Extending MSE to Evaluate Bag Limit Regulations

Application to California Halibut

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Executive Summary

Bag limits are one of several regulations that limit fishery exploitation of recreational fisheries in California state fisheries. Since 1996 a bag limit of 5 fish per angler per trip has been implemented in the southern management area (south of Point Sur). From 1996-2023 the bag limit for the northern management area was 3 fish per angler per trip. The expected efficacy of these approaches in terms of achieving sustainable yields and meeting biological conservation objectives is not well understood. CDFW is seeking to implement management strategy evaluation (MSE) to better inform regulation of fisheries including bag limits in the recreational fishery for halibut. This project aims to characterize the impact of bag limits on release rates using empirical data, and then codify these bag limit models inside the openMSE framework for testing of current and candidate bag limit regulations.

Data collected by the California Recreational Fisheries Survey (CRFS) and those originating from submitted angler logbooks were analyzed to quantify the relationship between observed catch rate and release rate. Only those data originating from the northern management area exhibited an apparent relationship between catch rate and release rate. Three independent sources of data CRFS party/charter (PC), CRFS private rental (PR) and logbook party/charter, provided broadly comparable relationships in release rate with catch rate. Fits to the individual data sources (3) were used to develop three bag limit models in order to capture bag limit model uncertainty.

The 2020 stock assessment for northern California halibut was converted to a ‘Base Case’ OpenMSE operating model. Since this model estimated very high recent abundance levels, a second ‘Depleted’ operating model was specified at a stock depletion level closer to those consistent with maximum sustainable yield. The simulated vulnerable biomass of the recreational fleet was calibrated to generate simulated recreational catch rates in closed-loop. Given these simulated catch rates as an input, the bag limit models predicted the corresponding discard (release) rate. The operating models were used to project various alternative bag limits and compare these to other regulations such as minimum size limits and effort controls.

Principal results and conclusions:

- Management Performance outcomes are relatively insensitive to alternative bag limits
- bag limits do not effectively reduce exploitation rate at low stock sizes and imply a harvest control rule that contrasts with conventional approaches.
- Effort control (e.g. access, number of vessel-days) is likely to be a superior basis for managing exploitation, providing higher yields for the same conservation performance.
- The current size limit of 55cm is well suited to maximizing yield at an intermediate level of biological risk.
- Projecting management outcomes for both the Base Case and Depleted operating models, suggests there is a relatively low risk of biomass dropping below MSY levels given current management regulations.

Documents and code are available from the project splash page: https://blue-matter.github.io/CaliBL/

1. Introduction

a. Background

Bag limits are used widely in the management of recreational fisheries throughout the world. Usually expressed as a maximum number of fish that can be retained on a daily trip for an individual angler, bag limits essentially set a maximum retained catch rate, reducing the potential for high catches by skilled fisheries, and/or those operating in times or locations of relatively high biomass. In this way, bag limits are a hybrid of output control (catches) and input control (effective effort) that are expected to limit exploitation most strongly at high stock sizes (higher catch rates).

Compared with size limits (Homans and Ruliffson 1999; Moreau & Matthias 2018) and the broader investigation of fishery management procedures that dynamically adjust catch limits (Punt et al. 2016, Carruthers et al. 2019), the efficacy of bag limits has not been investigated extensively. In general, there has been a greater focus on either theoretical modeling of economic aspects (e.g., Woodward and Griffin 2003; Scrogin et al. 2004) or compliance (e.g., Wilberg 2009, Holzer and McConnell 2017) and less attention on developing theoretical frameworks to predict the impact of alternative bag limit policies on fishery population dynamics.

Early work evaluating the impacts of bag limits on exploited populations assumed relatively simple models for population dynamics (e.g., Porch and Fox, 1990). When bag limit regulations have been evaluated in theoretical models of fishery and population dynamics, they have been found to be largely ineffectual in limiting exploitation (Cox et al. 2002). Current management decision tools are largely limited to simple arithmetic approaches such as The U.S. National Oceanic and Atmospheric Administration's bag limit calculator (NOAA 2022). Such tools do not examine the interaction between policies and stock dynamics and they can not evaluate dynamic bag limit regulations that respond to updated fishery data.

b. Bag limits for California recreational fisheries

The first laws impacting recreational fishing in California were enacted in the 1940s and bag limits were among these early laws, along with minimum size limits (Allen et al. 2006). Initially bag limits were created to minimize fish wastage, when anglers retained more than they could use, and were not based in biological understanding of sustainable catch limits (Miller and Gotshall 1964). Since then, both single species and multi-species bag limits have been widely implemented in California but the biological underpinnings of these limits remains understudied. A minimum size limit and bag limit were both implemented as the first regulations on recreational California halibut in 1971. That bag limit of three and five fish north and south of Point Sur, respectively, was unchanged until 2023 when the northern limit was reduced to two fish under an emergency, temporary rule change. The change was initially prompted by a salmon fishery closure and other restrictions to groundfish leading to concern that anglers might shift an unsustainable amount of effort to California halibut. This new limit is anticipated to become permanent in 2024 and there is a need to evaluate a potential change to the southern management area as well. The role of these bag limits in controlling exploitation and meeting conservation objectives has not been evaluated.

This analysis is based on the following trip-level data sets: logbook data from the party/charter (PC, aka CPFV) fleet; survey (CRFS) data from the PC and private/rental (PR) fleets.

c. Management Strategy Evaluation

Arguably the most coherent approach to evaluating current and candidate management strategies (data, assessment, harvest control rules, regulations and enforcement) is to test these dynamically within simulations that represent a plausible range of fishery and population dynamics. This approach, referred to as closed-loop simulation lies at the heart of Management Strategy Evaluation (MSE) - a participatory process to establish the robustness of candidate management approaches to prevailing uncertainties to evaluate management performance and performance tradeoffs (Punt et al. 2016). A central objective of this research is to develop bag limit models that can predict recreational fisheries release rate (discarding) and implement these within the open-source MSE framework OpenMSE (Hordyk et al. 2024). OpenMSE is used widely in the testing of fisheries management procedures and was the framework used by CDFW for establishing a management procedure for San Francisco Bay herring and for testing data-limited approaches for near shore state fisheries.

d. Research questions

This work establishes a theory of bag limits impact on release rates and the first to evaluate their comparative efficacy by closed-loop simulation.

Core research questions include:

- Do empirical data suggest that bag limits are consequential for the management of California halibut?
- Can theoretical models be developed that can approximate the impact of bag limits on release rates?
- Are bag limits an effective management measure for California halibut?
- How do bag limits compare to other management regulations in terms of their expected management performance outcomes?

2. Methods

a. Data sources

Data collected by the California Recreational Fisheries Survey (CRFS) and those originating from submitted angler logbooks were analyzed to quantify the relationship between observed catch rate and release rate (Table 1).

Table 1. Data sources used to develop bag limit models

Program	**Vessel Type**	**Description**
Log book	Party / charter (1980 - 2023)	'LB_PC' Commercial passenger fishing vessels (CPFVs) are vessels licensed by CDFW to take paying passengers on sport fishing trips. These vessels are also commonly known as party/charter (PC) boats. The owner of the boat is required by law to obtain an annual CPFV license from CDFW and is required by law to submit records of fishing activity (i.e., logs). CDFW is required to keep all license and fishing activity records confidential but may compile or publish summaries that do not disclose individual or business information. Logs are submitted for each fishing trip (or each day of fishing for multi day trips) and collects information including but not limited to vessel, date of fishing, port of landing, target species, fishing method, hours fished, number of fishers, and number of fish kept and released by species.
California Recreational Fisheries Survey	Party / charter (2016 - 2023)	'CRFS_PC' The California Recreational Fisheries Survey (CRFS) provides catch and effort estimates for California's marine recreational finfish fisheries. CRFS collects data on four major fishing modes including PC boats. PC effort estimates are derived from a combination of CPFV logs and a dockside effort check survey conducted at CPFV landings that results in an estimated compliance proportion (i.e., the fraction of the confirmed fishing trips from the effort check survey with a submitted CPFV log). An independent on-site, intercept survey is used to collect data on catch for catch rate calculations. The intercept survey is conducted either onboard CPFVs at sea or dockside at the end of the fishing trip. The effort and catch rate estimates are combined to produce estimates of total catch. The CRFS Methods Document provides a general overview of CRFS and information about sampling design, survey methods, key data elements collected and estimation procedures for the PC mode. Detailed sampling procedures are available in the CRFS Sampler Manual.
	Private / rental (2013 - 2023)	'CRFS_PR' The CRFS provides catch and effort estimates for California's marine recreational finfish fisheries. CRFS collects data on four major fishing modes including PR boats. Two statewide field surveys, augmented by an

		offsite survey for effort, collect data which enable estimation of both effort and catch for all PR boat trips in California's marine recreational fisheries. The field surveys cover effort and catch for PR boats returning to public access sites during daylight hours (PAD). Public-access sites are those sites that are accessible to the general public and can be either publicly or privately owned. Private-access sites are not accessible to the general public and include publicly and privately owned marinas and moorings and facilities at private residences. Effort for those trips is estimated by use of data from an offsite survey since it is neither economic nor logistically feasible to conduct field surveys which would intercept returning anglers at private-access sites or at night (PAN). The catch rates from the field surveys are used as the estimates of catch rates for PAN trips. The CRFS PAD and PAN estimates together yield overall estimates of effort and catch for PR boats. The CRFS Methods Document provides a general overview of CRFS and information about sampling design, survey methods, key data elements collected and estimation procedures for the PR mode. Detailed sampling procedures are available in the CRFS Sampler Manual.

b. Data processing

Trip-level data for the various sources were provided with spatial information regarding the port or origin of fishing vessels. Ports were used to assign northern and southern management areas defined as those trips originating from ports north/south of Point Sur, and it was assumed that boats did not traverse management areas. Trip level catch rates were calculated as the sum of retained and released fish divided by the number of operators (anglers) on the vessel. This assumes that anglers may share all landed fish among their individual bag limits.

c. Data properties

The data originating from the northern and southern management areas exhibit a number of key differences: the catch rates of the northern area are generally much higher than those of the southern area and the distribution of catch rates are much more consistent among data sources for the northern area (Figures 1 and 2). Patterns among data types are also inconsistent among areas. While in the northern area, the log book party/charter trips record relatively high catch rates compared to those of the CRFS private rental boats, they record lower catch rates in the southern area.

Only those data originating from the northern management area exhibited an apparent relationship between catch rate and release rate. Three independent sources of data CRFS party/charter, CRFS private rental and logbook party/charter, provided broadly comparable relationships in release rate with catch rate (Figure 3).

The distribution of trip-level catch rates (Figure 2) and the position of the mean catch rate relative to the bag limit, suggests that it would be relatively rare for anglers to reach their bag limit of 5-fish in the southern management area (Figure 3).

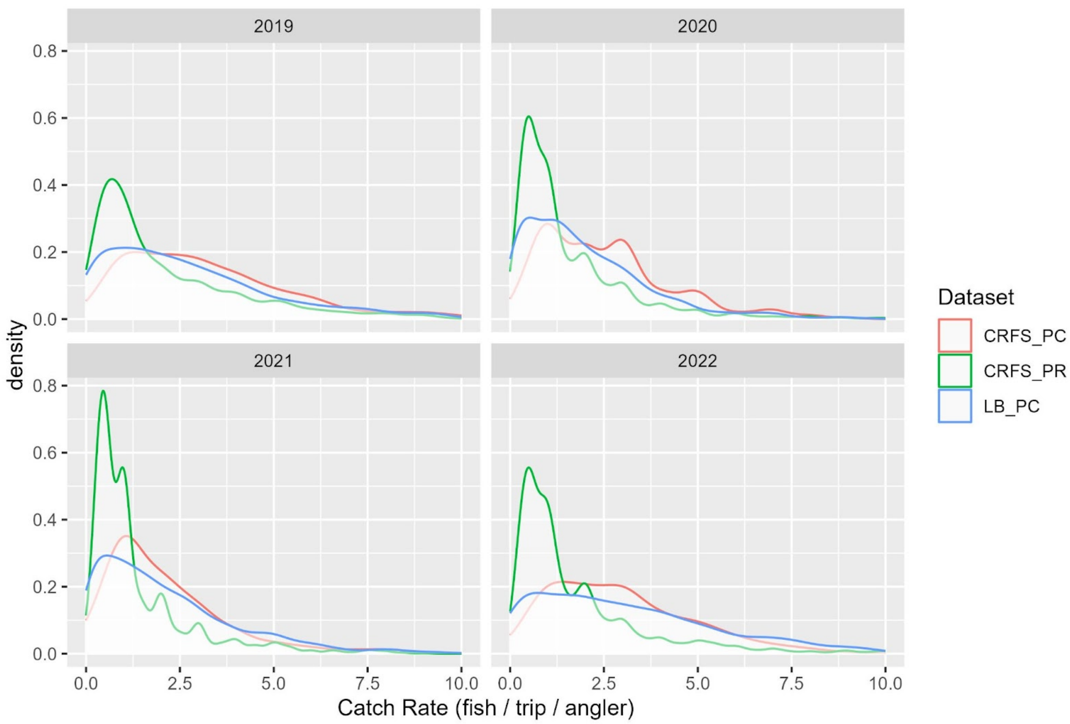

Figure 1. The distribution of catch rates in the northern management area (north of Point Sur). CRFS_PC and CRFS_PR refer to the California Recreational Fisheries Survey of party/charter and private rental boats, respectively. LB_PC refers to the log book data of the party/charter boats.

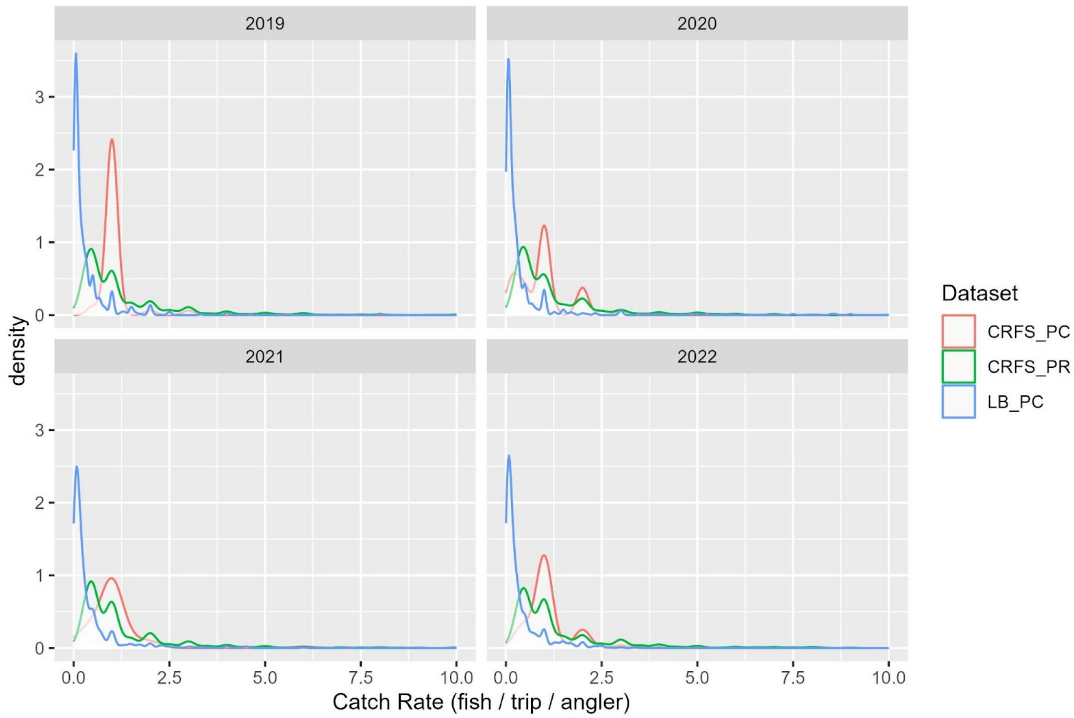

Figure 2. As Figure 1 but for the southern management area (south of Point Sur)

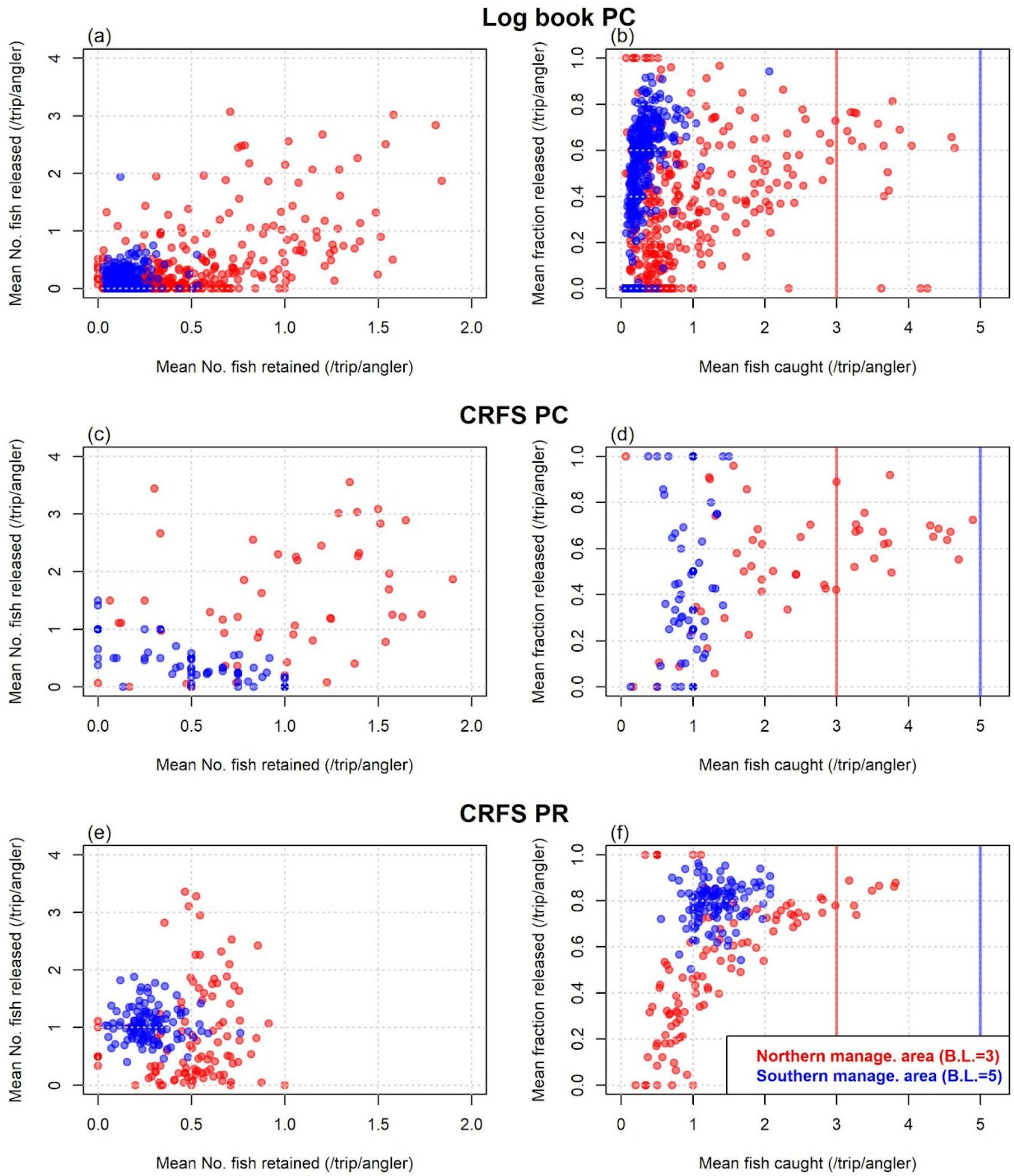

Figure 3. Monthly recreational angling data originating from three data sources: log book party/charter (PC), California Recreational Fisheries Survey (CRFS) and party/charter (PC) and CRFS private rental (PR). The right hand column of panels captures the core dynamics that bag limits models are attempting to characterize - the relationship between the angler catch rate (fish per angler per trip) and the fraction of fish that are released (release rate). The vertical lines represent the bag limits for the two management areas.

d. Bag Limit Models

Catch rate data are typically assumed to follow either binomial, negative binomial, Poisson (for discrete data) or log-normal distributions. Statistical distributions used elsewhere such as the binomial and negative binomial distributions (e.g., Porch and Fox 1990) very poorly approximated the observed distribution of catch rates (Figures 1 and 2) and were not considered further. A possible explanation for this may be that the data for this research are vessel-specific, not angler-specific and that the averaging of individual catch rates among multiple anglers on board vessels provides statistical properties more similar to a distribution of sample means, rather than individual samples. A number of Poisson and log-normal models were investigated to approximate the observed mean catch rate and mean release rate (Table 2). Here release rate refers to the proportion of caught fish by number that were released by number (sometimes referred to as 'potential catch', Lew and Larson 2014).

Table 2. Statistical models for predicting mean release rate (across all trips) from mean catch rate (across all trips). Models include two discrete Poisson models with and without a constant background release rate (Pois and PoisV, respectively), and five continuous lognormal distributions that: do not model background release rate (LN), include a constant background release rate (LNV), includes two parameters for background release rate for trips catching below/above 1 fish (LN2V), models background release rate as a linear relationship with mean catch rate (LNVS) and a similar approach with both intercept and slope in the relationship between background release rate and mean catch rate (LNVSI). Note that the numbers released (*r*) and retained (*k*) are calculated from the integral of the density and the catch rate. Since there is no closed-form solution to the integral of a normal distribution, integration was approximated numerically.

Code	Equation	Parameters
Discrete Poisson catch rate distribution		
	$r = 1 - k$ $k = \sum_{i=0}^{b}(1-V)\frac{e^{-\lambda}\lambda^{i}}{i!}$	r: release rate of fish. *k:* proportion of fish kept b: the bag limit (a discrete number of fish). λ: the mean (and assumed variance) of the observed catch rate distribution. μ: mean log catch rate. σ: log standard deviation. c: a vector *n* long of catch rate values from 1E-5 to 30. V: a vector of voluntary release rate at catch rate *c*. *n:* the size of the *c* and *V* vectors (1E5) V_0: constant voluntary release rate. V_1: the voluntary release rate of fishing trips with catch rates below 1 fish. V_2: the voluntary release rate of fishing trips with catch rates above 1 fish. α: slope in voluntary release rate with mean catch rate. β: intercept of voluntary release rate with catch rate.
Pois	$V = 0$	
PoisV	$V = V_0$	
Continuous log-normal catch rate distributions		
	$k = \frac{\sum_{i=1}^{B}(1-V_i)exp\left(-\frac{(ln(c_i)-\mu)^2}{2\sigma^2}\right)}{\sum_{i=1}^{n} exp\left(-\frac{(ln(c_i)-\mu)^2}{2\sigma^2}\right)}$	
LN	$V = 0$	
LNV	$V[1,2,\ldots n] = V_0$	
LN2V	$V[1,2,\ldots j] = V_1$ $V[j+1, j+2, \ldots n] = V_2$ where $c_j \leq 1$ and $c_{j+1} > 1$	
LNVS	$V_i = e^{\alpha c_i - 4}/(1+e^{\alpha c_i - 4})$	
LNVSI	$V_i = e^{\alpha c_i - \beta}/\left(1+e^{\alpha c_i - \beta}\right)$	

Several of the models include both releases due to the bag limit (the proportion of the predicted catch rate distribution above the bag limit) and also releases due to either a constant or changing background rate of background releases. For example, LNVS assumes a log-normal distribution of catch rates and a linearly increasing rate of background releases with mean observed catch rate (Figure 4).

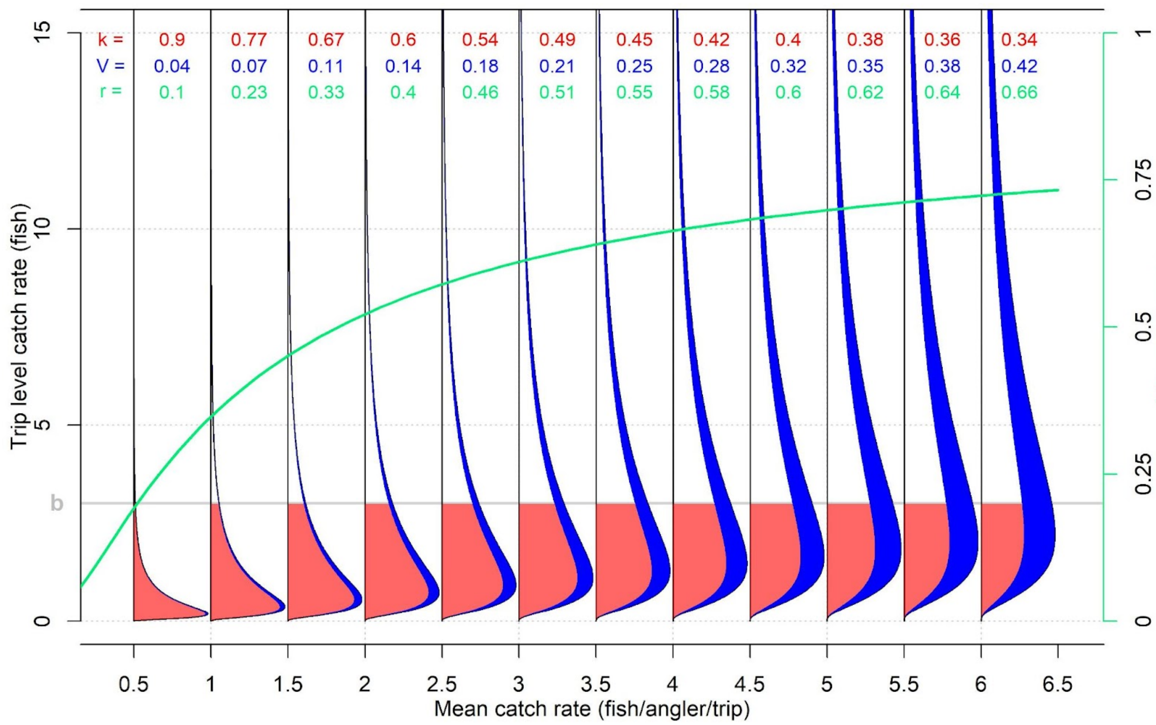

Figure 4. Components of the log-normal bag limit model LNVS that includes a linearly increasing background release rate (*V*, blue), the fraction of fish that are retained (*k*, red) and the release rate (*r*, green). Although the log-normal density is plotted here, the expected number of fish released and retained was calculated from the integral of the product of the density and the catch rate (i.e. based on expected numbers of fish retained and released, not the proportion of trips).

e. Fitting bag limit models to data

The bag limit models of Table 2 were fitted to northern management area data from the CRFS survey of private rental boats to provide an initial indication of which models should be pursued more formally via statistical fitting and model selection.

Based on the results of this initial study, four types of bag limit models (LNV, LN2V, LNVS, LNVSI, Table 2) were statistically fitted to data by minimizing a negative log likelihood (assuming a logistic-normal observation error model) of observed release rate given model predicted release rate. These fitted models were evaluated for patterns in residual error and overall fit to data, to identify a parsimonious model for incorporation in bag limit management procedures.

f. Accounting for uncertainty

Uncertainty in bag limit models was captured by (1) fitting multiple models of the same type (e.g. LNVS) to the various datasets (log book party/charter, CRFS party/charter, CRFS private rental) and, for each dataset (2) sampling model parameters from a bivariate normal distribution defined by the variance-covariance matrix (inverse Hessian) of the maximum likelihood model fit.

g. Operating models

To demonstrate the integration of the bag limit regulations into management procedures and the openMSE framework, the most recent assessment for the northern California stock was converted into an OpenMSE operating model (CDFW 2020) (Figure 5). The Stock Synthesis assessment was age-structured, sex-structured and fitted to catch, relative abundance indices and length composition data for five fleets: bottom trawl, gillnet, commercial handline, Commercial Passenger Fishing Vessels (CPFV) and 'Other recreational fishing'. The openMSE operating model exactly matched the maximum likelihood estimate of the stock assessment. The 'Base Case' stock assessment estimated a very healthy 2020 stock biomass that was above equilibrium unfished conditions (Figure 5) largely due to the estimation of a very strong 2016 year class (Figure 5, bottom left panel).

As the basis for providing management advice, the 2020 Base Case assessment did not pass peer-review. However, the Base Case model does accurately represent key dynamics of northern halibut for the purposes of investigating bag limits, such as longevity, somatic growth, recruitment variability and fishery selectivity. To better understand the properties of bag limit regulations at lower stock sizes where management decision making may be more critical, an alternative operating model ('Depleted') was specified with identical patterns in historical exploitation but with current stock depletion closer to MSY biomass levels.

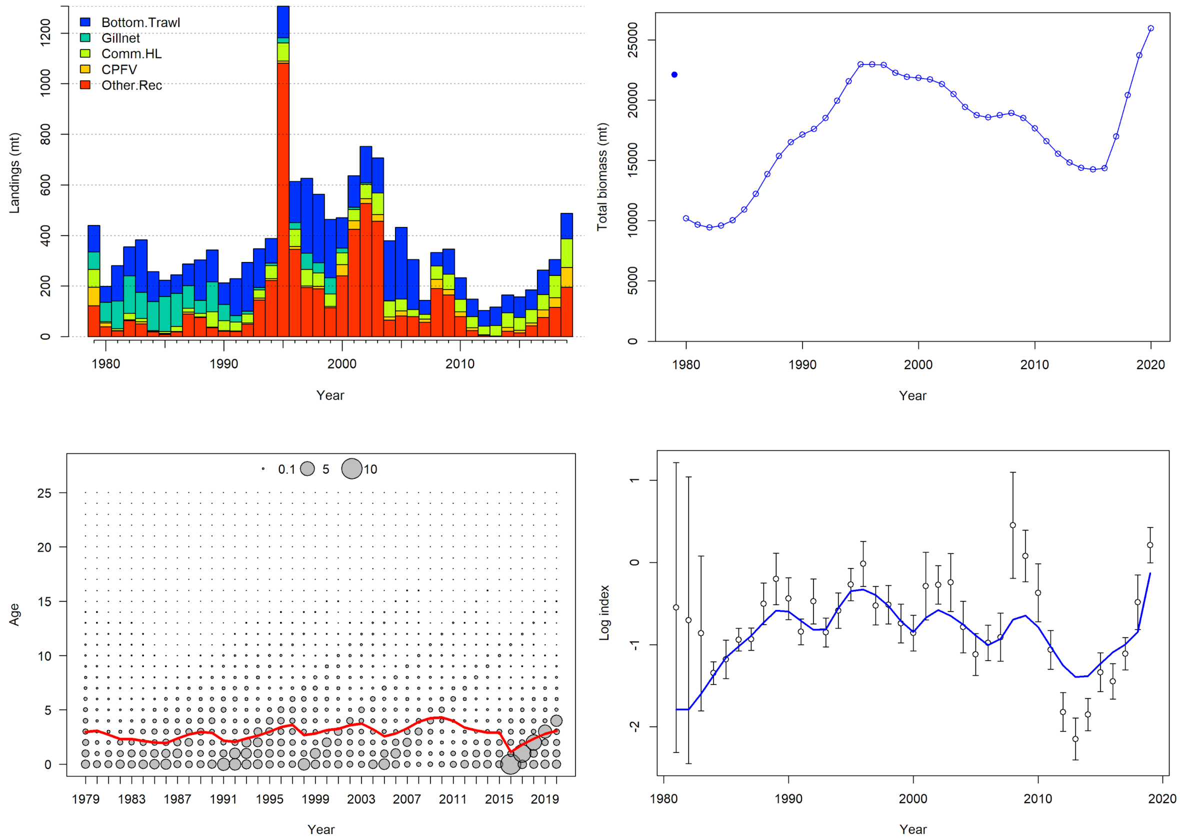

Figure 5. A selection of data and model estimates from the recent stock assessment for the northern California stock: catches by fleet (top left), maximum likelihood estimate (MLE) of total stock biomass (top right), MLE age structure (bottom left) and the MLE model fit (blue line) to the observed relative abundance index of the Commercial Passenger Fishing Vessel (CPFV) fleet (black points and bars) (bottom right). Note that total biomass in 2020 is estimated to be above equilibrium unfished conditions (the blue point plotted at 1979 on the top right panel).

h. Modeling bag limits in closed-loop MSE simulations

The operating model generates index (relative vulnerable biomass) observations for the Commercial Passenger Fishing Vessel (CPFV) fleet, subject to observation error and lag-1 autocorrelation in residual error (see fit to these data Figure 5). To simulate the true simulated catch rate of recreational fishing vessels (not observed catch rates) these data were simulated without observation error and autocorrelation. In this way, the simulated trend in vulnerable abundance was provided to the bag limit management procedures (MPs). Within the MPs, this trend was converted to a catch rate by calculating a calibration factor over the last 5 historical years of the operating model (2016-2020). This calibration factor was the ratio of observed mean recreational trip CPUE (2016-2020) to simulated vulnerable index (2016-2020).

Based on this true simulated catch rate, the bag limit models predict the corresponding release rate. Coupled with a specified post-release mortality rate (here assumed to be 5%) and a fraction of exploitation that can be assumed to be recreational (fraction of recent catches is around 60%), this release rate is submitted back to the operating model to update exploitation and population dynamics. In this way, a bag limit MP can be placed in closed-loop and alternative bag limits can be evaluated for their impact on the stock and fisheries in a dynamic MSE simulation, allowing for calculation of yield and biomass outcomes.

The default management procedure for conducting projections was that fitted to the CRFS private/rental data, assumed exploitation at FMSY (the rate of the most selected age class matches FMSY), a minimum size limit of 55 cm and a bag limit of 3 fish. The sensitivity of results to these various assumptions was evaluated.

3. Results

a. Empirical evaluation of the fraction of fish released due to reaching bag limits

The trip-level data for each data type were analyzed to quantify the theoretical expected fraction of released fish due to the bag limits of 3 fish in the northern area and 5 fish in the southern area. For trips where the total number of landed fish exceeded the bag limit, the difference (the theoretical number released) was recorded and summed by year and management area. In this way the theoretical fraction of releases due to the bag limit regulation could be calculated. The purpose of this analysis is to gain an intuition of how restrictive current regulations are at the level of the raw data.

Until 2010, log book data suggest that release rates in the northern area due to the bag limit would be expected to be close to zero for most years, with occasional years where release fractions could exceed 10%. After 2015, the theoretical release fractions in the northern area increases to between 20 and 30%, which is broadly consistent among log book and CRFS data sources (Figure 6, left hand panel). In contrast, logbook data for the southern area suggest that in theory there would be many fewer releases due to the bag limit, with two outlying estimates of 20% in 2018 and 2020 (Figure 6, right hand panel). There was also little consistency in the predicted release fraction amongst data types in the southern area: from 2012 - 2022, the theoretical releases of the CRFS private/rental vessels were around 10%, whereas the theoretical releases of the CRFS party/charter and log book party/charter vessels were generally less than 3% (Figure 6, right hand panel).

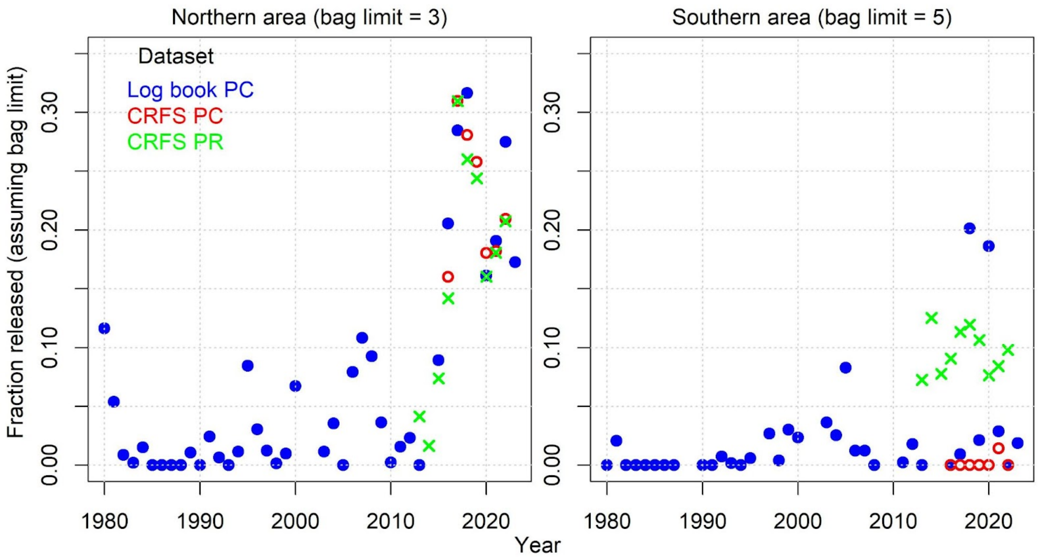

Figure 6. Empirical evaluation of theoretical release fraction given the specified bag limits only.

b. Approximating mean release rates based on mean catch rate: bag limit models

No clear relationship between mean catch rate and mean release rate was apparent for the data of the southern area and fitted models extrapolated well beyond the range of data (Figure 7, panels b and d, also shown in Figure 3).

For the northern area, the Poisson model (Pois) and lognormal models (LN) were not able to approximate relatively high release rates that were observed (grey and purple lines, respectively, Figure 7, panels a and c). To model higher release rates it was necessary to include a non-bag limit, background rate of releases, but in those cases the Poisson and log-normal models exhibit too flat a trend through the mean release rate data (red and blue lines, Figure 7). The background level of releases may include releases due to the minimum size limit (55 cm), high grading, or voluntary releases.

When added to the lognormal model, a constant release rate (LNV) produced higher release rates but these were again unable to approximate the observed increase in release rate as mean catch rates increase (blue line, Figure 7, panels a and c). To match the steep increases in release rate with increasing mean catch rates, it was necessary to model an increasing background release rate with mean catch rate.

The 3-parameter lognormal model that estimates background release rates for trip catches of below and above 1 fish (LN2V) provided a closer fit to the data (green line, Figure 7, panels a and c) but failed to capture data nearer the origin, providing negative residuals in model fit. To obtain a suitable approximation of the northern data, it was necessary to model background release rates as a linear function of mean catch rate (LNVS - no intercept, LNVSI - with intercept) (Figure 7, panels a and c). These bag limit models were further investigated for their ability to approximate relationships observed in the northern management area data for the party/charter data originating from log books and CRFS.

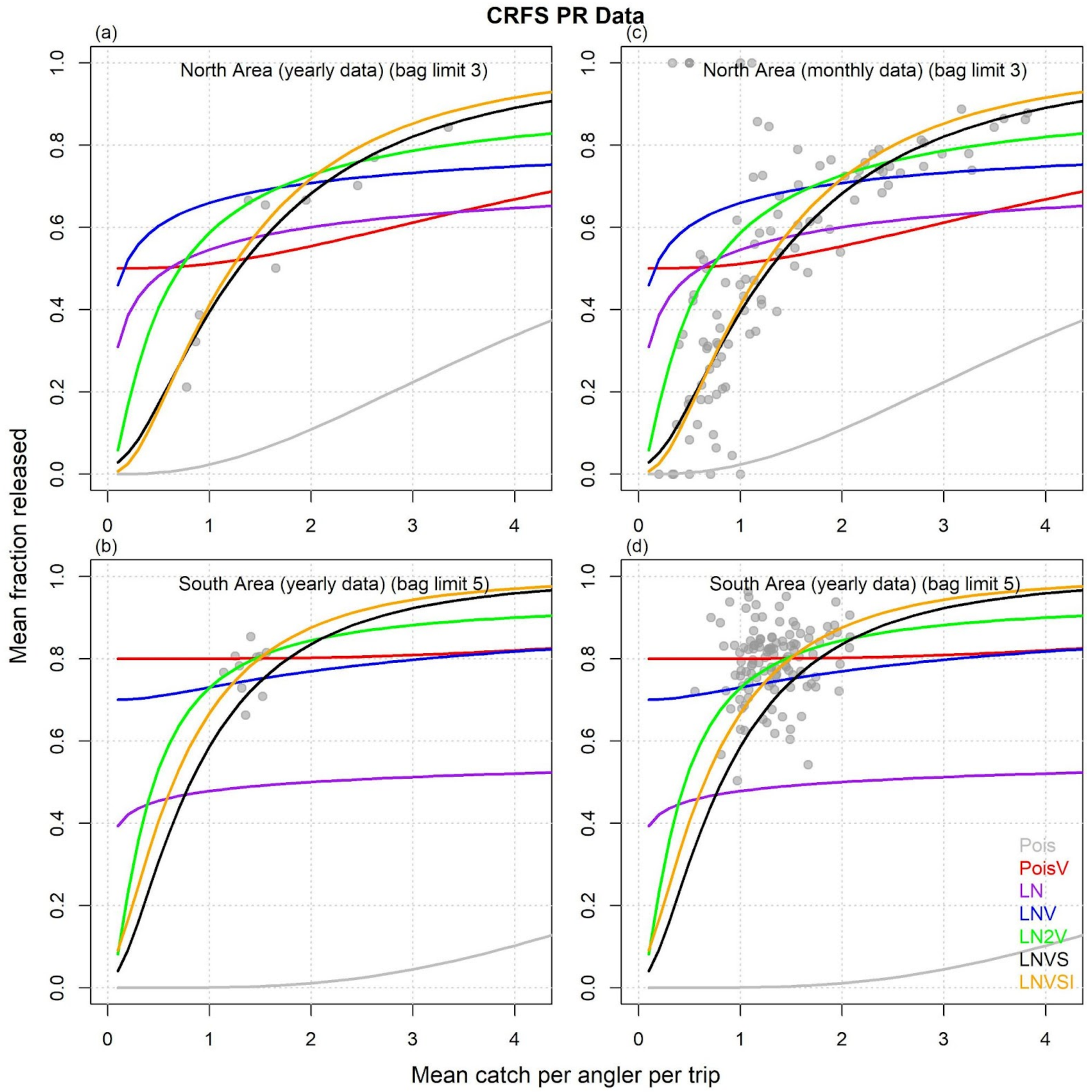

Figure 7. Exploration of model types for data from the California Recreational Fisheries Survey of private/rental vessels (2013 - 2023) for the northern and southern management areas (north / south of Point Sur).

c. Fitting bag limit models and selecting a parsimonious model

The four log normal bag limit models with background releases - that could approximate the patterns in mean catch rate and release rate for the northern data - were fitted to data using maximum likelihood estimation. The model with a constant background release rate failed to approximate the sharp increase in release rates at low catch rates for the CRFS private rental data (Figure 8, panel i). The model estimating two background release rates parameters for mean catch rates above and below 1 fish (LN2V), fitted the data much better, but achieved worse fit (nll = -53.02) to the CRFS private rental data compared with the LNVS model (nll = -53.02) and required the estimation of an additional parameter. Fits were comparable among the two models estimating a linear increase in background release rate with mean catch rate (LNVS, LNVSI) but the more complex model required estimation of an additional parameter for no appreciable improvement in model fit (Figure 8, bottom two rows). For these reasons the LNVS model (highlighted in blue in Figure 8) was selected for implementation in the bag limit models.

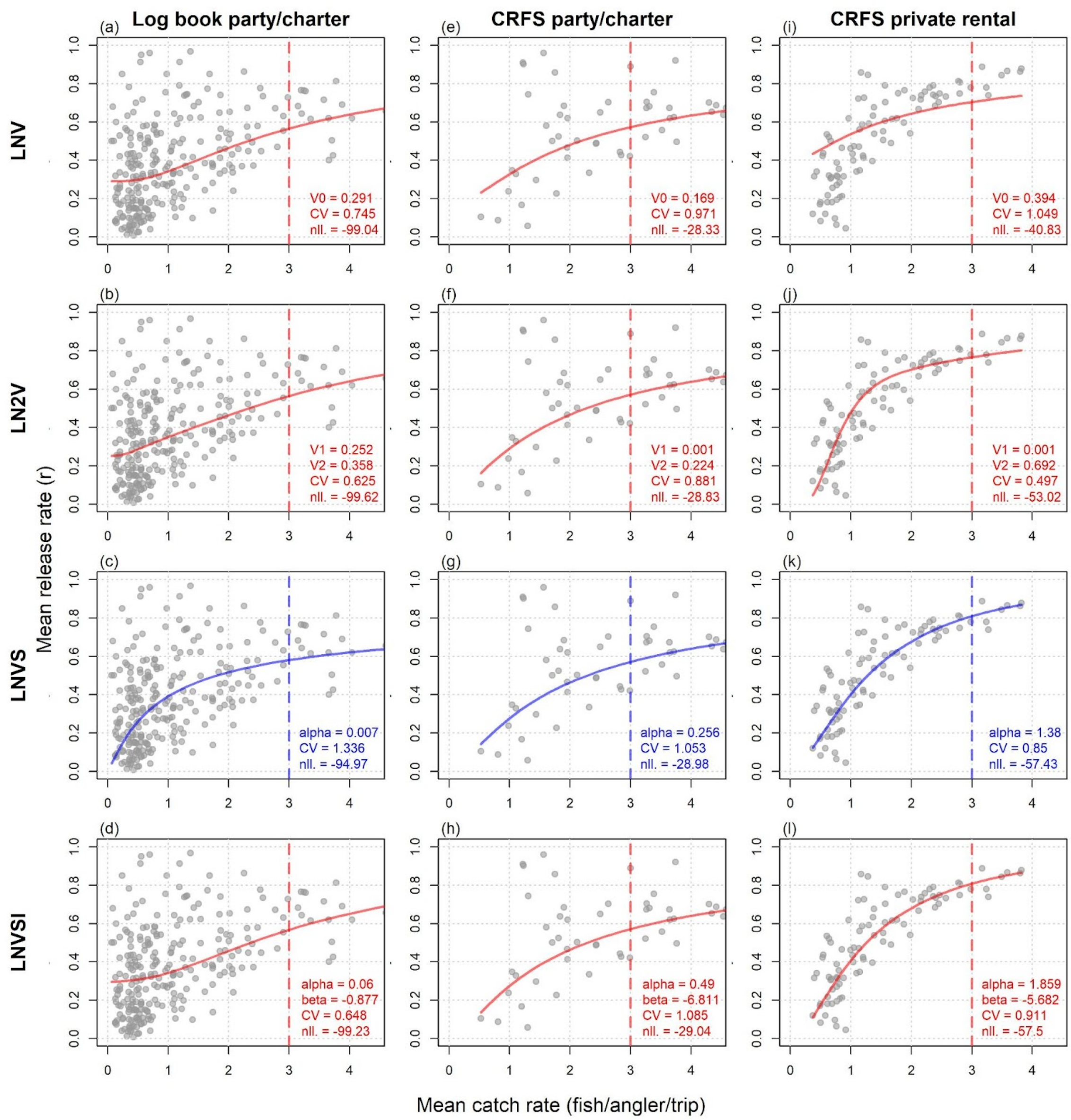

Figure 8. Model fitting results for the northern management area for three data types (columns) and four log-normal bag limit models (Table 2) that estimate: (LNV) a constant background release rate (parameter V0); (LN2V) constant background release rates for catch rates below (V1) and above (V2) 1 fish per angler per trip; (LNVS) a linearly increasing (inverse logit space) background release rate calculated from the slope (alpha) with mean catch rate; (LNVSI) the same model with an intercept (beta, inverse logit space). Grey points are observed monthly mean catch

rate and mean release rates (1980 - 2023 logbook, 2016-2023 CRFS party/charter, 2013-2023 CRFS private rental). The vertical dashed line denotes the 3-fish bag limit for the northern management area. The colored lines represent the maximum likelihood fit of each bag limit model through the data. Included in each panel are the estimated parameters including the log-normal coefficient of variation (CV) and negative log-likelihood (nll) of the model fit.

d. Closed-loop simulation results

Projecting from the maximum likelihood estimate of the stock assessments for the Base Case and Depleted operating models given a 3-fish bag limit (model fitted to CRFS private rental data) reveals that although projections start from strongly differing initial biomass conditions, after 20 projected years, the distribution of simulations is broadly comparable (Figure 9). The simulations begin the projection at the MLE estimated values. Due to recruitment variation among simulations, the uncertainty in biomass outcomes expands rapidly after 10 projected years, demonstrating the role of natural variability in determining population outcomes. After 30 projected years, the initial conditions of the projection (Base Case / Depleted) were no longer a determinant of yield and spawning biomass outcomes (Figure 9).

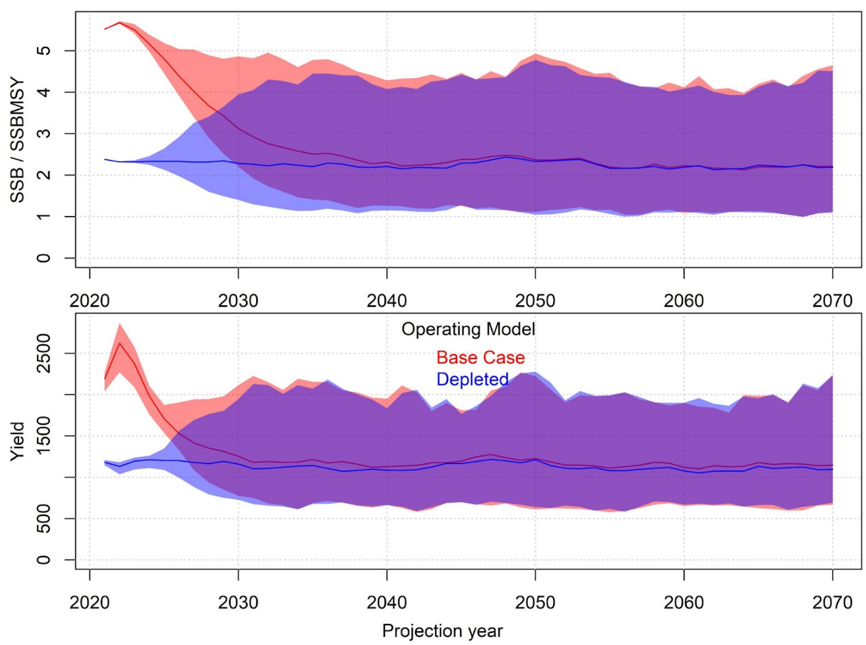

Figure 9. Projection of the bag limit model fitted to CRFS private rental data, with a bag limit of 3 fish for the Base Case (red) and Depleted (blue) operating models. The solid lines represent the median value over 144 simulations, the shaded regions are the 90% interquantile range.

Relative to natural variability, yield and biomass outcomes were largely invariant to the bag limit selected. In general, a bag limit of 4 fish obtained 15% more yield and 15% less biomass than a 2 fish bag limit (Figure 10). These bag limits (coupled with FMSY fishing and the 55 cm minimum size limit) kept spawning biomass above MSY levels for more than 99% of simulations in the projections (Figure 10). The lack of sensitivity to the bag limit suggests conservation performance appears to be primarily due to the regulation of size and fishing effort, rather than the choice of bag limit.

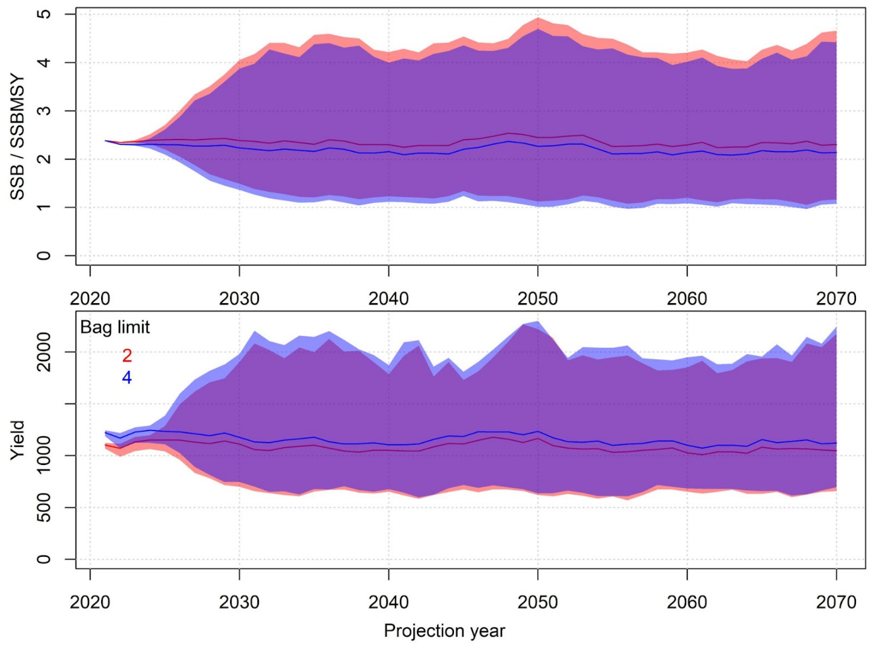

Figure 10. As Figure 9 but comparing projections of spawning stock biomass and yield given bag limits of 2 and 4 fish, for the Depleted operating model.

The long-term trade-off between yield and biomass (expected values from 2051-2060) among bag limits follows a similar pattern regardless of whether the projection starts from the Base Case or Depleted state (Figure 11). The trade-off is almost exactly linearly negative, trading 400 tons of catch for every unit of SSB / SSBMSY gained (Figure 11). The trade-off curve for the Base Case model is positioned about 5% higher in both yield and biomass due to the more favorable starting conditions (Figure 11).

Relatively modest changes to effort controls (80% - 120% of FMSY effort) provided a wider range of performance outcomes than a wide range of bag limits (1-6 fish) (Figure 12). Effort controls also provided a slightly superior performance trade-off with respect to biomass and yields; to obtain the same increase in expected stock biomass required a smaller reduction in catches (Figure 12).

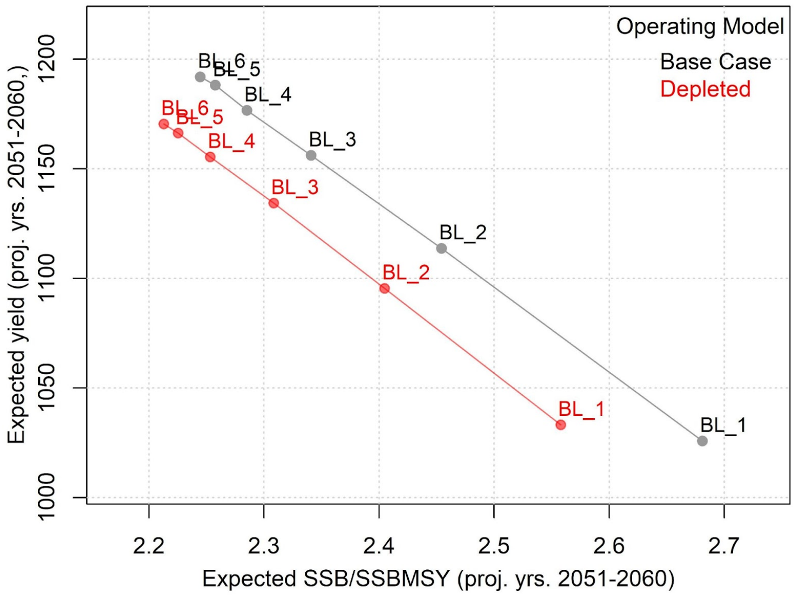

Figure 11. The impact of operating model and bag limits from 1-6 (BL_1, BL_2, … BL_6) on the long term (2051-2060) mean spawning biomass relative to MSY levels, and fishery yields, given fishing at FMSY effort levels. The Base-Case operating model started projections above unfished levels (black), the other 'Depleted' started from 40% unfished levels (red).

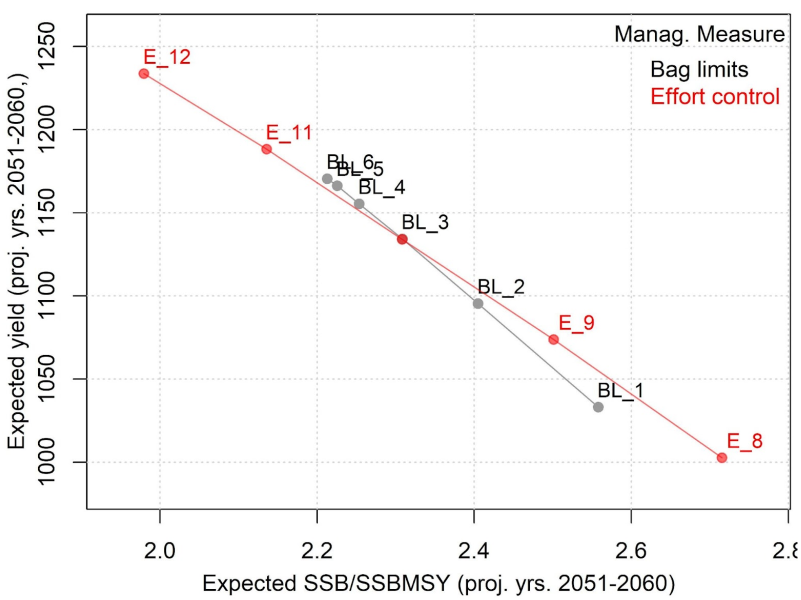

Figure 12. The impact of bag limits from 1-6 (BL_1, BL_2, … BL_6) (black) and overall effort control (as a % of FMSY fishing effort: E_8 is 80% FMSY, E_12 is 120% FMSY) (bag limit = 3) (red) on the long term (2051-2060) mean spawning biomass relative to MSY levels, and fishery yields. Closed-loop simulations (n=144) were carried out for the 'Depleted' operating model.

Modifying the size limit from 45 cm to 65 cm suggested that the current regulation of 55 cm corresponds approximately to maximum yield given the 3-fish bag limit and FMSY fishing (Figure 13). Increasing the minimum size limit to 60 cm provided better biomass conservation for a relatively small loss in long term expected yield. This trade-off was somewhat more steeply negative when increasing the minimum size limit to 65 cm. Reducing the size limit below 55 cm reduces both long term yield and biomass but outcomes were smaller than those seen when increasing the size limit (Figure 13).

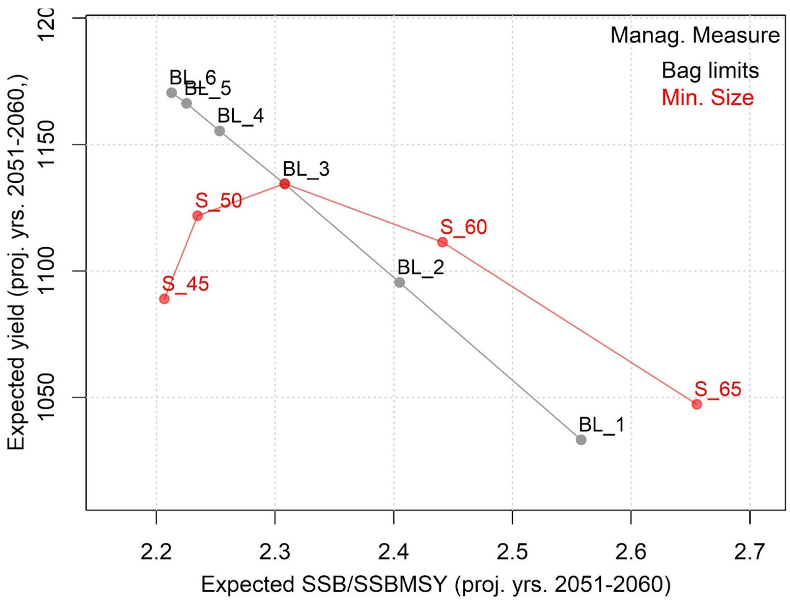

Figure 13. The impact of bag limits from 1-6 (BL_1, BL_2, … BL_6) (black) and minimum size limit control from 45cm to 65cm (S_45, S_50, … S65) (red) on the long term (2051-2060) mean spawning biomass relative to MSY levels, and fishery yields. Closed-loop simulations (n=144) were carried out for the 'Depleted' operating model starting from 40% unfished levels.

When fitted to the data for the three data sources the bag limit model (log-normal with slope parameter, LNVS) provided differing expected outcomes for biomass and yield but these were located on the same trade-off (Figure 14). For example, the current 3 fish bag limit provided expected yields of 1100, 1130 and 1195 tons for the log book party/charter, CRFS private rental and CRFS party/charter models, respectively. These yields correspond with spawning biomass outcomes of 2.40, 2.30 and 2.15 SSB MSY, respectively (Figure 14). This suggests that choice of bag limit model is at least as important as the specified bag limit, in determining expected performance outcomes and is an important source of uncertainty for any such analysis.

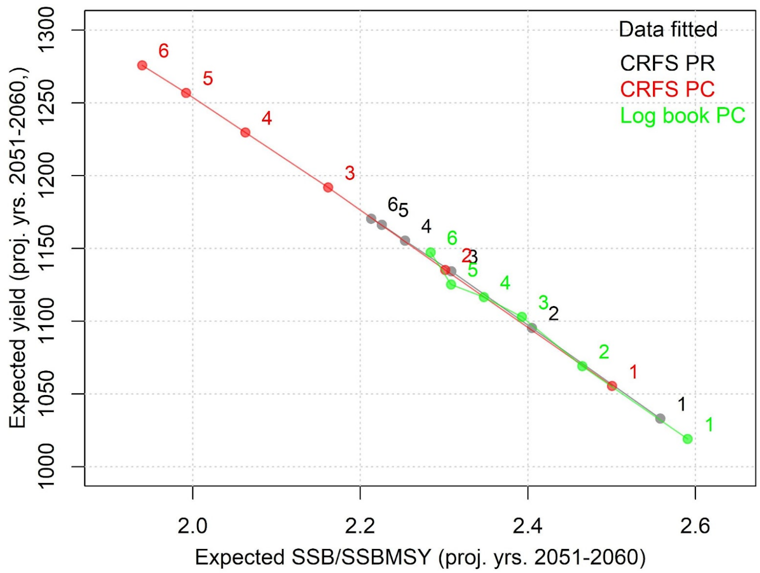

Figure 14. As Figure 13 but contrasting the effect of the bag limit model (dataset used to fit model) on performance outcomes.

Plotting the projected spawning biomass and fishing mortality rate outcomes by projection year and simulation illustrates the behavior of the bag limit regulation in controlling fishing effort (Figure 15). Regardless of the bag limit specified, this regulation type provides a pattern of fishery exploitation control that is the opposite of the harvest control rules typically specified for managing stocks, with sharply increasing exploitation rates at lower stock sizes.

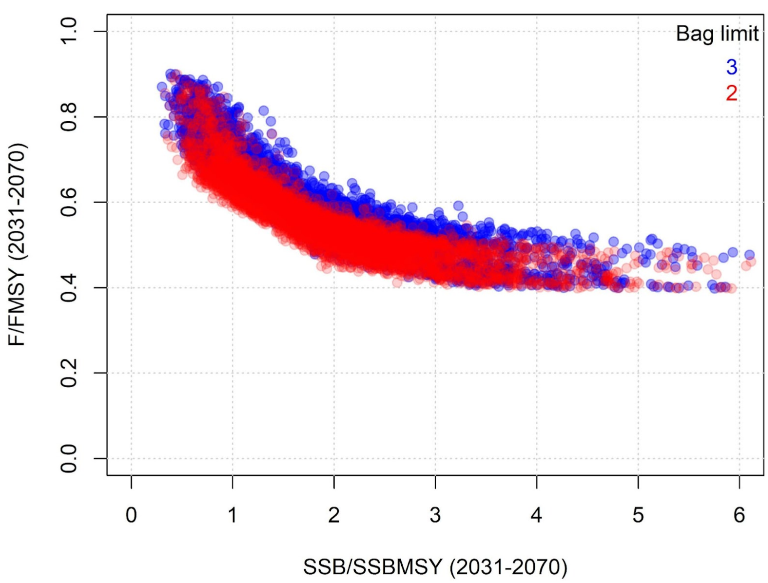

Figure 15. Implied harvest control rule of bag limits. The 2 and 3-fish bag limits of the default bag limit model (CRFS private/rental) were projected for the Depleted operating model at 150% FMSY fishing effort to reveal the relationship between projected spawning biomass and the fishing mortality rate arising from the bag limit. The higher exploitation rate was required to obtain simulations with biomass below MSY levels.

4. Discussion

This research developed the first bag limit management procedure for use in MSE that captured uncertainty in both data sources and model fit to data. The novel bag limit management procedures were implemented in openMSE and tested using empirically plausible operating models derived from recent stock assessments. The bag limit MPs were tested comparatively against other regulations such as minimum size limits to reveal management performance trade-offs. As such this work established a novel methodology that can be used to strategically inform a wider range of fishery regulations for a large number of potential recreational fisheries. These include several other California fisheries and those currently engaged in MSE processes such as the South Atlantic Snapper Grouper fishery (SAFMC 2024) and the Tasmanian sand flathead fishery.

A key finding of this study is that bag limits are unlikely to strongly constrain fishery exploitation rate, particularly at low stock sizes. This finding is consistent with previous studies (Cox et al. 2002). While most data-rich assessed fisheries in the U.S. have established harvest control rules that more strongly constrain exploitation at low stock sizes (e.g. the 40:10 rule, Berger et al. 2017, Punt and Ralston 2006), bag limits operate in the opposite way, impeding exploitation at high stock sizes and allowing for greater exploitation rates at low stock sizes. This property means that to obtain the same conservation outcome as other regulations such as size limits and effort controls, bag limits require larger reductions in expected catches. A possible solution is to establish dynamic bag limits that are increasingly restrictive (lower bag limits) as stocks decline. An extension of this work should test dynamic bag limit models to see if they can achieve better management performance trade-offs between yield and conservation objectives.

When projecting the operating models of the northern management area forward at FMSY fishing levels, current regulations (bag limit of 3 fish, 55 cm minimum size limit) appear unlikely to deplete the stock below BMSY levels. Comparative evaluation of current and alternative minimum size limits suggests that the current minimum size of 55 cm corresponds with maximum yield at intermediate biological risk. Unfortunately these results are the product of operating models that were established from a stock assessment for the northern stock that did not pass peer-review (CDFW 2020). It would be desirable to work towards an assessment model that can pass peer review based on more recent data. This would serve as both an evaluation of current stock status but also as a conditioning model from which to develop a range of operating models for testing the robustness of management approaches. In addition to typical axes of uncertainty such as stock resilience, natural mortality rate and future recruitment strength, additional aspects relevant to the bag limit model should also be included in robustness testing such as post-release mortality rate and the fraction of overall exploitation by the recreational component.

The data for the southern management area showed little apparent relationship between catch rates and release rate, and little consistency among the log book and CRFS data sets. For this reason it was not possible to develop a defensible bag limit model for the southern area. Empirical analysis suggests however, that the current bag limit of 5 fish would be very rarely triggered due to much lower catch rates (population density). Reaching bag limits in the southern management area is particularly rare due to the prevalence of CPFVs in the region and the allowance for vessels to share bags among all anglers onboard. Many vessels carry over 50 passengers leading to a very high number of fish that could be shared among passengers. Research also suggests that the southern stock is more greatly depleted and therefore even matching the northern bag limit of 3 fish is unlikely to limit this region. For this reason the analysis of bag limits for the southern management area is of secondary importance. However, managers might consider future changes to prohibit sharing of limits among anglers on a vessel by instituting a tagging program similar to what was in place for the red abalone recreational fishery.

Anecdotal evidence from operators of recreational fisheries in the South Atlantic suggest that vessels can exhibit complex switching behavior among target and secondary species as bag limits are reached. Other complicating factors are vessel-specific keep limits due to the size of refrigerated storage available onboard. For example, snapper fishing operators in Florida state that once they have filled their refrigerated chest, they return to port, placing an overall catch limit by volume of all species combined. In addition to such complexities, the models investigated here do not explicitly account for high-grading although the selected bag limit model includes increasing release proportions with mean catch rate which may in part be explained by high-grading phenomena. An extension of this work should investigate the data of the CRFS party/charter vessels to examine patterns in catch rates that may be consistent with switching behaviors.

A limitation of other bag limit models has been the inability to account for by catch of non-target species when fishing (for example continuing to catch halibut once the bag limit has been reached and other species are being targeted). This is less applicable to California halibut because they primarily occupy soft-bottom habitat which can be avoided while targeting other desirable pelagic and reef-associated species. It follows that these recreational fisheries have a relatively high degree of 'dexterity' and through location and gear, can effectively avoid overstepping bag limits once they have been reached.

A principal limitation of this work is that while the bag limit models are mechanistic, they are fitted to descriptive observations with only contrast in catch rate rather than experimental treatment of bag limits. An important improvement to this work would be to collect and fit models to experimental data where releases due to both size and bag limits were recorded at varying levels of the regulation. A recent change in the northern management area bag limit to 2 fish may provide some basis for better informing the mechanistic role of bag limits on releases.

5. Conclusions

- Management performance outcomes are relatively insensitive to alternative bag limits.
- Performance results were at least as sensitive to the bag limit model (source of data for model fitting) as the bag limit evaluated, and are therefore an important source of uncertainty.
- Bag limits do not effectively reduce exploitation rate at low stock sizes and imply a harvest control rule that contrasts with traditional approaches.
- Effort controls (e.g., N.o. vessel licenses, number of vessel-days) are likely to be a superior basis for managing exploitation.
- The current size limit of 55 cm is well suited to maximizing yield at an intermediate level of biological risk.
- Projecting management outcomes for both the Base Case and the Depleted operating models, suggests there is a relatively low risk of biomass dropping below MSY levels.

Code and Data

The code for all analyses is available from https://github.com/Blue-Matter/CDFW_Bag_Limits. The trip level data used in the fitting of bag limit models are confidential. However, derived code and objects such as openMSE operating models, bag limit management procedures and simulation outputs are all publicly available from the GitHub repository.

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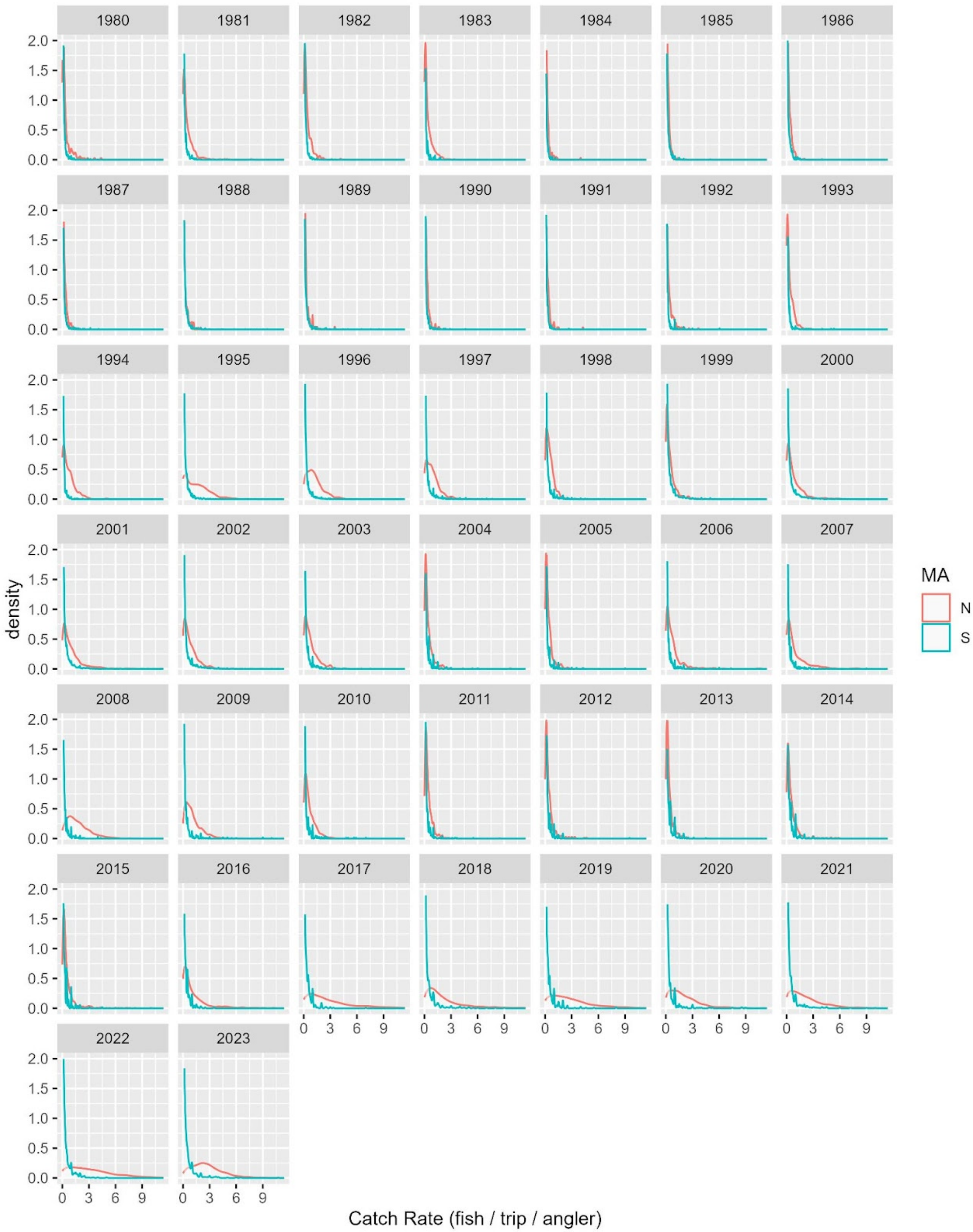
Appendix



App. Figure. 1. Log book party charter catch rate distributions by year for the northern (N) and southern management areas (S).