Evaluation of Alternative Catch Limits for the U.S. *Illex illecebrosus* fishery in 2023

by

Lisa Hendrickson
Illex illecebrosus assessment lead, Northeast Fisheries Science Center
and
Paul Rago
Chair, MAFMC Science and Statistical Committee

OVERVIEW

This report summarizes the results from an updated run, incorporating data through 2022, of the model that is used to evaluate alternative catch limits, annual Allowable Biological Catch (ABC), for the U.S. *Illex illecebrosus* fishery. The model, developed by Paul Rago (SSC Chair), involves an indirect method for bounding biomass and fishing mortality. It has been used by the Science and Statistical Committee (SSC) of the Mid-Atlantic Fishery Management Council (MAFMC) for establishing *I. illecebrosus* ABCs since 2020. This report was presented to the SSC at their March 7, 2023 meeting for use in establishing the 2023-2025 ABC.

Illex illecebrosus (Northern shortfin squid) is a difficult species to assess. It has a subannual lifespan, is semelparous and spawns year-round, resulting in two dominant intra-annual cohorts (Hendrickson 2004). Environmental conditions have a strong influence on the species' population dynamics (Brodziak and Hendrickson 1998; Hendrickson and Holmes 2004) and the early life stages are transported northeastward by the Gulf Stream (O'Dor and Dawe 1998). The combination of these factors contribute to high interannual variability in NEFSC spring and fall survey biomass indices that frequently vary by multiple orders of magnitude. Another assessment challenge is the fact that, like most commercially fished ommastrephids, *I. illecebrosus* is a transboundary stock comprised of Northern (Northwest Atlantic Fisheries Organization (NAFO) Subarea 3+4) and Southern (U.S.) Stock Components that are managed separately by different entities (Hendrickson and Showell 2019). Only the Southern Stock Component is addressed in this report. Specifically, the evaluation of alternative catch limits is based on data collected within the sampling domain of the Northeast Fishery Science Center's (NEFSC) bottom trawl surveys, between the Gulf of Maine and Cape Hatteras, North Carolina. This area encompasses the U.S. fishing grounds, but an unknown fraction of the stock lives outside the sampling domain.

The assessment of *I. illecebrosus* is further complicated by the timing of the fishery in relation to that of the NEFSC bottom trawl surveys. The NEFSC conducts research bottom trawl surveys on the Northeast U.S. shelf and upper slope during spring and fall. The spring survey typically begins on or about March 1 and continues for 8 to 10 weeks, consisting of 4 separate cruises with sampling progressing from south to north. The fall survey follows a similar cruise track and is of similar duration, but generally begins during the first week of September. In terms of annual migration patterns, the spring survey ends before much of the population has arrived in the survey sampling domain. The fall survey begins after much of the U.S. catch has been taken. During late fall, the species migrates to the winter spawning grounds located south of the NEFSC survey domain (O'Dor and Dawe 1998; Hendrickson 2004). Therefore, the NEFSC fall survey represents a post-

U.S. fishery survey (Hendrickson et al. 1996). Given the species' average lifespan of six months (Hendrickson 2004) and the 12-month interval between fall surveys, two generations of squid (i.e., both the winter and summer cohorts) occur within this time period (Hendrickson 2004).

I. illecebrosus landings from 1997 onward are the most accurate because mandatory reporting of the species' landings by fish dealers began that year. Since 1997, the U.S. *I. illecebrosus* fishery has occurred primarily between late May and September, but has ended as early as mid-August when fishery management closures have been implemented as a result of harvesting the quota.

Results from the model described below only apply to the portion of the stock that inhabits the domain of the NEFSC bottom trawl surveys. The model is a form of virtual population analysis and is used to estimate the population size (in terms of biomass) necessary to support the observed annual U.S. catch. Given B.0, representing initial population size, and the assumptions that will be described later, the proportion of the population that would have survived in the absence of the fishery is compared to the observed biomass. The ratio of observed biomass to this forward projection of population biomass is defined as a measure of spawner escapement from the fishery during the previous fall survey time period. The model extends the simple methodology for estimating virtual population size and spawner escapement to consider the uncertainty in catchability, availability, natural mortality, and the fall survey biomass estimates.. These analyses allow estimation of the relative risks of overfishing, defined as falling below a hypothetical escapement threshold.

The estimate of B.0 can also be used to evaluate the effects of hypothetical removals on potential escapements. If the hypothesized quotas are greater than the observed catches that defined B.0, then escapement estimates will be lower, and vice versa. The projected escapement, which is conditional on the assumed quota, can be compared to some threshold of acceptable escapement. For the U.S. stock component, there are currently no official Biological Reference Points (BRPs) that have been accepted for implementation by a stock assessment review panel and the BRPs that were most recently promulgated in Amendment 8 (MAFMC 1998) were deemed in a subsequent assessment as no longer appropriate. Therefore, the overfishing definitions and range of quotas analyzed within this report are identified as "hypothetical", but they have been used to manage either other squid stocks, in the case of proportional spawner escapement, or pelagic finfish stocks. For a review of the use of proportional escapement targets for squid stocks see Arkhipkin et al. (2015 and 2020).

An escapement target of 50% seems to be one of the most commonly used, but it does not appear to be the product of a stock-recruitment analysis. Instead, it is often justified based on life history considerations (e.g., short life span and intra-annual cohorts). It is worth noting that the overfishing definition for *I. illecebrosus* was historically set at $F_{20\%}$ with a target of $F_{50\%}$ in 1996 (refer to Amendment 6 of the Squid Mackerel and Butterfish Fishery Management Plan). $F_{50\%}$ was selected as a target based on the use of a 40% proportional escapement target to manage the *Illex argentinus* stock in the Falkland Islands. However, two years later an overfishing definition review panel changed the *I. illecebrosus* overfishing definition to F_{MSY} to conform to the requirements of the Sustainable Fisheries Act (Applegate et al. 1998) and this was promulgated in Amendment 8 of the MSB FMP (MAFMC 1998). Since then, %MSP-based BRPs have been recommended in the *I. illecebrosus* assessments to account for the species' life history.

METHODS

Data

Model input data included the 1997-2022 *I. illecebrosus* catches from the U.S. bottom trawl fishery and swept area biomass estimates for the NEFSC fall bottom trawl surveys. No biomass estimates were computed for the 2017 and 2020 fall surveys because of inadequate sampling of *I. illecebrosus* habitat and because no survey was conducted during the COVID-19 pandemic, respectively. Survey catchability (or equivalently in this case, efficiency) is assumed to be 1.0 and all of the population is assumed to be distributed within the survey area (i.e., availability = 1.0). Methods used to derive the survey and catch time series are described in the 2022 *I. illecebrosus* Research Track Assessment Working Group Report. However, the 2022 catch is preliminary because discard data collected by the Northeast Fisheries Observer Program are not yet available for the entire year. Therefore, discards were estimated as average proportion of the landings during 2017-2021 (0.042), which covers the recent change in fleet characteristics due to conversions of multiple freezer boats to RSW boats.

Model

Estimation of Initial Biomass, Fishing Mortality and Escapement

Let I_t represent observed index of biomass at time *t* and C_t represent the catch at time *t*. The estimated swept area total biomass consistent with the index is

$$B_t = \frac{I_t}{q}\frac{A}{a} \qquad (1)$$

where the catchability or efficiency **q**, is an assumed value. The average area swept per tow is **a** and the total area of the survey is **A**. To account for the fact that a sizable fraction of the *Illex* population lies outside of the survey area, an additional parameter **v** is introduced which represents the fraction of the resource measured by the survey. If the population is closed **v** is set to one and all of the population is assumed to be in the survey areas. Eq. 1 can be modified to account for this by dividing the right hand side by **v** such that:

$$B_t = \frac{I_t}{q}\frac{A}{a}\frac{1}{v} = \frac{AI_t}{qav} \qquad (2)$$

The NEFSC fall bottom trawl survey occurs after most of the fishery catch has been obtained and therefore can be considered a measure of post-fishery biomass. In order to account for the potential swept area biomass that existed at the start of the season, it is necessary to add the annual catch removed by the fishery. Thus, the estimate of biomass at the start of the fishing season is the post-fishery biomass plus what was extracted. Since the removals take place over a period of time and the squid are subject to natural mortality during that period, it is further necessary to inflate those removals.

To back-calculate the biomass estimate to the pre-fishery biomass estimate at start of the season, the actual catch needs to be adjusted for natural mortality then added back into B_t

$$B_t = B_0 \; e^{-Z\,t} \qquad (3)$$

where B_t is defined by Eq. 2.

The initial biomass consistent with observed catch can be obtained by rearranging the Baranov catch equation as

$$B_0 = \frac{C_t}{\frac{F}{F+M}\left(1-e^{-(F+M)}\right)} \qquad (4)$$

Substitution of Eq. 3 into 4 and rearranging results in

$$B_t e^{(F+M)} = \frac{C_t}{\frac{F}{F+M}\left(1-e^{-(F+M)}\right)} \qquad (5)$$

Further substitution of Eq 2 into 5 expresses B_t and B_0 as functions of observations of survey indices I_t and landings C_t and assumed values for q, v and M.

$$\frac{AI_t}{qav} e^{(F+M)} = \frac{C_t}{\frac{F}{F+M}\left(1-e^{-(F+M)}\right)} \qquad (6)$$

Fishing mortality, *F*, can now be computed directly by numerical methods (see function uniroot in R). Direct estimation of *F* was used in this analysis rather than Pope's approximation in view of the potential consequences of violating the parameter range over which the Pope's method is appropriate. Direct estimation of *F* also simplifies consideration of escapement under alternative assumed quotas.

Here, spawner escapement is defined as the ratio of the observed end of fishing season population biomass, B_t, for all sizes combined due to the rapid growth rate of this species (Hendrickson 2004), to the expected biomass if no fishing mortality had occurred. The projected population biomass in the absence of the fishery can be obtained by projecting B_0 in Eq. 10 by the fraction surviving natural mortality (not including spawning mortality):

$$B_{t,without\ fishery} = B_0 e^{-Mt} \qquad (7)$$

$Escapement_t$ is now computed as the ratio of the estimated B_t based on the NEFSC fall survey swept area biomass divided by the projected biomass that would have occurred in the absence of the fishery.

$$Escapement_t = \frac{B_t}{B_{t,without\ fishery}} \qquad (8)$$

Further substitution of Eqs. 3 and 7 into Eq. 8 results in

Escapement$_t$ = B_t/B_(t,without fishery) = (B_0 e$^{(-(F+M))}$)/(B_0 e$^{(-M)}$)) = e$^{(-F)}$ (9)

Estimates of B_0 can also be used to evaluate the effects of alternative catch levels on *Escapement*$_t$. Let C_H equal a hypothesized catch to be obtained from the estimated B_0. Substitution of C_H into Eq. 6 allows for estimation of the *F* necessary to obtain C_H, denoted as F_H.

$$B_0 = \frac{C_H}{\frac{F_H}{F_H+M}\left(1-e^{-(F_H+M)}\right)} \qquad (10)$$

Thus, *Escapement* given C_H is now defined as $\exp(-F_H)$. To investigate the implications of alternative higher catches, Eq. 10 was applied to each year, 1997-2022 using hypothetical quotas of 24,000 to 60,000 mt in increments of 1,000 mt.

Stochastic Methods for Estimation of Biomass, Fishing Mortality and Escapement

For a given set of assumed parameters {q,v,M} and fixed inputs for fall survey biomass and catch estimates $\{I_{f,t}, CV_{f,t}C_t\}$, it is possible to estimate $B_{0,t}$, F_t, *Escapement*$_t$, F/M and other outputs of possible utility for the ABC computations. The variable $CV_{f,t}$ is the coefficient of variation of the biomass estimate from the fall survey $I_{f,t}$. The range of $B_{0,t}$, F_t, *Escapement*$_t$, and F/M these can be established by examining a range of potential values for q, v, M, and $I_{f,t}$. By assuming that each of the parameters is drawn from an underlying distribution of values, it is possible to compute the resulting sampling distributions of each parameter (e.g., $B_{0,t}$, F_t, *Escapement*$_t$). One way of efficiently sampling over the entire range of values is known as Latin hypercube sampling. In simple terms, one assigns an equal probability to each value drawn from the underlying distribution by dividing the range of the parameter into equal probability intervals. The area under the curve (ie., the integral) for a probability density function over a defined range, for example (q_1, q_2), is the same for all intervals. Thus, each observation, defined as the midpoint of (q_1, q_2), now has the same probability. For a uniform distribution this means dividing the domain of the distribution (p_{min}, p_{max}) into equally spaced intervals.

This same principle can be applied to any hypothetical parameter, say r, (r_{min}, r_{max}) to obtain equal probability observations. By looping over the full range of r values for every value of p you obtain a measure of the expected value of some function Y for p over every value of r. If there are N_q intervals for parameter q, N_v for v and N_M for M, and N_I for If,t then the joint probability for any combination of $\{q_i, v_j, M_k, I_{f,t}\}$ is $(1/N_q)(1/N_v)(1/N_M)(1/N_I)$. Looping over all possible combinations yields a probability density function for any function of q, v, M, and $I_{f,t}$. In this case, N was set to 25, 20, 20, and 25 for (N_q), (N_v), (N_M), and (N_I), respectively. This results in 250,000 evaluations of the function for each year and each alternative catch. The models were implemented in R and the code is shown in Appendix 1 of Rago (2023a). The effects of adding the uncertainty in the fall indices are summarized in Rago (2023b).

Probability levels for hypothetical thresholds can be computed by counting the proportion of realizations that fall above for below a criterion. For example, the average probability that a given alternative quota induces *Escapement* below 50% can be found by estimating the proportion of cases that fall below 0.5 and averaging the probabilities over all years. This was done for each hypothetical quota level between 24,000 and 60,000 mt.

Constraints on parameters

Catchability

The *FSV H. B. Bigelow* to *RV Albatross IV* catch ratio (in biomass) for *I. illecebrosus* caught in the NEFSC fall surveys is 1/1.4093, which implies that the maximum *q* for the *R/V Albatross* IVis 0.71 if the *FSV H. B. Bigelow* *q* = 1 (Miller et al 2010). In addition, catch rates of *I. illecebrosus* are higher during the day than at night. Benoit and Swain (2003) compared day vs night catches during a comparative fishing study between the Canadian research vessels *CCGS Alfred Needler* and the *Lady Hammond*, both of which used a Yankee 36, similar to the *R/V Albatross IV* net, during 1971 to 2001. Estimated log catch ratios of night to day tows for the research vessels were -1.224 and -1.376, respectively ($P < 0.001$; see their Table A1, p. 1317). These imply day to night ratios of catch rates of 3.401 and 3.959. If roughly half the tows occurred during the day, then the expected catch expressed in daytime equivalents would by 2.2 to 2.5 times higher than the night catches. Using a model statistical method comparable to the "statistical control" model of Benoit and Swain (2003), Sagarese et al. (2016) computed an overall day to night coefficient of 1.2 (log scale) for *I. illecebrosus* catches in all of the strata sampled during the 1976-2008n NEFSC fall bottom trawl surveys ($P < 0.005$). The arithmetic day to night ratio is exp (1.2) = 3.32, similar to that found by Benoit and Swain (2003).

As noted in Hendrickson and Showell (2019), Benoit and Swain (2003) did not find significant differences for *I. illecebrosus* in pairwise comparison tests of bottom trawl survey catches during comparative fishing studies conducted in two different Canadian survey regions. However, this may have been a function of sample size (about 67 stations each in 1988 and 1992). Brodziak and Hendrickson (1998) reported NEFSC fall survey catch rates for pre-recruit (≤ 10 cm mantle length) *I. illecebrosus* to be 1.6 to 2.4 times higher in the day than during dusk and at night, respectively ($p < 0.001$). The same ratios for *I. illecebrosus* recruits (>10 cm), which dominate NEFSC spring and fall survey catches of the species, was not significant ($p = 0.106$) at $\alpha = 0.05$. Collectively, these studies suggest that nighttime catches are low by a factor of at least two. Combining this with the known information from the *Bigelow* to *Albatross* calibration coefficient for biomass (1/1.4093) results in a reasonable upper bound of 0.5/1.4093=0.355. This q value is similar to the 95% upper bound of 0.325 proposed by fishermen for vessels involved in the directed fishery (Manderson et al., 2021).

The likely lower bound on catchability has important implications for estimating the likely range of biomass bounds. Assuming very low values of q imply very high values of biomass. Manderson et al. (2021) reported a potential lower bound of 2% for q based expert opinion. While efficiencies may be this low for specific tows, it is unlikely to be the case over an entire survey within a year. The average estimate from the experts for commercial gear was 7.8%. Assuming that this is based on daytime tows, it would be reasonable to assume that research vessel tows, which are collected both day and night, the lower bound on research vessel tows should be less than 7.8%. It is not possible to determine if the differences in diel catch rates factored into the average defined by the expert panel.

Availability

Spatial analysis methods were used by Lowman et al. (2021) and Manderson et al. (2022) to compute estimates of the likely availability of *I. illecebrosus* to the NEFSC fall survey. Depending on the method used for the sensitivity-specificity threshold, availability estimates ranged from 34.5 to 46% with one method to 31-73% with another. The wider range (31-73%) was used in this report for setting bounds on availability because this allows for a wider range of possible biomass, fishing mortality and escapement estimates. Data and current knowledge of the resources are insufficient to select the narrower range (34.5-46%) that is encompassed by the wider range (31-73%).

Non-spawning Natural Mortality

The lower bound of assumed weekly non-spawning natural mortality rates (= 0.01) analyzed was based on the lowest assumed value for *I. illecebrosus* in Hendrickson and Hart (2006). The upper bound of 0.13 week^{-1} was obtained from the predictive equation of Hewitt and Hoenig (2005) given a maximum age of 221 days based on 2019-2020 age samples from the *I. illecebrosus* fishery.

Uncertainty in the Estimates of Fall Survey Biomass

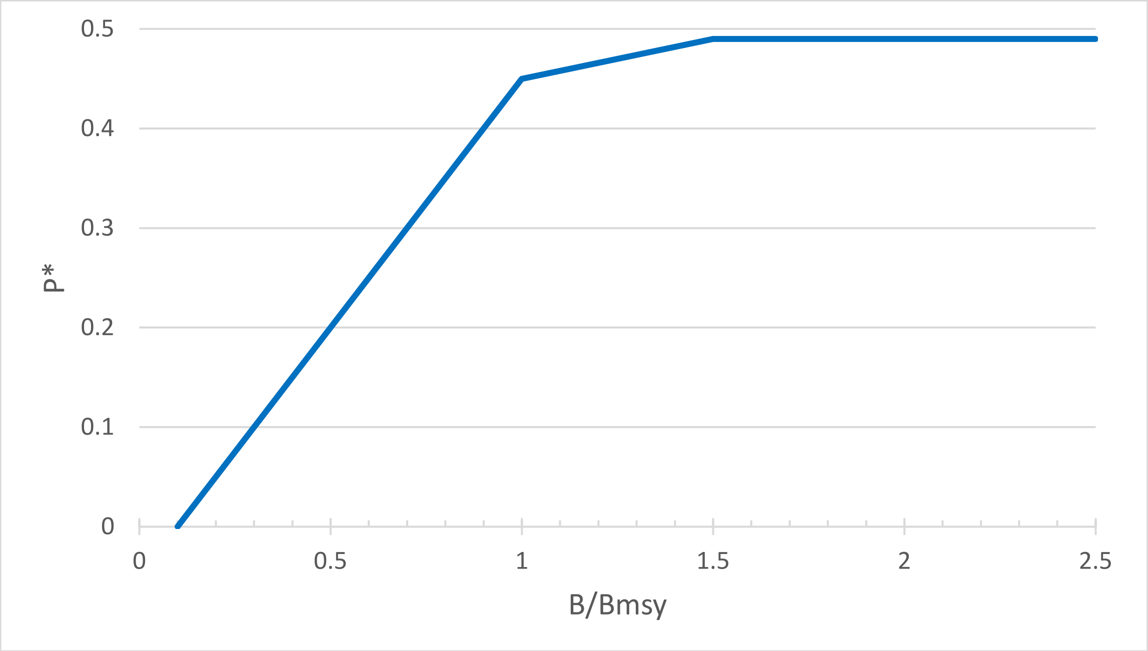
Per standard survey theory and the Central Limit Theorem, the means of stratified random samples are normally distributed irrespective of the underlying distribution of the random variable. For this analyses, the biomass estimates for the fall survey in each year $I_{f,t}$ were assumed to be normally distributed with means equal to the survey estimate and standard deviations equal to the coefficient of variation times the mean, such that $SD_{f,t} = CV_{f,t} * I_{f,t}$. Uncertainty was evaluated using values of I at N_I equal probability intervals over an 80% confidence interval.

Theoretical Thresholds for Spawner Escapement and F/M

Values for the theoretical *Escapement* levels included in the model, 50%, 40% and 35%, were obtained from the literature and stock assessment reports (e.g., see Cordue 2018 and references therein; also PFMC 2020). For the sake of completeness, a range of theoretical F/M ratios {0.33, 0.5, 0.66, 1.0, 1.5} were also evaluated.

Risk Analyses

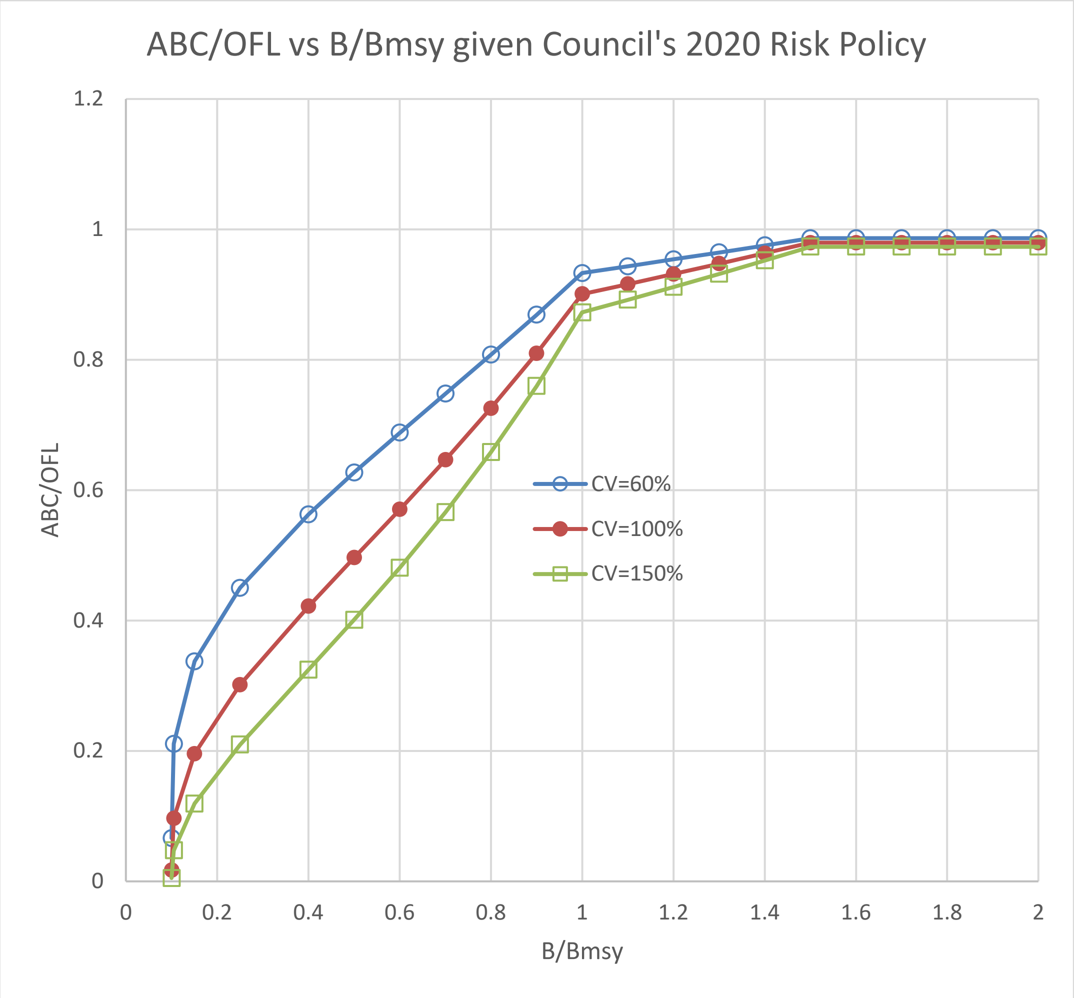
Decisions by the MAFMC regarding Acceptable Biological Catch (ABC) levels are governed by its Risk Policy that attempts to avoid overfishing over all levels of stock biomass. The risk of overfishing is defined as the probability of exceeding the overfishing limit (OFL) and is denoted as P*.



A description of the MAFMC's current OFL Risk Policy, which was promulgated in 2020, can be found at: https://www.ecfr.gov/current/title-50/chapter-VI/part-648/subpart-B/section-648.21 and https://www.govinfo.gov/content/pkg/FR-2020-12-15/pdf/2020-27562.pdf.

Under this Risk Policy, the probability of overfishing can be as high as 0.49 when B/Bmsy exceeds 1.5, but when below 1.5, the acceptable risk of overfishing declines to zero when B/Bmsy $\leq$ 0.1.

The SSC is responsible for recommending an ABC given an estimate of the OFL from a stock assessment. This is usually estimated as the total catch if the population is fished at its F_{MSY} or F_{MSY} proxy. The probability of overfishing is further defined by the uncertainty of the OFL. In most instances, the stock assessment is unlikely to fully characterize the uncertainty of the OFL because it is based on a single model and does not integrate over all possible states of nature. To overcome this philosophically unknowable cul-de-sac, the SSC has developed a rubric that derives an uncertainty level based on a meta-analysis of multiple model outcomes for simulated assessments. Three levels of uncertainty, CVs of 60, 100 and 150%, have been identified as representative. The reduction in OFLs, consistent with the Council's Risk Policy, is expressed as the ratio of ABC to OFL as shown below.



The risk of overfishing for *I. illecebrosus* can be expressed as the probability of *Escapement* falling below a specific potential threshold level (e.g., 35%, 40%, 50%) or the probability of exceeding F/M = 2/3, 1 or other values that attempt to preserve an adequate quantity of this species' biomass for forage by its predators. Finally, one can estimate the joint probability of exceeding an F/M threshold and falling below an *Escapement* threshold. The ***only*** other requirement to apply the Risk Policy it to guesstimate the likely current state of the resource (i.e., Bt/Bmsy).

RESULTS

The stochastic spawner escapement model was applied to each year between 1997-2022, with the exceptions of 2017 and 2020 because swept area biomass estimates for the NEFSC fall bottom trawl survey could not be computed due to inadequate sampling of *I. illecebrosus* habitat in 2017 and cancellation of the survey in 2020 due to the Covid-19 pandemic (Table 1). Figures 1-9 illustrate the behavior of the spawner *Escapement* model as a function the assumed ranges of catchability q=[0.078, 0.325], availability v = [0.37, 0.73], natural mortality M = [0.01, 0.13] per week, and the relative variation of the observed fall survey biomass and U.S. fishery catches 2022. Estimates of initial biomass B.0 decrease inversely with the product of q*v (Fig. 1, top). The empirical distribution of B.0 given the joint distribution of q, v, and M is strongly skewed (Fig. 1, bottom) with the mean exceeding the median. As expected, the distribution of F is inversely related to the product of q*v (Fig. 2, top). Estimated F is less strongly skewed (Fig. 2, bottom). Eq. 9 predicts *Escapement* will be inversely related to F as shown in Fig. 3 (top). The distribution of *Escapement* values is nearly the mirror image of the F values (Fig. 3, bottom).

F/M has been proposed as a "rule of thumb" reference point for forage finfish species (Fig. 4) and Patterson (1992) has proposed F = 2/3 M as a candidate reference point for small pelagic finfish stocks, but they are not semelparous.

Escapement declines as F/M increases, but the rate of decline depends on the assumed value of M. When M is low, the rate of decline is very slow; in contrast *Escapement* declines rapidly with F/M when the assumed M value is high (Fig. 5). Catch divided by swept area biomass has been used as a measure of exploitation rate in the NAFO *I. illecebrosus* assessments of the Northern Stock Component since 1998 (Hendrickson and Showell 2019) and in the assessment of longfin inshore squid, *Doryteuthis* (*Amerigo*) *pealeii*. Since the NEFSC fall survey is essentially a post-fishery survey for the portion of the population inhabiting the U.S. shelf, this ratio depends on the assumed M estimate (Fig. 6, top). In contrast, *Escapement* is directly related to F (Fig. 6, bottom, and Eq. 9).

The distribution of 2022 weekly F estimates correspond well with independent estimates of weekly F estimates derived by VMS analyses for the 2019 fishery (Rago 2021) (Fig. 7). With respect to M, *Escapement* increases as assumed M increases but the range of *Escapement* values decrease with M (Fig. 8, top). Estimated F declines with M but the range also decreases (Fig. 8, bottom).

Estimates of $B.0_t$ illustrate the magnitude of biomass necessary to support the observed catches and the estimated biomass as the end of the fall fishing season. Theoretically, in a closed population, the estimated biomass would be close to the biomass present at the start of the fishery, approximated by the spring survey biomass. As an illustration of the magnitude of the immigration necessary to support the fishery, the ratio of B.0 to spring survey biomass (B.s) ranges widely from 5 to 2,500 for three example years 2013, 2015 and 2019 (Fig. 9). This disparity is important because it

highlights the likely magnitude of other processes necessary to support the observed catch. The initial biomass B.0 is based on the observed catch and fall survey biomass given the assumptions about catchability q, availability v, and non-spawning natural mortality M. Each realized estimate of the spring survey biomass uses the same q and v parameters applied to estimate the fall survey biomass in a given year. Ratios of B.0 to spring survey biomass that are greater than one illustrate the amount of immigration, in-season recruitment and/or growth in weight necessary to support the fishery during the same year.
Changes in growth alone are insufficient to explain the large ratios. Even a 10-fold increase in average weight between the spring survey and midpoint of the fishery would have little impact on the distribution of B.0/B.s values. Collectively, the evidence suggests that the summertime fishery is supported by intermittent fluxes of recruits and this is supported by empirical data. Recruitment from within the survey area during the summer has been documented, whereby the winter cohort was found spawning on the shelf in the Mid-Atlantic Bight (Hendrickson 2004).

Initial biomass, fishing mortality, F/M and *Escapement* estimates for each year during 1997-2022 are presented in Figs. 10-12 and Tables 2-4. Apart from the wide confidence intervals, a notable feature of these estimates is a general absence of significant trend. Runs of observations above and below the median suggest a slight degree of autocorrelation. The 90% confidence interval for B.0 has about a 14 to 25-fold range (Table 2). Wide ranges in the lower and upper bounds in B.0 do not translate to comparable ranges of *Escapement* (Table 3). The median *Escapement* level across all years exceeded 0.7. Even the 5%-ile of *Escapement* was above 50% in most years (Table 3). These estimates suggest that the historical range of catches were unlikely to have resulted in *Escapement*s below 50%. The F/M ratio (95%-ile) infrequently exceeded 1 (Table 4).

These results beg the question about how the population might have responded to higher levels of historical catches. The effects of hypothetical quotas over the entire range of years are summarized in Table 5 for median *Escapement* rates and Table 6 for median F/M. Graphs of these probabilities are shown in Figs. 13 - 15. Even the highest quota levels (60,000 mt) do not induce probabilities of overfishing (i.e., *Escapement* below 50%) in most years. In fact, the problematic years are 1999, 2001 and 2013. If the *Escapement* threshold is lowered to 40%, then the overfishing criteria would only have been triggered in 1999 (Fig. 15).

Risk Analyses

The probabilities of overfishing having occurred historically were computed by estimating the proportion of simulated *Escapement*s that fell below *Escapement* thresholds of 0.35, 0.4, 0.5, 0.6 and 0.75 (Table 7) for each year during 1997-2021. A similar analysis was done for F/M exceeding 0.33, 0.50, 0.666, 1, and 1.5 for each year (Table 8). Finally, the joint probability of F/M exceeding 0.666 and *Escapement* of falling below thresholds of 0.35, 0.4, 0.5, 0.6, and 0.75 was computed for each year (Table 9). There was no evidence of historical catches inducing overfishing probabilities above 0.5; in fact, most of the probabilities for 50% and 60% *Escapement* and F/M = 0.666 were less than 0.1 (Tables 7-9).

The consequences of alternative quotas of 24,000-60, 000 mt on overfishing probabilities can also be estimated by averaging over all years (Tables 10-12). As an illustration, if 50% *Escapement* defines the overfishing threshold, then the maximum average risk of overfishing is 0.28 when the quota is 60,000 mt (Table 10). Similarly, if 0.666 defines the overfishing limit for F/M then a 60,000 mt quota results in an overfishing probability of 0.27 (Table 11). The joint probability of overfishing with *Escapement* < 0.50 and $F/M > 0.666$ is 0.15 when the quota is 60,000 mt (Table 12).

The other aspect of risk evaluation is the current status of the U.S Stock Component. If one assumes that the overall biomass is stable without significant trend (e.g., Fig. 10, Table 2) the next question is whether this portion of the stock is oscillating about a stable point near Bmsy or some fraction of it. If it is near Bmsy, then the Council's Risk Policy deems that an overfishing risk of 0.45 is appropriate. If the stock is oscillating about an equilibrium of 50% of Bmsy then the overfishing risk should not exceed 0.20. If the first scenario is true (i.e., B/Bmsy=1) then quotas up to 60,000 mt would be acceptable for *Escapement* Thresholds of 50% and 60%. If the second scenario is true (i.e, B/Bmsy=0.5) then quotas should not exceed 47,000 mt (Table 10) or 38,000 mt if the F/M=2/3 criterion is applied.

DISCUSSION

The methods used in this report build on the approaches considered by the SSC in 2021 and 2022. In 2021, only two alternative quotas were considered for the U.S. *I. illecebrosus* fishery and the risk of overfishing was defined by examining a range of extreme values in the parameter space for {q, v, M}. During 2022 and in this report, the approach is improved in following ways:

1. The ranges of catchability, availability and M are informed by work conducted by the Research Track Assessment for *I. illecebrosus*.
2. Pope's approximation of the VPA is replaced with a more accurate numerical solution of the catch equation for F.
3. The effects of uncertainty in the $\{q, v, M, I_{f,t}\}$ parameters on biomass, F, and *Escapement* estimation are examined by integrating over the full range of the distributions of each parameter. Uncertainty in the point estimate of biomass in the fall survey is explicitly considered in each available year for 1997-2022.
4. The risk of overfishing is compared with a wide array of hypothetical Biological Reference Points for *Escapement* and F/M.
5. A wide range of alternative quotas (24,000 mt to 60,000 mt) are evaluated.
6. The implications of the Council's Risk Policy are examined by considering a plausible range of B/B_{msy} levels
7. The ratio of B.0 based on the estimated biomass in the NEFSC fall survey to the estimated biomass in the spring survey in the same year indicates that current quotas are largely supported by immigration of recruits to the fishing areas rather than growth of the existing stock at the end of the spring survey.
8. Comparisons between an independent VMS-based estimate of fishing mortality, for 2019, compares favorably with the derived F based on the parametric model.
9. Catches and NEFSC fall survey biomass data for 2022 were added.
10. The model was implemented in R and the core code is presented in Appendix 1 of Rago (2023a). The complete version of the code will be distributed to the SSC.

The perception of risk is governed by many factors. Arkhipkin et al. (2020) review many considerations that affect risk in cephalopod management. Here, the implications of multiple factors related to a closed population (v), sampling efficiency (q) and uncertainty in natural mortality (M) are examined. We have also included information on the uncertainty of the fall bottom trawl survey indices. All of these factors are assumed to be independent of one another such that the integration of some function of these random variables provides meaningful insights about the various functions of interest (i.e., initial biomass, fishing mortality, escapement). The use of uniform distributions for these three parameters is consistent with what we think we know about them, but the model can easily be re-parameterized as new information becomes available. The uniform distribution is useful in that it is parameterized only by the upper and lower bounds. The Beta distribution can also be defined on the [a,b] interval, but its parameterization depends on two additional parameters to define its shape. In the absence of additional information about possible shape parameters, such an extension seems speculative.

Low q, low v and high M drive the high estimates of initial biomasses (Table 2). The extreme values, above one million mt seem highly unlikely, but the distribution of median values across years seems reasonable (70,000 - 824,000 mt). Perhaps more importantly, the range of values across years is consistent with the wide ranges of fluctuations in catch levels experienced in other squid fisheries. Median biomass estimates during the past 10 years ranged from 112,000 to 461,000 mt (Table 2) and median *Escapement* percentiles exceeded 0.76 during this same period (Table 3).

Escapement-based management procedures for other squid stocks are widely applied (e.g., Macewicz et al., 2004; Maxwell et al., 2005; Dorval et al., 2013; Arkhipkin et al., 2020) but the theoretical justification for the choice of 50% or 40% is often governed by general notions of sustainability and life history characteristics (e.g. Rago 2022) rather than actual stock-recruitment relationships.

The analyses herein provide general support for the notion that exploitation rates are generally low. One has to posit much higher average availability and catchability rates than used herein to significantly reduce median stock size or escapement. For reasons noted in Manderson et al. (2021) and Lowman et al. (2021), the availability estimates are probably high, particularly since the unknown portion of the stock that lives outside the survey areas is not considered in the subject analyses. One of the more useful deductions from these analyses is the reliance of the fishery on biological processes (recruitment, growth, and immigration) that occur after the spring survey (Fig. 9). The influx of squid into the Mid-Atlantic Bight fishing area (e.g., Hendrickson 2004, Hendrickson and Hart 2006) is the primary support for the catches that occur in the spring, summer and early fall fishery. Changes in average weight during the season are important contributors to the increase in biomass, but alone, are unlikely to be sufficient to support the observed catches.

The range of natural mortality rates included in the subject analyses is consistent with non-spawner natural mortality rates estimated in Hendrickson and Hart (2006). Their analyses supported much higher rates of mortality on spawning squid albeit for a short period of time following maturation. Analyses of average sizes during the *I. illecebrosus* fishery revealed a general absence of larger squid (Rago 2021 WP). Females grow faster and reach larger sizes than males (Hendrickson 2004). The absence of larger squid may be due to spawning mortality or migration out of the fishing areas. Based on samples from a stratified random survey of *I. illecebrosus* (Hendrickson 2004), Hendrickson and Hart (2006, p. 10-11) suggested that the “low number of older females in the survey samples was due to spawning mortality rather than a lack of selectivity to the gear.” Increasing M in the current model would increase the biomass estimates in Table 2.

The probability of overfishing (i.e., falling below a theoretical threshold *Escapement* level) is computed for each of the 24 years (1997-2022, excluding 2017 and 2020). The average probability thus depends on all of the realized estimates for this period. Moreover, it is assumed that all years are equally probable. Inclusion of an autocorrelative model might be useful but perhaps not warranted until the parameterizations of the model are further refined.

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Table 1. Swept area biomass (mt) for *I. illecebrosus* in NEFSC spring and fall bottom trawl surveys (mt) and U.S. catches during 1997-2022. Spring survey biomass estimates were not included in the model used to estimate potential annual catch limits for the U.S. fishery. Swept area biomass was not computed for the 2017 and 2020 fall surveys due to inadequate sampling of *I. illecebrosus* habitat and the lack of a survey during the COVID-19 pandemic, respectively. The 2022 catch is preliminary because discard data were not available for the entire year. The 2022 discards were estimated as the average proportion of the catch during 2017-2021.

Year	*Catch (mt)*	*NEFSC spring survey biomass (mt)*	*CV*	*NEFSC fall survey biomass (mt)*	*CV*
1997	14,358	511	46	2,730	17
1998	24,154	226	57	7,725	51
1999	8,482	149	17	929	16
2000	9,117	35	14	3,999	22
2001	4,475	110	38	1,422	15
2002	2,907	68	55	2,322	20
2003	6,557	23	34	10,913	68
2004	27,499	139	72	2,279	12
2005	13,861	14	24	3,696	46
2006	15,500	121	32	14,220	34
2007	9,661	147	32	7,311	8
2008	17,429	54	34	5,462	18
2009	19,090	404	38	5,170	20
2010	16,394	101	30	2,941	22
2011	19,487	294	29	2,937	18
2012	12,211	1,099	34	2,895	12
2013	4,107	22	27	1,827	13
2014	9,342			3,592	11
2015	2,873	217	20	2,795	14
2016	7,004	2,641	38	3,711	26
2017	23,371	314	26		
2018	25,524	382	23	7,146	13
2019	28,495	1,901	59	3,310	14
2020					
2021	31,421			3,531	17
2022	6,096			4,805	33

Table 2. Estimated percentiles of initial biomass estimates (mt, by year, given observed catch and fall survey biomass. Entries are based on 250,000 combinations of catchability, availability and natural mortality rates.

	Percentile				
Year	***1%***	***5%***	***50%***	***95%***	***99%***
1997	36,936	47,606	185,199	865,375	1,391,943
1998	68,670	100,773	461,803	2,511,512	4,309,863
1999	16,659	20,539	70,284	305,065	484,055
2000	39,716	54,571	245,669	1,235,322	2,019,005
2001	15,880	21,181	90,438	441,055	712,910
2002	20,474	28,830	137,883	708,998	1,160,249
2003	38,093	81,196	555,374	3,620,695	6,441,818
2004	48,560	58,474	185,866	766,910	1,202,999
2005	37,365	52,649	228,845	1,195,665	2,031,464
2006	112,292	165,629	823,876	4,395,210	7,367,541
2007	67,191	93,137	438,818	2,220,827	3,594,807
2008	60,798	81,274	347,123	1,696,752	2,754,724
2009	60,209	79,882	333,176	1,616,953	2,624,473
2010	40,379	52,028	200,551	937,797	1,515,733
2011	44,257	56,041	207,244	943,577	1,513,930
2012	36,093	47,085	190,855	906,125	1,456,294
2013	18,594	25,256	112,956	561,099	908,174
2014	38,171	51,336	224,932	1,106,103	1,785,947
2015	24,409	34,331	165,564	848,404	1,381,160
2016	34,526	48,299	223,883	1,145,734	1,888,454
2018	83,637	110,417	461,407	2,224,021	3,582,213
2019	57,584	71,257	247,196	1,080,734	1,715,310
2021	62,327	77,011	265,302	1,157,927	1,841,132
2022	39,283	57,304	280,654	1,486,312	2,484,105

Table 3. Estimated percentiles of spawner escapement, proportion by year, given observed catch and fall survey biomass. Entries are based on 250,000 combinations of catchability, availability and natural mortality rates.

	Percentile				
Year	***1%***	***5%***	***50%***	***95%***	***99%***
1997	0.545	0.621	0.841	0.950	0.967
1998	0.565	0.682	0.893	0.971	0.982
1999	0.412	0.489	0.756	0.917	0.945
2000	0.726	0.786	0.923	0.978	0.986
2001	0.667	0.732	0.898	0.969	0.980
2002	0.830	0.870	0.956	0.988	0.992
2003	0.762	0.880	0.976	0.995	0.997
2004	0.351	0.424	0.704	0.893	0.928
2005	0.547	0.656	0.876	0.965	0.978
2006	0.831	0.878	0.961	0.989	0.993
2007	0.829	0.867	0.954	0.987	0.991
2008	0.661	0.727	0.897	0.969	0.980
2009	0.625	0.697	0.882	0.964	0.977
2010	0.524	0.603	0.833	0.947	0.966
2011	0.487	0.565	0.809	0.938	0.959
2012	0.603	0.673	0.869	0.959	0.973
2013	0.738	0.793	0.925	0.978	0.986
2014	0.711	0.769	0.914	0.974	0.983
2015	0.860	0.892	0.964	0.990	0.993
2016	0.756	0.813	0.935	0.981	0.988
2018	0.641	0.707	0.886	0.965	0.977
2019	0.428	0.504	0.767	0.921	0.947
2021	0.417	0.494	0.761	0.919	0.946
2022	0.811	0.861	0.955	0.988	0.992

Table 4. Estimated percentiles of F/M ratio, by year, given observed catch and fall survey biomass. Entries are based on 250,000 combinations of catchability, availability and natural mortality rates.

Year	***1%***	***5%***	***50%***	***95%***	***99%***
1997	0.011	0.018	0.102	1.166	2.153
1998	0.006	0.010	0.068	0.836	1.664
1999	0.019	0.030	0.164	1.783	3.205
2000	0.005	0.008	0.047	0.576	1.093
2001	0.007	0.011	0.063	0.756	1.421
2002	0.003	0.004	0.026	0.331	0.636
2003	0.001	0.002	0.015	0.224	0.568
2004	0.024	0.039	0.205	2.169	3.835
2005	0.007	0.012	0.079	0.951	1.842
2006	0.002	0.004	0.024	0.301	0.590
2007	0.003	0.005	0.028	0.342	0.656
2008	0.007	0.011	0.064	0.769	1.444
2009	0.008	0.013	0.074	0.874	1.635
2010	0.011	0.019	0.107	1.231	2.270
2011	0.014	0.022	0.125	1.404	2.565
2012	0.009	0.014	0.083	0.967	1.800
2013	0.005	0.008	0.046	0.560	1.063
2014	0.006	0.009	0.053	0.637	1.203
2015	0.002	0.004	0.022	0.272	0.523
2016	0.004	0.007	0.040	0.490	0.937
2018	0.008	0.012	0.071	0.841	1.575
2019	0.018	0.029	0.156	1.704	3.071
2021	0.018	0.029	0.160	1.751	3.154
2022	0.003	0.004	0.027	0.346	0.675

Table 5. Estimated *Escapement* rates for the 50th percentile for alternative quotas, by year, based on assumed ranges of catchability, availability, and natural mortality. Table entries represent percentiles for 250,000 realizations of the estimated *Escapement* .

Alternative Quota (mt)	***1997***	***1998***	***1999***	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***
24,000	0.763	0.894	0.534	0.823	0.632	0.733	0.919	0.731	0.805	0.941	0.895	0.864
25,000	0.756	0.890	0.525	0.817	0.623	0.725	0.916	0.723	0.798	0.939	0.891	0.859
26,000	0.749	0.886	0.515	0.811	0.614	0.717	0.913	0.715	0.792	0.936	0.887	0.854
27,000	0.742	0.882	0.507	0.805	0.606	0.710	0.910	0.708	0.786	0.934	0.883	0.849
28,000	0.735	0.878	0.498	0.800	0.598	0.703	0.907	0.700	0.780	0.932	0.879	0.845
29,000	0.728	0.875	0.490	0.794	0.590	0.696	0.904	0.693	0.774	0.930	0.876	0.840
30,000	0.722	0.871	0.482	0.789	0.582	0.689	0.901	0.686	0.768	0.927	0.872	0.836
31,000	0.715	0.867	0.474	0.783	0.574	0.682	0.898	0.679	0.763	0.925	0.868	0.831
32,000	0.709	0.863	0.467	0.778	0.567	0.675	0.895	0.673	0.757	0.923	0.865	0.827
33,000	0.703	0.860	0.460	0.773	0.560	0.669	0.892	0.666	0.752	0.921	0.861	0.822
34,000	0.697	0.856	0.453	0.768	0.553	0.662	0.889	0.660	0.746	0.919	0.858	0.818
35,000	0.691	0.853	0.446	0.763	0.546	0.656	0.886	0.654	0.741	0.916	0.854	0.814
36,000	0.685	0.849	0.439	0.758	0.539	0.650	0.883	0.647	0.736	0.914	0.851	0.810
37,000	0.679	0.846	0.433	0.753	0.533	0.644	0.881	0.641	0.730	0.912	0.847	0.806
38,000	0.674	0.842	0.427	0.748	0.527	0.638	0.878	0.636	0.725	0.910	0.844	0.801
39,000	0.668	0.839	0.421	0.743	0.521	0.632	0.875	0.630	0.720	0.908	0.840	0.797
40,000	0.663	0.836	0.415	0.739	0.515	0.627	0.872	0.624	0.715	0.906	0.837	0.793
41,000	0.658	0.832	0.410	0.734	0.509	0.621	0.870	0.619	0.710	0.904	0.834	0.789
42,000	0.652	0.829	0.404	0.729	0.503	0.616	0.867	0.613	0.706	0.902	0.830	0.785
43,000	0.647	0.826	0.399	0.725	0.497	0.611	0.864	0.608	0.701	0.899	0.827	0.782
44,000	0.642	0.822	0.394	0.720	0.492	0.605	0.861	0.603	0.696	0.897	0.824	0.778
45,000	0.637	0.819	0.389	0.716	0.487	0.600	0.859	0.597	0.692	0.895	0.821	0.774
46,000	0.632	0.816	0.384	0.712	0.482	0.595	0.856	0.592	0.687	0.893	0.817	0.770
47,000	0.628	0.813	0.379	0.707	0.477	0.590	0.854	0.587	0.683	0.891	0.814	0.766
48,000	0.623	0.810	0.375	0.703	0.472	0.585	0.851	0.583	0.678	0.889	0.811	0.763
49,000	0.618	0.807	0.370	0.699	0.467	0.581	0.848	0.578	0.674	0.887	0.808	0.759
50,000	0.614	0.803	0.366	0.695	0.462	0.576	0.846	0.573	0.670	0.885	0.805	0.756
51,000	0.609	0.800	0.362	0.691	0.458	0.571	0.843	0.569	0.666	0.883	0.802	0.752
52,000	0.605	0.797	0.357	0.687	0.453	0.567	0.841	0.564	0.661	0.881	0.799	0.748
53,000	0.600	0.794	0.353	0.683	0.449	0.562	0.838	0.560	0.657	0.879	0.796	0.745
54,000	0.596	0.791	0.349	0.679	0.444	0.558	0.836	0.555	0.653	0.877	0.793	0.742
55,000	0.592	0.788	0.346	0.675	0.440	0.554	0.833	0.551	0.649	0.875	0.790	0.738
56,000	0.588	0.785	0.342	0.671	0.436	0.550	0.831	0.547	0.645	0.873	0.787	0.735
57,000	0.584	0.782	0.338	0.668	0.432	0.546	0.828	0.543	0.641	0.871	0.784	0.731
58,000	0.580	0.780	0.335	0.664	0.428	0.541	0.826	0.539	0.638	0.869	0.781	0.728
59,000	0.576	0.777	0.331	0.660	0.424	0.537	0.823	0.535	0.634	0.868	0.779	0.725
60,000	0.572	0.774	0.328	0.657	0.420	0.533	0.821	0.531	0.630	0.866	0.776	0.722

Table 5. (cont.) Estimated *Escapement* rates for the 50th percentile for alternative quotas, by year, based on assumed ranges of catchability, availability, and natural mortality. Table entries represent percentiles for 250,000 realizations of the estimated *Escapement* .

Alternative Quota (mt)	***2009***	***2010***	***2011***	***2012***	***2013***	***2014***	***2015***	***2016***	***2018***	***2019***	***2021***	***2022***	***Average***
24,000	0.857	0.775	0.775	0.774	0.686	0.808	0.767	0.811	0.892	0.795	0.805	0.845	0.797
25,000	0.852	0.768	0.768	0.767	0.678	0.802	0.760	0.805	0.888	0.789	0.799	0.840	0.791
26,000	0.847	0.761	0.761	0.760	0.670	0.796	0.753	0.799	0.884	0.782	0.793	0.835	0.785
27,000	0.842	0.754	0.755	0.753	0.662	0.790	0.746	0.793	0.880	0.776	0.786	0.830	0.779
28,000	0.837	0.748	0.748	0.746	0.654	0.784	0.740	0.787	0.877	0.770	0.780	0.825	0.773
29,000	0.832	0.741	0.742	0.740	0.646	0.778	0.733	0.781	0.873	0.764	0.775	0.820	0.767
30,000	0.828	0.735	0.735	0.734	0.639	0.773	0.727	0.776	0.869	0.758	0.769	0.815	0.762
31,000	0.823	0.729	0.729	0.727	0.632	0.767	0.720	0.770	0.865	0.752	0.763	0.810	0.756
32,000	0.819	0.723	0.723	0.721	0.624	0.761	0.714	0.765	0.862	0.746	0.757	0.805	0.751
33,000	0.814	0.717	0.717	0.715	0.617	0.756	0.708	0.759	0.858	0.741	0.752	0.800	0.746
34,000	0.810	0.711	0.711	0.709	0.611	0.750	0.702	0.754	0.855	0.735	0.747	0.796	0.740
35,000	0.805	0.705	0.705	0.704	0.604	0.745	0.696	0.749	0.851	0.730	0.741	0.791	0.735
36,000	0.801	0.699	0.700	0.698	0.598	0.740	0.690	0.743	0.847	0.724	0.736	0.786	0.730
37,000	0.797	0.694	0.694	0.692	0.591	0.735	0.685	0.738	0.844	0.719	0.731	0.782	0.725
38,000	0.792	0.688	0.689	0.687	0.585	0.730	0.679	0.733	0.840	0.714	0.726	0.777	0.720
39,000	0.788	0.683	0.683	0.681	0.579	0.725	0.674	0.728	0.837	0.708	0.721	0.773	0.716
40,000	0.784	0.678	0.678	0.676	0.573	0.720	0.668	0.723	0.834	0.703	0.716	0.769	0.711
41,000	0.780	0.672	0.673	0.671	0.568	0.715	0.663	0.719	0.830	0.698	0.711	0.764	0.706
42,000	0.776	0.667	0.668	0.666	0.562	0.710	0.658	0.714	0.827	0.693	0.706	0.760	0.702
43,000	0.772	0.662	0.663	0.661	0.557	0.706	0.653	0.709	0.824	0.689	0.701	0.756	0.697
44,000	0.768	0.657	0.658	0.656	0.551	0.701	0.648	0.705	0.820	0.684	0.697	0.752	0.693
45,000	0.764	0.652	0.653	0.651	0.546	0.696	0.643	0.700	0.817	0.679	0.692	0.748	0.689
46,000	0.760	0.648	0.648	0.646	0.541	0.692	0.638	0.696	0.814	0.675	0.688	0.744	0.684
47,000	0.756	0.643	0.644	0.641	0.536	0.688	0.633	0.691	0.811	0.670	0.683	0.740	0.680
48,000	0.753	0.638	0.639	0.637	0.531	0.683	0.629	0.687	0.807	0.666	0.679	0.736	0.676
49,000	0.749	0.634	0.634	0.632	0.526	0.679	0.624	0.683	0.804	0.661	0.674	0.732	0.672
50,000	0.745	0.629	0.630	0.628	0.521	0.675	0.620	0.679	0.801	0.657	0.670	0.728	0.668
51,000	0.742	0.625	0.626	0.623	0.517	0.670	0.615	0.674	0.798	0.653	0.666	0.724	0.664
52,000	0.738	0.620	0.621	0.619	0.512	0.666	0.611	0.670	0.795	0.648	0.662	0.721	0.660
53,000	0.734	0.616	0.617	0.615	0.508	0.662	0.606	0.666	0.792	0.644	0.658	0.717	0.656
54,000	0.731	0.612	0.613	0.610	0.503	0.658	0.602	0.662	0.789	0.640	0.654	0.713	0.653
55,000	0.727	0.608	0.608	0.606	0.499	0.654	0.598	0.658	0.786	0.636	0.650	0.710	0.649
56,000	0.724	0.604	0.604	0.602	0.495	0.650	0.594	0.654	0.783	0.632	0.646	0.706	0.645
57,000	0.720	0.600	0.600	0.598	0.490	0.647	0.590	0.651	0.780	0.628	0.642	0.702	0.642
58,000	0.717	0.596	0.596	0.594	0.486	0.643	0.586	0.647	0.777	0.624	0.638	0.699	0.638
59,000	0.714	0.592	0.592	0.590	0.482	0.639	0.582	0.643	0.774	0.620	0.634	0.695	0.634
60,000	0.710	0.588	0.589	0.586	0.478	0.635	0.578	0.639	0.771	0.617	0.631	0.692	0.631

Table 6. Estimated F/M ratios for the 50th percentile for alternative quotas, by year, based on assumed ranges of catchability, availablity and natural mortality. Table entries repesent percentiles for 250,000 realizations of the estimated F/M ratio.

Alternative Quota (mt)	***1997***	***1998***	***1999***	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***
24,000	0.159	0.067	0.364	0.115	0.267	0.182	0.053	0.184	0.129	0.036	0.066	0.086
25,000	0.164	0.070	0.375	0.119	0.276	0.188	0.055	0.190	0.133	0.038	0.068	0.090
26,000	0.170	0.073	0.385	0.123	0.284	0.194	0.058	0.196	0.138	0.039	0.071	0.093
27,000	0.175	0.075	0.395	0.127	0.292	0.200	0.060	0.202	0.143	0.040	0.073	0.096
28,000	0.180	0.078	0.405	0.131	0.300	0.206	0.062	0.208	0.147	0.042	0.076	0.099
29,000	0.186	0.080	0.414	0.135	0.308	0.212	0.064	0.214	0.151	0.043	0.078	0.102
30,000	0.191	0.083	0.424	0.139	0.315	0.218	0.066	0.220	0.156	0.045	0.081	0.106
31,000	0.196	0.085	0.433	0.143	0.323	0.224	0.068	0.226	0.160	0.046	0.083	0.109
32,000	0.201	0.088	0.442	0.147	0.330	0.229	0.070	0.231	0.165	0.048	0.086	0.112
33,000	0.206	0.090	0.451	0.151	0.338	0.235	0.072	0.237	0.169	0.049	0.088	0.115
34,000	0.211	0.093	0.459	0.155	0.345	0.241	0.074	0.243	0.173	0.050	0.090	0.118
35,000	0.216	0.095	0.468	0.159	0.352	0.246	0.076	0.248	0.177	0.052	0.093	0.121
36,000	0.221	0.098	0.476	0.163	0.359	0.251	0.078	0.254	0.181	0.053	0.095	0.124
37,000	0.226	0.100	0.485	0.166	0.366	0.257	0.080	0.259	0.186	0.054	0.098	0.127
38,000	0.231	0.103	0.493	0.170	0.373	0.262	0.082	0.264	0.190	0.056	0.100	0.130
39,000	0.235	0.105	0.501	0.174	0.379	0.267	0.084	0.270	0.194	0.057	0.102	0.133
40,000	0.240	0.107	0.509	0.178	0.386	0.272	0.086	0.275	0.198	0.059	0.105	0.136
41,000	0.245	0.110	0.516	0.181	0.393	0.278	0.088	0.280	0.202	0.060	0.107	0.139
42,000	0.249	0.112	0.524	0.185	0.399	0.283	0.089	0.285	0.206	0.061	0.109	0.142
43,000	0.254	0.114	0.532	0.188	0.405	0.288	0.091	0.290	0.210	0.063	0.111	0.145
44,000	0.258	0.117	0.539	0.192	0.412	0.293	0.093	0.295	0.213	0.064	0.114	0.148
45,000	0.263	0.119	0.546	0.195	0.418	0.297	0.095	0.300	0.217	0.065	0.116	0.150
46,000	0.267	0.121	0.553	0.199	0.424	0.302	0.097	0.305	0.221	0.067	0.118	0.153
47,000	0.272	0.124	0.561	0.202	0.430	0.307	0.099	0.310	0.225	0.068	0.121	0.156
48,000	0.276	0.126	0.568	0.206	0.436	0.312	0.101	0.314	0.229	0.069	0.123	0.159
49,000	0.280	0.128	0.574	0.209	0.442	0.317	0.103	0.319	0.232	0.071	0.125	0.162
50,000	0.285	0.130	0.581	0.213	0.448	0.321	0.105	0.324	0.236	0.072	0.127	0.164
51,000	0.289	0.133	0.588	0.216	0.453	0.326	0.107	0.328	0.240	0.073	0.129	0.167
52,000	0.293	0.135	0.594	0.220	0.459	0.330	0.108	0.333	0.244	0.075	0.132	0.170
53,000	0.297	0.137	0.601	0.223	0.465	0.335	0.110	0.338	0.247	0.076	0.134	0.172
54,000	0.301	0.139	0.607	0.226	0.470	0.339	0.112	0.342	0.251	0.077	0.136	0.175
55,000	0.305	0.142	0.614	0.229	0.476	0.344	0.114	0.347	0.254	0.079	0.138	0.178
56,000	0.309	0.144	0.620	0.233	0.481	0.348	0.116	0.351	0.258	0.080	0.140	0.181
57,000	0.313	0.146	0.626	0.236	0.486	0.353	0.118	0.355	0.261	0.081	0.143	0.183
58,000	0.317	0.148	0.632	0.239	0.492	0.357	0.119	0.360	0.265	0.083	0.145	0.186
59,000	0.321	0.150	0.638	0.242	0.497	0.361	0.121	0.364	0.268	0.084	0.147	0.188
60,000	0.325	0.153	0.644	0.246	0.502	0.365	0.123	0.368	0.272	0.085	0.149	0.191

Table 6. (cont.) Estimated F/M ratios for the 50th percentile for alternative quotas, by year, based on assumed ranges of catchability, availablity and natural mortality. Table entries repesent percentiles for 250,000 realizations of the estimated F/M ratio.

Alternative Quota (mt)	***2009***	***2010***	***2011***	***2012***	***2013***	***2014***	***2015***	***2016***	***2018***	***2019***	***2021***	***2022***	***Average***
24,000	0.091	0.150	0.149	0.150	0.220	0.125	0.155	0.123	0.067	0.134	0.127	0.099	0.137
25,000	0.094	0.155	0.155	0.156	0.227	0.129	0.161	0.128	0.070	0.139	0.132	0.103	0.142
26,000	0.098	0.160	0.160	0.161	0.234	0.134	0.166	0.132	0.072	0.144	0.136	0.106	0.147
27,000	0.101	0.165	0.165	0.166	0.241	0.138	0.171	0.136	0.075	0.149	0.141	0.110	0.152
28,000	0.105	0.170	0.170	0.171	0.248	0.143	0.177	0.141	0.077	0.153	0.145	0.114	0.156
29,000	0.108	0.175	0.175	0.176	0.255	0.147	0.182	0.145	0.080	0.158	0.150	0.117	0.161
30,000	0.111	0.180	0.180	0.181	0.261	0.151	0.187	0.149	0.083	0.162	0.154	0.121	0.165
31,000	0.114	0.185	0.185	0.186	0.268	0.156	0.192	0.153	0.085	0.167	0.158	0.124	0.170
32,000	0.118	0.190	0.190	0.191	0.275	0.160	0.197	0.158	0.088	0.171	0.163	0.128	0.174
33,000	0.121	0.195	0.195	0.196	0.281	0.164	0.202	0.162	0.090	0.176	0.167	0.131	0.178
34,000	0.124	0.200	0.199	0.201	0.287	0.168	0.207	0.166	0.092	0.180	0.171	0.135	0.183
35,000	0.127	0.205	0.204	0.206	0.293	0.172	0.212	0.170	0.095	0.185	0.175	0.138	0.187
36,000	0.130	0.209	0.209	0.210	0.300	0.176	0.217	0.174	0.097	0.189	0.180	0.141	0.191
37,000	0.133	0.214	0.213	0.215	0.306	0.180	0.221	0.178	0.100	0.193	0.184	0.145	0.195
38,000	0.137	0.218	0.218	0.220	0.312	0.184	0.226	0.182	0.102	0.197	0.188	0.148	0.199
39,000	0.140	0.223	0.222	0.224	0.318	0.188	0.231	0.186	0.105	0.202	0.192	0.151	0.203
40,000	0.143	0.228	0.227	0.229	0.323	0.192	0.235	0.190	0.107	0.206	0.196	0.155	0.207
41,000	0.146	0.232	0.231	0.233	0.329	0.196	0.240	0.194	0.109	0.210	0.200	0.158	0.211
42,000	0.149	0.236	0.236	0.238	0.335	0.200	0.244	0.197	0.112	0.214	0.204	0.161	0.215
43,000	0.152	0.241	0.240	0.242	0.341	0.204	0.249	0.201	0.114	0.218	0.207	0.164	0.219
44,000	0.155	0.245	0.244	0.246	0.346	0.208	0.253	0.205	0.116	0.222	0.211	0.168	0.223
45,000	0.158	0.249	0.249	0.251	0.352	0.211	0.258	0.209	0.119	0.226	0.215	0.171	0.227
46,000	0.161	0.254	0.253	0.255	0.357	0.215	0.262	0.212	0.121	0.230	0.219	0.174	0.231
47,000	0.164	0.258	0.257	0.259	0.363	0.219	0.266	0.216	0.123	0.234	0.223	0.177	0.235
48,000	0.167	0.262	0.261	0.263	0.368	0.223	0.271	0.220	0.126	0.238	0.226	0.180	0.238
49,000	0.169	0.266	0.265	0.267	0.373	0.226	0.275	0.223	0.128	0.242	0.230	0.183	0.242
50,000	0.172	0.270	0.270	0.271	0.378	0.230	0.279	0.227	0.130	0.245	0.234	0.186	0.246
51,000	0.175	0.274	0.274	0.276	0.384	0.233	0.283	0.230	0.132	0.249	0.237	0.189	0.249
52,000	0.178	0.278	0.278	0.280	0.389	0.237	0.287	0.234	0.135	0.253	0.241	0.192	0.253
53,000	0.181	0.282	0.282	0.284	0.394	0.240	0.292	0.237	0.137	0.257	0.245	0.195	0.257
54,000	0.184	0.286	0.286	0.288	0.399	0.244	0.296	0.241	0.139	0.260	0.248	0.198	0.260
55,000	0.186	0.290	0.289	0.292	0.404	0.248	0.300	0.244	0.141	0.264	0.252	0.201	0.264
56,000	0.189	0.294	0.293	0.295	0.409	0.251	0.304	0.248	0.144	0.268	0.255	0.204	0.267
57,000	0.192	0.298	0.297	0.299	0.413	0.254	0.307	0.251	0.146	0.271	0.259	0.207	0.271
58,000	0.195	0.302	0.301	0.303	0.418	0.258	0.311	0.255	0.148	0.275	0.262	0.210	0.274
59,000	0.197	0.306	0.305	0.307	0.423	0.261	0.315	0.258	0.150	0.278	0.266	0.213	0.278
60,000	0.200	0.309	0.309	0.311	0.428	0.265	0.319	0.261	0.152	0.282	0.269	0.216	0.281

Table 7. Estimated probabilities of falling below Escapement thresholds based on observed catches.

	Escapement Threshold				
Year	***0.35***	***0.4***	***0.5***	***0.6***	***0.75***
1997	0.000	0.000	0.002	0.035	0.240
1998	0.000	0.000	0.003	0.017	0.113
1999	0.001	0.007	0.059	0.179	0.484
2000	0.000	0.000	0.000	0.000	0.020
2001	0.000	0.000	0.000	0.000	0.071
2002	0.000	0.000	0.000	0.000	0.000
2003	0.000	0.000	0.000	0.001	0.009
2004	0.010	0.033	0.131	0.285	0.613
2005	0.000	0.000	0.004	0.023	0.152
2006	0.000	0.000	0.000	0.000	0.000
2007	0.000	0.000	0.000	0.000	0.000
2008	0.000	0.000	0.000	0.001	0.076
2009	0.000	0.000	0.000	0.005	0.116
2010	0.000	0.000	0.005	0.047	0.266
2011	0.000	0.000	0.014	0.082	0.338
2012	0.000	0.000	0.000	0.009	0.155
2013	0.000	0.000	0.000	0.000	0.015
2014	0.000	0.000	0.000	0.000	0.032
2015	0.000	0.000	0.000	0.000	0.000
2016	0.000	0.000	0.000	0.000	0.008
2018	0.000	0.000	0.000	0.002	0.103
2019	0.000	0.004	0.047	0.157	0.455
2021	0.001	0.006	0.054	0.170	0.472
2022	0.000	0.000	0.000	0.000	0.001

Table 8. Estimated probabilities of exceeding F/M thresholds based on observed catches.

	F/M Threshold				
Year	***0.33***	***0.5***	***0.666***	***1***	***1.5***
1997	0.224	0.153	0.112	0.065	0.030
1998	0.161	0.103	0.071	0.036	0.014
1999	0.320	0.231	0.178	0.116	0.067
2000	0.110	0.063	0.038	0.014	0.001
2001	0.149	0.093	0.062	0.029	0.008
2002	0.050	0.021	0.008	0.000	0.000
2003	0.027	0.013	0.007	0.003	0.001
2004	0.372	0.274	0.215	0.145	0.089
2005	0.183	0.121	0.085	0.046	0.019
2006	0.043	0.017	0.006	0.001	0.000
2007	0.053	0.023	0.009	0.000	0.000
2008	0.151	0.095	0.063	0.030	0.008
2009	0.171	0.111	0.077	0.039	0.014
2010	0.235	0.161	0.119	0.070	0.034
2011	0.263	0.184	0.138	0.085	0.044
2012	0.190	0.125	0.089	0.047	0.019
2013	0.107	0.060	0.037	0.013	0.001
2014	0.124	0.074	0.046	0.019	0.002
2015	0.035	0.012	0.003	0.000	0.000
2016	0.090	0.048	0.027	0.008	0.000
2018	0.166	0.106	0.073	0.036	0.012
2019	0.309	0.221	0.170	0.109	0.062
2021	0.315	0.227	0.175	0.113	0.065
2022	0.054	0.024	0.010	0.001	0.000

Table 9. Estimated joint probabilities of falling below *Escapement* thresholds AND exceeding F/M=0.666 based on Observed catches.

	Escapement Threshold				
Year	***0.35***	***0.4***	***0.5***	***0.6***	***0.75***
1997	0.000	0.000	0.002	0.025	0.061
1998	0.000	0.000	0.003	0.010	0.031
1999	0.001	0.007	0.049	0.091	0.114
2000	0.000	0.000	0.000	0.000	0.008
2001	0.000	0.000	0.000	0.000	0.023
2002	0.000	0.000	0.000	0.000	0.000
2003	0.000	0.000	0.000	0.001	0.002
2004	0.010	0.033	0.094	0.129	0.144
2005	0.000	0.000	0.004	0.014	0.041
2006	0.000	0.000	0.000	0.000	0.000
2007	0.000	0.000	0.000	0.000	0.000
2008	0.000	0.000	0.000	0.001	0.024
2009	0.000	0.000	0.000	0.004	0.033
2010	0.000	0.000	0.005	0.031	0.066
2011	0.000	0.000	0.013	0.050	0.082
2012	0.000	0.000	0.000	0.008	0.042
2013	0.000	0.000	0.000	0.000	0.007
2014	0.000	0.000	0.000	0.000	0.012
2015	0.000	0.000	0.000	0.000	0.000
2016	0.000	0.000	0.000	0.000	0.004
2018	0.000	0.000	0.000	0.002	0.031
2019	0.000	0.004	0.040	0.083	0.108
2021	0.001	0.006	0.046	0.088	0.112
2022	0.000	0.000	0.000	0.000	0.000

Table 10. Estimated probabilities of falling below Escapement thresholds based on alternative quota values. Probabilities are averaged across all years.

Alternative Quota (mt)	***Escapement Threshold***				
	0.35	***0.4***	***0.5***	***0.6***	***0.75***
24000	0.0106	0.0198	0.0574	0.1350	0.3602
25000	0.0120	0.0221	0.0630	0.1449	0.3757
26000	0.0134	0.0245	0.0688	0.1548	0.3906
27000	0.0149	0.0271	0.0748	0.1647	0.4052
28000	0.0165	0.0298	0.0808	0.1746	0.4192
29000	0.0181	0.0326	0.0870	0.1843	0.4329
30000	0.0199	0.0356	0.0932	0.1941	0.4462
31000	0.0217	0.0387	0.0995	0.2037	0.4591
32000	0.0237	0.0418	0.1059	0.2132	0.4716
33000	0.0257	0.0451	0.1123	0.2227	0.4837
34000	0.0278	0.0485	0.1187	0.2320	0.4955
35000	0.0299	0.0520	0.1252	0.2412	0.5070
36000	0.0322	0.0555	0.1316	0.2503	0.5181
37000	0.0346	0.0592	0.1381	0.2594	0.5288
38000	0.0370	0.0629	0.1446	0.2683	0.5393
39000	0.0395	0.0667	0.1511	0.2771	0.5495
40000	0.0420	0.0705	0.1575	0.2857	0.5594
41000	0.0447	0.0744	0.1640	0.2943	0.5690
42000	0.0473	0.0783	0.1704	0.3027	0.5784
43000	0.0501	0.0823	0.1768	0.3110	0.5874
44000	0.0529	0.0863	0.1832	0.3192	0.5963
45000	0.0557	0.0904	0.1895	0.3273	0.6048
46000	0.0586	0.0944	0.1958	0.3353	0.6132
47000	0.0616	0.0985	0.2021	0.3432	0.6213
48000	0.0646	0.1027	0.2083	0.3509	0.6292
49000	0.0676	0.1068	0.2145	0.3585	0.6368
50000	0.0707	0.1110	0.2206	0.3661	0.6443
51000	0.0738	0.1152	0.2267	0.3735	0.6515
52000	0.0769	0.1194	0.2328	0.3808	0.6586
53000	0.0801	0.1236	0.2388	0.3880	0.6654
54000	0.0832	0.1278	0.2448	0.3951	0.6721
55000	0.0865	0.1320	0.2507	0.4021	0.6786
56000	0.0897	0.1362	0.2565	0.4089	0.6850
57000	0.0929	0.1404	0.2624	0.4157	0.6911
58000	0.0962	0.1446	0.2681	0.4224	0.6971
59000	0.0995	0.1488	0.2739	0.4290	0.7030
60000	0.1028	0.1530	0.2795	0.4355	0.7086

Table 11. Estimated probabilities of exceeding F/M ratio thresholds based on alternative quota values. Probabilities are averaged across all years.

Alternative Quota (mt)	***F/M Threshold***				
	0.33	***0.5***	***0.666***	***1***	***1.5***
24000	0.2694	0.1906	0.1446	0.0912	0.0510
25000	0.2763	0.1962	0.1494	0.0947	0.0536
26000	0.2830	0.2017	0.1540	0.0983	0.0561
27000	0.2895	0.2070	0.1585	0.1017	0.0586
28000	0.2958	0.2122	0.1629	0.1050	0.0610
29000	0.3020	0.2172	0.1672	0.1083	0.0634
30000	0.3080	0.2221	0.1714	0.1115	0.0657
31000	0.3138	0.2269	0.1755	0.1147	0.0680
32000	0.3195	0.2316	0.1795	0.1178	0.0702
33000	0.3251	0.2362	0.1834	0.1208	0.0725
34000	0.3305	0.2407	0.1873	0.1238	0.0746
35000	0.3358	0.2451	0.1910	0.1267	0.0768
36000	0.3410	0.2494	0.1947	0.1295	0.0789
37000	0.3460	0.2536	0.1983	0.1323	0.0809
38000	0.3510	0.2577	0.2019	0.1351	0.0830
39000	0.3559	0.2618	0.2053	0.1378	0.0850
40000	0.3606	0.2657	0.2087	0.1405	0.0870
41000	0.3653	0.2696	0.2121	0.1431	0.0889
42000	0.3698	0.2734	0.2154	0.1457	0.0908
43000	0.3743	0.2772	0.2186	0.1482	0.0927
44000	0.3787	0.2809	0.2218	0.1507	0.0946
45000	0.3830	0.2845	0.2249	0.1531	0.0964
46000	0.3873	0.2880	0.2280	0.1555	0.0982
47000	0.3914	0.2915	0.2310	0.1579	0.1000
48000	0.3955	0.2949	0.2339	0.1602	0.1017
49000	0.3996	0.2983	0.2369	0.1625	0.1035
50000	0.4035	0.3016	0.2397	0.1648	0.1052
51000	0.4074	0.3049	0.2426	0.1670	0.1069
52000	0.4112	0.3081	0.2454	0.1692	0.1085
53000	0.4150	0.3113	0.2481	0.1714	0.1102
54000	0.4187	0.3144	0.2508	0.1735	0.1118
55000	0.4223	0.3175	0.2535	0.1756	0.1134
56000	0.4259	0.3205	0.2561	0.1777	0.1150
57000	0.4294	0.3235	0.2587	0.1798	0.1165
58000	0.4329	0.3264	0.2613	0.1818	0.1181
59000	0.4363	0.3294	0.2638	0.1838	0.1196
60000	0.4397	0.3322	0.2663	0.1858	0.1211

Table 12. Estimated JOINT probabilities of falling below *Escapement* thresholds AND F/M > 0.666 based on alternative quota values. Probabilities are averaged across all years.

Alternative	***Escapement Threshold***				
Quota (mt)	***0.35***	***0.4***	***0.5***	***0.6***	***0.75***
24000	0.0098	0.0164	0.0388	0.0650	0.0885
25000	0.0109	0.0183	0.0423	0.0691	0.0922
26000	0.0121	0.0202	0.0460	0.0731	0.0958
27000	0.0134	0.0222	0.0496	0.0771	0.0994
28000	0.0147	0.0244	0.0532	0.0810	0.1028
29000	0.0162	0.0266	0.0569	0.0848	0.1062
30000	0.0176	0.0289	0.0605	0.0886	0.1095
31000	0.0192	0.0313	0.0642	0.0922	0.1127
32000	0.0208	0.0338	0.0678	0.0959	0.1159
33000	0.0225	0.0364	0.0714	0.0994	0.1190
34000	0.0243	0.0390	0.0749	0.1029	0.1221
35000	0.0261	0.0417	0.0785	0.1064	0.1250
36000	0.0280	0.0444	0.0819	0.1097	0.1280
37000	0.0300	0.0472	0.0854	0.1131	0.1308
38000	0.0320	0.0500	0.0888	0.1163	0.1337
39000	0.0341	0.0528	0.0922	0.1195	0.1364
40000	0.0362	0.0557	0.0955	0.1227	0.1392
41000	0.0384	0.0586	0.0988	0.1257	0.1418
42000	0.0406	0.0615	0.1020	0.1288	0.1444
43000	0.0429	0.0644	0.1052	0.1318	0.1470
44000	0.0452	0.0673	0.1084	0.1347	0.1496
45000	0.0476	0.0702	0.1115	0.1375	0.1520
46000	0.0499	0.0731	0.1146	0.1404	0.1545
47000	0.0524	0.0760	0.1177	0.1431	0.1569
48000	0.0548	0.0789	0.1207	0.1459	0.1593
49000	0.0572	0.0818	0.1236	0.1485	0.1616
50000	0.0597	0.0846	0.1265	0.1512	0.1639
51000	0.0622	0.0875	0.1294	0.1538	0.1661
52000	0.0647	0.0903	0.1323	0.1563	0.1684
53000	0.0672	0.0931	0.1351	0.1588	0.1706
54000	0.0697	0.0960	0.1378	0.1613	0.1727
55000	0.0723	0.0987	0.1406	0.1637	0.1749
56000	0.0748	0.1015	0.1433	0.1661	0.1770
57000	0.0773	0.1043	0.1459	0.1684	0.1791
58000	0.0799	0.1070	0.1485	0.1707	0.1811
59000	0.0824	0.1097	0.1511	0.1730	0.1831
60000	0.0849	0.1124	0.1537	0.1752	0.1851

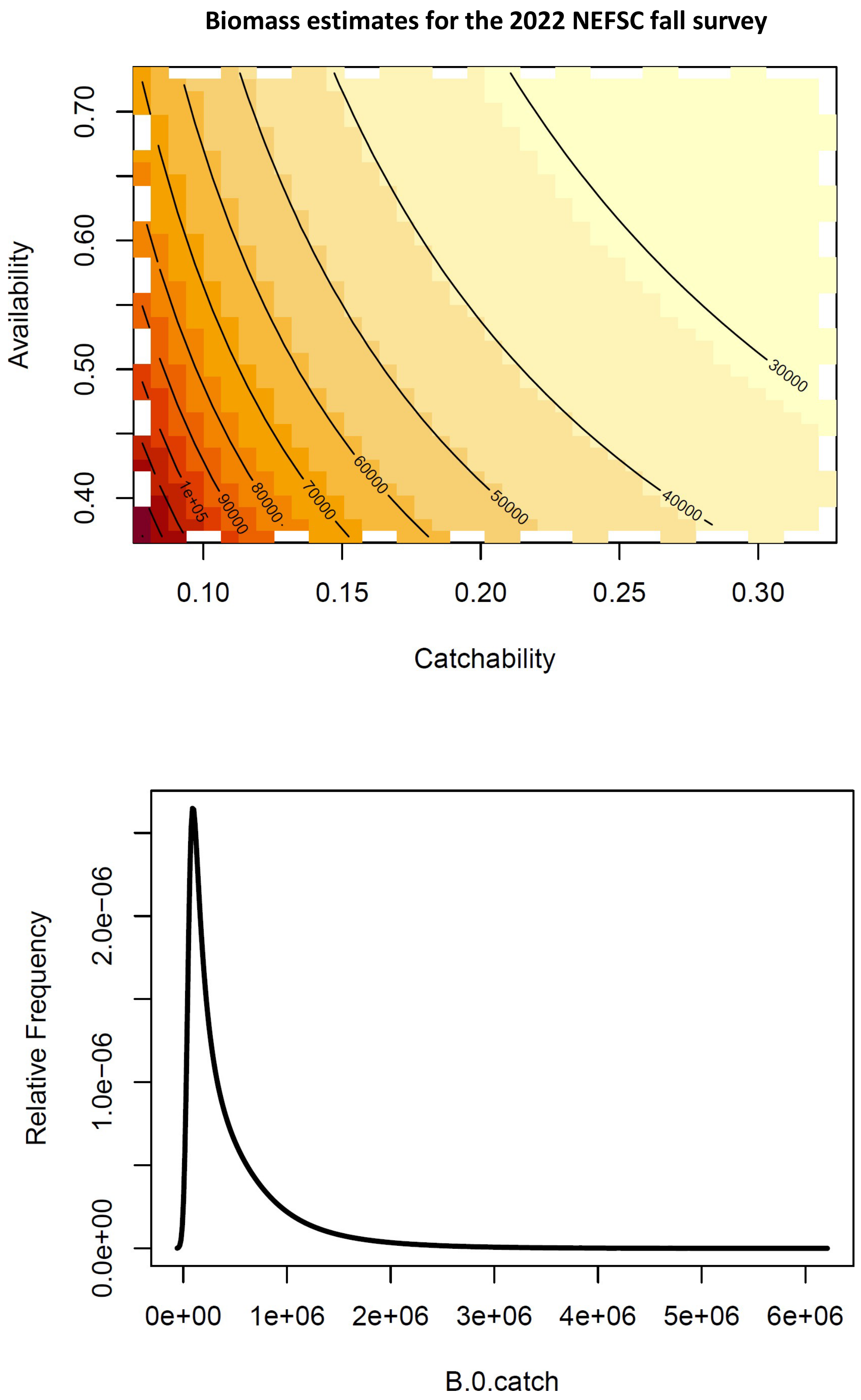


Figure 1. Isopleths of *I. illecebrosus* biomass (mt) estimates for combinations of q and v for 2022 (top) and marginal distribution of biomass estimates over all combinations of q, v, and M (bottom).

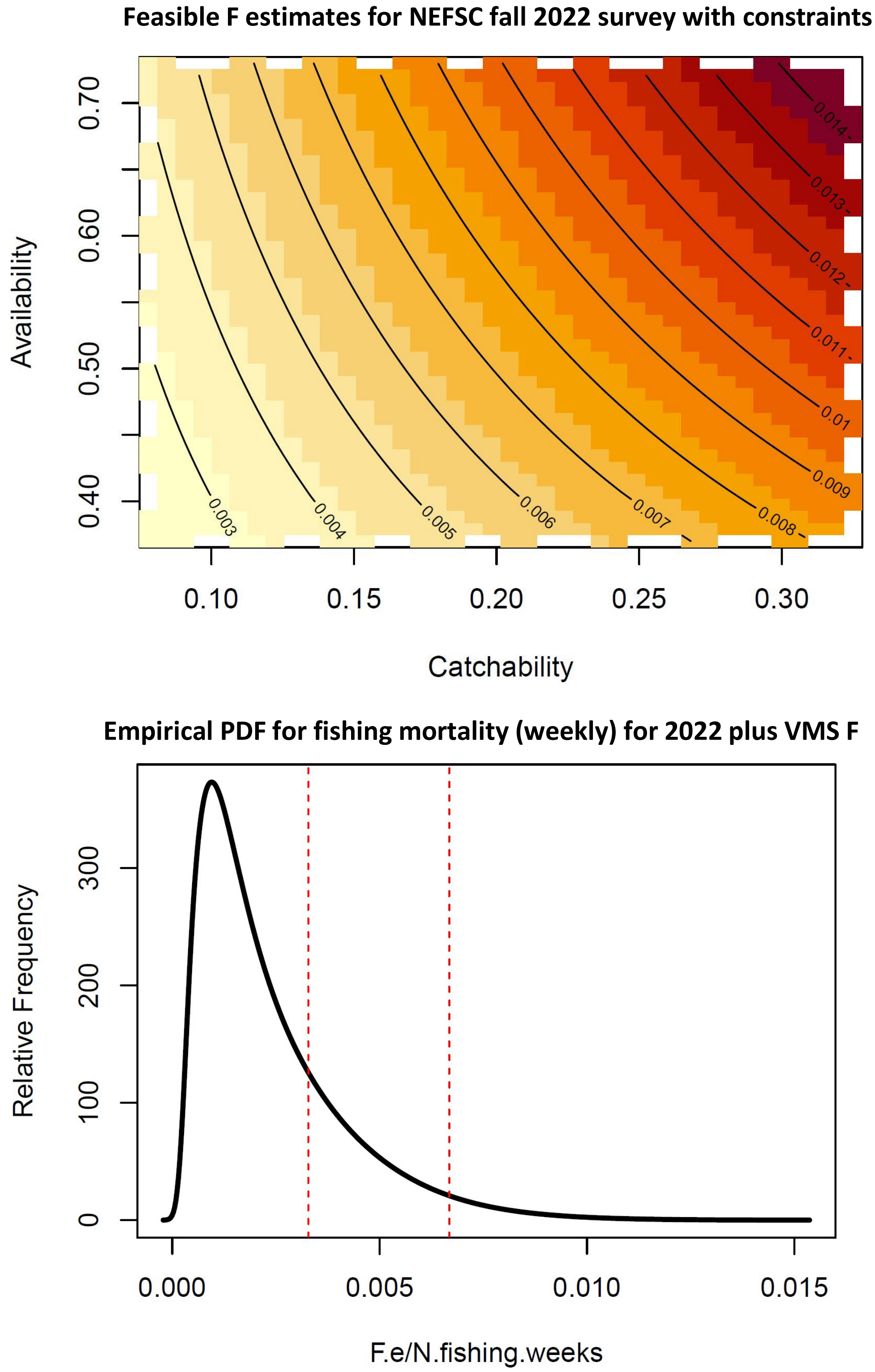


Figure 2. Isopleths of *I. illecebrosus* fishing mortality estimates (per week) for various combinations of q and v for 2022 (top) and derived distribution of fishing mortality rates (per week) for 2022. Red vertical lines depict the range of F values derived from VMS analyses for 2019. Weekly F range = [0.082/25, 0.167/25].

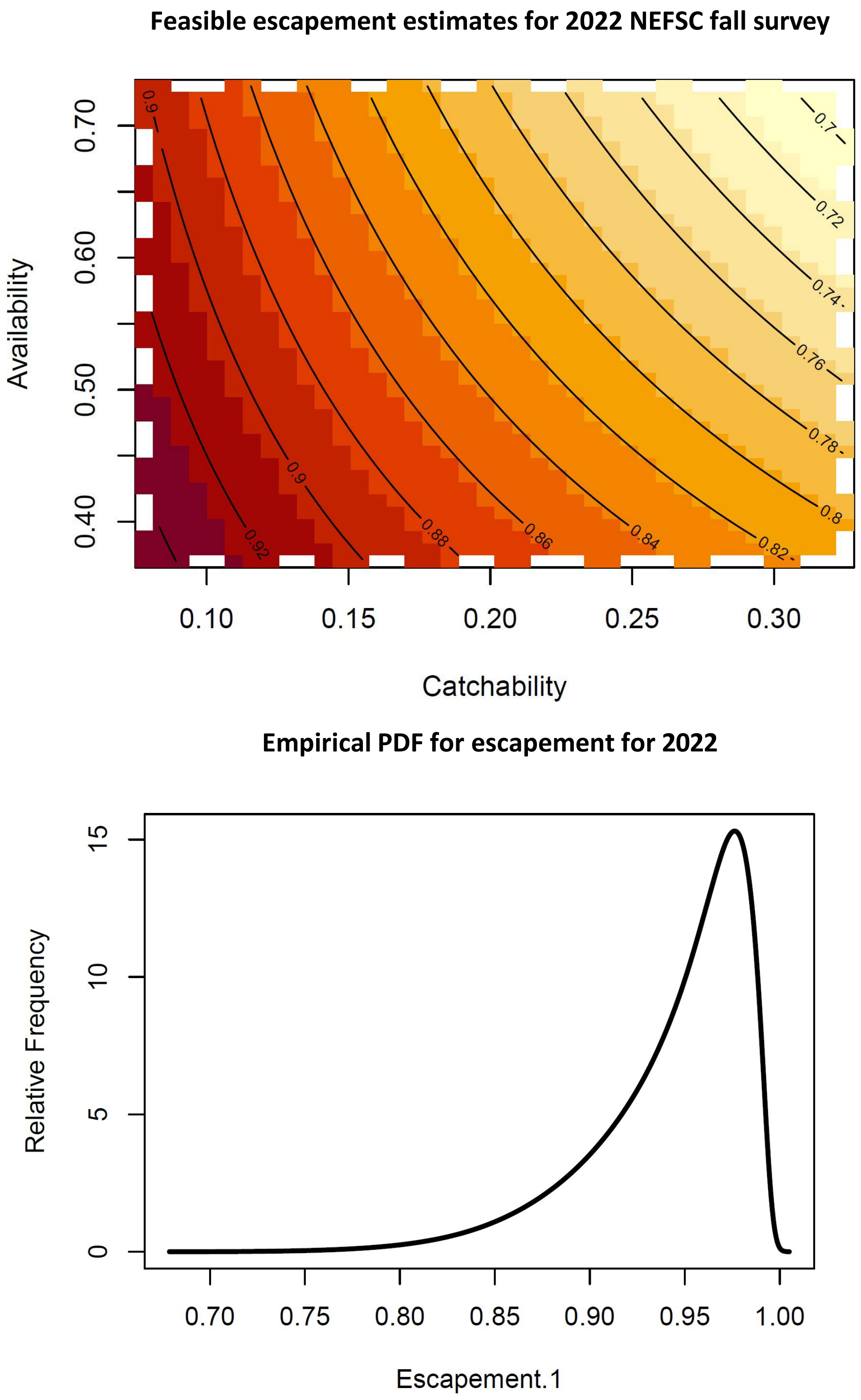


Figure 3. Isopleths of *Escapement* as a function of catchability and availability (top) and empirical distribution of *Escapement* based on observed catches in 2022 and observed NEFSC fall bottom trawl indices (bottom).

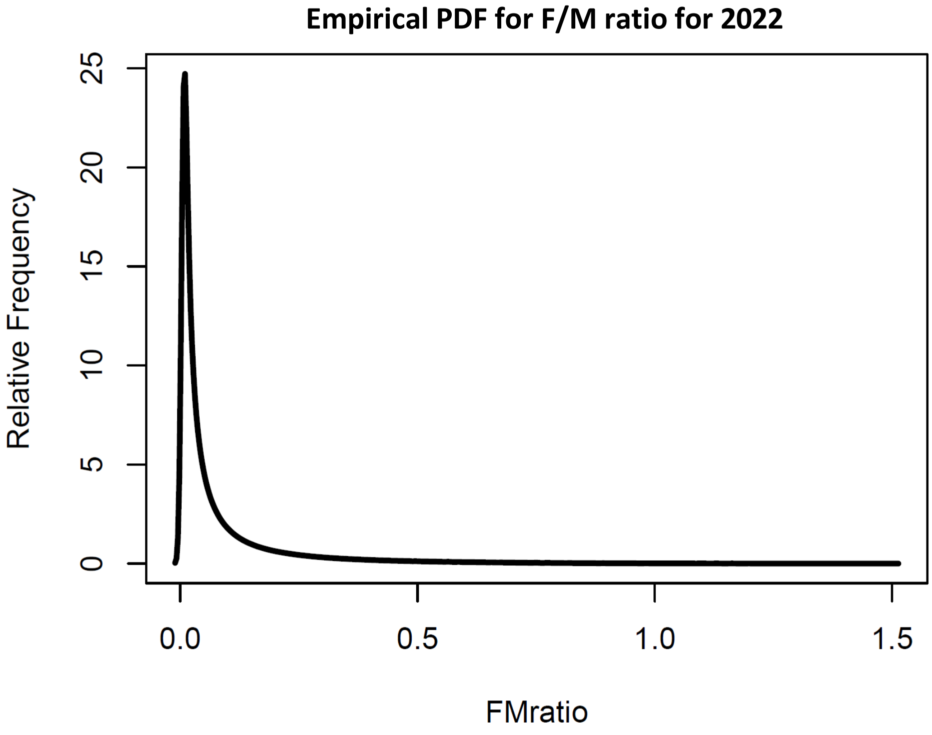


Figure 4. Empirical distribution of F/M ratio for 2022.

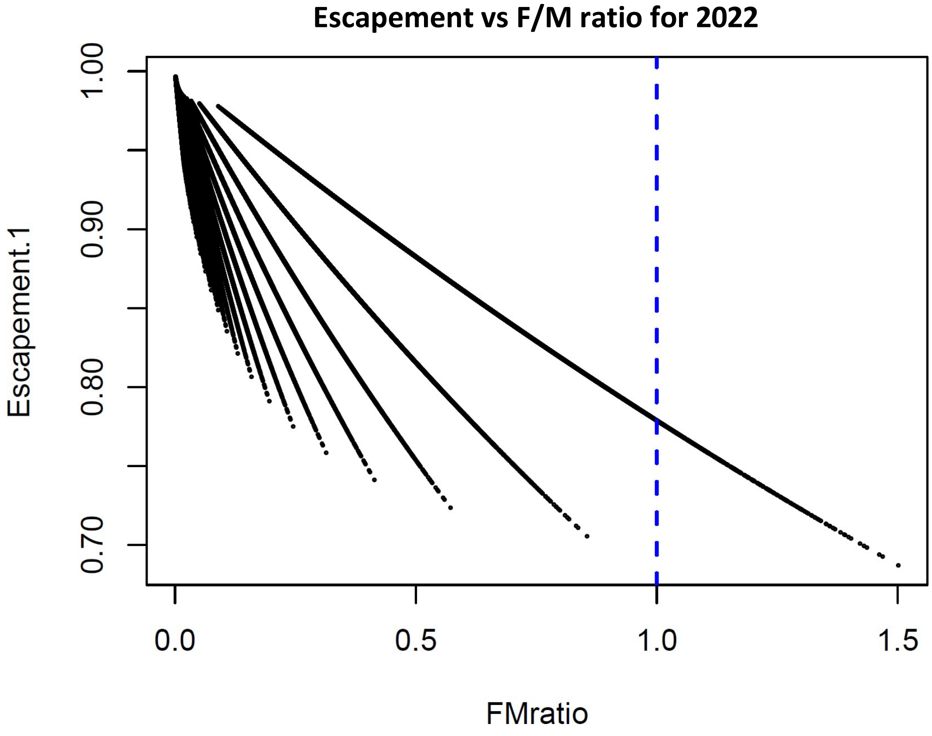


Figure 5. Relationship between *Escapememt* and estimated fishing mortality/assumed M over all 250,000 combinations of q, v, and M for 2022. The bands represent isopleths for assumed levels M. Low M (0.01 week^{-1}) on right and high M (0.13 week^{-1}) on left.

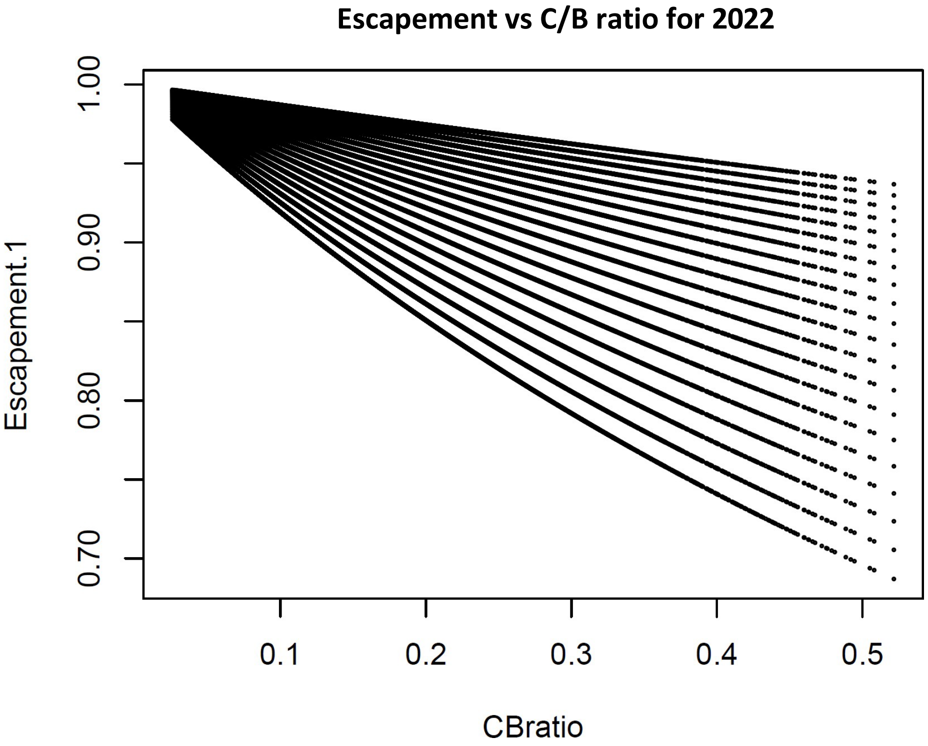
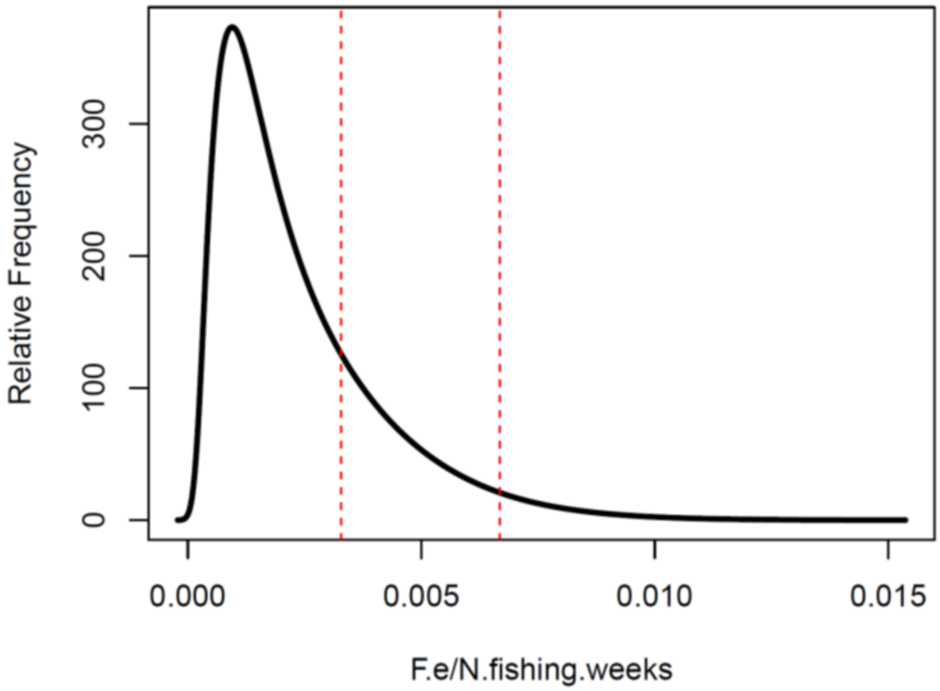
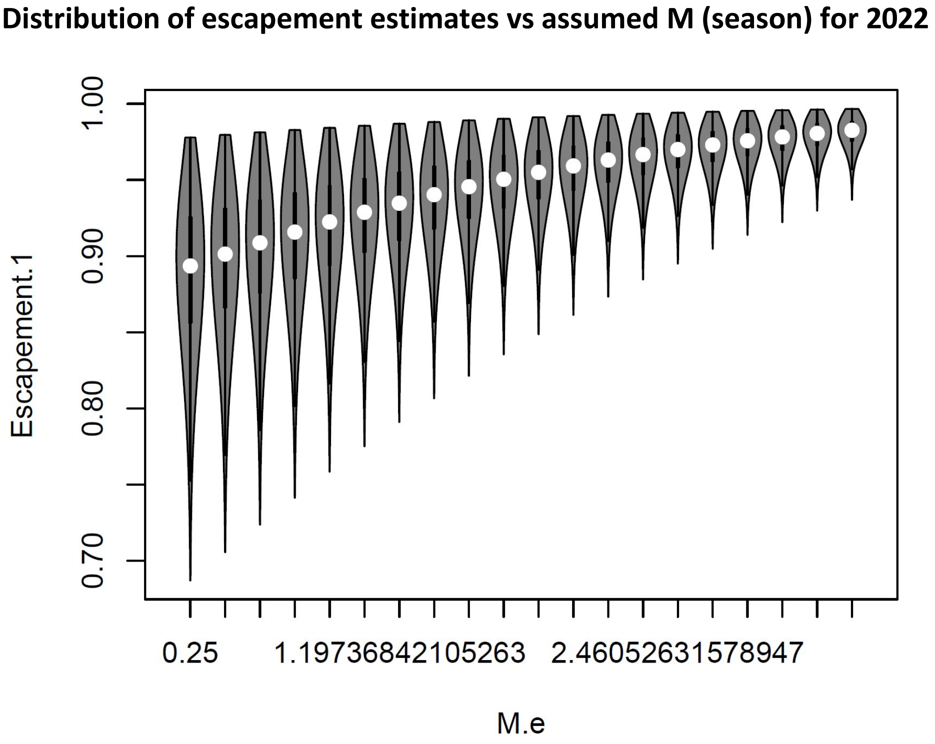


Figure 6. Relationship between *Escapement* and measures of exploitation for 2022. Catch divided by NEFSC fall survey biomass [top]. The trajectories correspond to assumed levels of M.



Empirical PDF for fishing mortality (weekly) for 2022 plus VMS F

Figure 7. Empirical probability density function for F (week^{-1}) estimates based on assumed ranges of q, v and M for 2022. Red vertical lines depict the range of F values derived from VMS analyses for 2019. Weekly F range = [0.082/25, 0.167/25].



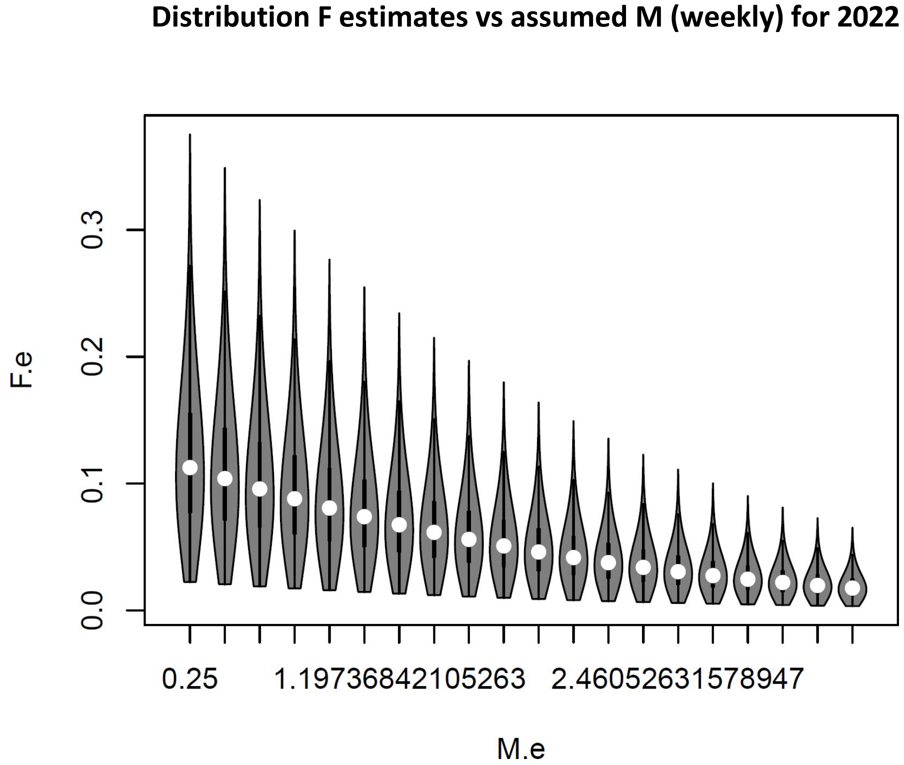


Figure 8. Relationship between estimated *Escapement* and assumed M (per 25 week season) for 2022 [top]. Relationship between estimated F and assumed M (per season of 25 weeks) [bottom]. Variation in F.e is induced by range of q and v estimates.

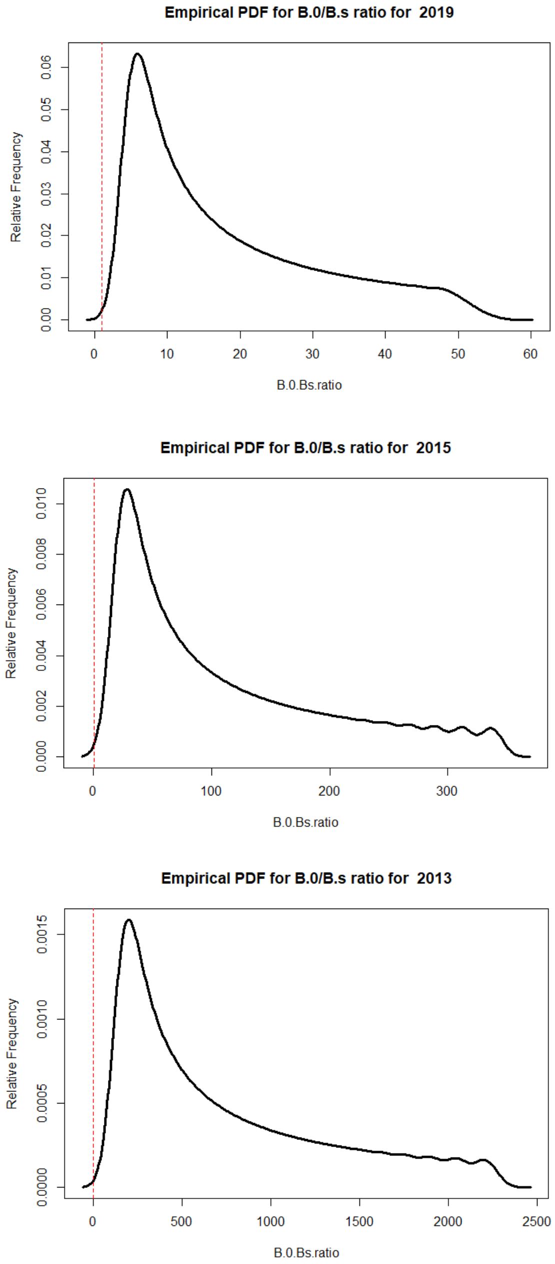


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Figure 9. Distribution of ratio of estimated biomass necessary to support the observed fishery catches (B.0) to the initial biomass defined by the spring survey (B.s). Three examples (2019, 2015, 2013) illustrate the orders of magnitude range of differences among years.

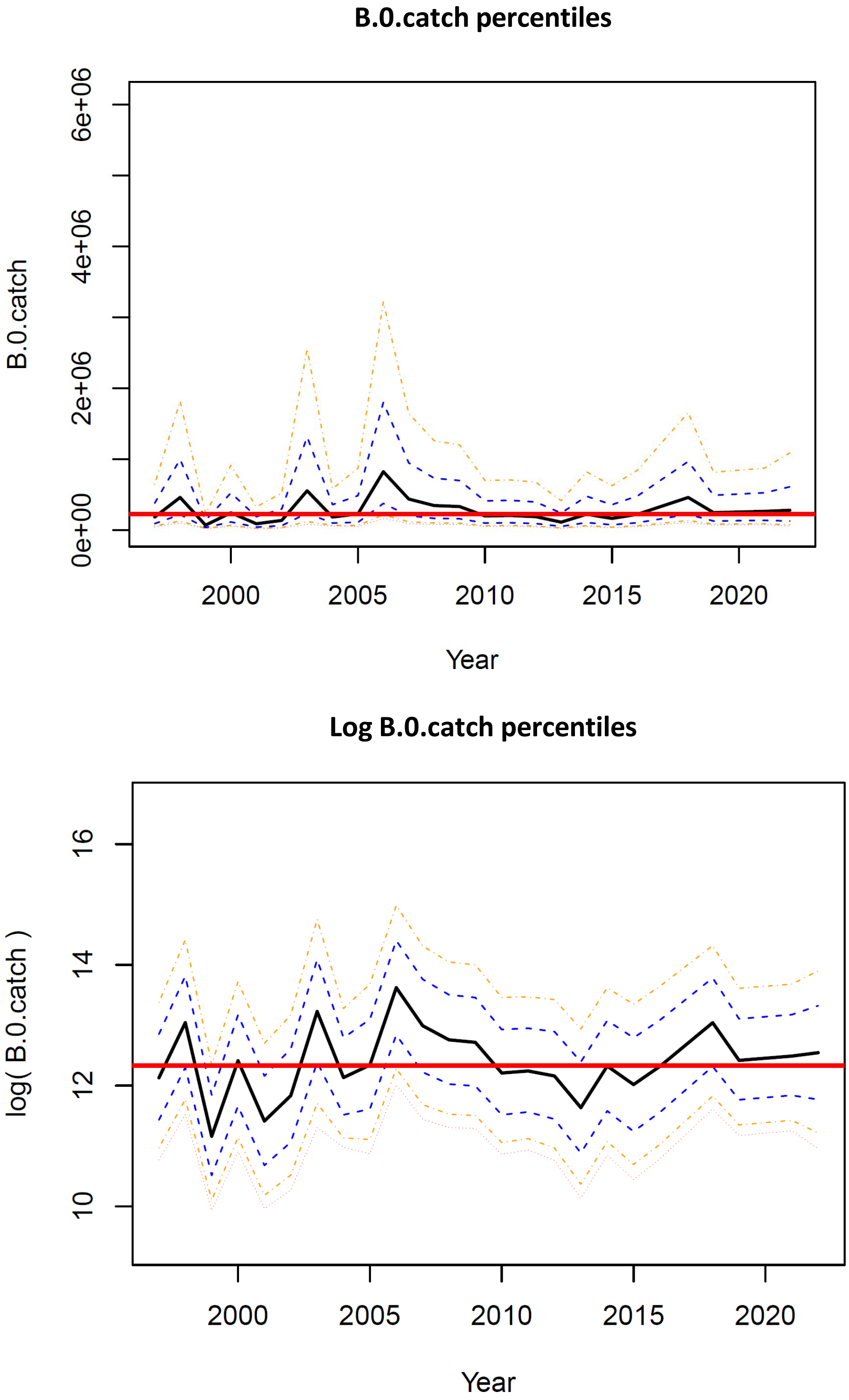

Figure 10. Estimated biomass levels in mt (1997-2022) based on 64,000 combinations of q, v, and M for each year [top]. Estimated percentiles for log biomass [bottom]. Surveys were missing for 2017 and 2020. The black line represents the median. Blue lines represent the interquartile range. The orange lines represent the 80% confidence bounds. The dotted red lines represent the 90% confidence interval. The solid red line is the median of the annual medians.

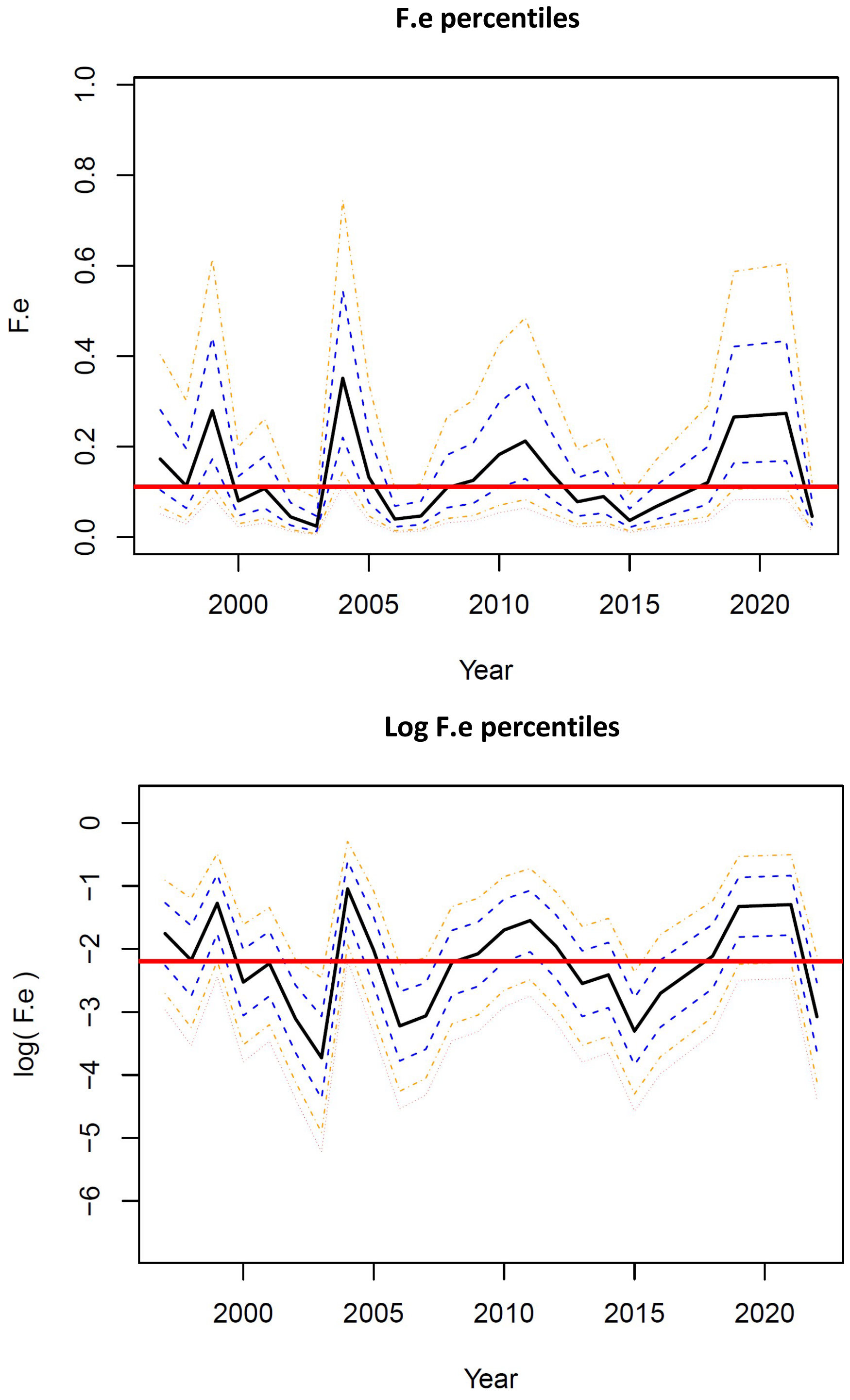

Figure 11. Estimated fishing mortality rates (per 25-week season), during 1997-2022, based on 64,000 combinations of q, v, and M for each year [top]. Log seasonal fishing mortality rates [bottom]. Surveys were missing for 2017 and 2020. The black line represents the median. The blue lines represent the interquartile range. The orange lines represent the 80% confidence bounds. The dotted red lines represent the 90% confidence interval. The solid red line is the median of the annual medians. The average weekly F is obtained by dividing the total by 25 weeks.

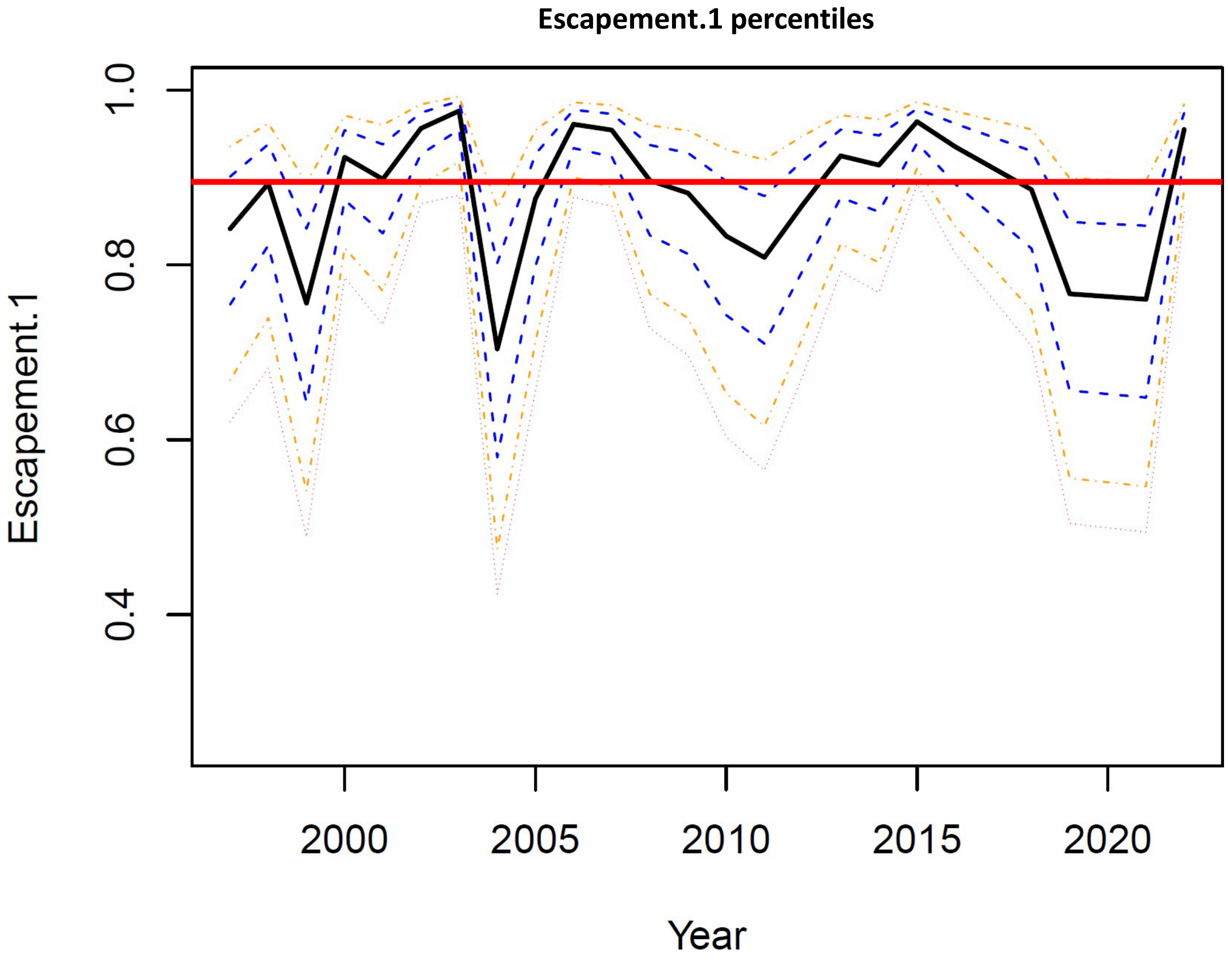

Figure 12. Estimated *Escapement* ratios for 1997-2022 based on 64,000 combinations of q, v, and M for each year. Fall surveys were missing for 2017 and 2020. The black line represents the median. The blue lines represent the interquartile range. The orange lines represent the 80% confidence bounds. The dotted red lines represent the 90% confidence interval. The solid red line is the median of the annual medians. Note that the lowest dashed line is the 5th percentile of the *Escapement* fraction.

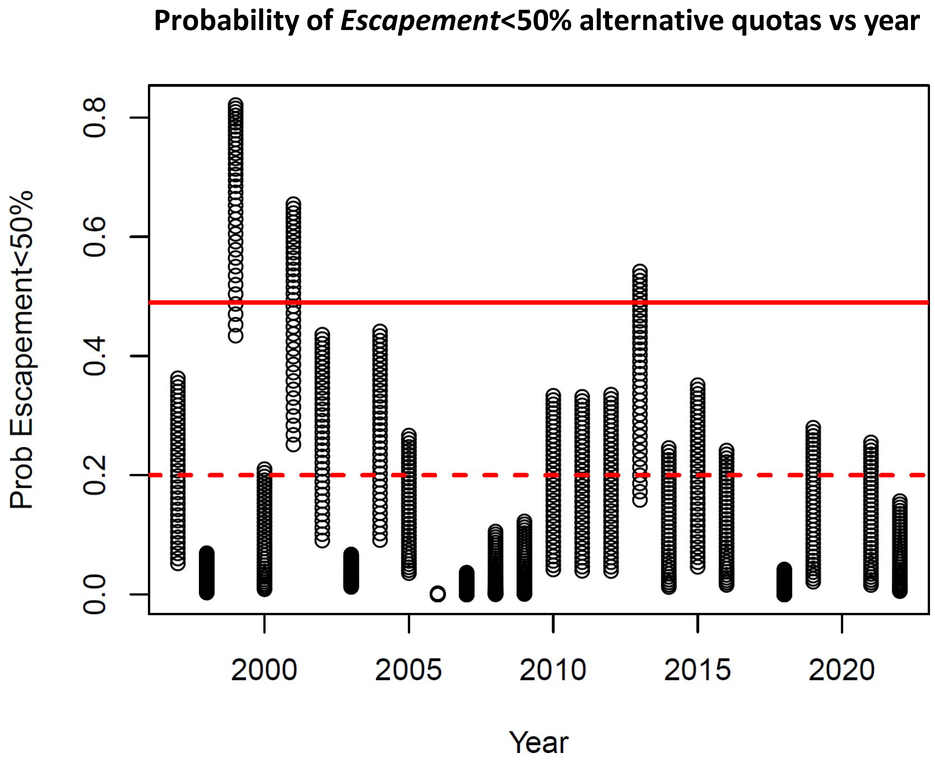

Figure 13. Estimated probability of *Escapement* less than **50%**, during 1997-2022, given alternative catch limits for each year ranging from 24,000 to 60,000. Each dot represents an alternative quota with lowest quotas at bottom and highest at top for each year. The initial population size in each year is based on the observed catch and the range of assumed q, v, and M values. The solid red line corresponds to the MAFMC's P* Risk Policy when B/Bmsy > 1.5. The dashed red line is the P* value corresponding to B/Bmsy=0.5.

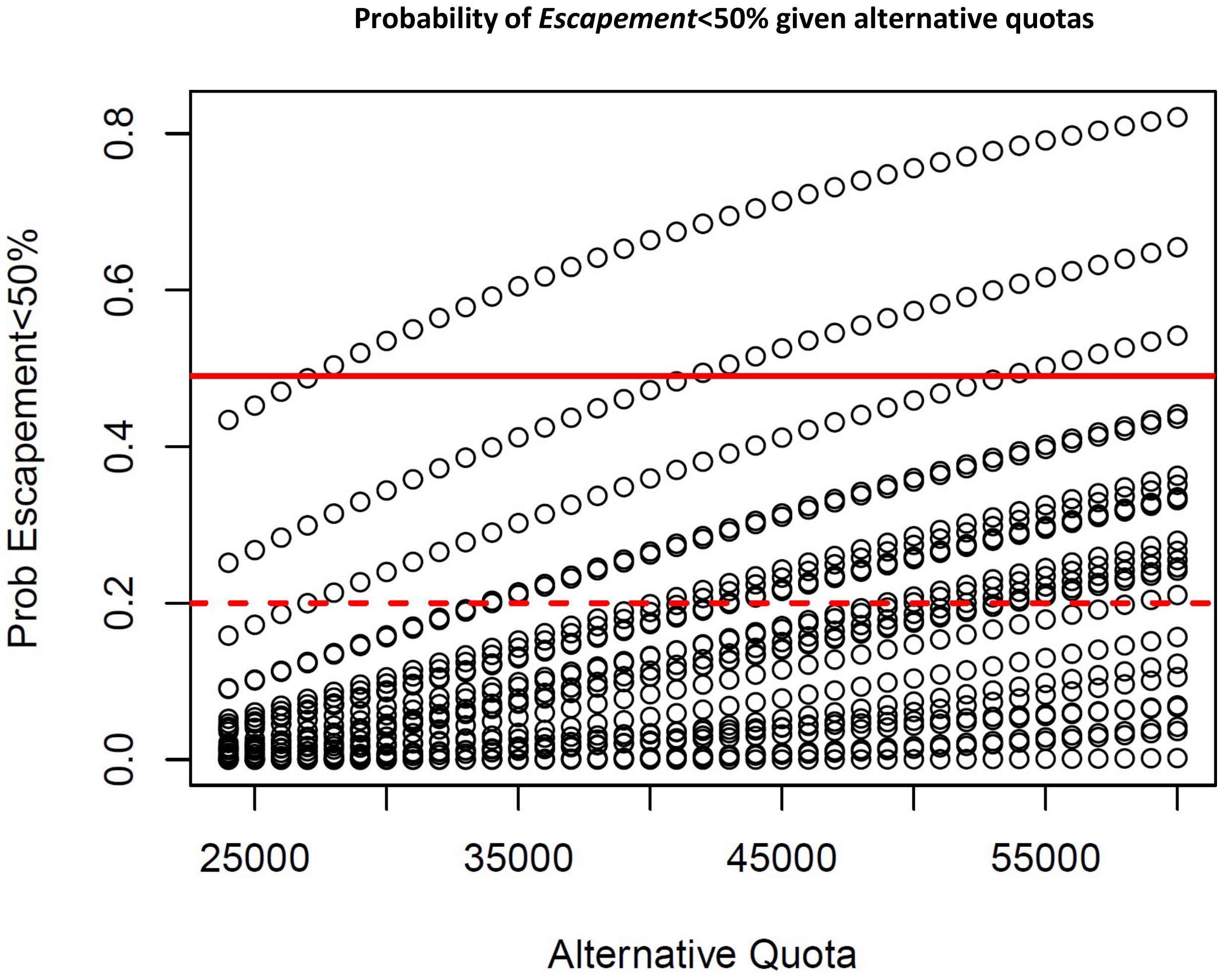

Figure 14. Estimated probability of *Escapement* being less than **50%**, during 1997-2022, given alternative catch limits from 24,000 to 60,000 mt. Each line is the trajectory of a given year reflecting the effect of different B.0 by year. The top line is 1999 which had the lowest B.0 starting value. The initial population size in each year is based on the observed catch and the range of assumed q, v, and M values.

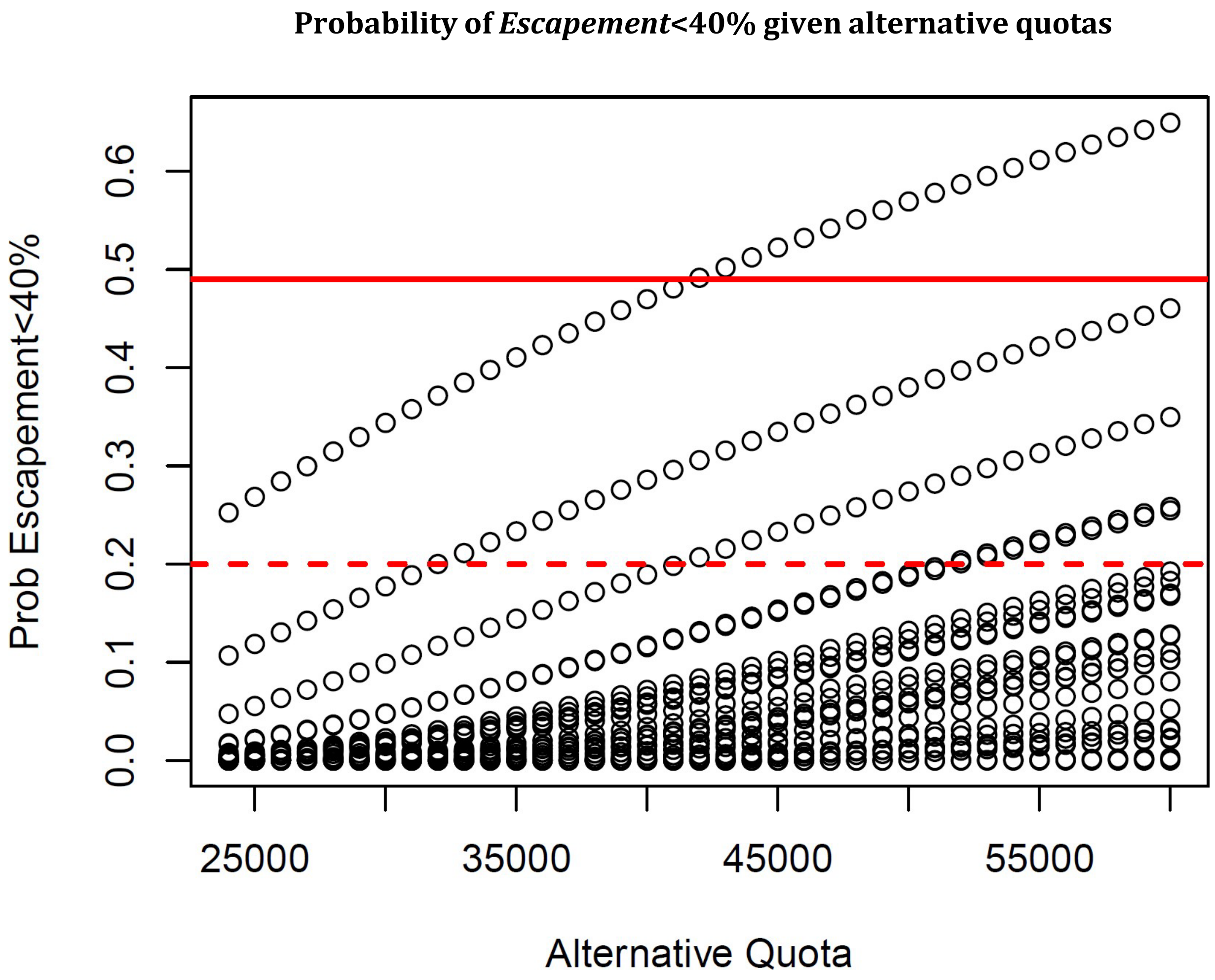

Figure 15. Estimated probability of *Escapement* less than **40%**, during 1997-2022, given alternative catch limits for each year ranging from 24,000 to 60,000. Each dot represents an alternative quota with lowest quotas at bottom and highest at top for each year. The initial population size in each year is based on the observed catch and the range of assumed q, v, and M values. The solid red line corresponds to the MAFMC's P*risk policy when B/Bmsy> 1.5. The dashed red line is the P* value corresponding to B/Bmsy=0.5.