen 2003; Post et al. 2002; Soga and Gaston 2018).

Fortunately, recent advancements in data-limited methodologies have filled the need for quantitative assessment tools that can indicate signs of overfishing and population declines (Pereira and Hansen 2003; Pons et al. 2020; Prince et al. 2015). Some of these tools assess the spawning potential ratio (SPR) of a population—the reproductive potential left in a fished population compared to the reproductive potential if that same population was unfished (Goodyear 1993; Mace 1996; Mace and Sissenwine 1993). SPR is a simple metric that represents the effect of fishing mortality on reproductive success for a population and, with reference points, can be used as an indicator for recruitment overfishing (Goodyear 1993; Mace 1996; Mace and Sissenwine 1993; Prince 2021b; Walters and Martell 2004). When biomass trends are unavailable, SPR is a useful index of fishing pressure because it incorporates selectivity and directly tracks the reproductive potential of a population (Mace 1994; Prince and Hordyk 2019).

Length-frequency data, requiring sampling from only a subset of the fishery, is one of the most available forms of data and is useful even when there is limited knowledge of fishery operations (Hordyk et al. 2015a; Quinn and Deriso 1999). In recreational fisheries, length data is a vital source of information that can be used to assess stock health and management performance. An emerging length-structured modeling method, Length-Based Spawning Potential Ratio (LBSPR), has made it possible to use length composition and life history data to generate estimates of SPR and relative fishing pressure (Hordyk et al. 2015a; Hordyk et al. 2015b; Hordyk et al. 2015c; Hordyk et al. 2016; Prince et al. 2015). Applications of this method in recreational fisheries management can support efforts to assess stock health, evaluate management performance, and evaluate alternative length-based management scenarios. LBSPR does not incorporate catch trends, so this method can be used even in the absence of catch data. However, doing so increases the risk of making potentially misinformed management decisions;

for example, in cases when stock declines are not evident in the size structure of catch (Erisman et al. 2011).

In recreational fisheries, minimum size limits (MSLs) are a fundamental harvest control method intended to support fishery sustainability, usually by allowing fish to reach maturity and reproduce before they may be harvested (Beverton and Holt 1957; Myers and Mertz 1998). When appropriately set, MSLs allow for population replacement while also producing high yields (Froese et al. 2016). However, MSLs can be set too low, and must subsequently be increased over time (Van Poorten et al. 2013), for example, size limits for Kelp Bass (*Paralabrax clathratus*), Barred Sand Bass (*Paralabrax nebulifer*), Cabezon (*Scorpaenichthys marmoratus*), and White Seabass (*Atractoscion nobilis*) have become more restrictive over time. Size limits are not universally used across California's fisheries, and most that do exist were set decades ago without any formal assessment effort aimed at optimizing the control rule. Except for those few state-managed species with formal stock assessments, it thus remains unclear how well existing length-based control rules are performing, and to what extent those species without such control rules would benefit from MSLs.

In this paper, we combine recreational length-frequency data with the LBSPR assessment method to assess the equilibrium status of five important data-limited recreational fisheries in California and evaluate alternative size limit options for fishery management. While there are no current SPR-based reference points used for California's recreational fisheries, we conduct the status assessment in relation to generally accepted SPR target and depletion reference points to evaluate management performance. Doing so, we use a stochastic LBSPR framework to assess equilibrium stock status and evaluate the likelihood that existing management regulations meet these generally accepted reference points. We expand the stochastic framework by using the estimated fishing pressure from status assessments to simulate new or alternative MSL options under variable life history parameters, evaluating potential benefits and drawbacks. Furthermore, we leverage data on *Paralabrax clathratus* and *P. nebulifer* from before and after an increase in MSL regulations to validate method utility. In doing so, we evaluate the use of data-limited tools for species with different life-history strategies and fishing legacies, and we identify species that appear to have a high likelihood of overfishing.

2. Methods

Our analysis has two primary components. First, we use stochastic LBSPR methods to assess the stock status of five recreationally important and data-limited species while accounting for uncertainty in life-history parameters (Cope 2020; Hordyk 2022). Second, we conduct stochastic size limit simulations to evaluate the potential benefit of alternative size limit scenarios while accounting for uncertainty in life history parameters. We conducted all analyses using RStudio (R Core Team 2022).

2.1 Length-Based Spawning Potential Ratio

The specification of life-history parameters, such as growth, natural mortality, asymptotic length, and maturity, is essential for conducting stock assessments and managing fish populations (Beverton and Holt 1957; Hilborn and Walters 1992). Patterns between individual life-history parameters have been observed, with much done to understand and apply these life-history ratios and avoid the difficulty of estimating individual parameters (Beverton 1992; Hordyk et al. 2015b; Pauly 1980; Prince et al. 2015; Roff 1984). Of particular importance are the ratio of maturity to asymptotic length and the ratio of natural mortality (M) to the von

Bertalanffy growth coefficient (K) (M/K), which determines the shape of the von Bertalanffy growth curve and is known to vary less between closely related stocks (Beverton and Holt 1957; Hordyk et al. 2015b; Prince et al. 2015). Hordyk et al. (2015a) explored links between life history ratios, population length composition, and SPR. Life-history ratios are known to vary predictably with size, age, and reproductive potential (Prince et al. 2015). With the strong theoretical connections between life history ratios and SPR established, Hordyk et al. (2015b) developed an age-structured LBSPR model to estimate SPR from length-frequency data, which was later extended as a length-structured model to account for size-dependent selectivity, as is common in most fisheries (Hordyk et al. 2016). The LBSPR method requires relatively few inputs to estimate SPR (**Table 1**): the ratio of natural mortality to the von Bertalanffy growth coefficient (M/K), asymptotic length (L_{inf}), an estimate of the maturity schedule, and a sample of length-frequency data. LBSPR uses the connection between life history ratios and the expected size composition to estimate the unfished length distribution of a given stock or species, and then uses available length-frequency data to make comparisons between the fished and unfished populations and estimate selectivity, relative fishing mortality (F/M), and SPR (Hordyk et al. 2015a; Hordyk et al. 2015b; Hordyk et al. 2015c; Hordyk et al. 2016; Prince et al. 2015). LBSPR methodology relies on several simplifying assumptions, most notably, the model is equilibrium based and requires a representative sample of data (Hordyk et al. 2015a; Hordyk et al. 2015c; Hordyk et al. 2016).

Table 1: Description of LBSPR parameter inputs.

Parameter	**L_{inf}**	**L_{50}**	**L_{95}**	**M**	**K**	**M/K**
Description	von Bertalanffy asymptotic length	Length at 50% maturity	Length at 95% maturity	Natural mortality	von Bertalanffy growth coefficient	Ratio of natural mortality to the von Bertalanffy growth coefficient

2.2 Species Selection

This analysis requires minimal input parameters (**Table 1**) which can originate from life history studies or meta-analysis in data-poor situations. Data-limited analyses are more informative for unassessed stocks; therefore, we chose a subset of heavily targeted species that do not currently have a formal stock assessment. However, a similar analysis may still be useful for simulating size limit scenarios on assessed species. Model assumptions must be considered when choosing species to perform this analysis on. For example, a representative sample of data is required, so species that display dome-shaped selectivity or form spawning aggregations may produce erroneous results. LBSPR is unable to fit multimodal data, so species that exhibit size-segregation also may not perform well, such as California Yellowtail, *Seriola dorsalis*. Unless sex can be specified with precision for both length data and life-history inputs, sequential hermaphrodites may also lead to erroneous results.

2.3 Length Data and Life History Parameters

Length frequency data from the California Recreational Fisheries Survey (CRFS) is publicly available on the Recreational Fisheries Information Network (RecFIN). Data for each species caught in California from 2004 through 2021 were downloaded. Data quality control steps were performed to filter out potential data entry errors, such as removal of unreasonably large and small length records (see species specific paragraph below for details on filtering). A column in the downloaded data files specifies whether each record is within the known size range; this was used to filter out length records larger than the max possible size (Pacific States Marine Fisheries Commission 2023). Because the CRFS data are provided as fork lengths (FL), we used length conversion equations to generate total lengths (TL) to match the life history parameter inputs (**Table 9A**). The definition of total length used in previous life history studies is unclear. As such, we assumed total length was defined as the tip of the nose to the longest end of the caudal in its natural position, unpinched, and clarify that this is the definition of total length we use in our study. We aggregated data across all years for each species under the assumption that the resulting data sets more closely meet the equilibrium assumptions of LBSPR (Hordyk et al. 2015a; Hordyk et al. 2016; Punt et al. 2013). For each species, following data cleaning and conversions, we sorted all measurements into length bins for LBSPR analysis. Species that underwent a change in the MSL regulation during the study period were split into aggregates before and after the size limit change so as to not introduce bias in the data (Hordyk et al. 2015a).

Input life-history parameters were collected from a literature review of each species, with the most recent study conducted in California being chosen when multiple were available (**Table 8A**). The variation in length at age, specified with a coefficient of variation in asymptotic length (CV L_{inf}), was set at 0.1 for all scenarios. Steepness was set at 0.7 for relative yield calculations. When length at age is sexually dimorphic, the LBSPR method should only be applied to lengths from females (Hordyk et al. 2015c). However, the CRFS data do not specify the sex of each length record. As such, when parameter values were available for both males and females, we used the average of the two values as the LBSPR model input. We note, however, that this method should be used with caution as it assumes the sex ratio of the catch is equal.

2.3.1 *Paralabrax clathratus* (Kelp Bass) and *Paralabrax nebulifer* (Barred Sand Bass)

To filter out potential data entry errors, we removed length records smaller than 100mm and larger than the max possible size (Pacific States Marine Fisheries Commission 2023). The CRFS length frequency data were converted to total lengths using the equation in Love et al. (1996) (**Table 9A**). This equation is in centimeters, so the data were first converted to centimeters, then converted back to millimeters after using the conversion equation and subsequently rounded to the nearest millimeter. In March of 2013, the MSL was increased from 12 inches total length to 14 inches total length. Accordingly, the data were split into two parts: one before the size limit change (2004–February 2013) and one after the size limit change (March 2013–2021). For simplicity, we refer to the period before the size limit change as 2004–2012 and the period after the size limit change as 2013–2021. In each time period, we sorted the data into 10mm length bins.

2.3.2 *Caulolatilus princeps* (Ocean Whitefish)

To filter out potential data entry errors, we removed length records smaller than 100mm and larger than the max possible size (Pacific States Marine Fisheries Commission 2023). No conversion between fork length and total length was found for Ocean Whitefish. Using data we collected on California Collaborative Fisheries Research Program (CCFRP) surveys of the San Diego region in 2022, we used a simple linear regression to establish a conversion between fork length and total length (**Figure 9A**, **Table 9A**). After applying this conversion to the CRFS length data, each record was rounded to the nearest millimeter and then placed into 10mm length bins. No maturity ogive is available for this species, so inputs for length at 50% and 95% maturity were assumed to be equivalent to the maturity range presented by Cooksey (1980).

2.3.3 *Sphyraena argentea* (Pacific Barracuda)

To filter out potential data entry errors, we removed length records smaller than 300mm and larger than the max possible size (Pacific States Marine Fisheries Commission 2023). The data were converted from fork lengths to total lengths using the equation found on FishBase (**Table 9A**) (Binohlan et al. 2011). After applying this conversion, each record was rounded to the nearest millimeter and placed into 20mm length bins. The most recent total length growth equation present in the literature does not specify sex, so we assume this equation applies to all individuals, regardless of sex.

2.3.4 *Sebastes serranoides* (Olive Rockfish)

To filter out potential data entry errors, we removed length records smaller than 100mm and larger than the max possible size (Pacific States Marine Fisheries Commission 2023). The CRFS length frequency data were converted to total lengths using the equation in Echeverria and Lenarz (1984) (**Table 9A**). After applying this conversion, each record was rounded to the nearest millimeter, and data were placed into 10mm length bins. There is a high degree of sexual dimorphism between males and females of this species, so the assumption of a shared average parameter across sexes may result in untrustworthy model performance. The M/K ratio is expected to be equivalent for different sexes of the same species (Prince et al. 2015), so a lower growth coefficient (K) for female Olive Rockfish should equate to a lower natural mortality rate

(M). Using a max age based natural mortality estimator, this translates to an older max age for females. Therefore, the max age based natural mortality rate (M) and the female growth coefficient (K) were used for the M/K parameter.

2.4 Stochastic Stock Status Assessments and Evaluations

Because the LBSPR methodology is sensitive to parameter inputs (Hordyk et al. 2015a; Hordyk et al. 2016), we applied a stochastic framework to assess the status of each species under a range of possible parameter combinations and display uncertainty (Cope 2020). This stochastic approach uses Monte Carlo simulations to randomly draw 1000 combinations of asymptotic length and M/K parameter values from a multivariate random normal distribution. The distribution was created using life history parameters (**Table 8A**) and a covariance matrix defined by parameters in **Table 10A**. CV L_{inf} was set to 0.1 following previous studies (Hordyk et al. 2015a; Hordyk et al. 2015c; Hordyk et al. 2016), CV M/K was set to 0.2 to allow for a wide range of M/K values (Cope 2020), and the correlation between L_{inf} and M/K was set to 0.2 to account for parameter covariation (Cope 2020). We held the ratio of maturity parameters to asymptotic length constant. We then fed the random parameter draws into the LBSPR model to assess the length-frequency data under each combination of life history parameters. Iterations resulting in SPR=1/FM=0 were discarded. To obtain estimates of median relative yield, we fed the median values of SPR and selectivity, along with the life history parameter inputs (**Table 9A**), into LBSPR simulations.

Previous studies on SPR-based reference points have suggested 30–40% as a target and 20% as an overfishing threshold (Gabriel and Mace 1999; Goodyear 1993; Mace 1994; Mace and Sissenwine 1993). However, less resilient species may require higher targets and thresholds

(Clark 2002). For this study, we use 40% SPR as a reference target and 20% SPR as a reference overfishing threshold. Doing so, we classify SPR estimates into three performance zones. Less than 20% SPR signifies low performance, 20% to 40% SPR indicates moderate performance, and greater than 40% SPR suggests good performance. For most species, SPR less than 20% indicates poor spawning potential and a high risk of recruitment overfishing (Goodyear 1993). SPR between 20% and 40% may warrant caution; more conservative (higher) SPR targets reduce the probability of recruitment failure (Prince and Hordyk 2019). For most species, SPR above 40% is sustainable and should approach MSY, although yield will start to suffer towards the upper boundary (Clark 2002; Gabriel and Mace 1999; Goodyear 1993; Mace 1994; Mace and Sissenwine 1993). Based on these reference points, we evaluated the status of each stock and the performance of associated management regulations. We define status assessment as our method of using LBSPR to obtain estimates of relative fishing mortality and SPR, and performance evaluation as the analysis and classification of stock status estimates into performance ranks based on generally accepted reference points. We evaluated our confidence in LBSPR assessments by considering existing literature, possible violations of model assumptions, and uncertainty with respect to performance zones.

This section of our analyses is intended to be a snapshot view of the equilibrium state of each fishery from 2004 to 2021 and does not account for natural year-to-year fluctuations, nor does it necessarily represent the current state of each fishery. In some cases, data may not represent the extent of the biological stock. Nonetheless, SPR is an index of fishing pressure (Mace 1996), so this study represents the performance of management regulations in achieving equilibrium stock status relative to generally accepted reference points, and this assessment captures a distribution of likely fishing pressure, which is useful for evaluating size limits.

2.5 Stochastic Size Limit Simulations

The stochastic stock status assessments used Monte Carlo simulations to randomly draw a combination of likely life history parameters, then estimated relative fishing mortality (FM), among other metrics, under each combination of parameters. For each species, this combination of life history ratios and relative fishing mortality was looped into LBSPR under alternative selectivity patterns. Under the assumption of constant equilibrium fishing pressure after the implementation of an alternative size limit, we simulated size limit scenarios by keeping FM constant and setting 50% selectivity to the length of the proposed size limit and 95% selectivity to 1mm above the size limit to approximate knife edge selectivity. This assumes perfect size limit implementation, no retention of undersized fish, and no discard mortality. For species that presently have a MSL, we also simulated knife-edge selectivity at the size limit to validate our methods and provide a conservative evaluation of the MSL if the fishery shifted to knife-edge selectivity. Similar to the stock status assessments, we obtained estimates of median relative yield under alternative size limit scenarios by utilizing the deterministic LBSPR model to conduct simulations using life history parameter priors, the assigned size limit selectivity values, and the median SPR value.

3. Results

3.1 Methods Validation

We validated the use of knife-edge selectivity in our size limit simulations by simulating a knife-edge selectivity pattern for species that already have a MSL (Kelp Bass, Barred Sand Bass, Pacific Barracuda). As seen in **Tables 2**, **3**, and **5**, selectivity is not always knife-edge at the MSL. This can be due to a variety of factors such as imperfect implementation, retention below the MSL, fishing patterns, growth, and general size availability. Simulating knife-edge selectivity on Kelp Bass produces median SPR estimates within 0.03 of the median stock status estimates. For Barred Sand Bass, simulating knife-edge selectivity produces a median SPR estimate approximately 0.05 units from the median stock status SPR estimate. For Pacific Barracuda, simulating knife-edge selectivity produces a less reliable median SPR estimate; around 0.15 units from the median stock status estimate. Kelp Bass size structure more closely resembles knife-edge selectivity at the MSL than do Barred Sand Bass and Pacific Barracuda. When catch size structure is clearly defined by the MSL, the assumption of knife-edge selectivity produces reliable estimates of SPR. In all cases, the simulation of knife-edge selectivity produces more conservative estimates of SPR compared to the stock status assessments at equivalent levels of relative fishing mortality. In data-limited scenarios, conservative estimates may be preferred (Hordyk et al. 2016). Even when established selectivity does not approximate a knife-edge pattern, the assumption of knife-edge selectivity for size-limit simulations is still valid for conservative estimates and resembles the lower end of possible SPR values. Thus, knife-edge selectivity should be preferred for size limit simulations.

We leverage data on *Paralabrax clathratus* and *P. nebulifer* from before and after a recent increase in the MSL regulations to evaluate method utility. In 2013, the MSL for both species was increased from 12 inches total length to 14 inches total length. **Figure 1** and **Tables 2–3** compare the results of Kelp Bass and Barred Sand Bass stock status evaluations from an actual 14-inch MSL to the results from a simulated 14-inch MSL. For Kelp Bass, the median SPR values differ by only 0.030, and the density distributions seen in **Figure 1** closely match. The simulated median relative yield is 0.16 units less than the estimated median relative yield. **Figure 2** compares median catch distributions from the simulated 14-inch MSL to the actual 14-

inch MSL for both Kelp Bass and Barred Sand Bass. In Kelp Bass, the simulated catch distribution closely resembles the actual catch distribution. Similar results occurred for Barred Sand Bass. The median SPR values differ by 0.047 and the density distributions are similar. The simulated median relative yield is 0.12 units more than the estimated median relative yield. However, the simulated catch distribution is distinguishable from the actual catch distribution due to a substantial departure from knife-edge selectivity (**Figure 2**).

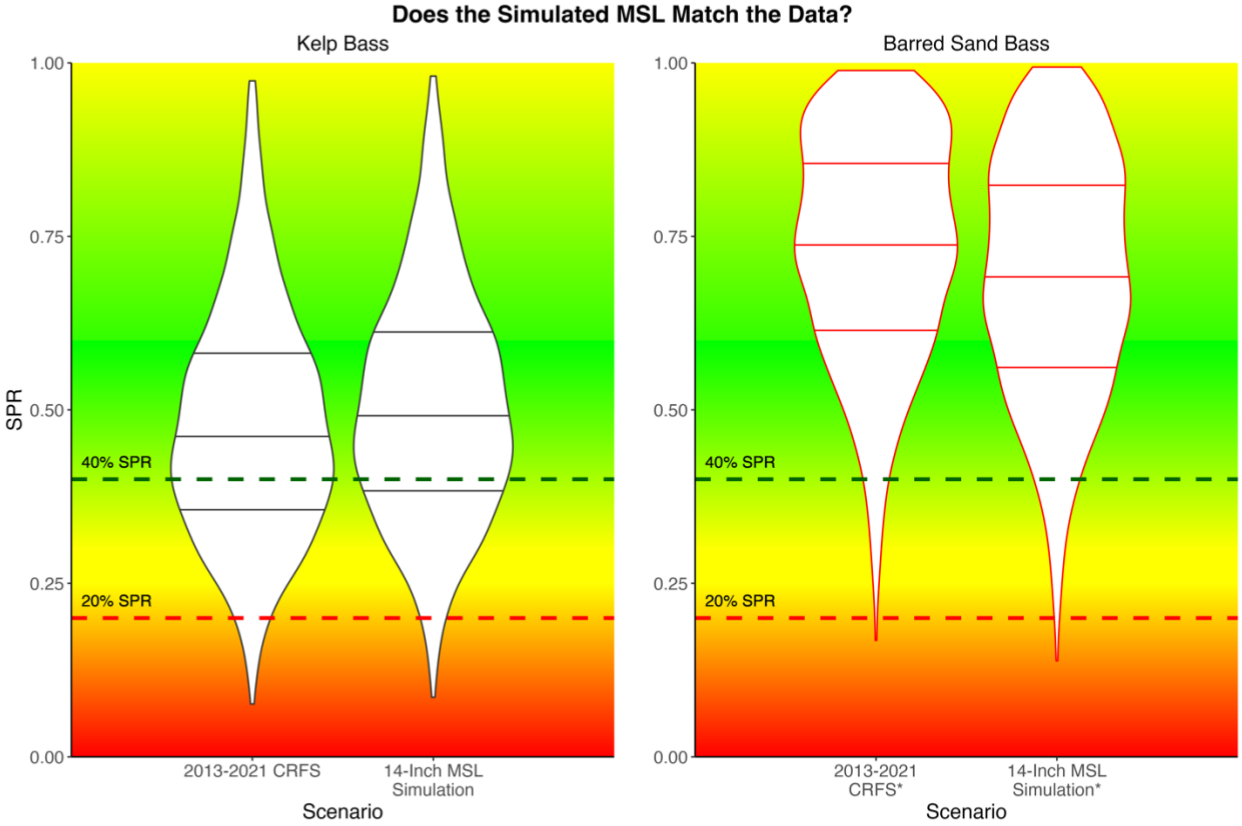


Figure 1: Stochastic comparison of a real 14-inch MSL (2013–2021) to a simulated 14-inch MSL for Kelp Bass and Barred Sand Bass. Note: The * denotes that the estimates for Barred Sand Bass are artificially high because the fishery collapse is not evident in the length data used by LBSPR.

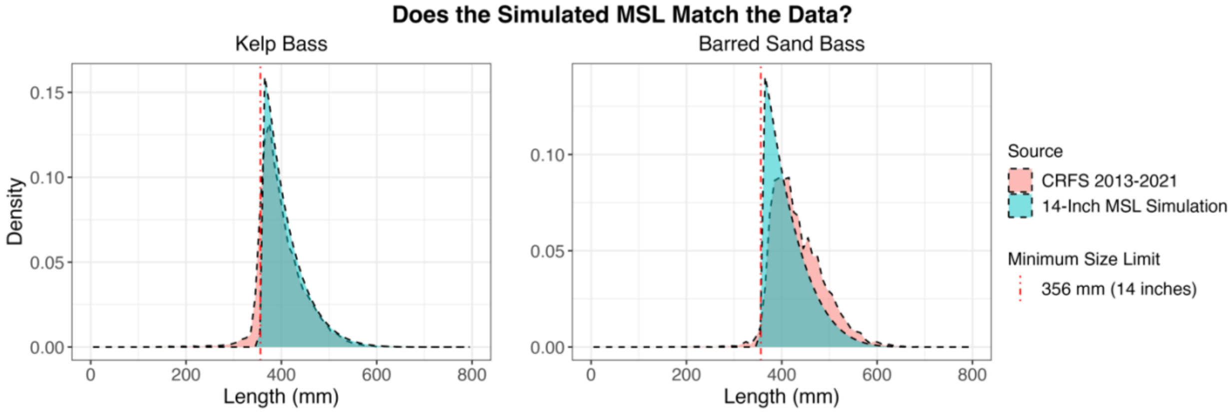


Figure 2: Comparison of median catch distributions between a real 14-inch MSL (2013–2021) and a simulated 14-inch MSL for Kelp Bass and Barred Sand Bass.

3.2 Stock Status Assessments and Evaluations

The results of stochastic stock status assessments and evaluations are presented in **Figure 3** and **Tables 2–6.** Each plot represents the probability density of possible SPR values for each species and scenario with the given distribution of possible life history parameters. Using the target and depletion reference points of 40% and 20% SPR, color illustrates the performance of management measures in protecting sufficient spawning potential. Red represents poor performance and low SPR; yellow represents moderate performance and moderate SPR; green represents good performance and high SPR. Yield declines as SPR approaches 1.00, so performance was downgraded for SPR values approaching 1. Horizontal lines represent the 75th, 50th, and 25th percentile intervals. Plots outlined in red violate equilibrium assumptions and thus do not produce reliable estimates.

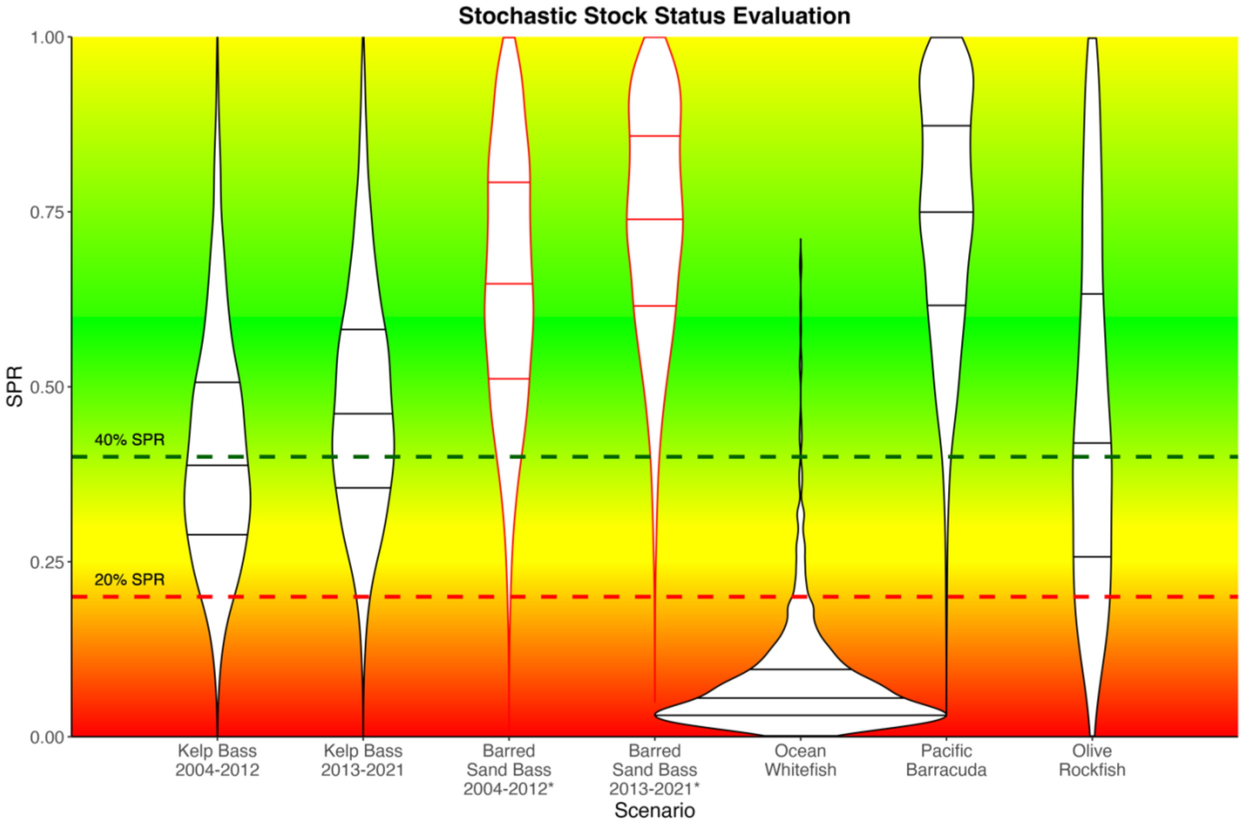


Figure 3: Evaluation of stock status using a stochastic approach to display uncertainty in life-history parameters. Horizontal lines represent 75th, 50th, and 25th percentiles. Barred Sand Bass are presented in red with an asterisk because the estimates have very low confidence due to poor model.

3.2.1 *Paralabrax clathratus* (Kelp Bass)

From **Table 2** and **Figure 3**, the 12-inch MSL (2004–2012) produced a median SPR of 0.389 with the interquartile range spanning from moderate to high performance. The 14-inch MSL (2013–2021) increased median SPR to 0.463 with the interquartile range spanning from moderate-high to high performance. Relative yield was at or near the maximum for both the 12-inch and 14-inch MSLs.

Table 2: Results of stochastic stock status assessments and minimum size limit simulations for Kelp Bass under varying management strategies and size limit scenarios. When applicable, 25th, 50th, and 75th percentile intervals are given, with the median in bold.

Description	Scenario	SL_{50} (mm)	SL_{95} (mm)	F/M	SPR	Median Relative Yield
Stock Status Assessment	**2004–2012 (Actual 12-Inch MSL)**	312.82 **313.38** 313.80	338.28 **339.28** 340.15	0.960 **1.350** 1.780	0.292 **0.389** 0.505	~1.00
Size Limit Simulation	**12-Inch MSL Simulation**	305	306	0.960 **1.350** 1.780	0.278 **0.373** 0.487	~1.00
Size Limit Simulation	**14-Inch MSL Simulation**	356	357	0.960 **1.350** 1.780	0.386 **0.493** 0.611	~0.83
Stock Status Assessment	**2013–2021 (Actual 14-Inch MSL)**	359.63 **360.11** 360.50	392.02 **392.81** 393.49	1.16 **1.60** 2.11	0.359 **0.463** 0.579	~0.99
Size Limit Simulation	**16-Inch MSL Simulation**	406	407	1.16 **1.60** 2.11	0.475 **0.586** 0.700	~0.77

3.2.2 *Paralabrax nebulifer* (Barred Sand Bass)

From **Table 3** and **Figure 3**, the 12-inch MSL (2004–2012) produced a median SPR of 0.649 with the interquartile range entirely in the high-performance zone. The 14-inch MSL (2013–2021) increased median SPR to 0.742 with the interquartile range spanning from high performance to moderate-high at the upper boundary. Median relative yield was 0.77 under the 12-inch MSL and decreased to 0.67 under the 14-inch MSL. It should be noted that the high estimates of SPR seen here are not in consensus with a decreasing CPUE noted for this period (Erisman et al. 2011; Jarvis et al. 2014; Miller and Erisman 2014).

Table 3: Results of stochastic stock status assessments and minimum size limit simulations for Barred Sand Bass under varying management strategies and size limit scenarios. When applicable, 25th, 50th, and 75th percentile intervals are given, with the median in bold.

Description	Scenario	SL_{50} (mm)	SL_{95} (mm)	F/M	SPR	Median Relative Yield
Stock Status Assessment	**2004–2012 (Actual 12-Inch MSL)**	333.88	365.61	0.280	0.513	~0.77
		335.57	**368.52**	**0.560**	**0.649**	
		336.99	371.05	0.880	0.801	
Size Limit Simulation	**12-Inch MSL Simulation**	305	306	0.280	0.455	~0.78
				0.560	**0.596**	
				0.880	0.762	
Size Limit Simulation	**14-Inch MSL Simulation**	356	357	0.280	0.564	~0.54
				0.560	**0.695**	
				0.880	0.835	
Stock Status Assessment	**2013–2021 (Actual 14-Inch MSL)**	376.67	408.66	0.220	0.620	~0.64
		377.98	**410.75**	**0.470**	**0.746**	
		379.05	412.58	0.760	0.871	
Size Limit Simulation	**16-Inch MSL Simulation**	406	407	0.220	0.684	~0.44
				0.470	**0.798**	
				0.760	0.902	

3.2.3 *Caulolatilus princeps* (Ocean Whitefish)

From **Table 4** and **Figure 3**, current management of no MSL produced a median SPR of 0.054 with the interquartile range entirely in the poor performance zone. Median relative yield was 0.00.

Table 4: Results of stochastic stock status assessments and minimum size limit simulations for Ocean Whitefish under varying management strategies and size limit scenarios. When applicable, 25th, 50th, and 75th percentile intervals are given, with the median in bold.

Description	**Scenario**	**SL_{50} (mm)**	**SL_{95} (mm)**	**F/M**	**SPR**	**Median Relative Yield**
Stock Status Assessment	**2004–2021**	255.20 **256.61** 257.80	300.96 **303.46** 305.64	1.598 **2.070** 2.620	0.030 **0.054** 0.094	~0.00
Size Limit Simulation	**12-Inch MSL Simulation**	305	306	1.598 **2.070** 2.620	0.045 **0.078** 0.132	~0.00
Size Limit Simulation	**14-Inch MSL Simulation**	356	357	1.598 **2.070** 2.620	0.075 **0.123** 0.201	~0.23
Size Limit Simulation	**16-Inch MSL Simulation**	406	407	1.598 **2.070** 2.620	0.120 **0.190** 0.292	~0.75
Size Limit Simulation	**18-Inch MSL Simulation**	457	458	1.598 **2.070** 2.620	0.192 **0.286** 0.409	~0.98
Size Limit Simulation	**20-Inch MSL Simulation**	508	509	1.598 **2.070** 2.620	0.291 **0.403** 0.542	~0.91

3.2.4 *Sphyraena argentea* (Pacific Barracuda)

From **Table 5** and **Figure 3**, current management of a 28-inch MSL produced a median SPR of 0.756 with the interquartile range spanning from high performance to moderate-high performance at the upper boundary. Median relative yield was 0.95.

Table 5: Results of stochastic stock status assessments and minimum size limit simulations for Pacific Barracuda under varying management strategies and size limit scenarios. When applicable, 25th, 50th, and 75th percentile intervals are given, with the median in bold.

Description	**Scenario**	**SL$_{50}$ (mm)**	**SL$_{95}$ (mm)**	**F/M**	**SPR**	**Median Relative Yield**
Stock Status Assessment	**2004–2021 (28-Inch MSL)**	829.730 **842.030** 848.680	965.930 **983.790** 995.810	0.490 **1.320** 2.360	0.624 **0.756** 0.890	~0.95
Size Limit Simulation	**28-Inch MSL Simulation**	711	712	0.490 **1.320** 2.360	0.461 **0.607** 0.805	~0.79
Size Limit Simulation	**26-Inch MSL Simulation**	660	661	0.490 **1.320** 2.360	0.364 **0.514** 0.744	~0.80

3.2.5 *Sebastes serranoides* (Olive Rockfish)

From **Table 6** and **Figure 3**, current management of no MSL produced a median SPR of 0.417 with the interquartile range spanning from moderate to high performance. Median relative yield was 0.98. Compared to the other species evaluated, the interquartile range is much larger, and considerable density lies outside the interquartile range, indicating high uncertainty in the estimate.

Table 6: Results of stochastic stock status assessments and minimum size limit simulations for Olive Rockfish under varying management strategies and size limit scenarios. When applicable, 25th, 50th, and 75th percentile intervals are given, with the median in bold.

Description	Scenario	SL_{50} (mm)	SL_{95} (mm)	F/M	SPR	Median Relative Yield
Stock Status Assessment	**2004–2021**	265.030 **275.050** 286.495	320.930 **339.570** 361.110	0.30 **0.63** 1.07	0.258 **0.417** 0.637	~0.98
Size Limit Simulation	**12-Inch MSL Simulation**	305	306	0.30 **0.63** 1.07	0.278 **0.455** 0.677	~0.94
Size Limit Simulation	**14-Inch MSL Simulation**	356	357	0.30 **0.63** 1.07	0.381 **0.558** 0.753	~0.75
Size Limit Simulation	**16-Inch MSL Simulation**	406	407	0.30 **0.63** 1.07	0.504 **0.675** 0.834	~0.55

3.3 Size Limit Simulations

The results of stochastic size limit simulations are presented in **Tables 2–6** and **Figures 4–6**. Following the design of **Figure 3**, **Figure 4** illustrates the change in probability density of possible SPR values under current and alternative MSLs, with color representing performance in protecting sufficient spawning potential. **Figures 5–6** illustrate the change in median catch distribution under each size limit scenario in respect to the mean length at 50% maturity used in this study.

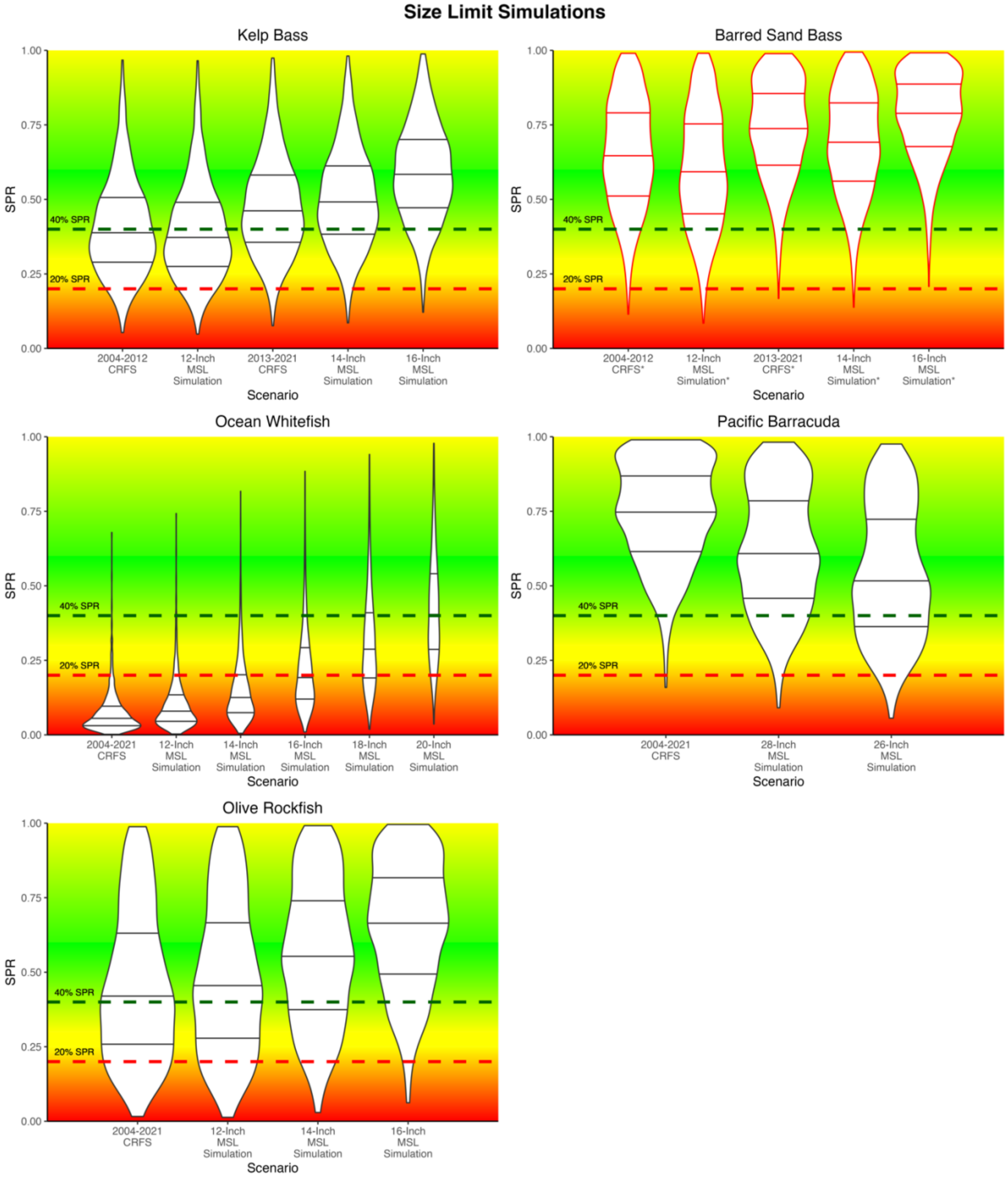


Figure 4: Comparison of stock status evaluations and size limit simulations using a stochastic approach to display uncertainty in life-history parameters. Horizontal lines represent 75th, 50th, and 25th percentiles. Note: Barred Sand Bass are displayed in red with an asterisk because estimates have very low confidence due to poor model performance for this species.

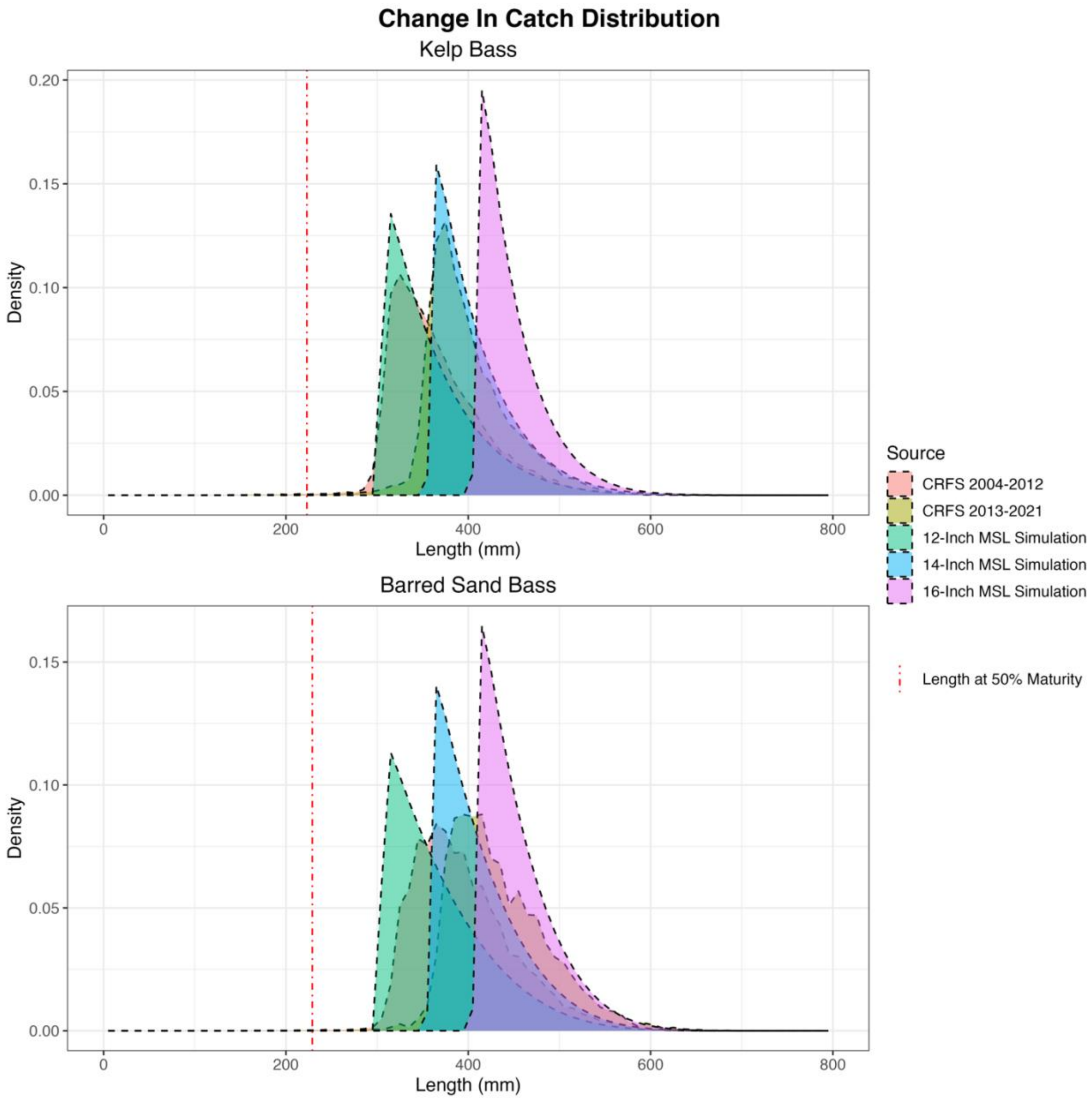


Figure 5: The change in catch distribution density for each scenario in Kelp Bass and Barred Sand Bass with respect to the mean length at 50% maturity used in this study.

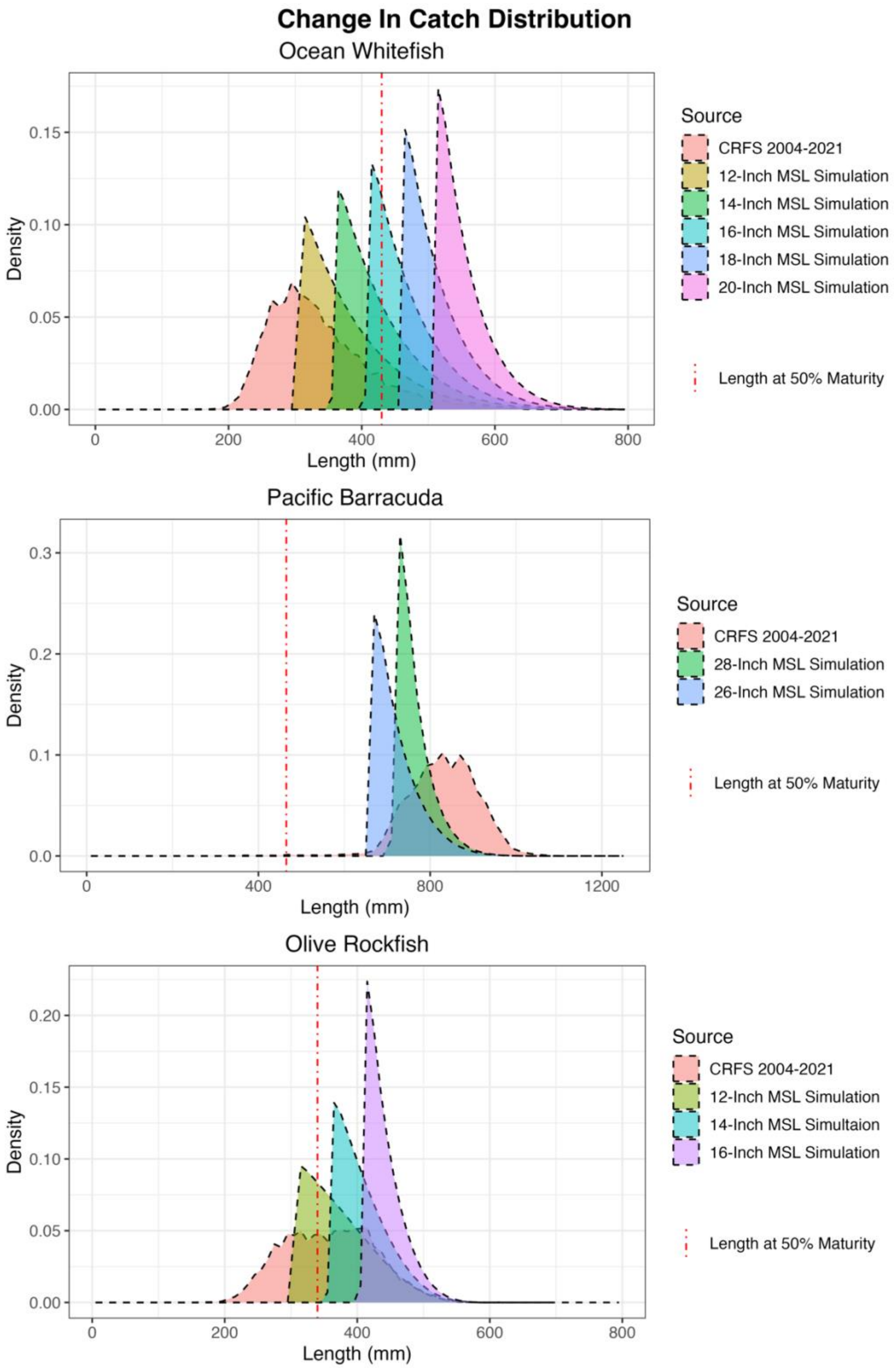


Figure 6: The change in catch distribution density for each scenario in Ocean Whitefish, Pacific Barracuda, and Olive Rockfish with respect to the mean length at 50% maturity used in this study.

3.3.1 *Paralabrax clathratus* (Kelp Bass)

From **Table 2** and **Figures 4–5**, a simulated knife-edge 12-inch MSL produced a median SPR of 0.373 with the interquartile range spanning from moderate to high performance. A simulated 14-inch MSL produced a median SPR of 0.493 with the interquartile range spanning from moderate-high to high performance. A simulated 16-inch MSL produced a median SPR of 0.586 with the interquartile range entirely in the high-performance zone. Median relative yield was optimized under a simulated knife-edge 12-inch MSL and decreased following an increase in the MSL.

3.3.2 *Paralabrax nebulifer* (Barred Sand Bass)

Estimates of SPR for this species are erroneous due to poor model performance related to fishery hyperstability, but we feel there is value in reporting these results to illustrate the magnitude of the overestimation for a fishery that has collapsed, yet the collapse is not evident in the length data, and the critically important point that LBSPR should be used with extreme caution for species that form seasonal spawning aggregations.

From **Table 3** and **Figures 4–5**, a simulated knife-edge 12-inch MSL produced a median SPR of 0.596 with the interquartile range entirely in the high-performance zone. A simulated 14-inch MSL produced a median SPR of 0.695 with the interquartile range spanning from high performance to moderate-high at the upper boundary. A simulated 16-inch MSL produced a median SPR of 0.795 with the interquartile range spanning from high performance to moderate-high at the upper boundary. Median relative yield was highest at a 12-inch MSL and decreased following an increase in the size limit.

3.3.3 *Caulolatilus princeps* (Ocean Whitefish)

From **Table 4**, **Figure 4**, and **Figure 6**, a simulated 12-inch MSL produced a median SPR of 0.078 with the interquartile range entirely in the poor-performance zone. A simulated 14-inch MSL produced a median SPR of 0.123 with the interquartile range spanning from poor performance to moderate-poor at the upper boundary. A simulated 16-inch MSL produced a median SPR of 0.190 with the interquartile range spanning from poor performance to moderate-high at the upper boundary. A simulated 18-inch MSL produced a median SPR of 0.286 with the interquartile range spanning from moderate-poor performance to high performance at the upper boundary. A simulated 20-inch MSL produced a median SPR of 0.403 with the interquartile range spanning from moderate to high performance at the upper boundary. Median relative yield increased with an increasing size limit until subsequently declining at a 20-inch MSL.

3.3.4 *Sphyraena argentea* (Pacific Barracuda)

From **Table 5**, **Figure 4**, and **Figure 6**, a simulated knife-edge 28-inch MSL produced a median SPR of 0.607 with the interquartile range entirely in the high-performance zone. A simulated 26-inch MSL produced a median SPR of 0.514 with the interquartile range spanning from moderate-high performance to high performance at the upper boundary. Relative yields are similar for both simulated size limits.

3.3.5 *Sebastes serranoides* (Olive Rockfish)

From **Table 6**, **Figure 4**, and **Figure 6**, a simulated 12-inch MSL produced a median SPR of 0.455 with the interquartile range spanning from moderate to high performance. A simulated 14-inch MSL produced a median SPR of 0.558 with the interquartile range spanning for moderate-high performance to high performance. A simulated 16-inch MSL produced a median SPR of 0.675 with the interquartile range spanning from high to moderate-high performance and the upper boundary. Median relative yield decreased with an increasing size limit.

4. Discussion

4.1 Methods Validation

Our results validate the utility of our size limit methodology with LBSPR as a process for evaluating the impact of adjusted MSL regulations on SPR and catch distribution. While median relative yield can also be simulated for MSL scenarios, slight differences in selectivity and fishing mortality make it imprecise. It should be used to indicate general trends rather than exact values. When the MSL is set above the length at maturity, SPR is relatively insensitive to varying relative fishing mortality, so the assumption of equivalent fishing pressure can be used without sacrificing accuracy in SPR. This is because the spawning potential produced by individuals not yet available to the fishery will always be conserved at any level of fishing pressure. SPR is also relatively insensitive to small variations in selectivity, so the assumption of knife-edge selectivity can be used without a significant loss of realism in SPR. When selectivity does not approximate a knife-edge pattern, the simulated catch distribution will be less realistic, but will still provide a conservative look into potential catch. Despite other regulation changes going into effect (bag limits, MPAs, etc.), our size limit simulations still provide reliable estimates of change in SPR (with one exception described below for Barred Sand Bass).

4.2 *Paralabrax clathratus* (Kelp Bass) and *Paralabrax nebulifer* (Barred Sand Bass)

Beginning in March of 2013, the MSL for *Paralabrax spp.* was increased from 12 inches to 14 inches in response to declines in CPUE and catch for both Kelp Bass and Barred Sand Bass (Bellquist et al. 2017; Erisman et al. 2011; Jarvis et al. 2014; Miller and Erisman 2014). While Kelp Bass declined gradually over several decades, Barred Sand Bass declined drastically in the early to mid 2000s, and catch has not recovered since (Bellquist et al. 2017; Erisman et al. 2011). The difference in decline rate may be attributed to the difference in spawning strategies between the two species. Although they are both known to form spawning aggregations, Barred Sand Bass form large and predictable aggregations, while Kelp Bass form much smaller and less predictable 'aggregations' that are more akin to group spawning events (Erisman and Allen 2006; Jarvis et al. 2010; Love et al. 1996). Spawning aggregations are comprised of large, mature fish, often with a disproportionate number of mega-spawners when compared to the entire population. The concentrated density of large fish makes capture easy, allows for high-grading, and results in catch and length frequency distributions biased to larger individuals being maintained despite masked effects on abundance. These heavily fished spawning aggregations are known to exhibit hyperstability, in which catch metrics remain high or elevated despite stock declines (Erisman et al. 2011; Miller and Erisman 2014). Our results show elevated levels of SPR for Barred Sand Bass despite a known decline in abundance, a sign of hyperstability in the catch distribution. The resulting data falsely suggest large fish are plentiful and the stock has a healthy or even elevated level of SPR. Hyperstability in Barred Sand Bass length data can be seen since the rise of the Barred Sand Bass fishery. Ally et al. (1991) state, "[The CPFV fleet] cite the ease in which legal sand bass can be caught, and the relative scarcity of legal kelp bass as the major reasons for the increased effort toward barred sand bass." Targeting dense spawning aggregations comprised of mature fish allow for an elevated length composition that is unrepresentative of the entire population. The hyperstability of Barred Sand Bass length composition is corroborated by Jarvis et al. (2014), who found that modal length and the proportion of mega-spawners in the catch both increased during recruitment failure. Evidence of recruitment failure further violate LBSPR equilibrium assumptions and may bias estimates of selectivity. Due to violations of LBSPR assumptions caused by hyperstability in an aggregation-based fishery and recruitment failure, we have very low confidence in the resulting estimates for Barred Sand Bass, which are likely to be elevated above reality. These results suggest that length-based analysis may be inappropriate when fishery-dependent data is used in fisheries that target seasonal spawning aggregations. The use of nonrepresentative data for length-based methods has long been warned (Gerritsen and McGrath 2007; Hilborn and Walters 1992; Hordyk et al. 2015a).

Although Kelp Bass are also suggested to exhibit hyperstability (Erisman et al. 2011), our results show no indication of hyperstability in Kelp Bass catch distribution. Poor recruitment was also noted for Kelp Bass (Jarvis et al. 2014), although we see no indication that younger fish are missing from our data. Compared to Barred Sand Bass, size composition and catch of Kelp Bass has been more stable over time (Jarvis et al. 2014; Miller and Erisman 2014). The differing reproductive strategy may be preventing a misrepresentation of larger fish in the catch structure. This was also noted by Ally et al. (1991), stating that legal-sized Kelp Bass are more difficult to catch than legal-sized Barred Sand Bass on spawning aggregations. Due to the lack of evidence for hyperstability in the length data, we have more confidence in our assessment for Kelp Bass. Both the 2004–2012 and 2013–2021 stock status estimates have interquartile ranges spanning multiple performance zones, so we denote moderate confidence for this species. Despite similar life and exploitation histories, the contrast between Kelp Bass and Barred Sand Bass suggests that the magnitude of spawning aggregation strategy significantly affects resilience to fishing pressure and the utility of length-based methodologies.

Results for Kelp Bass suggest a 12-inch MSL achieved moderate performance in protecting SPR and maximizing yield. The adjusted 14-inch MSL improved performance slightly by increasing SPR without sacrificing relative yield, and may improve resiliency to depletion. Our results contrast a previous study that implicates hyperstability in masking the decline in Kelp Bass (Erisman et al. 2011), yet they concur with another study that did not find evidence of hyperstability in Kelp Bass (Jarvis et al. 2014). While we find that recruitment overfishing would have been unlikely under equilibrium conditions when managed with a 12-inch MSL, it is clear that Kelp Bass were probably not in a state of equilibrium prior to 2013. The adjusted 14-inch MSL increased equilibrium SPR moderately. We believe this is an improvement over the previous 12-inch MSL because relative yield was not sacrificed, and the increase in SPR should lead to increased resilience. The increased resilience can be seen in **Figure 7**, which shows that near target levels of SPR can be maintained at very high levels of fishing pressure under a 14-inch MSL. A 12-inch MSL maintains SPR above the depletion threshold at high fishing pressure, although not near target levels (**Figure 7**). Our results suggest that the current 14-inch MSL should continue to protect sufficient levels of SPR with a very low risk of recruitment overfishing. Further increase in the MSL would lead to decreasing yields with increasing conservation of SPR. We have low confidence in our findings for Barred Sand Bass due to poor model performance, so any conclusion on the current or past performance of the stock based on our stock status evaluations would be ill-informed. However, in similarity to Kelp Bass, **Figure 8** suggests that, under equilibrium conditions and the theoretical absence of hyperstability and subsequent fishery collapse, sufficient spawning potential could have been maintained even at high fishing pressure under a 12-inch MSL, and further improved under a 14-inch MSL. However, because we know that the Barred Sand Bass fishery has collapsed in association with hyperstability and exploitation on spawning aggregations, these erroneous model outputs illustrate the management and conservation risks associated with using LBSPR alone without concurrently considering species reproductive strategies and catch/effort histories. **Table 7** presents an evaluation of stock performance and associated confidence in our assessments.

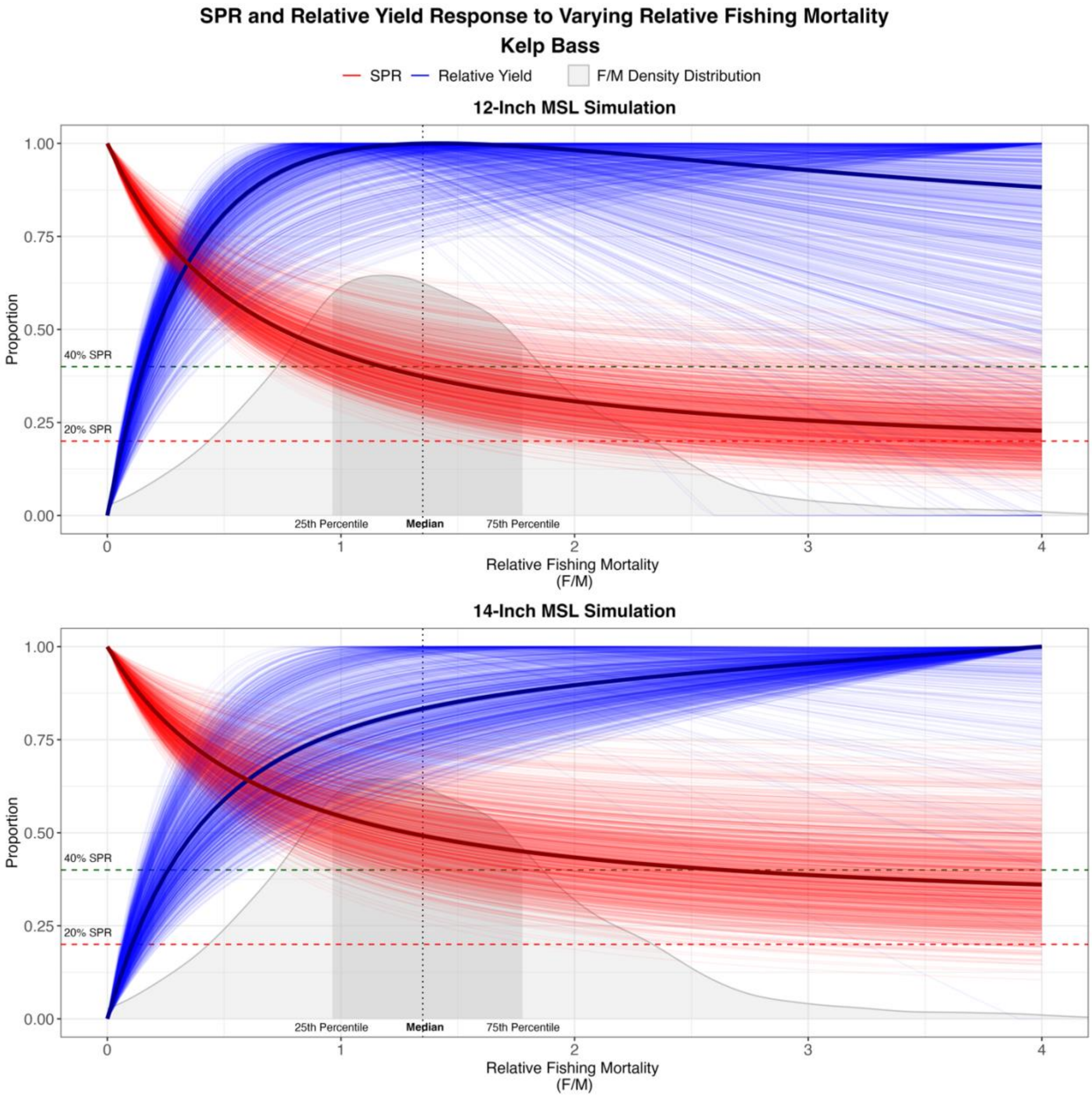


Figure 7: Kelp Bass relative yield and SPR response to varying levels of relative fishing mortality under a simulated knife-edge 12-inch and 14-inch MSL, with uncertainty. Each curve represents one combination of LH parameters at fixed selectivity approximating a knife-edge MSL. Dark curves represent LH parameter priors and should approximate the median curve. Grey represents the density distribution of relative fishing mortality from the 2004-2012 stock status assessment, with the darkened grey being the interquartile range.

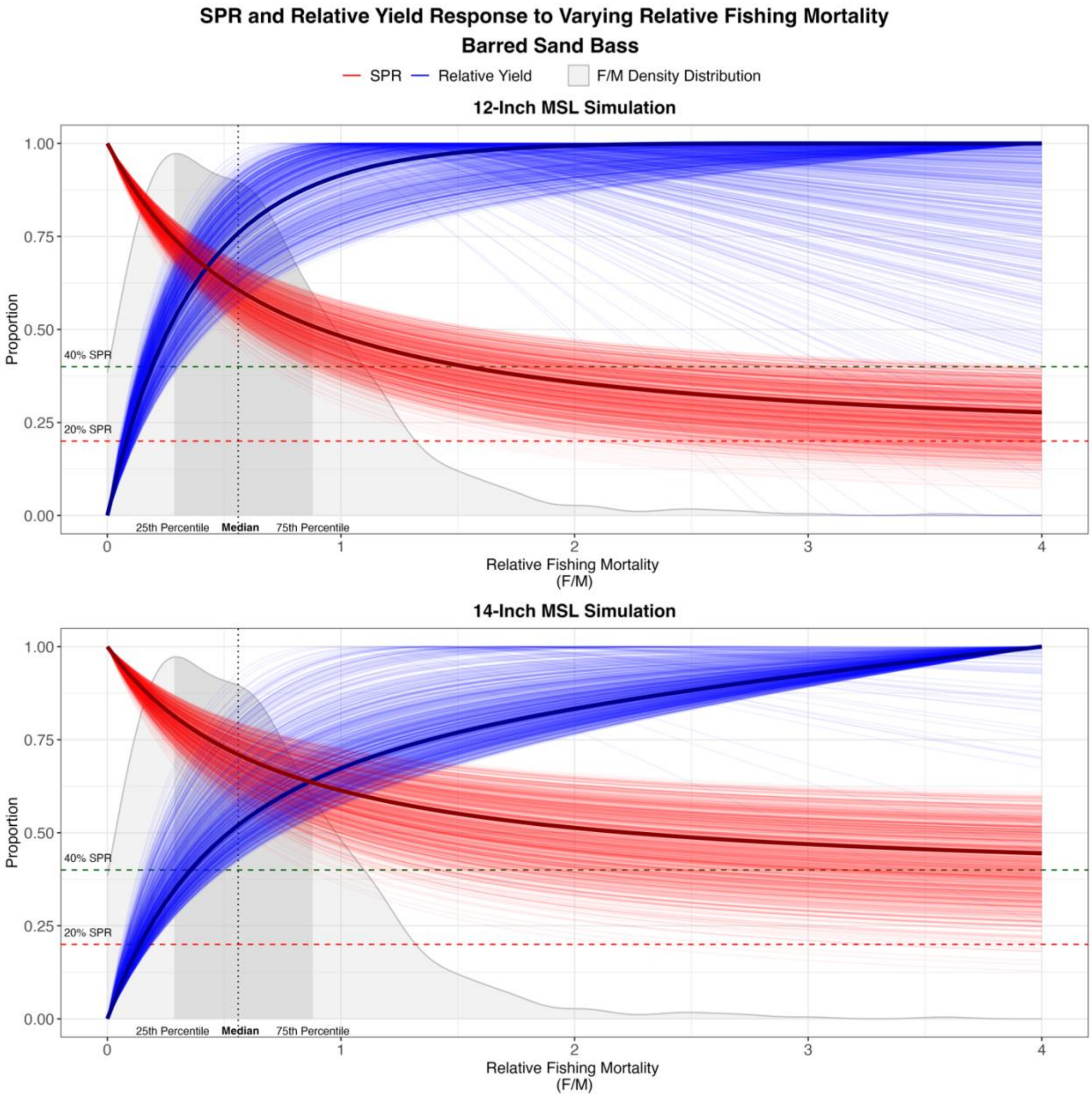


Figure 8: Barred Sand Bass relative yield and SPR response to varying levels of relative fishing mortality under a simulated knife-edge 12-inch and 14-inch MSL, with uncertainty. Each curve represents one combination of LH parameters at fixed selectivity approximating a knife-edge MSL. Dark curves represent LH parameter priors and should approximate the median curve. Grey represents the density distribution of relative fishing mortality from the 2004-2012 stock status assessment, with the darkened grey being the interquartile range. Disclaimer: The outputs of the F/M density distribution are purely for illustration purposes – they represent artifacts of only using length data for a species that has exhibited hyperstability-induced stock collapse due to overfishing on spawning aggregations, i.e. the management risk of using only a length-based approach for evaluating a seasonally aggregating species.

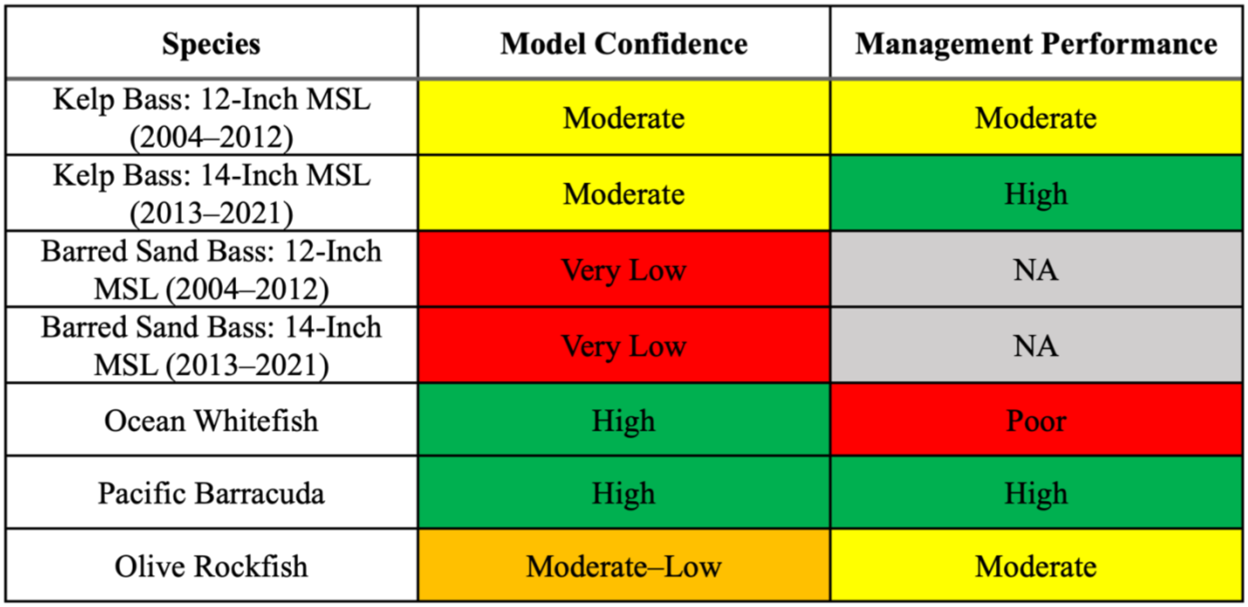
After implementation of the new MSL for *Paralabrax*, Kelp Bass showed signs of recovery while Barred Sand Bass continued to decline (Bellquist et al. 2017). A MSL increase was expected to impact Barred Sand Bass to a lesser extent due to the fishery targeting large, mature individuals on spawning aggregations (Bellquist et al. 2017). Upon examination of Barred Sand Bass data from 2004–2012 (**Table 3**), we see that, despite a 12-inch MSL regulation, most fish caught were already above 13 inches (330mm). Intuitively, a new 14-inch MSL would be expected to have less of a net effect on Barred Sand Bass than for Kelp Bass. We also find that 95% selectivity increased less for Barred Sand Bass than for Kelp Bass, as did the difference in modal lengths (**Figure 5**), which support the idea the new MSL had a lesser effect for Barred Sand Bass. However, established selectivity resulting from the new 14-inch MSL is more similar to a 15-inch MSL (381mm) than to a 14-inch MSL. The elevation of selectivity above the MSL may be a combination of hyperstability in the spawning aggregations, resulting in an increased proportion of larger fish in the sample, and recruitment failure, leading to the absence of smaller fish. The culmination of previous studies suggests that exploitation from the aggregation-based Barred Sand Bass fishery and poor recruitment events led to decreased resilience and a decline in the fishery (Bellquist et al. 2017; Erisman et al. 2011; Jarvis et al. 2014; Miller and Erisman 2014). Environmental influence likely plays a significant role in recruitment, as other studies suggest a regional decline in coastal species, including non-targeted species, during the past several decades due to changing environmental conditions (Brooks et al. 2002; Dotson and Charter 2003; Miller and McGowan 2013; Sweetnam 2010). In this case, the increase in MSL was likely not effective at quickly increasing spawning potential to more sustainable levels, especially when the stock was already depleted, and aggregations had disappeared. For Kelp Bass, a 2-inch increase in the MSL led to a net increase in median SPR by

0.074, and the increase in MSL was expected to impact Barred Sand Bass even less. For a stock in peril, that may be too little too late. LBSPR estimates spawning potential at equilibrium state, so an increase in SPR may take many years to materialize, or even longer when a stock is at low abundance. Our analysis suggests that equilibrium Kelp Bass spawning potential was moderately protected against recruitment overfishing under a 12-inch MSL. Although the population had declined over several decades, the implementation of a 14-inch MSL was an improvement over the 12-inch MSL, and the population was able to recover quickly towards a higher equilibrium state. Our results also show that using length-based approaches for aggregating species, particularly those that are targeted during spawning aggregations, can produce erroneous results that would misinform fisheries managers in the absence of catch data and known reproductive strategies. While MSLs for aggregation-based fisheries are not inherently flawed, empirical evidence suggests they may offer a false sense of security when complex spawning dynamics and density-dependence are not well understood. Aggregating species also subject to high recruitment variability may require more even conservative levels of spawning potential to endure multi-year periods of poor recruitment.

LBSPR is sensitive to misspecifications in life history parameters. Although our methods incorporate a range of potential life history parameters, misspecification can result in largely biased estimates. A recent study suggests that functional maturity may occur at lengths 15% larger than biological maturity obtained from histologic studies, potentially causing large overestimations of spawning potential (Prince et al. 2022). The lack of Barred Sand Bass at lengths equivalent to the MSL, even at a 12-inch size limit, could suggest that functional maturity at spawning aggregations begins later than previously thought. The quick recovery of Kelp Bass after the implementation of an increased MSL may suggest that Kelp Bass were suffering from recruitment overfishing during their decline. Our analysis suggests that overfishing was more likely if the life history inputs differ from parameters specified in life-history studies. For example, a lower M/K ratio near 1.5 would yield a much lower equilibrium SPR, as would an increased ratio of length at maturity to asymptotic length.

LBSPR is an equilibrium-based model that assumes constant fishing pressure and does not account for temporal variability. Kelp Bass and Barred Sand Bass, among other recreational fisheries, are highly seasonal, with peak fishing pressure occurring during the spawning season. Functionally, SPR also varies with varying fishing pressure (Hordyk et al. 2016), with SPR decreasing during high fishing pressure and increasing when fishing pressure relaxes. However, LBSPR estimates an average fishing pressure and SPR across all seasons. Since spawning potential is only biologically relevant during spawning seasons, failing to include temporal variability in fishing pressure will elevate the estimated SPR above the biologically relevant SPR. The sensitivity to temporal variability in fishing pressure has not yet been investigated. **Figures 7–8** show high fishing pressure on simulated 12-inch and 14-inch MSLs for both species of *Paralabrax*. SPR is more resilient to high fishing pressure under the increased size limit because more spawning potential is protected before individuals become available to the fishery. Under a 12-inch MSL, both species are more likely to have been overfished under high levels of fishing pressure more akin to exploitation during the spawning season.

Table 7: Summary of LBSPR stock performance evaluations, with rankings of confidence in the LBSPR estimates for each assessment. We use performance here to mean the performance of existing regulations in meeting a generally accepted SPR-based target reference point.



Species	Model Confidence	Management Performance
Kelp Bass: 12-Inch MSL (2004–2012)	Moderate	Moderate
Kelp Bass: 14-Inch MSL (2013–2021)	Moderate	High
Barred Sand Bass: 12-Inch MSL (2004–2012)	Very Low	NA
Barred Sand Bass: 14-Inch MSL (2013–2021)	Very Low	NA
Ocean Whitefish	High	Poor
Pacific Barracuda	High	High
Olive Rockfish	Moderate–Low	Moderate

4.3 *Caulolatilus princeps* (Ocean Whitefish)

Our results show that Ocean Whitefish likely have very low spawning potential and a high possibility of recruitment overfishing. Despite low resolution life history data, almost all possible combinations of life history parameters result in SPR levels well below the depletion threshold (**Figures 3–4**). Simply, this is because the catch is composed of mainly immature individuals. LBSPR assumes the absence of mature individuals is due to fishing pressure. There is no evidence to suggest that Ocean Whitefish move out of the range of the fishery upon reaching maturity, so this assumption remains valid. The consistency in our estimates gives us high confidence in our evaluation. **Table 7** presents an evaluation of stock performance and associated confidence in our assessment. Our simulations suggest that a MSL would need to be set at 18 inches, approximately the size at maturity, in order to improve spawning potential and yield at current levels of fishing pressure.

Ocean Whitefish have a long history of exploitation in southern California and were an important food source for indigenous groups residing within the Channel Islands (Fitch et al. 1971). In the past, Ocean Whitefish were poorly regarded by recreational anglers and even considered an underutilized resource (Ally et al. 1991; Fitch et al. 1971; Leet et al. 1992). As early as 1965, catches began to increase due to a decline in more desirable species (Ally et al. 1991). Subsequent declines were seen beginning in 1986 (Ally et al. 1991). Although they continue to be an important species among recreational anglers, Ocean Whitefish have never been managed with a MSL. This lack of management attention can be partly attributed to a study which found that ocean whitefish in southern California are recruited from central and northern Baja (Moser et al. 1986). As such, it is believed that Ocean Whitefish in southern California do not successfully spawn (California Department of Fish and Wildlife 2019; Moser et al. 1986). However, some evidence does exist for successful recruitment during warm water years, and newly settled juveniles are common despite the absence of larvae found in surveys (Bellquist et al. 2008). Many questions remain regarding Ocean Whitefish reproduction. Our findings suggest that, if they are able to spawn, they are rarely given the opportunity to do so. Although sporadic recruitment may be characteristic for this species, a history of persistent overfishing has impacted long-term fishery sustainability.

4.4 *Sphyraena argentea* (Pacific Barracuda)

Our results suggest that the Pacific Barracuda are maintained at high levels of spawning potential and have a low likelihood of recruitment overfishing. Although uncertainty is substantial, nearly all combinations of possible life history parameters result in SPR levels well above the target (**Figures 3–4**). We therefore have a high level of confidence in our evaluation.

Table 7 presents an evaluation of stock performance and associated confidence in our assessment. Selectivity within the fishery is not knife-edge at the MSL. If the fishery did shift to a knife-edge pattern, the current 28-inch MSL would still be more than adequate. Rather than an increased MSL scenario, we evaluated a decreased MSL due to the high SPR achieved by the current size limit. A 26-inch MSL at knife-edge selectivity is still likely to maintain SPR near target levels; however, a trend in relative yield is unclear and a substantial portion of the SPR density decreases into the moderate range.

Pacific Barracuda are a coastal pelagic species most commonly occurring from Baja California to southern California (Leet et al. 1992; Pinkas 1966). Evident by a significant correlation between catch in southern California and water temperature, individuals are thought to be from one population that migrates northward during periods of warm water (Pinkas 1966). Pacific Barracuda faced a history of intense fishing pressure, initially as a commercial fishery which shifted to a recreational fishery following World War II (Bottinelli and Allen 2007; Pinkas 1966). Various size limits have been used throughout the history of this fishery; an 18-inch MSL beginning in 1915, a 3-pound MSL beginning in 1918, a 28-inch MSL (with some retention of fish below the MSL allowed) beginning in 1949, and the current 28-inch total length MSL (with no undersized retention allowed) beginning in 1971 (Ally et al. 1991; Pinkas 1966). Since the Pacific Barracuda stock is coastally migratory, all size classes are not continually available to the US fishery, and selectivity is biased towards larger fish. We attribute the non-knife-edge selectivity seen in this fishery to the migratory life-history rather than to hyperstability. This assessment does not take the Mexican fishery into account and is unlikely to represent the health of the entire stock. Rather, it should be seen as an evaluation of California Department of Fish and Wildlife's MSL in its goal to reduce the likelihood of recruitment overfishing and maximize yield, primarily in southern California. Although management policies may have less population-wide effects due US-Mexico stock dynamics, the current 28-inch MSL serves its purpose in protecting ample spawning potential and reducing the likelihood of overfishing (Leet et al. 1992; Pinkas 1966).

4.5 *Sebastes serranoides* (Olive Rockfish)

Although the median estimate of SPR suggests good performance, there is considerable uncertainty surrounding this evaluation. The probability density (**Figures 3–4**) is relatively constant throughout the entire moderate performance range between 20% SPR and 40% SPR, so a single value is ineffective at communicating maximum likelihood. The median estimates of SPR (**Table 6)** are biased due to high uncertainty; a visual inspection of the density distribution is more informative. Median relative yield is also heavily biased, so little weight should be placed on that metric here. Estimates are highly dependent on the input life history parameters, so even small misspecifications result in vastly different outcomes. This can be attributed to sexual dimorphism and the lack of gender specificity in the data. Due to the high uncertainty, we have moderate to low confidence in our assessment. The lack of a defined mode makes evaluation difficult. Under current management, the highest density is seen between SPR values of 0.20 and 0.42, indicating moderate performance is most likely. **Table 7** presents an evaluation of stock performance and associated confidence in our assessment. Performance improves at a 14–16-inch MSL, roughly the size at maturity; a 12-inch MSL offers virtually no improvement. Uncertainty throughout the MSL simulations remains very high, and any MSL would need to consider post-release mortality below a theoretical MSL. Nonetheless, these estimates may suggest that moderate levels of SPR are conserved, even without a MSL. Further evaluation of other rockfish species in California is warranted given historical overfishing, vulnerable life history characteristics, and a complex history of diverse management tools.

Previous studies suggest that Olive Rockfish are vulnerable to overfishing (Ally et al. 1991; Leet et al. 1992; Love 1980). Indicators of catch decline were seen as early as 1978, and mature individuals are frequently absent in catch distributions (Ally et al. 1991; Love 1980). As with other *Sebastes* species, Olive Rockfish have a low M/K ratio and are vulnerable to overfishing (Clark 2002; Prince et al. 2015). Less resilient species may require higher levels of spawning potential to achieve performance objectives (Clark 2002). The size dimorphism in Olive Rockfish complicates our results and potentially hides indications of recruitment overfishing seen in previous studies. For species that exhibit sexual dimorphism, sex-specific data are required for better model performance.

4.6 Catch and Release Mortality

Catch-and-release mortality has been clearly shown to have negative population-level effects, even at relatively low rates of release mortality (Coggins Jr et al. 2007; Muoneke and Childress 1994; Prince and Hordyk 2019; Schroeder and Love 2002). While catch-and-release mortality is not evaluated here, MSLs should not be established without considering its potential effects, as establishing or increasing a MSL may lead to increased discarding. Catch-and-release mortality may be preventing management from establishing MSLs for species susceptible to barotrauma, such as *Sebastes*. Under normal conditions, barotrauma may make release mortality nearly guaranteed. However, studies show that descending devices significantly increase post-release survival (Bellquist et al. 2019; Dick 2017; Jarvis and Lowe 2008; Wegner et al. 2021). Use of descending devices is already mandated in Alaska, British Columbia, Washington, and

Oregon with successful results, but recreational use in California is still voluntary, although several studies have been published quantifying post-release mortality linked to barotrauma in several California rockfish species (Bellquist et al. 2019; Jarvis and Lowe 2008; Wegner et al. 2021). Mandatory use of descending devices in California may make MSLs for these species more feasible.

5. Conclusion

Our study validates the use of our size limit methodology with LBSPR, when applied properly, as a process of evaluating the impact of adapted MSLs. When limited resources are available, LBSPR has utility for data-limited recreational fisheries to evaluate current and potential MSLs. We provide valuable insight on the performance of 5 unassessed yet recreationally important fishery stocks in California. We identify situations where LBSPR can be successfully applied and where it fails, reiterating the significance of model assumptions and the critical importance of considering life history characteristics (e.g., species reproductive strategies and/or sex-dependent growth) and catch histories when relying on length-based approaches. Failing to understand model assumptions may produce erroneous results that can be easily misunderstood, for example, hyperstability in Barred Sand Bass and temporally variable fishing pressure in both species of *Paralabrax*.

Recreational fisheries have a diverse suite of management tools, with size selectivity through MSLs representing a simple, transparent, and effective tool that fisheries stakeholders are already familiar with, and for which fisheries managers already have an implementation process. In addition, fishing communities generally support the idea of allowing a species to spawn before being caught, so MSLs are generally less contentious than other management tools, such as marine protected areas. Our study reiterates the findings of previous studies (Hordyk et al. 2017; Prince and Hordyk 2019). When not used, MSLs set appropriately above size at maturity can conserve sufficient levels of spawning potential. When MSLs are already in use, small changes in the MSL can optimize performance; however, they are unlikely to quickly yield the substantial increases in spawning potential required when a stock is significantly depleted. Large changes in selectivity are needed when a stock has collapsed, or other management tools, such as spawning season restrictions, must be utilized to reduce fishing pressure.

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Appendix

Table 8A: Input life history parameters, along with respective source and description, for each species. Bolded values indicate the parameter inputs used in the model.

Species	**L_{inf}**	**L_{50}**	**L_{95}**	**M**	**K**	**M/K**	**Units**
Paralabrax clathratus (Kelp Bass)	**698** (TL, sexes pooled by author) (Love et al. 1996)	226 (TL, females) 220 (TL, males) **223** (TL, mean of sexes) (Love et al. 1996)	240.1 (TL, females) 236.3 (TL, males) **238.2** (TL, mean of sexes) (Love et al. 1996)	5.4/Age$_{MAX}$ (Hamel and Cope 2022) Age$_{MAX}$ = 34 (Love et al. 1996) 5.4/34 =**.1588**	**.06** (TL, sexes pooled by author) (Love et al. 1996)	**2.647**	mm
Paralabrax nebulifer (Barred Sand Bass)	**606** (TL, sexes pooled by author) (Walker et al. 2020)	239 (TL, females) 219 (TL, males) **229** (TL, mean of sexes) (Love et al. 1996)	251.1 (TL, females) 231.6 (TL, males) **241.35** (TL, mean of sexes) (Love et al. 1996)	5.4/Age$_{MAX}$ (Hamel and Cope 2022) Age$_{MAX}$ = 25 (Love et al. 1996) 5.4/25 = **.216**	**.09** (TL, sexes pooled by author) (Walker et al. 2020)	**2.400**	mm
Caulolatilus princeps (Ocean Whitefish)	784.56 (TL, males) 772.92 (TL, females) **779** (TL, mean of sexes) (Cooksey 1980)	472* (TL, males) 388* (TL, females) **430*** (TL, mean of sexes) (Cooksey 1980) *Rough Estimate	558* (TL, males) 468* (TL, females) **513*** (TL, mean of sexes) (Cooksey 1980) *Rough Estimate	5.4/Age$_{MAX}$ (Hamel and Cope 2022) Age$_{MAX}$ = 13 (Love 2011) 5.4/13=**.4154**	.234 (TL, males) .231 (TL, females) **.2325** (TL, mean of both sexes) (Cooksey 1980)	**1.787**	mm
Sphyraena argentea (Pacific Barracuda)	**902.1** (TL, sex unclear) (Bottinelli and Allen 2007)	490 (TL, females) 440 (TL, males) **465** (TL, mean of sexes) (Walford 1931)	540 (TL, females) 490 (TL, males) **515** (TL, mean of sexes) (Walford 1931)	5.4/Age$_{MAX}$ (Hamel and Cope 2022) Age$_{MAX}$ = 18 (Bottinelli and Allen 2007) 5.4/18=**.3**	**.2457** (TL, sex unclear) (Bottinelli and Allen 2007)	**1.221**	mm
Sebastes serranoides (Olive Rockfish)	539 (TL, females) 440 (TL, males) **489.5** (TL, mean of sexes) (Lea et al. 1999)	350 (TL, females) 330 (TL, males) **340** (TL, mean of sexes) (Echeverria 1987)	390 (TL, females) 380 (TL, males) **385** (TL, mean of sexes) (Echeverria 1987)	5.4/Age$_{MAX}$ (Hamel and Cope 2022) Age$_{MAX}$ = 30 (Love 2011) 5.4/30 = **.18** (females)	**.1667** (TL, females) .2610 (TL, males) (Lea et al. 1999)	**1.08**	mm

Table 9A: Length conversion equations and respective sources.

Species	Conversion Equation	Source
Paralabrax clathratus (Kelp Bass)	TL (cm) = FL*1.01 + .83	(Love et al. 1996)
Paralabrax nebulifer (Barred Sand Bass)	TL (cm) = FL*1.05 + .46	(Love et al. 1996)
Caulolatilus princeps (Ocean Whitefish)	TL (mm) = -10.16473 + 1.07437*FL	Present Study
Sphyraena argentea (Pacific Barracuda)	TL (mm) = 1.077*FL	(Binohlan et al. 2011)
Sebastes serranoides (Olive Rockfish)	TL (mm) = FL*1.029 + 1.419	(Echeverria and Lenarz 1984)

Table 10A: Parameters for the covariance matrix in the multivariate random normal distribution.

CV L_{inf}	CV M/K	Correlation L_{inf}–M/K
0.1	0.2	0.2

Table 11A: Sample size of CRFS length frequency data for each species.

Species	Sample Size
***Paralabrax clathratus* (Kelp Bass) 2004–2012**	37,463
***Paralabrax clathratus* (Kelp Bass) 2013–2021**	13,219
***Paralabrax nebulifer* (Barred Sand Bass) 2004–2012**	45,264
***Paralabrax nebulifer* (Barred Sand Bass) 2013–2021**	8,347
***Caulolatilus princeps* (Ocean Whitefish)**	30,625
***Sphyraena argentea* (Pacific Barracuda)**	13,807
***Sebastes serranoides* (Olive Rockfish)**	37,396

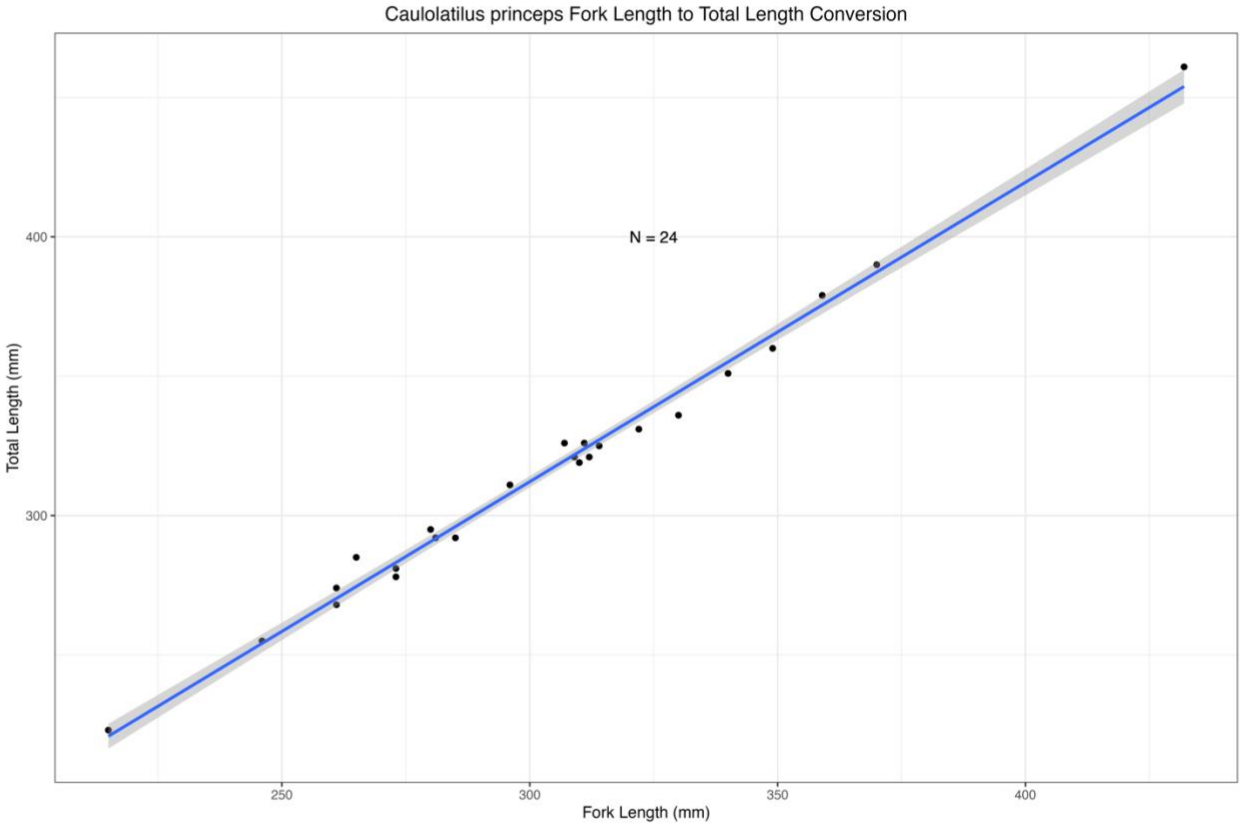

Figure 9A: The linear regression of total length against fork length for Ocean Whitefish. 95% confidence is highlighted in grey. The resulting equation was used to convert fork lengths to total lengths.

TL = -10.16473+1.0743*FL

R^2 = .9908

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