Indirect Methods for Bounding Biomass and Fishing Mortality for Illex Squid and Implications of an Alternative Quota in 2022

Report to the Scientific and Statistical Committee

MidAtlantic Fishery Management Council

Paul Rago

May 11, 2021

Last updated May 4, 2021

Executive Summary

One of the most fundamental issues in stock assessment is trying to discern whether a realized catch is the result of a high rate of fishing applied to a small population or a low rate of fishing applied to a large population. In the former instance, rapidly falling catches over time and reduced economic viability are pretty good signs that overfishing was occurring. In the latter instance, persistence of catches over time might be attributable to sound management or luck. When basic assumptions are met and the underlying data are sound, most fisheries assessment models can help distinguish between these alternatives. When they are not, a variety of data poor methods have been used. Even these methods fail to adequately address problems of open populations. The techniques applied herein are designed to illustrate the logical consequences of the intersections of alternative hypotheses about survey and catch observations. Where possible, independent experiments and analyses and values from the literature are used to inform and refine critical model parameters. The various approaches employed in this working paper may ultimately form a basis for an integrated assessment model. But the conceptual basis for that integration remains to be developed and the uncertainties of the multiple perspectives applied herein seem appropriate.

This report summarizes the decisions of the SSC in 2020 regarding Illex squid quotas, updates the analyses with revised data, and attempts to integrate various approaches for developing logical bounds on population biomass and fishing mortality rates. The results are extended to consideration of an alternative quota of 33,000 mt for 2022. Fishery independent surveys, total landings, and Vessel Monitoring System summary data are the primary bases for these analyses.

Realistic ranges of biomass and fishing mortality estimates are developed by first examining the implications of a broad range of feasible, but not necessarily likely, parameter values for gear efficiency, availability, and natural mortality and fishing mortality. The resulting ranges from one set of assumptions are then compared to ranges derived from another set of assumptions. Logical bounds on biomass are based on upper and lower ranges constrained by excluding values that lie outside the bounds of extreme values from alternative assumptions. In other words, a feasible range of biomass estimates is deduced from estimates that satisfy the joint effects of alternative bases of population abundance. Key parameters include estimates of survey gear efficiency, availability of the population to the shelf area sampling region, potential ranges of M and hypothesized ranges of F, and a variety of parameters related to relative density of squid in areas fished vs unfished.

Traditional **Leslie-Davis depletion** models do not work very well for Illex because key assumptions for model application are violated. A **Mass Balance Model** illustrates the magnitude of migration, growth and recruitment effects necessary to offset the differences in relative abundance between the spring and fall NEFSC bottom trawl indices. An **Envelope Model** approach is used to establish logical bounds on biomass based on assumed ranges of catchability, availability, and fishing and natural mortality rates. The basic constructs of the Envelope Model can be used to establish potential ranges of **Escapement** for existing and hypothesized ABC values. Escapement is defined as the ratio of the observed abundance estimate to the abundance that would have been present in the absence of fishing mortality. Finally, **Vessel Monitoring System** data are analyzed to estimate effective fishing mortality rates over the entire population.

Evaluations of potential escapements for alternative ABCs of 30 kt and 33 kt suggest that over the range of observed post-fishery fall survey indices, there is a low likelihood that either ABC level would induce a significant fraction of escapements below a 40% MSP threshold.

Main Conclusions

1. The overall Illex population is likely to be large.
2. Observations suggest relatively low chances of high fishing mortality rates over a broad range of assumed parameter extremes.
3. Spatial analyses of survey and fishery footprint suggest high escapement (Lowman et al. 2021, Manderson et al. 2021)
4. None of the estimates of area wide fishing mortality suggest fishing mortality rates greater that life history-based biological reference point proxies.
5. Increases of quotas to 33,000 create risks to falling below F 40% but the risk is lower than the risks of overfishing associated with current Harvest Control Rules used by the SSC and the risk policy adopted by the Council

1.0 Introduction

The objectives of this working paper are to 1) review the decisions of the SSC in 2020 to increase the Illex quota from 26,000 mt to 30,000 mt for 2020, 2) update the supporting analyses from 2020 with additional information, and 3) evaluate the implications of alternative quota of 33,000 mt for 2021 and beyond.

1) During 2019 and early 2020, the SSC recommended and Council approved formation of an Illex Quota Working Group to investigate the basis for existing quotas and to outline potential approaches for developing a real-time quota monitoring (RTM) process. Real-time monitoring relies on the rapid acquisition and processing of in-season metrics of relative abundance and fishery performance that could be used to evaluate current condition of the resource and recommend appropriate recommendations to the current quota. In May 2020 the SSC (see link to this report in Appendix) concluded that real-time management was desirable but insufficiently supported noting "*that the specifics of the implementation of real time management for Illex remain sufficiently poorly identified which prevents implementation in the 2020 fishing year.*" Work on RTM will continue in 2021under the auspices of the Research Track Assessment for Illex (Term of Reference #6) but no additional work on this topic has been done to date.
2) The Research Track Assessment for Illex will focus on the dynamics of the stock during the period where scientists and managers have the greatest confidence in the underlying data. This includes research survey, vessel trip report data, and industry supplied information on average weights by week since 1997. Because of Covid-related interruptions in surveys and decreased collection of fishery-dependent data, the Research Track Assessment will not include 2020 data when addressing the Terms of Reference. However, a working paper considered by the SSC in 2020 has since been published in a

peer-reviewed journal (Lowman et al. 2021) and estimates from that paper will be used to refine the range of potential biomass and fishing mortality estimates examined in 2020.

3) Under the Council's risk policy and other national standards, the SSC has the ability to evaluate an increase in the current quota by 10%. The implications of this increased quota are evaluated with respect to its implications for biomass fishing mortality rates, and reasonable biological reference points.

The Illex squid harvested in the US EEZ can be characterized as a data poor stock. Illex are an oceanic species that makes seasonal migrations onto the continental shelf where it is fished primarily on the shelf break. Illex however are found over a much broader range extending northward to NAFO areas 3 and 4, where it has been harvested at modest levels (about 12%) relative to catches in the NAFO areas 5 and 6 (Henrickson and Showell, 2020, ref. Table 1). Data and analyses described below suggest that harvesting of Illex occurs over a small fraction of the known inshore habitat and a relatively short season. Collectively these considerations suggest that Illex are lightly exploited.

In 2020 the SSC noted that "*A review of the life history of Illex suggested that it is likely highly resilient to low levels of exploitation because of the presence of multiple cohorts, batch spawning and increased fecundity levels resulting from the presence of larger squid in the population than were present when fecundity was estimated originally*." The potential robustness of the stock to contemporary harvest rates must also be evaluated in the context of our incomplete understanding of the life history of Illex, the interannual changes in apparent availability of the offshore stock to fishable and surveyable areas, and mechanisms for wide variations in apparent growth rates.

The analyses summarized herein, represent a review and updating, when possible, of the information considered by the SSC in 2020. While little is known about key sources of uncertainty, such as availability or gear efficiency, it is possible to interpret existing data in light of the broad range of values. The basic principle underlying these analyses is consideration of a broad range of potential parameters on the estimation of abundance and fishing mortality, followed by a refinement of the parameter range to a more plausible set of values. "Plausible" values are informed either by inconsistencies among initial parameter ranges or by external information derived from empirical studies. Inconsistencies can arise when abundance estimates derived on the basis of an assumed extreme range of F, lie outside of a range generated by an assumed extreme range of gear efficiency and availability. The mismatch suggests that as least one of the parameter combinations are "too extreme" such that a constraint is appropriate. The Lowman et al (2021) study illustrates the value of empirical constraints that can be used to refine the plausible range of availability. Similarly various studies supported by the Northeast Trawl Advisory Panel (NTAP) can be used to develop a narrower range of possible gear efficiencies.

2.0 Overview of Assessment Framework

Interrelationships among the various approaches are shown in Figure 2.1. Data inputs and other information sources are summarized in the boxes on the left column. The center column defines the various models (boxes) and the input parameters (ovals). Outputs are summarized in the boxes on the right column. The arrows denote the flow of information and identify the dependencies among models. No single model is considered sufficient to capture the within season dynamics of the Illex fishery. Instead, each model identifies a different facet of the relationships among state variables. Model outputs can also be used to further refine inputs for other models (dashed lines). At best this array of models can be used to bound the likely range of biomass and F estimates that a more sophisticated comprehensive model might estimate.

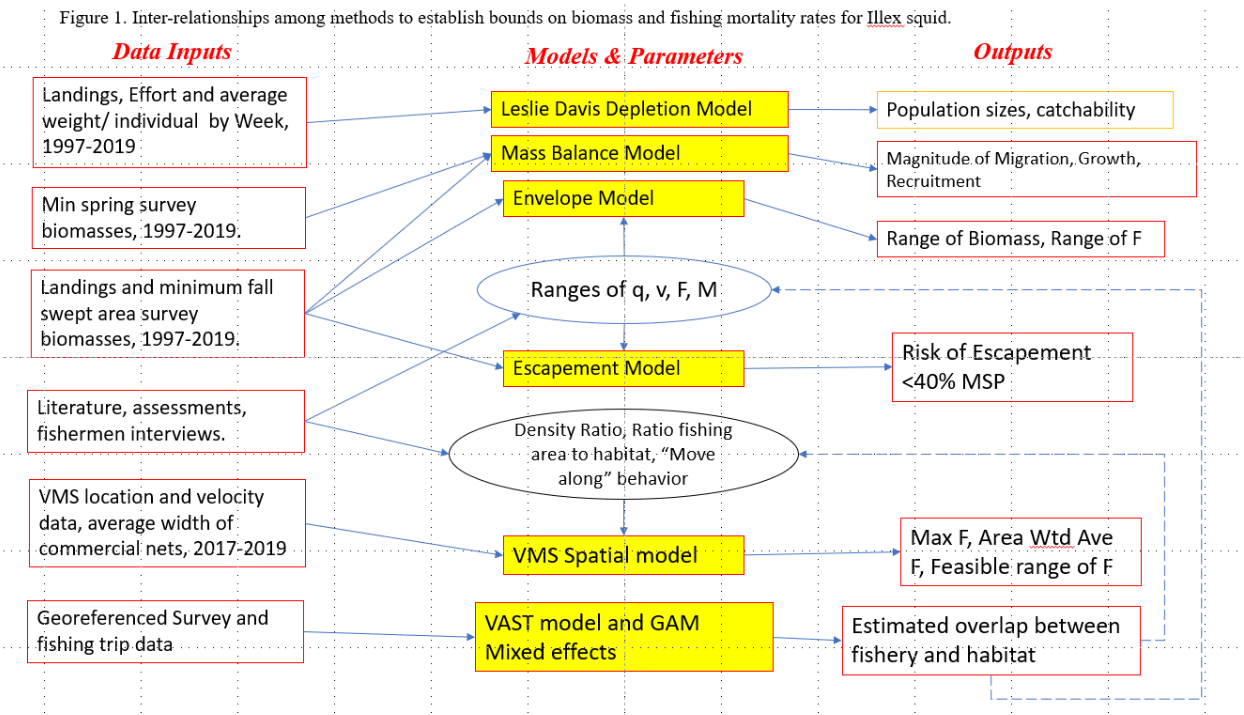

Figure 2.1 Inter-relationships among methods used to establish bounds on biomass and fishing mortality rates for Illex squid.

The various models identify the potential magnitude of processes not accounted for in the models. For example, failure of the **Leslie-Davis Depletion** models suggests that migrations into the fishing area, variations in growth, and recruitment overwhelm the depletions associated with the fishery. The **Mass Balance** model illustrates the potential magnitude of the combined effects of these processes. The **Envelope** model compares the upper and lower bounds of biomass estimates derived from assumed ranges of fishing mortality and catchability. The indeterminacy of the catch equation provides a basis for assuming a range of F values to estimate the biomass necessary to support the observed catch. In simple terms, an observed catch can be the product of a lightly fished large population or a heavily fished small population. Hence an assumed range of extreme fishing mortality rates can be used to estimate minimum and maximum biomass estimates. Similarly, survey biomasses are assumed to be proportional to true biomass via the catchability parameter that combines the effects of both gear efficiency (i.e., probability of capture given encounter) and availability of Illex within the survey domain. The true biomass is the observed survey biomass divided by product of gear efficiency and availability. By assuming a plausible range of these parameters, informed by knowledge of empirical gear comparisons and analyses of spatial overlap, one can derive high and low biomass estimates. If the biomass of one imputed series exceeds the maximum value of the other then it suggests that assumptions of the first series were too extreme and would need to be reduced. Similarly, if the biomass estimates of a given series, say based on a high F fell below the minimum value of the series created by the maximum feasible value of catchability, then one would conclude that the assumed F was too high. The set of thus constrained biomass estimates now creates a envelope of estimates bound by the an internally consistent set of assumptions. An overview of the data sources, input parameters and outputs for the various models is provided in Table 2.1

The **Envelope Model** data can also be used to evaluate the risk of overfishing under various assumptions about catchability, F and M. The **Escapement Model** back calculates the minimum population size necessary to support the observed catch, and then projects that estimate of abundance forward without catch using only the assumed M used to estimate the initial biomass. The ratio of the observed biomass to the forward projection of population size without catch is a measure of the escapement that can be compared to reference points based on some fraction of maximum spawning potential.

Further refinement of the possible range of fishing mortalities on the population is addressed in the **VMS Spatial Model**. This model estimates the potential magnitude of fishing mortality based on the spatial distribution of fishing effort expressed in terms of swept area. Individual records of VMS tracks where fishing is occurring are linked to estimated net widths. Key external parameters are the ratio of estimated densities of squid inside and outside the fished areas as well as the behaviors of fisherman to move between areas during successive tows. VMS data suggest a high degree of overlap of fishing areas within season which suggests not only predictable fishing sites but replenishment of the stock by migration of squid through the area. Result of the **VAST Model** application are valuable for refining the parameter estimates of overlap between the fishery and the resource area. The **VAST Model** also provides refinement of the availability parameter v that in turn can be used to refine the bounds in the **Envelope Model**. No formal estimation procedures have been estimated for this assemblage of models (or estimators), but some form of Bayesian state-space model may be feasible for the Research Track Assessment.

Table 2.1. Data sources, input parameters and outputs for the various models used to derive bounds on biomass and fishing mortality for Illex squid.

Method/Model	***Data***	***Years***	***Input Parameters***	***Output***	***Comments***
Depletion Model	• Landings by week • Effort by week for trips, days fished, days absent • Ave wt/indiv by week	1997-2018. Exclude 2006-2007.	None	• Estimated q for Effort • Initial Pop Size • Proportional depletion	• Violation of assumptions evident in most years • Lack of fit suggests low intensity of fishing mortality and high level of migration/recruitment into the fishing area
Envelope	• Fall Survey swept area biomass • Landings	1997-2019	Min and Max F Min and max M Min and Max q Min and Max v	• Upper limit Biomass • Lower Limit Biomass	• Constrained upper and lower bounds of biomass suggest feasible range of population behavior for any population dynamics model.
Escapement	• Fall Survey swept area biomass • Landings	1997-2019	Min and max M Min and Max q Min and Max v	• Realized fraction escapapement by year • Evaluation of alternative harvest scenarios	• Evaluate likelihood of exceeding target escapement for alternative quotas over historical period. • Compare with other management, eg with 50% escapement.
Mass Balance	• Min swept area Spring survey • Min Swept area Fall survey • Total Catch	1997-2019	• Ratio of F/M • Min and Max qv	• Estimates of migration, growth and recruitment necessary to balance catch and natural Mortality	• Uses simple mass balance to illustrate potential magnitude of inshore and offshore movements and growth.
VMS	• VMS locations of fishing speeds and durations • Average net width by permit number	2017-2019	• Availability • Move along rule—acceptable rate of depletion during fishing • Area of fishing activity relative to total habitat area. • Ratio of density in fished to unfished areas	• Maximum F • Area weighted average F	• Fishing mortality estimates are for entire season. Divide by 24 to obtain weekly F for comparisons

3.0 Summary of 2020 SSC Discussion and Decisions

In May 2020 the SSC reviewed a series of working papers (Rago etc, Wright et al.) designed to develop logical bounds on the potential stock size and fishing mortality. The following text recapitulates the statements of the SSC and previews any revisions of the analyses in 2021.

3.1 Overlap of Fishery and Survey Abundance: 2020 SSC Comments

"Bottom trawl survey data from NEFSC and NEAMAP partners were combined to develop an overall probability of occurrence spatial map for the Northeast shelf using a software package known as VAST (Vector Autoregressive Spatio-Temporal). Comparison of these maps with estimates of the spatial footprint of the fishery (based on VTR data) revealed a low degree of overlap with the survey area irrespective of the cutoff criterion used for the probability of occurrence. Youden's J statistic was suggested as an additional measure of spatial overlap for consideration. Because the surveyed areas represent only a fraction of the known distribution of Illex, the results of these analyses suggest substantial opportunity for escapement of squid to unfished areas."

<u>Update for 2021</u>: Results of this publication were published (Wright et al. 2021). Analyses were expanded to include 3 additional surveys. Cumulative survey data for Fall bottom trawl were post stratified into areas inside and outside the observed fishing areas to estimate average squid densities. (See VMS Model)

3.2 Depletion Models: 2020 SSC Comments

"Leslis-Davis depletion models have been used in some assessments worldwide but violations of underlying assumptions suggested that this methodology did not reliably detect the influence of catch on LPUE. Commenters noted that the absence of significant results was an indirect indicator of likely low fishing mortality."

<u>Update for 2021</u>: No new data were available to update the model. The lack of model fit per se suggests low fishing mortality relative to other processes. The potential magnitude of these changes were evaluated using a **Mass Balance Model** described below.

3.3 Envelope Method: 2020 SSC Comments

"The envelope method, previously utilized by the SSC for analysis of butterfish, reinforced the notion that fishing mortality was likely very low. Survey and catch data were independently used to develop a plausible range of population sizes based on a broad range of assumed fishing and natural mortality rates, gear efficiency and availability. The resulting envelope of population sizes could then be used to derive a range of feasible fishing mortality rates for comparison with reference points. Results suggested that maximum weekly fishing mortality rates of about 0.06 were less than half of proposed reference points based on 40% MSP published in the literature."

<u>Update for 2021</u>: Minimum swept area biomass estimates were provided by Lisa Hendrickson of NEFSC for the period 1997 to 2019 using day night conversion factors using a more refined set of survey strata. Previous estimates were based on rescaled average weight per tow data using a coarser estimate of survey sampling domain.

3.4 Vessel Monitoring System : 2020 SSC Comments

"Vessel Monitoring System (VMS) data can be filtered by vessel speed and combined with average net widths by permit, to derive swept area estimates of fishing effort spatially. Using data from 2017 to 2019, analyses suggested that fishing activity was highly concentrated in a relatively small number of cells (6.99 nm^2 each), but that the overall area swept by the fishery was small (<960 nm^2 in 2019). Additional sensitivity analyses suggested that the maximum fishing mortality rate over the entire stock area was less than 0.54 over a 24-week fishing season (or about 0.023 per week). The VMS analyses could be useful for incorporating results from other studies of fishermen behavior (e.g. decisions to move to new fishing areas), estimates of density differences between fished and unfished areas, and potentially, the effects of price on fishing behavior."

Update for 2021: No new data were available for analyses. Fishing trips were reviewed to obtain an estimate of repeat tows in 3 nm sqr cells within a given trip.

3.5 Overall Conclusions of SSC in May 2020

The overall conclusions of the SSC in May 2020 regarding the rationale for revising the ABC were summarized in the text related to Term of Reference 1 as noted below. For completeness, the response of the SSC is repeated verbatim below.

1. *"Review the current 2020 Illex Acceptable Biological Catch (ABC) of 26,000 MT and determine if an ABC adjustment is warranted. If so, please specify an adjusted 2020 Illex ABC and provide any rationale and justification for the adjustment. If appropriate, specify any metrics the GARFO could monitor in 2020 to trigger an in-season ABC modification;*

The SSC reviewed the material developed by the MAFMC Illex Working Group (WG) and the NEFSC and found clear evidence to support an adjustment of the 2020 ABC (26,000 mt). The WG analyses strengthened SSC contention in its 2017 ABC specification that the stock has been lightly exploited. Analyses conducted by the WG indicated that fishing activity from 2000-2018 occurred in 2-10% of the available shelf habitat occupied by Illex squid (Wright et al. 2020 ms). True values of the availability of squid to the fishery are likely lower given the full distributional range of this species. An analysis of VMS data, together with assumptions regarding gear efficiency, potential depletion thresholds, and the relative densities of squid in fished and unfished areas suggested that credible ranges of seasonal fishing mortality rates on squid that vary by about 30-fold, ranging from F~0.01 – 0.3 with a values <F=0.1 being most likely (Rago 2020a; Rago 2020 b). Other methods to estimate F often led to negative estimates, most likely because fishing mortality rates are insufficiently high to provide a clear signal to be reliably estimated in such models (Rago 2020d). A review of the life history of Illex suggested that it is likely highly resilient to low levels of exploitation because of the presence of multiple cohorts, batch spawning and increased fecundity levels resulting from the presence of larger squid in the population than were present when fecundity was estimated originally.

*The SSC recommends an ABC for Illex squid for 2020 of **30,000 mt**, based on the upper limit of values evaluated in the EA documents currently approved by GARFO. Evidence reviewed by the SSC leads it to believe that harvests in the range of 18,000-30,000 mt are unlikely to result in overfishing of the Illex stock. The SSC requested additional analysis from Paul Rago which confirmed that this level of ABC did not materially affect the range of estimates of F in the envelope analysis.*

The SSC applauds the continued cooperation among the industry and federal and academic scientists to support exploration of real time management (e.g., Rago 2020e, f). However, the SSC believes that the specifics of the implementation of real time management for Illex remain sufficiently poorly identified which *prevents implementation in the 2020 fishing year. The SSC strongly supports, as an active, ongoing research recommendation, to continue exploration of options by the Illex WG to support real time management of this stock, including factors that would trigger an in-season change in regulations, and the magnitude and direction of such a change."*

4.0 Methods

Appendices 1 to 5 contain links to the original papers and presentations prepared for consideration by the SSC in 2020. In order to facilitate the integration of the methods, the underlying equations are summarized here. Table 1 summarizes the basic information and notation for each of the models. All of the data (survey, catch, vessel trip report, and Vessel Monitoring System) used in this report were kindly provided by Lisa Hendrickson of the NEFSC. Through a joint effort of industry and the NEFSC (Hendrickson, Holmes and others), biological samples from freezer boats (SeaFreeze Ltd, Lapp per comm) were used to derive average weights by week for the same period of years, excluding 2006 and 2007.

4.1 Depletion Model_methods

Vessel Trip Report data for 1997 to 2018 Catches are reported in catch per trip by vessel and date landed. Estimates of fishing effort include total days absent, and days fished. Days absent is computable to a resolution of one day, whereas finer scale information on days fished is supplied by fisherman reports. Crude measures of CPUE were estimated as the total catch divided by the number of trips, the total days absent over all trips, or the total days fished summed over all trips within a given standardized week (i.e., week 1 = Jan 1 to 7, week 2 = Jan 8-14, etc). The primary fishing season for these analyses was restricted to standard weeks 22 to 44. Historically this window constitutes 95% of the annual landings by weight.

Catches in weight were converted to catches in number by dividing the total catch by the estimated average weight. When weekly average weight samples were not available, average weights were borrowed from the next available week. Capture probabilities are applicable to individuals rather than biomass, all quantities in the Leslie Davis model were expressed in terms of numbers of individuals. The Leslie-Davis model is written as

$$CPUE_t = qN_0 - q\sum_{i=1}^{t-1} C_i$$

Which is a simple linear regression $CPUE_t$=a +b K_{t-1} where K_{t-1} is equal the sum of catches up to t-1. In theory, the estimated total number of individuals in the population occurs when all of the individuals are captured. This corresponds to CPUE=0, so that he estimate of N_0 is simply equal to -a/b.

The preferred method for estimating the parameters of the Leslie Davis model is to use maximum likelihood estimation because the variance of CPUE changes with each observation (Gould and Pollock, 1997). In practice, a simple linear regression of CPUE vs cumulative catch is sufficient to get estimates fairly close to the ML estimates. For the purposes of this working paper, the simple linear regression was judged sufficient.

4.2 Mass Balance Model_methods

The NEFSC conducts synoptic bottom trawl surveys in the Northeast US. The spring survey typically begins about March 1 and continues for 8 to 10 weeks with 4 separate cruises with sampling progressing from south to north. The fall survey is similarly executed but begins in first week of September. In terms of Illex migrations, the spring survey ends well before the bulk of the offshore population arrives in the sampling domain. The fall survey begins after much of the catch has been taken and Illex are thought to be moving out of the sampling area. The commercial fishery is prosecuted primarily between May and September in most years, although catches can occur well into fall in some years. These concerns, and the inconsistent and often infeasible results of the simple depletion models used in 2020 (Rago 2020a) beg the question—what are the implications of large catches in the summer for the amount of biomass that much be produced to support it?

Consider a simple mass balance problem wherein the biomass in the fall $\mathbf{B_F}$ in any year is equal to the initial biomass in the spring $\mathbf{B_S}$ less the losses from the fishery **C** and natural mortality **L**. These losses are offset by growth in average weight over the course of the fishery **G**, net migration of squid **Mig** into the stock area and new recruits **R**. The mass balance equation is

$$\mathbf{B_F = B_S - C - L + G + Mig + R} \qquad (1)$$

Natural mortality is poorly known but modeling results (Hendrickson and Hart 2006) suggest it is high relative to fishing mortality. One way of exploring the implications of this premise is to express loses due to natural mortality as a function of the observed catch. From Baranov's catch equation we know that

$$\mathbf{C=(F/Z)(1-exp(-Z))\ B} \qquad (2)$$

Since **F+M = Z**, the comparable equation for natural mortality losses is

$$\mathbf{L=(M/Z)(1-exp(-Z))\ B} \qquad (3)$$

If we assume that **M** is some scalar multiplier of **F**, say $\mathbf{M=\alpha F}$, then we can get a handle on the magnitude of unseen losses as

$$\mathbf{L=(\alpha F/Z)(1-exp(-Z))\ B = \alpha C} \qquad (4)$$

The terms G, Mig and R summarize the processes necessary to offset the losses from the fishery but there is precious little data to estimate the individual components. Instead, consider the them as a pool X such that

$$\mathbf{X= G + Mig + R} \qquad (5)$$

Plugging Eq. 4 and 5 into Eq. 1 gives

$$\mathbf{B_F=B_S - C - \alpha C + X} \qquad (6)$$

With a little algebra this becomes

$$\mathbf{X = B_F - B_S + (1+\alpha)\ C} \qquad (7)$$

The final consideration is that the BF and BS are estimated quantities based on minimum swept areas in the spring and fall surveys. Two factors affect these quantities: gear efficiency **q** and availability **v**. Using conventional assumptions let $\mathbf{I_S=B_S/(qv)}$ and $\mathbf{I_F=B_F/(qv)}$. Plugging these values into Eq. 7 gives

$$\mathbf{X = (I_F - I_S)/(qv) + (1+\alpha)\ C} \qquad (8)$$

Thus **X** represents amount of production necessary to offset the sum of biomass differences between the fall and spring surveys and the total removals, both seen **C** and unseen **L**, written as a function of **qv** and α.

4.3 Envelope Model_methods

Let I_t represent the 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

$$B_t = \frac{I_t}{q}\frac{A}{a} \qquad (9)$$

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. 9 can be modified to account for this by dividing the right hand side by **v** such that:

$$B_t = \frac{I_t}{q}\frac{A}{a}\frac{1}{v} = \frac{AI_t}{qav} \qquad (10)$$

The NEFSC fall bottom trawl survey occurs after most of the fishery occurs and therefore can be considered a measure of post-fishery abundance. In order to account for the potential swept area biomass that existed at the start of the season, it is necessary to add the total landings removed from the fishery. Thus, the estimate of abundance at the start of fishing season is what was left 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 up" the abundance estimate to what it would have been at the start of the season, one needs to adjust the actual catch for natural mortality and add it back into $\mathbf{B_t}$. The natural mortality adjustment factor is approximated as exp(M/2 * fishery duration). The virtual swept area estimate of abundance at the start of the fishery can be written using Pope's approximation (Lassen and Medley, 2001) so that

$$B_0 = B_t\ e^{M\,t} + C_t\, e^{\frac{M}{2}t} \qquad (11)$$

Where $\mathbf{B_t}$ is defined by Eq. 10.

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

$$B_0 = \frac{C_t}{\frac{F}{F+M}\left(1-e^{-(F+M)}\right)} \qquad (12)$$

In this expression **F** and **M** are unknown.

Thus, biomass can be written as a function of arbitrary scalars **v, q, M,** and **F.** These equations can be generalized and written as

$$\hat{B}_{1,t} = B(I_t, q_{Low}, v_{Low}, M_{High})$$
$$\hat{B}_{2,t} = B(I_t, q_{High}, v_{High}, M_{Low})$$

$$\hat{B}_{3,t} = B'(C_t, F_{Low}, M_{High}) \quad (13)$$
$$\hat{B}_{4,t} = B'(C_t, F_{High}, M_{Low}).$$

Prior information on the suitable range for **q** can be obtained from analyses of relative survey catchability as detailed in the main body of the SARC 49 report (NEFSC 2010). The suitable range of **F** values can be obtained from analogy with other fisheries, or more simply by picking a wide range of values.

By inspection it is evident that $B_{1,t}$ and $B_{3,t}$ constitute an upper range, and $B_{2,t}$ and $B_{4,t}$ constitute a lower range. Upper and lower bounds consistent with these estimates are

$$\begin{aligned}\hat{B}_{upper,t} &= \min(B_{1,t}, B_{3,t}) \\ \hat{B}_{lower,t} &= \max(B_{2,t}, B_{4,t})\end{aligned}. \quad (14)$$

Values of biomass that exceed the $\hat{B}_{upper,t}$ imply catchabilities smaller than than q_{low} or fishing mortalities less than F_{low}. Conversely, values of biomass less than $\hat{B}_{lower,t}$ imply catchabilities greater than q_{high} or fishing mortalities greater than F_{high}. These bounds describe a set of feasible options that are consistent with the assumed ranges of q, v, M, and F. In theory, a more sophisticated population model should lie within this feasible range.

4.4 Escapement Model_methods

For the purposes of this paper, escapement is defined as the ratio of the observed end of fishing season population B_t to that expected if no fishing mortality occurred. The projected population if no fishing occurred can be obtained by projecting B0 in Equation 10 by the fraction surviving natural mortality:

$$B_{t,without\ fishery} = B_0 e^{-Mt} \quad (15)$$

The "escapement" is now computed as the ratio of the estimated Bt based on the survey divided by the projected biomass that would have occurred in the absence of the fishery.

$$Escapement = \frac{B_t}{B_{t,without\ fishery}} \quad (16)$$

Equation 16 can be further simplified by plugging Eq. 10 and 11 into Eq. 16 to obtain:

$$Escapement = \frac{\frac{AI_t}{aqv}}{\frac{AI_t}{aqv} + C_t e^{-M/2}} \quad (17)$$

Where the quantity $(A/a)I_t$ is the minimum swept area assuming qv=1.

4.5 VMS Spatial Model_methods

VMS data provide a rich database for exploring the spatial patterns of fishing effort and its potential consequences for fishing mortality. A working paper presented to the SSC in 2020 (Rago 2020b) described the patterns of fishing concentration for 2017-2019. The VMS data for this working paper were kindly provided by Lisa Hendrickson and Alicia Miller of the Northeast Fisheries Science Center, National Marine Fisheries Service. VMS data from 2017 to 2019 for May through October were filtered for putative towing speeds of 2.6 to 3.3 knots. Each VMS ping represents an interval censored observation since speed is derived from the distance between successive pings divided by the time between pings (one hour). Hence the average speed at a ping can reflect a mixture of steaming at higher speeds and actual towing, as well as processing time at lower speeds. (See Palmer and Wigley 2009 for more details).

Locations were binned into 3-minute squares of latitude and longitude. As distance between longitude degrees varies as a function of latitude, it was assumed the average fishing latitude was 39 degrees. At this latitude the average 3 minute square is cos(39°) x 3 minutes longitude x 3 minutes latitude ~6.99 nm^2. This approximation is used for all computations of swept area.

Lisa Hendrickson also provided estimates of average net width for each permit using records from the Fisheries Observer database. By linking these data to permit number and vessel speed for each ping it was possible to compute nominal estimates of swept area per ping (i.e., hour fished). The total area swept in any cell and time interval was computed as the sum of the vessel-specific swept area estimates. Vessel permits without information on net width were assigned the average width for the measured set of permits. No vessel names were included in the database and no permit numbers are reported herein. Since the focus of this analysis is the spatial pattern of effort, expressed as swept area, differences among vessel types (freezer, RSW, ice) are not considered.

The working paper (Rago 2020b) revealed a high degree of spatial concentration with a Gini index =0.822 across all years and even higher rates for individual years. The intense concentration of fishing effort in a relatively small number of cells provides insights about potential effects on overall fishing mortality and movement of squid from adjacent cells.

To begin, consider a population in a 3 minute square of size **A** (6.99 nm^2) that does not mix with adjacent 3 minute squares and is uniformly mixed within that square. Assuming that a trawl tow of size **a** is 100% efficient (i.e.,**q**=1.0) in capturing everything in its path, then each tow would represent a proportional reduction in the remaining population. The fraction **f** of a cell's population removed can be defined by the efficiency **q** times the ratio of the tow area **a** to the total cell area **A** is defined as

$$f = q\frac{a}{A} \qquad (18)$$

By definition the fraction of the population remaining after one tow is **1-f** = **(1-q a/A)**

Applying the removal process recursively, the fraction remaining after n tows is

$$(1-f)^n = \left(1-\frac{q\,a}{A}\right)^n \qquad (19)$$

As the fraction **q a/A** becomes small, the above equation can be expressed using instantaneous rates so that the fraction of the population remaining after n tows is

$$\left(1-\frac{q\,a}{A}\right)^n = e^{\left(-\frac{q\,a\,n}{A}\right)} \qquad (20)$$

Note that the product **a** x **n** is simply the total swept area (**TS**) if all of the tows are of equal size **a**. Building on this concept, then the total swept area after **n** tows of varying size $\mathbf{a_i}$ is

$$TS = \sum_{i=1}^{n} a_i \qquad (21)$$

Note that this generalization allows us to examine the fraction of the population remaining after it has been exploited **n** times by a gear with efficiency **q** and a swept area per tow of $\mathbf{a_i}$.

$$e^{\left(-\frac{q\,TS}{A}\right)} \qquad (22)$$

Thus the fraction of the population remaining after an area swept of **TS** or a ratio of **TS/A** times is given by Eq. 22. In the most heavily fished cells, the implied reductions in abundance are equivalent to the implied reductions in catch per unit effort. For the top 50 cells where fishing was concentrated the "implied" depletion, i.e., the average fraction of the initial population remaining is predicted to be 0.064 in Rago (2020b). These depletion ratios would occur ONLY if the population was static and did not depend on a flux of squid from other areas. Although a firm criterion for continuation of fishing activity during a season is not possible to estimate, one might safely assume that depletions of more than 90% do not occur during the course of the season. Clearly an individual vessel would move to another cell well before this type of reduction occurred.

Let γ represent the ratio of CPUE that induces a movement of a vessel into a new area. Conceptually, this might be related to an economic incentive related to the profitability and an expected profitability of the next tow. Conversations with fishermen suggested that this may not be a hard and fast rule since many different factors can affect the decision to move to another fishing area. Let $CPUE_o$ represent the initial CPUE and $CPUE_t$ represent the CPUE after time t has elapsed. The ratio of $CPUE_t/CPUE_o = \boldsymbol{\gamma}$ such that a new area is fished when the ratio falls below γ. For economy this ratio can be called a "move along" criterion.

Using the swept area notation from Eq. 22 the CPUE ratio can be written as

$$\gamma = \frac{CPUE_t}{CPUE_o} = e^{\left(-q\frac{TS}{A}\right)} \qquad (23)$$

Where q is the gear efficiency, TS is the total area swept in time step **t** and **A** is the area of the cell. Equation 23 can be rearranged to solve for A such that

$$A_V = \frac{-q\,TS}{\ln(\gamma)} \qquad (24)$$

If we assume that abundance in a cell is replenished by transfer of squid from adjacent areas, then the estimate of **A** can be called a virtual **A** or $\mathbf{A_V}$ which implies the total area of all cells that would be impacted by a total swept area TS by a gear with efficiency **q** and a "move along" criterion of $\boldsymbol{\gamma}$. As the acceptable ratio of CPUE decline becomes smaller, the virtual area the population that replenishes the cell fished becomes smaller.

Consider a few examples. Suppose that the estimated total swept area for a cell is 3 times the total area of the cell or **TS/A**=3.0. Assuming that the gear was 50% efficient (**q**=0.5), then the predicted depletion ratio from Eq. 22 is exp(-0.5 *3) = 0.22. This is what would occur if the population were closed to immigration. Clearly, fishing activity would move to another area if higher yields were available elsewhere. If a vessel "moves along" when the CPUE ration drops by only 10% then $\boldsymbol{\gamma}$=0.9 and ln($\boldsymbol{\gamma}$)=-0.105. By Eq. 24 the virtual area of the cell increases by a factor of 9.49 (=1/0.105). Thus, a fleet that moves along when fishing declines by 10% and yet returns to fish such that it covers the entire area 3 times over the course of the season, is in fact fishing a virtual area 9.49 times greater than the size of the cell. For a three-minute square this is 66.34 nm^2. Alternatively, a fleet that moves along when the CPUE ratio is 0.5 will have a virtual fishing area that is 1/ln(0.5)=1.44 times higher than the cell size.

The concept of virtual area fished can now be expanded to compute an area weighted fishing mortality rate. For each cell it is possible to compute the virtual area swept from Eq. 24. When the virtual area fished exceeds the actual cell size the magnitude of the fishing mortality in a given cell **i** is constrained by the defined threshold parameter $\boldsymbol{\gamma}$. This can be expressed as

$$F_i = \min\left(-\ln(\gamma), q\, TS_i / A\right) \qquad (25)$$

The area weighted average F (**F_{ave}**) over the entire set of cells fished in a given year can now be estimated as

$$F_{ave} = \frac{\sum_i^n F_i A_{Vi}}{\sum_i^n A_{Vi}} \qquad (26)$$

The estimates of **F_{ave}** in the area fished are, of course, inadequate to estimate the fishing mortality on the entire stock. The magnitude of fishing mortality on the stock depends on the overlap of the area that is fished to the total habitat and the fraction of the population in the area that is fished. High fishing effort on high concentrations of the resource induce a higher total fishing mortality than if the population was uniformly distributed. It is probably safe to assume that Illex are not uniformly distributed over all areas of habitat. Otherwise fishing would not exhibit the high degree of concentration observed. One can further assume that fishing is most likely to occur in preferred habitats, or at least in areas where Illex temporarily aggregate prior to a more general movement onto the shelf. The distributional patterns of abundance that define the overall F on the population are unknown, but the available data from the VMS and the fishing vs habitat overlap estimates of Wright et al 2020 are sufficient to at least bound the problem. Wright et al (2020, Table 3) estimated that availability, defined as the proportion of habitat that overlaps spatially with fishing effort, ranges between 0.9% to 9.6% depending on year (2000-2019) and the probability threshold (40-80%) used for habitat definition.

With a little algebra, the joint effects of overlap of fishing effort with habitat and the differences in abundance in the fished and unfished areas can now be addressed. Beverton and Holt (1957, p 148-151) were perhaps the first to introduce the concept of an "effective F" for fishing over spatially distributed population.

Let **A** represent the total habitat area of Illex and **A_f** and **A_u** denote the areas were fishing does and does not occur, respectively. Thus

$$A = A_f + A_u \quad (27)$$

Further, let **D_f** and **D_u** represent the densities of Illex in the fished and unfished areas, respectively. Density can be expressed in either numbers or weight per unit area without loss of generality as long as average weights per individual are the same in each habitat area. The total population size **P** is thus defined as

$$P = A_f D_f + A_u D_u \qquad (28)$$

Beverton and Holt defined effective fishing mortality as the product of the fishing mortality times catch per unit effort summed over all spatial units, divided the sum of catch per unit effort over all spatial units. This is equivalent to a biomass weighted **F**. If we let **F_f** and **F_u** represent the fishing mortality rates in the fished and unfished areas, then the effective **F**, defined as **F_{eff}** is

$$F_{eff} = \frac{F_f A_f D_f + F_u A_u D_u}{A_f D_f + A_u D_u} \qquad (29)$$

Equation 29 can be simplified by letting **$D_u = \phi D_f$**, **$A_f = \theta A$**, **$A_u = (1-\theta)A$** and noting that **F_u**=0 by definition. Substituting these expressions into Eq. 29 gives

$$F_{eff} = \frac{F_f \theta A\, D_f + 0\,(1-\theta) A \phi D_f}{\theta A D_f + (1-\theta) A \phi D_f} \qquad (30)$$

Canceling out the relevant symbols leads to

$$F_{eff} = \frac{F_f\theta}{\theta+(1-\theta)\phi} \qquad (31)$$

Thus the effective **F** on the entire population $\mathbf{F_{eff}}$ is a function of the **F** in the area fished $\mathbf{F_f}$, the relative density ratio in the fished and unfished areas ϕ, and the fraction of the total habitat in the fished area θ. As a starting point one can assume that the density in the unfished habitat area is less than or equal to one and that the Wright et al range of values for θ is between (0.01 and 0.2). The upper bound of 0.2 is roughly twice that estimated by Wright et al under any scenario.

4.5.1 Parameters for VMS Spatial Model

4.5.1.1 "Move along rule" parameter γ (Eq. 23)

The "move along" rule might be amenable to a survey questionnaire of fisherman's general behaviors with respect to repeat tows within small areas. Preliminary discussions with fishermen reveal a wide variety of factors underlying such behaviors. Alternatively the actual behavior of vessels was used to estimate an empirical basis for a "move along rule" = γ. VMS records were ordered by permit and day. With any given calendar day, the number of unique cells visited were summarized for each trip. The frequency of visits to each unique cell were also tallied. The range of g can be estimated as the potential range of depletion that occurs with the 3nm sqr cell. Equation 20 can be used to define a range of potential in cell depletions by a given vessel on a given day. Using the average net width and a speed of 3 knots, the fraction of area swept in a single pass is 0.0975 nm sqr. If the gear efficiency is 1.0 a single pass would reduce the population by 0.0975/6.99 = 0.01395. In this case γ is 1-0.01395=0.986. For a two pass scenario, the depletion is $(1-0.01395)^2$ =0.972. Summary statistics for 1,886 permit day trips (text table below) revealed that the average cell was "pinged" 1.94 times with a range of 1 to 12 times. For those cells that were pinged most frequently with a permit day, the average number of pings was 3.27. In other words, preferred cells were fished an average of 3.27 times per day giving an average maximum depletion of $(1-0.01395)^{3.27}$ =0.955. For the most heavily fish cell (n=12 pings), the maximum depletion ratio is 0.844.

As noted above, the average cell was pinged 1.94 times. Could this be due to chance alone owing to the size of the cell and the vessel velocity, e.g., pinged after entry to cell and before exit? A small simulation was done to evaluate the likelihood of falling outside the cell give the speed at the time of the ping. Starting locations were defined on a 13 x 13 grid within the 6.99 nm sqr cell. The total distance traveled was equal to the initial speed at the time of the first ping times a one hour duration. To evaluate the effect of random directions, the vector was rotated 360 degrees in 2.5-degree increments. The end point of the vector was then evaluated with respect the boundaries of the cell. Finally, to account for different initial velocities, the above simulation was evaluated at vessels speeds of 2.6 to 3.3 knots. The overall average fraction of points outside the cell was weighted by the frequency distribution of vessel speeds. Under these conditions, the overall fraction of times that a cell would be expected to have two consecutive pings is 0.077. Hence, the observation of an average of 1.94 pings per cell within a given day is not due to chance alone and indicates a high probability that multiple tows within cells are the result of fishermen's decisions.

This table summarizes the total number of cells hit within a trip during a given day. The range of depletion depends on the number of hits per cell.
Fishermen behavior is inferred from the maximum number of hits per cell per day. This assumes that the last tow was sufficiently low to result
in a "move along" rule. Fishing removal is estimated by assuming an average net width and area swept = 0.097549 nm sqr.
Dividing the average area swept per hour by the total area of a 3 min sqr (6.99 nm sqr) gives an average fraction swept = 0.013955
If the net is 100% efficient, then the reduction in biomass is proportional to the fraction of area swept.

	max # Pings per cell	Total Pings per Day	ave # pings/cell	#Cells	Maximum Depletion Fraction	Average Depletion Fraction
min	1	1	1	1	0.0140	0.0140
max	12	37	7	17	0.1552	0.0937
average	3.27	10.26	1.94	5.19	0.0445	0.0268
Std Dev	2.03	6.80	0.94	2.79	0.0269	0.0128

4.5.1.2_Ratio of densities inside and outside fished area ϕ (Eq. 30)

The ratio of densities of Illex in fished and unfished areas during the period of peak fishing activity is not known because there are no fishery independent surveys coincident with the fishery. However, the NEFSC fall survey overlaps with the fishery in some years and can be used as a first approximation of the parameter ϕ (Eq. 30).

Georeferenced NEFSC survey data for 2008 to 2019 were partitioned into observation inside and outside areas where fishing occurred. Areas fished were defined by the resolution of VTR data with 5 min sqr cells. Data for this exercise were kindly provided by John Manderson, Open Ocean Inc. In nearly all years the tows with the stratified random design were allocated proportional to stratum size (PPS) such that an stratum twice is large as another would have twice as many tow locations. This suggests that the differing inclusion probabilities for tows can be assumed to be equal as a first approximation. From this the average catch per tow in the areas inside the fishing area $\mathbf{D_f}$ is simply the arithmetic average of all tows. Average density in the unfished areas $\mathbf{D_u}$ can be computed similarly. Computations for 2008 to 2019, excluding 2017, are summarized below:

	Ave weight/tow			
Year	***outside D_u***	***inside D_f***	***ratio IN:OUT***	***phi***
2008	5.00	45.28	9.06	0.1103
2009	14.06	105.50	7.50	0.1333
2010	12.20	153.14	12.55	0.0797
2011	15.68	83.85	5.35	0.1870
2012	9.39	127.21	13.55	0.0738
2013	4.97	67.74	13.63	0.0734
2014	10.29	91.68	8.91	0.1123
2015	10.48	37.00	3.53	0.2833
2016	14.20	132.24	9.31	0.1074
2017				
2018	25.57	59.32	2.32	0.4310
2019	10.66	41.81	3.92	0.2550
Grand Total	**11.59**	**87.38**	**7.54**	0.1326
Average	12.05	85.89	8.15	0.17
SD	5.65	39.77	4.03	0.11
min	4.97	37.00	2.32	0.07
max	25.57	153.14	13.63	0.43

On average, Illex density inside the areas where fishing occurred were 8 times higher than in the unfished areas.

4.5.1.3 Ratio of Area Fished to Total Habitat Area (parameter θ , Eq.30)

The analyses of Lowman et al. (2021) was revised by John Manderson to include additional habitat areas surveyed by NEAMAP, MA DMF and DFO Canada (NAFO Area 4VWX). Summary data for this exercise for the fall surveys were kindly provided by Dr. Manderson are summarized below. Details on the methodology used to estimate overlap are provided in Manderson (2021). The different methods result is relative little differences between methods and surprisingly low variations across years. The overall range of θ is 0.27 to 0.48

	Ratio of Fishing area to habitat (theta)	
Year	Overlap: Method 1	Overlap: Method 2
2008	0.30381	0.36934
2009	0.27681	0.36109
2010	0.28897	0.34653
2011	0.34128	0.34622
2012	0.41122	0.38100
2013	0.44802	0.43115
2014	0.48467	0.45846
2015	0.46423	0.44658
2016	0.40276	0.40538
2017	0.34940	0.36314
2018	0.31333	0.35189
2019	0.31620	0.35108
average	0.36672	0.38432
min	0.27681	0.34622
max	0.48467	0.45846

5.0 Results

5.1 Depletion Model_results

A detailed summary of the results for the various depletion models may be found in Rago (2020a). Table yy summarizes the key information about model fit and feasibility. The expected pattern of continuous linear depletion and tight fit (r^2>0.7) occurred in only 4 of the 19 years examined (1998, 2010, 2017 and 2018). Three of these years had been judged by fishermen to be excellent harvest years (1998, 2017, 2018). The proportion of variance in CPUE explained by total removals was about 50% in 2011 and 2016 but in all other years r2<0.2. From a broad overview, the model would be judged statistically significant in 4 of the 19 years, marginal in 2 and unacceptable in the remaining 13 years. In 7 years the Leslie Davis depletion model had positive slopes for at least one of the CPUE measures. Additional details may be found in the Appendix link.

5.2 Mass Balance Model_results

Results suggest a substantial lack of understanding of the movements inshore and offshore, growth and recruitment of Illex in the survey and fishing area of the US. The magnitude of the uncertainty increases with catch as it is the primary driver of the disparity between the estimates of relative abundance between the spring and fall surveys.

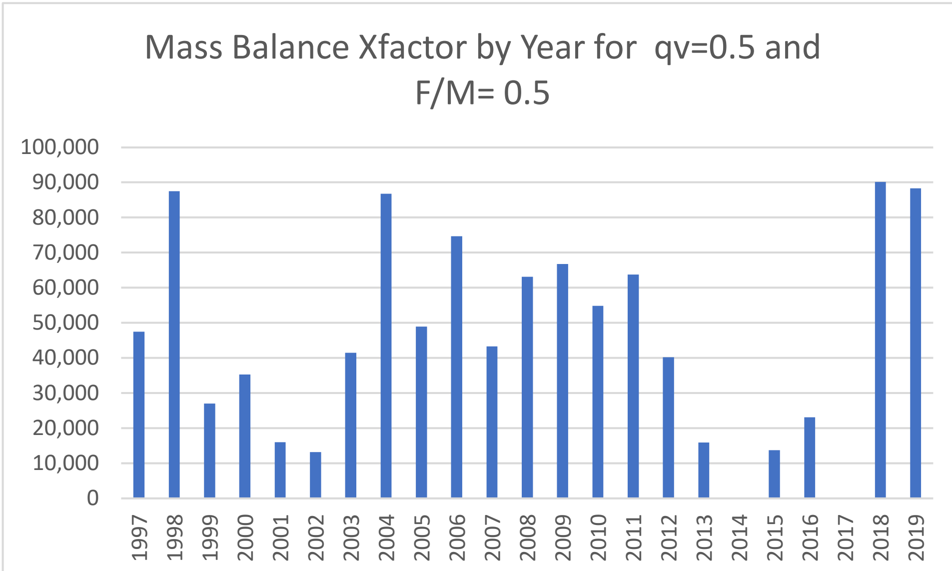

Figure 5.2.1 Example estimates of X factor by year for assumed catchability x availability product =0.5 and fishing mortality to natural mortality ratio of 0.5.

The average X factor increases as qv decreases and as the ratio of F to M decreases (Table 5.2.1). The Mass Balance model is indicative of the potential magnitude of the missing production, but it does not have immediate utility for assessment. Instead, it may be useful for diagnosing the behavior of a more complicated two area model informed by estimates of both growth and oceanographic factors possibly influencing migrations.

Table 5.2.1. Evaluation of average X factor over all years (1997-2019) for assumed ranges of qv and F/M.

Table 1. Estimation of average X factor to balance removals, 1997-2019 given alternative values of F/M and catchability =efficiency x availability

		qv=efficiency x availability													
	49,605	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
ratio of F to M	0.10	234411	192945	179122	172211	168065	165300	163326	161845	160693	159771	159017	158389	157857	157402
	0.20	165558	124091	110269	103358	99211	96447	94472	92991	91839	90918	90164	89535	89004	88548
	0.30	142607	101140	87318	80406	76260	73495	71521	70040	68888	67966	67213	66584	66053	65597
	0.40	131131	89664	75842	68931	64784	62020	60045	58564	57412	56491	55737	55109	54577	54121
	0.50	124246	82779	68957	62046	57899	55134	53160	51679	50527	49605	48852	48223	47692	47236
	0.60	119655	78189	64366	57455	53309	50544	48570	47089	45937	45015	44261	43633	43101	42646
	0.70	116377	74910	61088	54177	50030	47265	45291	43810	42658	41737	40983	40354	39823	39367
	0.80	113918	72451	58629	51717	47571	44806	42832	41351	40199	39277	38524	37895	37364	36908
	0.90	112005	70538	56716	49805	45658	42894	40919	39438	38286	37365	36611	35983	35451	34995
	1.00	110475	69008	55186	48275	44128	41364	39389	37908	36756	35835	35081	34453	33921	33465
	1.10	109223	67756	53934	47023	42876	40112	38137	36656	35504	34583	33829	33201	32669	32213
	1.20	108180	66713	52891	45980	41833	39069	37094	35613	34461	33540	32786	32157	31626	31170

5.3 Envelope Model_results

Details on the parameterization of the Envelope model may be found in Appendix 2. The model assumes a 24 week fishery. **F** and **M** estimates are the assumed weekly rates times 24. Maximum and minimum survey trawl efficiency estimates are consistent with results of interviews with fishermen and experiments conducted under the guidance of NTAP. Min and max estimates of availability are influenced by results of Wright et al and Manderson 2021. The effects of the consistency constraint can be seen in the following figure of biomass trajectories and by comparison of the average biomass estimates for the period 1997-2019. Note that the range of biomass estimates for the constrained set is only 2% of the interval defined by the assumed range of **qv**. (.i.e., 0.021=(284,301-56,059)/(10,982,522-55,984). There does not appear to be a significant trend in any of the biomass estimates.

Table 5.3.1. Summary of Envelope model inputs, outputs and assumed parameter values. Minimum swept area estimates of survey biomass were provide by Lisa Hendrickson, NEFSC.

	Total Survey Area (nm sq)	Swept Area/tow (nm sq)	Raising Factor	Raising Factor	Natural Mortality: 24 ks @0.01/wk +0.63	Natural Mortality 24 wks @0.14/wk +0.56			
	62400	0.01	1	1	0.87	3.92			
	Assume a 6 month = 24 wk fishery		Max Efficiency	Min Efficiency	Max F (total for 24 wks)	Min F (total for 24 wks)			
			0.6	0.2	1.74	0.196			
			Availability max	Availability min	Exploitation Rate (max)	Exploitation Rate (min)			
			0.5	0.1	0.617643637	0.0468424			
		Product(qv)	***0.3***	***0.02***	0				ave ratio
	Input Data		Swept area based estimates of biomass		Catch based estimates of Biomass		Constrained Estimates of Biomass		5.268556
Year	Fall Min Swept Area (mt)	Catch (mt)	Swept Area Min (mt) adj for catch	Swept Area Max (mt) adj for catch	Min Pop|Fhi	Max Pop|Flo	Joint Min B	Joint Max B	ratio of Joint Max to Joint Min
1997	2,730	14,358	43900	6980396	23246	306517	43900	306517	6.98
1998	7,725	24,154	98778	19638175	39107	515644	98778	515644	5.22
1999	929	8,482	20498	2402149	13733	181075	20498	181075	8.83
2000	3,999	9,117	45899	10141096	14761	194631	45899	194631	4.24
2001	1,422	4,475	18229	3615680	7245	95533	18229	95533	5.24
2002	2,322	2,907	22966	5872197	4707	62059	22966	62059	2.70
2003	10,913	6,557	96954	27546318	10616	139980	96954	139980	1.44
2004	2,279	27,499	60614	5937145	44522	587054	60614	587054	9.69
2005	3,696	13,861	50820	9411804	22442	295907	50820	295907	5.82
2006	14,220	15,500	137084	35943874	25095	330897	137084	330897	2.41
2007	7,311	9,661	73097	18493129	15642	206245	73097	206245	2.82
2008	5,462	17,429	70384	13887771	28219	372077	70384	372077	5.29
2009	5,170	19,090	70627	13163648	30908	407537	70627	407537	5.77
2010	2,941	16,394	48728	7527820	26543	349982	48728	349982	7.18
2011	2,937	19,487	53473	7539310	31551	416012	53473	416012	7.78
2012	2,895	12,211	41900	7382255	19770	260683	41900	260683	6.22
2013	1,827	4,107	20883	4633745	6649	87677	20883	87677	4.20
2014	3,592	9,342	43009	9117155	15125	199435	43009	199435	4.64
2015	2,795	2,873	26673	7062702	4652	61333	26673	61333	2.30
2016	3,711	7,004	40350	9402341	11340	149523	40350	149523	3.71
2017		23,371	36107	165918	37839	498928	37839	165918	4.38
2018	7,146	25,524	96289	18189054	41325	544891	96289	544891	5.66
2019	3,310	28,495	70362	8544331	46135	608316	70362	608316	8.65
Average			55,984	10,982,522	22,660	298,780	56,059	284,301	

Figure 5.3.1. Summary output estimates for Envelope model estimates defined in Table 5.3.1.

5.4 Escapement Model_results

The following table illustrates application of Eq. 17 to the survey data using a value of 0.25 for qv and M=0.87. Note that the NEFSC spring bottom trawl survey does not enter into the computation below.

Table 5.4.1. Summary estimates of escapement by year for assumed value of M=0.87 and qv=0.25.

							M estimate
							0.87
BASELINE DATA FROM LISA HENDRICKSON							qv
							0.25
		Min. biomass (mt)		Adjusted Survey and Tot Removal			
Year	US Catch	NEFSC Spring survey	NEFSC Fall survey	NEFSC Spring survey	NEFSC Fall survey	Escapement	
1997	14,358	511	2,730	2,045	10,918	0.540192	
1998	24,154	226	7,725	903	30,899	0.664025	
1999	8,482	149	929	597	3,717	0.403731	
2000	9,117	35	3,999	139	15,994	0.730484	
2001	4,475	110	1,422	442	5,689	0.662616	
2002	2,907	68	2,322	274	9,288	0.831545	
2003	6,557	23	10,913	91	43,650	0.911386	
2004	27,499	139	2,279	554	9,114	0.338647	
2005	13,861	14	3,696	54	14,783	0.622319	
2006	15,500	121	14,220	484	56,879	0.850061	
2007	9,661	147	7,311	589	29,245	0.823844	
2008	17,429	54	5,462	216	21,847	0.659474	
2009	19,090	404	5,170	1,614	20,679	0.625971	
2010	16,394	101	2,941	405	11,764	0.525761	
2011	19,487	294	2,937	1,177	11,747	0.482230	
2012	12,211	1,099	2,895	4,396	11,580	0.594345	
2013	4,107	22	1,827	88	7,309	0.733292	
2014	9,342		3,592		14,366	0.703780	
2015	2,873	217	2,795	868	11,178	0.857369	
2016	7,004	2,641	3,711	10,564	14,845	0.766061	
2017	23,371	314		1,258			
2018	25,524	382	7,146	1,528	28,584	0.633721	
2019	28,495	1,901	3,310	7,603	13,241	0.417901	
Average			Average	1,631	18,060	**0.65358**	
			Min	54	3,717	**0.33865**	
			Max	10,564	56,879	0.91139	
			N years where escapement <40%			1	
			Fraction yrs with escapement <40%			**0.04545**	

Sensitivity analyses of the historical escapement estimates to a range of qv and M are shown in the following 4 tables. The average escapement (Table 2) falls below 40% only when M is relatively low (<0.4, i.e., 0.017/week) and when qv is improbably high (>0.6). Table 3 examines the lowest escapement in the time series as the table entry. This would be the worst case scenario in which at least one year experienced escapement less than 40%. Table 4 examines the fraction of years in which escapement falls below the 40% MSP proxy. As expected, the highest risk occurs when qv is improbably high and M is improbably low. The proportions of overfished status expected can be compared directly with the implied risks of overfishing in the ABC control rule developed by the SSC.

Table 5.4.2. Predicted average escapement fractions given the joint range of assumed values of qv and M using the data in Table 5.4.1. Worst case scenarios represent the minimum value observed under each parameter combination. The fraction of years in which escapement falls below 40% is estimated by counting the number of occurrences and dividing by the number of years.

Table 2. Predicted average escapement fraction given alternative values of M and qv.

		qv=efficiency x availability													
	0.6536	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.85863	0.76150	0.68844	0.63058	0.58318	0.54339	0.50937	0.47985	0.45393	0.43094	0.41039	0.39188	0.37510	0.35981
	0.40	0.86969	0.77775	0.70747	0.65117	0.60464	0.56530	0.53146	0.50195	0.47592	0.45275	0.43196	0.41318	0.39610	0.38050
	0.60	0.88004	0.79325	0.72586	0.67127	0.62575	0.58700	0.55346	0.52406	0.49802	0.47474	0.45378	0.43478	0.41747	0.40160
	0.80	0.88970	0.80799	0.74358	0.69082	0.64645	0.60840	0.57528	0.54610	0.52013	0.49683	0.47578	0.45663	0.43913	0.42305
	1.00	0.89871	0.82198	0.76059	0.70977	0.66666	0.62944	0.59685	0.56799	0.54219	0.51895	0.49787	0.47864	0.46101	0.44477
	1.20	0.90709	0.83520	0.77688	0.72808	0.68634	0.65006	0.61810	0.58965	0.56411	0.54101	0.51998	0.50074	0.48305	0.46671
	1.40	0.91486	0.84768	0.79242	0.74571	0.70544	0.67018	0.63895	0.61101	0.58582	0.56294	0.54204	0.52285	0.50516	0.48877
	1.60	0.92206	0.85941	0.80721	0.76264	0.72390	0.68976	0.65935	0.63201	0.60724	0.58466	0.56396	0.54490	0.52726	0.51088
	1.80	0.92872	0.87042	0.82123	0.77883	0.74169	0.70875	0.67923	0.65256	0.62830	0.60610	0.58567	0.56680	0.54928	0.53297
	2.00	0.93487	0.88072	0.83450	0.79428	0.75879	0.72710	0.69855	0.67263	0.64894	0.62718	0.60710	0.58847	0.57114	0.55496
	2.20	0.94053	0.89034	0.84701	0.80898	0.77515	0.74477	0.71724	0.69214	0.66910	0.64785	0.62816	0.60985	0.59277	0.57677
	2.40	0.94574	0.89931	0.85879	0.82291	0.79078	0.76173	0.73528	0.71104	0.68871	0.66803	0.64881	0.63087	0.61408	0.59832

Mass Balance Xfactor by Year for qv=0.25 and F/M= 0.87

Table 3. Predicted worst case scenario for escapement given alternative values of M and qv. Entries represent the minimum escapement over the 1997-2019 period.

		qv=efficiency x availability													
	0.3386	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.64682	0.47800	0.37907	0.31406	0.26809	0.23386	0.20738	0.18628	0.16909	0.15480	0.14273	0.13241	0.12348	0.11568
	0.40	0.66932	0.50299	0.40287	0.33600	0.28816	0.25225	0.22430	0.20192	0.18360	0.16833	0.15541	0.14433	0.13472	0.12631
	0.60	0.69107	0.52796	0.42715	0.35866	0.30910	0.27157	0.24217	0.21852	0.19907	0.18280	0.16899	0.15712	0.14681	0.13777
	0.80	0.71200	0.55279	0.45177	0.38197	0.33085	0.29180	0.26100	0.23607	0.21549	0.19822	0.18350	0.17082	0.15978	0.15008
	1.00	0.73206	0.57736	0.47664	0.40584	0.35335	0.31289	0.28074	0.25458	0.23288	0.21459	0.19896	0.18546	0.17367	0.16329
	1.20	0.75122	0.60156	0.50162	0.43016	0.37652	0.33478	0.30137	0.27402	0.25122	0.23192	0.21538	0.20104	0.18849	0.17742
	1.40	0.76943	0.62527	0.52660	0.45483	0.40027	0.35740	0.32283	0.29435	0.27049	0.25021	0.23276	0.21758	0.20427	0.19248
	1.60	0.78669	0.64839	0.55144	0.47971	0.42450	0.38068	0.34507	0.31554	0.29067	0.26944	0.25109	0.23509	0.22100	0.20851
	1.80	0.80299	0.67083	0.57603	0.50470	0.44909	0.40452	0.36800	0.33753	0.31171	0.28957	0.27036	0.25354	0.23870	0.22549
	2.00	0.81834	0.69253	0.60025	0.52967	0.47394	0.42882	0.39155	0.36024	0.33356	0.31057	0.29054	0.27293	0.25734	0.24343
	2.20	0.83273	0.71340	0.62398	0.55449	0.49892	0.45347	0.41561	0.38359	0.35615	0.33237	0.31157	0.29322	0.27691	0.26232
	2.40	0.84620	0.73340	0.64714	0.57904	0.52390	0.47835	0.44009	0.40749	0.37940	0.35492	0.33341	0.31436	0.29737	0.28212

Table 4. Fraction of years in which escapement is less than 40% for the period 1997-2019.

		qv=efficiency x availability													
	0.0455	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.00000	0.00000	0.04545	0.13636	0.18182	0.22727	0.27273	0.31818	0.40909	0.45455	0.59091	0.59091	0.63636	0.63636
	0.40	0.00000	0.00000	0.00000	0.04545	0.13636	0.18182	0.27273	0.27273	0.31818	0.40909	0.45455	0.59091	0.59091	0.59091
	0.60	0.00000	0.00000	0.00000	0.04545	0.13636	0.13636	0.18182	0.27273	0.27273	0.31818	0.40909	0.45455	0.59091	0.59091
	0.80	0.00000	0.00000	0.00000	0.04545	0.09091	0.13636	0.18182	0.18182	0.27273	0.27273	0.31818	0.36364	0.45455	0.45455
	1.00	0.00000	0.00000	0.00000	0.00000	0.04545	0.13636	0.13636	0.18182	0.22727	0.27273	0.27273	0.31818	0.31818	0.45455
	1.20	0.00000	0.00000	0.00000	0.00000	0.04545	0.09091	0.13636	0.13636	0.18182	0.22727	0.27273	0.27273	0.31818	0.31818
	1.40	0.00000	0.00000	0.00000	0.00000	0.00000	0.04545	0.09091	0.13636	0.13636	0.18182	0.22727	0.27273	0.27273	0.27273
	1.60	0.00000	0.00000	0.00000	0.00000	0.00000	0.04545	0.04545	0.13636	0.13636	0.13636	0.18182	0.22727	0.27273	0.27273
	1.80	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04545	0.04545	0.13636	0.13636	0.13636	0.18182	0.18182	0.22727
	2.00	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04545	0.04545	0.09091	0.13636	0.13636	0.13636	0.18182	0.18182
	2.20	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04545	0.04545	0.09091	0.13636	0.13636	0.13636	0.18182
	2.40	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04545	0.04545	0.09091	0.13636	0.13636	0.13636

At the May 2020 SSC meeting an additional analyses of the potential effects of a 30,000 mt quota was conducted. Those analyses are repeated in Section 5.6 below. For that scenario, it is assumed that a 30,000 mt quota was taken in all years. In addition, an analysis of a hypothetical 33,000 mt quota is also evaluated.

5.5 VMS Spatial Model_results

Actual values for gear efficiency **q** and move along thresholds **γ** are unknown, but their consequences can be evaluated for the observed fishing patterns for 2017-2019. Table 3 illustrates the effect of assumed gear efficiency and the depletion ratio threshold on estimated virtual area swept. The virtual area swept ranges from 101.9 km^2 to 45,755 km^2. Wright et al (2020, their Table 2) independently reported fishing areas 12,993 to 15,313 km^2 for 2017 to 2019. These estimates were derived by binning the data into 5 minute squares (roughly 19.42 nm^2 or 2.8 times larger than the 3 minute square used herein.) Wright et al.'s method provided estimates of presence/absence in a given cell rather that estimates of swept area but are useful for comparison. If the Wright et al. average of 14,315 km^2 is used, the feasible range of **q** and **γ** parameters range from 0.3 to 1 for **q** and 0.95 to 0.8 for **γ**.

Table 5.5.1. Virtual area swept (km2) as a function of assumed gear efficiency and threshold for decline in CPUE with a trip for movement to a new fishing area. Combined years 2017-2019.

	Effective Area	Assumed Gear Efficiency									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Depletion Ratio Threshold	0.95	4575.5	9151.1	13726.6	18302.1	22877.7	27453.2	32028.7	36604.3	41179.8	45755.3
	0.85	1444.1	2888.2	4332.3	5776.4	7220.5	8664.6	10108.7	11552.8	12996.9	14441.0
	0.75	815.8	1631.6	2447.4	3263.2	4079.1	4894.9	5710.7	6526.5	7342.3	8158.1
	0.65	544.8	1089.6	1634.4	2179.2	2724.0	3268.9	3813.7	4358.5	4903.3	5448.1
	0.55	392.6	785.1	1177.7	1570.3	1962.9	2355.4	2748.0	3140.6	3533.2	3925.7
	0.45	293.9	587.8	881.7	1175.7	1469.6	1763.5	2057.4	2351.3	2645.2	2939.2
	0.35	223.6	447.1	670.7	894.2	1117.8	1341.3	1564.9	1788.4	2012.0	2235.6
	0.25	169.3	338.6	507.9	677.2	846.5	1015.8	1185.1	1354.4	1523.7	1693.0
	0.15	123.7	247.4	371.1	494.8	618.6	742.3	866.0	989.7	1113.4	1237.1

Estimates of spatially weighted average F (Eq. 26) for 2017-2019 by year are given Table 4 below. As expected, the average F is greatest under the assumption that gear efficiency **q** is 1.0 and that the depletion ratio threshold **γ** is small. The lowest estimates of average F occur when gear efficiency is assumed to be low and the depletion ratio is large (Table 5.4.2).

Table 5.4.2. Spatially weighted F over all fishing areas as a function of gear efficiency and threshold for decline in CPUE within a trip for movement to a new fishing area. 2017-2019 combined.

	Spatially weighted average F	Assumed Gear Efficiency									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Depletion Ratio Threshold	0.95	0.0436	0.0468	0.0479	0.0486	0.0491	0.0494	0.0496	0.0498	0.0500	0.0501
	0.85	0.1066	0.1280	0.1370	0.1420	0.1455	0.1477	0.1493	0.1505	0.1514	0.1522
	0.75	0.1388	0.1968	0.2198	0.2312	0.2404	0.2465	0.2511	0.2549	0.2580	0.2603
	0.65	0.1511	0.2469	0.2949	0.3211	0.3359	0.3465	0.3560	0.3637	0.3693	0.3741
	0.55	0.1511	0.2818	0.3572	0.4042	0.4339	0.4534	0.4670	0.4776	0.4878	0.4967
	0.45	0.1511	0.3024	0.4053	0.4769	0.5278	0.5607	0.5871	0.6056	0.6197	0.6310
	0.35	0.1511	0.3024	0.4442	0.5379	0.6110	0.6683	0.7094	0.7410	0.7676	0.7880
	0.25	0.1511	0.3024	0.4540	0.5911	0.6860	0.7659	0.8321	0.8868	0.9287	0.9614
	0.15	0.1511	0.3024	0.4540	0.6059	0.7531	0.8652	0.9535	1.0344	1.1036	1.1643
	0.1	0.1511	0.3024	0.4540	0.6059	0.7579	0.9063	1.0218	1.1144	1.2007	1.2765

To address the potential range of effective fishing mortalities, $\mathbf{F_{eff}}$ I chose the maximum value of $\mathbf{F_f}$ from Table 5.4.2 for various combinations of assumed gear efficiency $\mathbf{q}$ and depletion ratio γ. By inspection, it is clear that $\mathbf{F_{eff}}$ reaches its maximum value when θ =1(i.e. all of the habitat is fished) or when $\phi = 0$ (i.e., no Illex are in the unfished area). Under either of these conditions, the effective F over the whole area is equal to the fishing mortality in the area where fishing occurs. For all other combinations of ϕ **(0,1)** and θ **(0,1)** the effective F will be less than the F in the fishing area because some fish are protected from fishing. Over the assumed range of parameter values, the maximum F in the area fished (=1.28 from Table 5.4.2) is reduced to a maximum value of 0.912 in Table 5.4.3. Based on these calculations and examination of the results for 2017 to 2019 individually, Appendix 1, it appears unlikely that the overall F on the population exceeds 1.2 in any of the recent 3 years.

Table 5.4.3. Estimated fishing mortality on the entire population within the US resource area. Estimates based on the highest spatially weighted F in Table 4 = 1.2765.

		Ratio of Density in Unfished Area to Density in Fished Area (phi)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
Ratio of Area Fished to Total Habitat (theta)	0.01	0.117	0.061	0.042	0.031	0.025	0.021	0.018	0.016	0.014	0.013
	0.03	0.302	0.171	0.119	0.092	0.074	0.063	0.054	0.048	0.042	0.040
	0.05	0.440	0.266	0.191	0.148	0.122	0.103	0.089	0.079	0.071	0.067
	0.07	0.548	0.349	0.256	0.202	0.167	0.142	0.124	0.110	0.099	0.094
	0.09	0.635	0.422	0.316	0.253	0.211	0.181	0.158	0.140	0.126	0.120
	0.11	0.706	0.488	0.372	0.301	0.253	0.218	0.192	0.171	0.154	0.147
	0.14	0.791	0.573	0.449	0.369	0.314	0.272	0.241	0.216	0.196	0.187
	0.15	0.815	0.598	0.473	0.391	0.333	0.290	0.257	0.231	0.209	0.200
	0.16	0.837	0.623	0.496	0.412	0.352	0.308	0.273	0.245	0.223	0.213
	0.17	0.858	0.646	0.518	0.432	0.371	0.325	0.289	0.260	0.237	0.226
	0.18	0.877	0.668	0.539	0.452	0.389	0.342	0.305	0.275	0.250	0.240
	0.2	0.912	0.709	0.580	0.491	0.426	0.375	0.336	0.304	0.278	0.266

5.6_Integration of Results

As described in the Schematic (Fig. 2.1) the range of biomasses, Fs and risks can be refined by combining information from the various models. Notably, the VMS data provides a way of refining the seasonal effective F estimate based on the spatial patterns of fishing effort and the derived parameters in Sections 4.5.1.1 to 4.5.1.3. Using the derived bounds on feasible Fs and likely ranges of Survey gear efficiency, the envelope analyses (Section 5.3) can be refined as well as the escapement risks. (Section 5.4)

5.6.1 Evaluation of 30kt and 33Kt ABCs for risk policy

5.6.1.1 30,000 mt quota

Table 5.6.1.1.1 Summary estimates of escapement by year for assumed value of M=0.87 and qv=0.25. Escapements are estimated for all years by assuming a catch of 30,000 mt.

							M estimat
							0.2
BASELINE DATA FROM LISA HENDRICKSON							qv
							0.7
		Min. biomass (mt)		Adjusted Survey and Tot Removal			
Year	US Catch	NEFSC Spring survey	NEFSC Fall survey	NEFSC Spring survey	NEFSC Fall survey	Escapement	
1997	30,000	511	2,730	731	3,899	0.125604	
1998	30,000	226	7,725	322	11,035	0.289033	
1999	30,000	149	929	213	1,328	0.046628	
2000	30,000	35	3,999	50	5,712	0.173848	
2001	30,000	110	1,422	158	2,032	0.069633	
2002	30,000	68	2,322	98	3,317	0.108895	
2003	30,000	23	10,913	32	15,589	0.364795	
2004	30,000	139	2,279	198	3,255	0.107073	
2005	30,000	14	3,696	19	5,280	0.162828	
2006	30,000	121	14,220	173	20,314	0.428029	
2007	30,000	147	7,311	210	10,445	0.277859	
2008	30,000	54	5,462	77	7,803	0.223267	
2009	30,000	404	5,170	577	7,385	0.213882	
2010	30,000	101	2,941	145	4,201	0.134032	
2011	30,000	294	2,937	420	4,196	0.133868	
2012	30,000	1,099	2,895	1,570	4,136	0.132214	
2013	30,000	22	1,827	32	2,610	0.087725	
2014	30,000		3,592		5,131	0.158967	
2015	30,000	217	2,795	310	3,992	0.128213	
2016	30,000	2,641	3,711	3,773	5,302	0.163401	
2017	30,000	314		449			
2018	30,000	382	7,146	546	10,208	0.273292	
2019	30,000	1,901	3,310	2,715	4,729	0.148365	
Average			Average	583	6,450	0.17961	
			Min	19	1,328	0.04663	
			Max	3,773	20,314	0.42803	
			N years where escapement <40			21	
			Fraction yrs with escapement <4			0.95455	

Table 5.6.1.1.2. Predicted average escapement fractions given the joint range of assumed values of qv and M using the data in Table 5.6.1.1.1. Worst case scenarios represent the minimum value observed under each parameter combination. The fraction of years in which escapement falls below 40% is estimated by counting the number of occurrences and dividing by the number of years. Escapements are estimated for all years by assuming a catch of 30,000 mt.

Table 2. Predicted average escapement fraction given alternative values of M and qv.

		qv=efficiency x availability													
	0.1796	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.71429	0.56863	0.47618	0.41126	0.36275	0.32496	0.29459	0.26959	0.24862	0.23076	0.21536	0.20193	0.19010	0.17961
	0.40	0.73291	0.59101	0.49906	0.43360	0.38422	0.34546	0.31412	0.28819	0.26636	0.24769	0.23154	0.21742	0.20496	0.19387
	0.60	0.75079	0.61304	0.52194	0.45621	0.40613	0.36652	0.33429	0.30749	0.28483	0.26539	0.24851	0.23370	0.22060	0.20893
	0.80	0.76789	0.63466	0.54475	0.47900	0.42840	0.38807	0.35505	0.32745	0.30401	0.28382	0.26623	0.25077	0.23704	0.22479
	1.00	0.78420	0.65579	0.56740	0.50188	0.45096	0.41004	0.37634	0.34802	0.32386	0.30297	0.28470	0.26859	0.25426	0.24143
	1.20	0.79971	0.67636	0.58979	0.52476	0.47371	0.43237	0.39809	0.36914	0.34432	0.32278	0.30388	0.28716	0.27224	0.25885
	1.40	0.81440	0.69631	0.61185	0.54755	0.49658	0.45497	0.42024	0.39075	0.36535	0.34321	0.32372	0.30642	0.29095	0.27701
	1.60	0.82829	0.71559	0.63349	0.57017	0.51947	0.47775	0.44270	0.41278	0.38688	0.36421	0.34418	0.32635	0.31035	0.29590
	1.80	0.84137	0.73416	0.65465	0.59253	0.54229	0.50062	0.46539	0.43514	0.40883	0.38571	0.36521	0.34688	0.33040	0.31548
	2.00	0.85367	0.75199	0.67525	0.61454	0.56496	0.52351	0.48823	0.45777	0.43114	0.40765	0.38673	0.36798	0.35105	0.33569
	2.20	0.86520	0.76904	0.69524	0.63612	0.58738	0.54631	0.51112	0.48056	0.45373	0.42994	0.40868	0.38956	0.37225	0.35649
	2.40	0.87598	0.78529	0.71456	0.65722	0.60948	0.56894	0.53398	0.50344	0.47650	0.45251	0.43099	0.41156	0.39392	0.37782

Mass Balance Xfactor by Year for qv=0.7 and F/M= 0.2

Table 3. Predicted worst case scenario for escapement given alternative values of M and qv. Entries represent the minimum escapement over the 1997-2019 period.

		qv=efficiency x availability													
	0.0466	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.40643	0.25504	0.18583	0.14616	0.12045	0.10243	0.08910	0.07884	0.07070	0.06408	0.05860	0.05398	0.05003	0.04663
	0.40	0.43076	0.27450	0.20143	0.15909	0.13145	0.11200	0.09756	0.08642	0.07756	0.07035	0.06437	0.05932	0.05501	0.05128
	0.60	0.45543	0.29486	0.21800	0.17292	0.14329	0.12233	0.10672	0.09464	0.08502	0.07718	0.07066	0.06515	0.06044	0.05637
	0.80	0.48032	0.31607	0.23553	0.18770	0.15601	0.13348	0.11664	0.10357	0.09313	0.08461	0.07751	0.07151	0.06638	0.06193
	1.00	0.50531	0.33807	0.25400	0.20342	0.16964	0.14548	0.12734	0.11323	0.10193	0.09268	0.08497	0.07845	0.07285	0.06800
	1.20	0.53027	0.36080	0.27341	0.22011	0.18419	0.15836	0.13887	0.12366	0.11145	0.10144	0.09308	0.08599	0.07990	0.07462
	1.40	0.55509	0.38417	0.29372	0.23775	0.19970	0.17214	0.15127	0.13491	0.12175	0.11092	0.10187	0.09418	0.08757	0.08182
	1.60	0.57963	0.40808	0.31489	0.25635	0.21616	0.18686	0.16456	0.14702	0.13285	0.12118	0.11139	0.10306	0.09589	0.08966
	1.80	0.60378	0.43244	0.33685	0.27587	0.23358	0.20254	0.17878	0.16000	0.14480	0.13223	0.12168	0.11268	0.10492	0.09816
	2.00	0.62744	0.45713	0.35954	0.29629	0.25196	0.21917	0.19393	0.17391	0.15763	0.14414	0.13277	0.12307	0.11469	0.10738
	2.20	0.65050	0.48203	0.38287	0.31755	0.27127	0.23676	0.21004	0.18874	0.17137	0.15692	0.14472	0.13428	0.12524	0.11735
	2.40	0.67288	0.50702	0.40676	0.33961	0.29148	0.25530	0.22712	0.20453	0.18604	0.17061	0.15754	0.14633	0.13661	0.12811

Table 4. Fraction of years in which escapement is less than 40% for the period 1997-2019.

		qv=efficiency x availability													
	0.9545	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.00000	0.09091	0.22727	0.54545	0.68182	0.72727	0.77273	0.81818	0.90909	0.90909	0.90909	0.90909	0.95455	0.95455
	0.40	0.00000	0.09091	0.22727	0.45455	0.68182	0.68182	0.77273	0.77273	0.86364	0.90909	0.90909	0.90909	0.90909	0.95455
	0.60	0.00000	0.09091	0.13636	0.45455	0.59091	0.68182	0.72727	0.77273	0.77273	0.86364	0.90909	0.90909	0.90909	0.90909
	0.80	0.00000	0.04545	0.13636	0.22727	0.50000	0.68182	0.68182	0.72727	0.77273	0.77273	0.86364	0.90909	0.90909	0.90909
	1.00	0.00000	0.04545	0.09091	0.22727	0.45455	0.54545	0.68182	0.68182	0.72727	0.77273	0.77273	0.81818	0.90909	0.90909
	1.20	0.00000	0.04545	0.09091	0.13636	0.27273	0.45455	0.63636	0.68182	0.68182	0.77273	0.77273	0.77273	0.77273	0.86364
	1.40	0.00000	0.04545	0.09091	0.13636	0.22727	0.45455	0.50000	0.63636	0.68182	0.68182	0.77273	0.77273	0.77273	0.77273
	1.60	0.00000	0.00000	0.04545	0.09091	0.13636	0.22727	0.45455	0.54545	0.68182	0.68182	0.68182	0.72727	0.77273	0.77273
	1.80	0.00000	0.00000	0.04545	0.09091	0.13636	0.22727	0.31818	0.45455	0.54545	0.68182	0.68182	0.68182	0.72727	0.77273
	2.00	0.00000	0.00000	0.04545	0.09091	0.13636	0.13636	0.22727	0.45455	0.50000	0.54545	0.68182	0.68182	0.68182	0.68182
	2.20	0.00000	0.00000	0.04545	0.04545	0.09091	0.13636	0.22727	0.22727	0.45455	0.50000	0.54545	0.63636	0.68182	0.68182
	2.40	0.00000	0.00000	0.00000	0.04545	0.09091	0.09091	0.13636	0.22727	0.22727	0.45455	0.50000	0.54545	0.63636	0.68182

5.6.1.2 33,000 mt quota

Table 5.6.1.2.1 Summary estimates of escapement by year for assumed value of M=0.87 and qv=0.25. Escapements are estimated for all years by assuming a catch of 30,000 mt.

							M estimate
							0.2
BASELINE DATA FROM LISA HENDRICKSON							qv
							0.7
		Min. biomass (mt)		Adjusted Survey and Tot Removal			
Year	US Catch	NEFSC Spring survey	NEFSC Fall survey	NEFSC Spring survey	NEFSC Fall survey	Escapement	
1997	33,000	511	2,730	731	3,899	0.115505	
1998	33,000	226	7,725	322	11,035	0.269848	
1999	33,000	149	929	213	1,328	0.042569	
2000	33,000	35	3,999	50	5,712	0.160582	
2001	33,000	110	1,422	158	2,032	0.063706	
2002	33,000	68	2,322	98	3,317	0.099985	
2003	33,000	23	10,913	32	15,589	0.343007	
2004	33,000	139	2,279	198	3,255	0.098296	
2005	33,000	14	3,696	19	5,280	0.150249	
2006	33,000	121	14,220	173	20,314	0.404871	
2007	33,000	147	7,311	210	10,445	0.259145	
2008	33,000	54	5,462	77	7,803	0.207175	
2009	33,000	404	5,170	577	7,385	0.198294	
2010	33,000	101	2,941	145	4,201	0.123351	
2011	33,000	294	2,937	420	4,196	0.123198	
2012	33,000	1,099	2,895	1,570	4,136	0.121657	
2013	33,000	22	1,827	32	2,610	0.080391	
2014	33,000		3,592		5,131	0.146635	
2015	33,000	217	2,795	310	3,992	0.117932	
2016	33,000	2,641	3,711	3,773	5,302	0.150787	
2017	33,000	314		449			
2018	33,000	382	7,146	546	10,208	0.254777	
2019	33,000	1,901	3,310	2,715	4,729	0.136721	
Average			Average	583	6,450	0.16676	
			Min	19	1,328	0.04257	
			Max	3,773	20,314	0.40487	
			N years where escapement <40%			21	
			Fraction yrs with escapement <4			0.95455	

Table 5.6.1.2.2. Predicted average escapement fractions given the joint range of assumed values of qv and M using the data in Table 5.6.1.2.1. Worst case scenarios represent the minimum value observed under each parameter combination. The fraction of years in which escapement falls below 40% is estimated by counting the number of occurrences and dividing by the number of years. Escapements are estimated for all years by assuming a catch of 33,000 mt.

Table 2. Predicted average escapement fraction given alternative values of M and qv.

		qv=efficiency x availability													
	0.1668	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.69588	0.54706	0.45448	0.39028	0.34276	0.30600	0.27661	0.25254	0.23243	0.21536	0.20068	0.18791	0.17669	0.16676
	0.40	0.71518	0.56968	0.47725	0.41230	0.36375	0.32591	0.29549	0.27044	0.24944	0.23154	0.21610	0.20264	0.19078	0.18026
	0.60	0.73377	0.59205	0.50013	0.43465	0.38524	0.34643	0.31505	0.28908	0.26721	0.24851	0.23232	0.21816	0.20567	0.19456
	0.80	0.75161	0.61407	0.52301	0.45727	0.40717	0.36752	0.33525	0.30841	0.28571	0.26623	0.24932	0.23448	0.22136	0.20966
	1.00	0.76867	0.63566	0.54582	0.48007	0.42945	0.38909	0.35603	0.32841	0.30493	0.28470	0.26708	0.25158	0.23783	0.22555
	1.20	0.78495	0.65677	0.56845	0.50295	0.45202	0.41108	0.37735	0.34900	0.32480	0.30388	0.28559	0.26945	0.25509	0.24223
	1.40	0.80041	0.67731	0.59083	0.52583	0.47478	0.43343	0.39913	0.37015	0.34530	0.32372	0.30480	0.28804	0.27310	0.25968
	1.60	0.81507	0.69723	0.61287	0.54862	0.49765	0.45603	0.42129	0.39178	0.36635	0.34418	0.32467	0.30734	0.29184	0.27788
	1.80	0.82892	0.71648	0.63449	0.57123	0.52054	0.47882	0.44376	0.41382	0.38790	0.36521	0.34516	0.32730	0.31127	0.29681
	2.00	0.84197	0.73502	0.65563	0.59357	0.54336	0.50170	0.46646	0.43620	0.40987	0.38673	0.36621	0.34786	0.33135	0.31641
	2.20	0.85423	0.75280	0.67620	0.61556	0.56601	0.52458	0.48930	0.45883	0.43220	0.40868	0.38775	0.36898	0.35203	0.33665
	2.40	0.86572	0.76982	0.69616	0.63713	0.58843	0.54738	0.51219	0.48163	0.45479	0.43099	0.40972	0.39058	0.37325	0.35748

Mass Balance Xfactor by Year for qv=0.7 and F/M= 0.2

Table 3. Predicted worst case scenario for escapement given alternative values of M and qv. Entries represent the minimum escapement over the 1997-2019 period.

		qv=efficiency x availability													
	0.0426	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.38365	0.23736	0.17183	0.13466	0.11071	0.09399	0.08166	0.07219	0.06469	0.05860	0.05356	0.04931	0.04569	0.04257
	0.40	0.40756	0.25593	0.18654	0.14675	0.12095	0.10286	0.08948	0.07918	0.07101	0.06437	0.05886	0.05422	0.05026	0.04684
	0.60	0.43191	0.27544	0.20219	0.15971	0.13199	0.11246	0.09797	0.08679	0.07790	0.07066	0.06465	0.05958	0.05525	0.05151
	0.80	0.45659	0.29583	0.21880	0.17359	0.14387	0.12284	0.10717	0.09505	0.08539	0.07751	0.07096	0.06544	0.06071	0.05662
	1.00	0.48149	0.31708	0.23637	0.18841	0.15663	0.13403	0.11712	0.10400	0.09353	0.08497	0.07785	0.07183	0.06667	0.06220
	1.20	0.50648	0.33912	0.25489	0.20418	0.17030	0.14606	0.12786	0.11370	0.10236	0.09308	0.08534	0.07878	0.07317	0.06830
	1.40	0.53144	0.36188	0.27435	0.22091	0.18490	0.15898	0.13944	0.12417	0.11192	0.10187	0.09347	0.08636	0.08025	0.07494
	1.60	0.55624	0.38528	0.29470	0.23860	0.20045	0.17281	0.15187	0.13546	0.12225	0.11139	0.10230	0.09458	0.08794	0.08218
	1.80	0.58077	0.40921	0.31590	0.25724	0.21695	0.18758	0.16521	0.14761	0.13339	0.12168	0.11185	0.10350	0.09630	0.09004
	2.00	0.60490	0.43359	0.33790	0.27681	0.23442	0.20330	0.17946	0.16064	0.14538	0.13277	0.12218	0.11315	0.10536	0.09858
	2.20	0.62853	0.45829	0.36062	0.29726	0.25284	0.21997	0.19467	0.17458	0.15825	0.14472	0.13331	0.12358	0.11517	0.10783
	2.40	0.65157	0.48320	0.38398	0.31857	0.27220	0.23761	0.21082	0.18946	0.17203	0.15754	0.14530	0.13482	0.12576	0.11783

Table 4. Fraction of years in which escapement is less than 40% for the period 1997-2019.

		qv=efficiency x availability													
	0.9545	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
M	0.20	0.04545	0.13636	0.45455	0.63636	0.68182	0.77273	0.77273	0.90909	0.90909	0.90909	0.95455	0.95455	0.95455	0.95455
	0.40	0.00000	0.09091	0.22727	0.54545	0.68182	0.72727	0.77273	0.81818	0.90909	0.90909	0.90909	0.90909	0.95455	0.95455
	0.60	0.00000	0.09091	0.22727	0.45455	0.68182	0.68182	0.77273	0.77273	0.86364	0.90909	0.90909	0.90909	0.90909	0.95455
	0.80	0.00000	0.09091	0.13636	0.45455	0.54545	0.68182	0.68182	0.77273	0.77273	0.86364	0.90909	0.90909	0.90909	0.90909
	1.00	0.00000	0.04545	0.13636	0.22727	0.50000	0.68182	0.68182	0.72727	0.77273	0.77273	0.86364	0.90909	0.90909	0.90909
	1.20	0.00000	0.04545	0.09091	0.22727	0.45455	0.54545	0.68182	0.68182	0.72727	0.77273	0.77273	0.81818	0.90909	0.90909
	1.40	0.00000	0.04545	0.09091	0.13636	0.27273	0.45455	0.63636	0.68182	0.68182	0.77273	0.77273	0.77273	0.77273	0.86364
	1.60	0.00000	0.04545	0.09091	0.13636	0.22727	0.45455	0.50000	0.63636	0.68182	0.68182	0.72727	0.77273	0.77273	0.77273
	1.80	0.00000	0.00000	0.04545	0.09091	0.13636	0.22727	0.45455	0.50000	0.68182	0.68182	0.68182	0.72727	0.77273	0.77273
	2.00	0.00000	0.00000	0.04545	0.09091	0.13636	0.22727	0.31818	0.45455	0.54545	0.68182	0.68182	0.68182	0.72727	0.77273
	2.20	0.00000	0.00000	0.04545	0.09091	0.13636	0.13636	0.22727	0.36364	0.45455	0.54545	0.68182	0.68182	0.68182	0.68182
	2.40	0.00000	0.00000	0.04545	0.04545	0.09091	0.13636	0.18182	0.22727	0.45455	0.50000	0.54545	0.63636	0.68182	0.68182

An ABC of 33,000 mt would pose a high risk of falling below a 40% escapement rate only if qv exceeded 0.2 and M was less than 0.6. Integration of the results from the spatial overlap and VMS data can provide some additional insights.

5.6.2 Effects of Refined Parameter Ranges on Estimates of Stock Biomass and Fishing Mortality

The preceding analyses have been based on a broad range of parameter estimates, often nearly spanning the entire feasible range. An example would be catchability ranging from 0.05 to 0.95. Various empirical results noted herein and literature values suggest more likely ranges summarized below.

Parameter	*Symbol*	*Equation Number*	*Min Value*	*Max Value*	*Source/Comment*
Catchability (Survey)	**q**	9	0.2	0.5	NTAP experiments, fishermen interviews
Availability	**v**	10	0.27	0.48	Manderson Working Paper 2021
Catchability x Availability	**qv**	10	0.054	0.240	Min and max value products
Move Along Threshold	**γ**	23	0.01	0.15	Analyses herein 4.5.1.1
Ratio of Average Density outside to inside	**ϕ**	30	0.07	0.43	Analyses herein 4.5.1.2. Post stratified NEFSC fall survey: inside vs outside fishing cells. Mean for 2008-2019 =0.017
Ratio of fishing area to survey area	**θ**	30	0.014	0.363	Lowman et al. 2021.
Natural Mortality	**M**	11	0.87	3.92	Hendrickson and Hart 2006

The consequences of these revised ranges of parameters can be evaluated within the Envelope, Escapement, and VMS models to derive updated ranges of key output parameters. Using the min and max values above, the minimum and maximum values the envelope biomass estimates increase from (56kt, 284kt) to (138kt, 652kt) owing to the lower estimates of qv and the narrower range of F derived from the VMS analyses (0.082, 0.167). (Text Table below). These analyses suggest a large, lightly-fished stock. The escapement analyses examine the estimated average escapement levels over all years under the simple assumption that the initial biomass cand be derived in a VPA like approximation, using only the observed end of season biomass (i.e., rescaled fall survey biomass), and the M adjusted value of landings (See Eq. 11). When the refined estimates of M and qv are applied the results suggest that average escapement range is 0.66 to 0.97. Over this range of parameters the maximum number of years in which escapement fell below 40% MSP was 1. (ie. 1/22 =0.04545).

This historical range of fall survey biomasses for 1997-2019 can be evaluated against hypothesized 30kt and 33 kt ABCs. This counter factual exercise provide some insights into the potential consequences for average escapement and the fraction of years in which excapement fell below 40% MSP. For a 30kt ABC the minimum average escapement was 0.45 and the maximum average escapement is 0.93. Over the entire parameter space, the average of all computed average escapements was 0.72. The maximum fraction of years in which escapement fell below the 40% MSP threshold was 0.45. Over the full joint range of parameter space for qv and M, the average fraction of years falling below the threshold was 0.04 when ABC = 30kt.

The same counterfactual scenario was repeated for an assumed quota of 33kt. For the original range of parameters, the average escapement spans the interval 0.17 to 0.87. For the revised range of input parameters, the average escapement estimates span the interval 0.42 to 0.93.   Over the joint range of qv and M the overall average escapement is expected to be 0.70. The range for fraction of years in which escapement is below 40% MSP is 0.0 to 0.5. Hence none of the scenarios fell below the threshold more than 50% of the time. The average percent escapement over the joint parameter space of M and qv was 0.054. In fact, the maximum value of 0.5 occurred in only one of the 168 scenarios evaluated.

Comparison of original outputs with outputs based on revised ranges of parameters

Model	***Output Variable***	***ABC***	***Original Output Range***		***Revised Output Range***	
			Min Value_orig	***Max Value_orig***	***Min Value_rev***	***Max Value_rev***
Envelope	Average Biomass (1997-2019) mt	NA	56,059	284,301	137,961	652,468
Escapement	Average Escapement	Observed Landings	0.3598	0.94574	0.6618	0.9715
	Fraction Yrs <40% MSP	Observed Landings	0	0.6364	0	0.04545
	Average Escapement	30,000 mt	0.17961	0.87598	0.44548	0.93184
	Fraction Yrs <40% MSP	30,000 mt	0	0.95455	0	0.45455
	Average Escapement	33,000 mt	0.16676	0.86572	0.42404	0.92570
	Fraction Yrs <40% MSP	33,000 mt	0	0.95455	0.	0.5
VMS	Spatially Weighted F (24 wk)	NA	0.0436	1.2765	0.0098	0.1455
	Effective F (24 wk) on population.	NA	0.0130	0.9120	0.0820	0.1670

6.0 Discussion

The dynamics of Illex squid are poorly known in the Northwest Atlantic. The analyses herein systematically explore the uncertainties of key parameters that influence the stock dynamics. The basic principle underlying these analyses is consideration of a broad range of potential parameters on the estimation of abundance and fishing mortality, followed by a refinement of the parameter range to a more plausible set of values. "Plausible" values are informed either by inconsistencies among initial parameter ranges or by external information derived from empirical studies. Inconsistencies can arise when abundance estimates derived on the basis of an assumed extreme range of F, lie outside of a range generated by an assumed extreme range of gear efficiency and availability. The mismatch suggests that as least one of the parameter combinations are "too extreme" such that a constraint is appropriate.

An attempt has been made throughout to focus on parameters that can be derived from empirical studies such as gear comparison experiments or deduced from detailed analyses of harvester behaviors (e.g., study fleets). The Lowman et al (2021) study illustrates the value of empirical constraints that can be used to refine the plausible range of availability. Similarly, various studies supported by the Northeast Trawl Advisory Panel (NTAP) can be used to develop a narrower range of possible gear efficiencies. Finally, the spatial patterns of fishing activity can be used to infer potential fishing mortality rates. Spatial analyses in particular proved to be valuable for defining ranges of fishing mortality on the stock present in US waters.

There are no approved Biological Reference Points (BRP) or proxies for Illex in US waters. The work of Hendrickson and Hart (2006) suggests a range of fishing mortality rates consistent with estimated rates of natural mortality in this semelparous species. The 24-week F estimates based on VMS data are about an order of magnitude lower than the reference points in Hendrickson and Hart (2006).

The Escapement model, which uses a VPA approximation to estimate the size of the population necessary to support the observed catch, relies heavily on a range of possible Fs for the entire season taken from Hendrickson and Hart (2006). The escapement ratio is also a virtual concept since the denominator is a quantity that is deducible from first principles but unlikely to be estimable for the foreseeable future. The hypothetical evaluations of potential escapements for constant quotas of 30 kt and 33 kt do suggest that over the range of observed post fishery fall survey indices, there is a low likelihood that either ABC level would induce a significant fraction of escapements below a 40% MSP threshold.

Main Conclusions:

1. The overall Illex population is likely to be large.
2. Observations suggest relatively low chances of high fishing mortality rates over a broad range of assumed parameter extremes.
3. Spatial analyses of survey and fishery footprint suggest high escapement (Lowman et al. 2021, Manderson et al. 2021)
4. None of the estimates of area wide fishing mortality suggest fishing mortality rates greater that life history based biological reference point proxies.
5. Increases of quotas to 33,000 create risks to falling below F 40% but the risk is lower than the risks of overfishing associated with current Harvest Control Rules used by the SSC and the risk policy adopted by the Council

7.0 References

Beverton, R. J. H. and Holt, S. J. 1957. “Some problems concerning the relationship between fishing mortality and fishing intensity”. In *On the Dynamics of Exploited Fish Populations* 19 U.K. Minist. Agric. Fish. Food Fish. Invest. (Ser. 2)

Gould, W. R. and K. H. Pollock. 1997. Catch-effort maximum likelihood estimation of important population parameters. Can. J. Fish. Aquat. Sci. 54:898-906.

Hendrickson, L., and D. R. Hart. 2006. An age-based cohort model for estimating the spawning mortality of semelparous cephalopods with an application to per-recruit calculations for the northern shortfin squid, Illex illecebrosus. Fisheries Research 78:4-13.

Hendrickson L.C. and M. A. Showell. 2019. 2019 Assessment of Northern Shortfin Squid (*Illex illecebrosus*) in Subareas 3+4. NAFO SCR Doc 19/042, Serial No. N6973. 38 p.

Lassen, H. and P. Medley. 2001. Virtual population analysis. A practical manual for stock assessment. *FAO Fisheries Technical Paper.* No. 400. Rome, FAO. 129p. http://www.fao.org/3/x9026e/x9026e06.htm

Leslie, P. H. and D. H. S. Davis. 1939. An attempt to determine the absolute number of rats on a given area. J. Anim. Ecol. 8:94-113.

Lowman B.A., A. W. Jones , J.P. Pessutti, A.M. Mercer, J.P. Manderson, B. Galuardi (2021) Northern Shortfin Squid (Illex illecebrosus) Fishery Footprint on the Northeast US Continental Shelf. Frontiers in Marine Science 8: 85: DOI=10.3389/fmars.2021.631657

Palmer, Michael & Wigley, Susan. (2009). Using Positional Data from Vessel Monitoring Systems to Validate the Logbook-Reported Area Fished and the Stock Allocation of Commercial Fisheries Landings. North American Journal of Fisheries Management. 29. 928-942.

Rago, P. J., J. R. Weinberg, and C. Weidman. 2006. A spatial model to estimate gear efficiency and animal density from depletion experiments. Can. J. Fish. Aquat. Sci. 63:2377-2388.

Wright, B.L., A. Jones, A. Mercer, and J. Manderson. 2020. Shortfin squid (Illex illecebrosus) fishery footprint on the Northeast US continental shelf. Working Paper for MAFMC Illex Working Group.

8.0 Acknowledgements

I wish to thank John Manderson, Brooke Lowman and Anna Mercer for valuable discussions and insights during the preparation of this working paper. I thank all of the members of Council's Illex Quota Working Group and the NRCC's Research Track Assessment Working Group for Illex squid for their comments on earlier versions of these methods. Lisa Hendrickson's provision of all the essential data and her career-long commitment to assessment of Illex are especially appreciated. My colleagues on the MAFMC SSC provided valuable feedback on these approaches in May 2020 that help guide this work. Finally, I thank Jason Didden and Brandon Muffley for their leadership, guidance and support for the preparation of this report.

9.0 Appendices

1. Depletion models
   a. SSC Link-Paper
      https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ea6f5e1ceb3573cba3b21d0/1588000226002/n_Potential_Leslie_Davis_Rago.pdf

   b. SSC Link-Presentation
      https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ec2b57f0e617337fef47fee/1589818751732/Illex14_Working+Paper_Leslie+Davis.pdf

2. Envelope Method
   a. SSC Link-Paper
      https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ea6f5d1471c3332192f8842/1588000210732/l_Application_of_Envelope_Method_to_Illex_Squid_1967-2018_Rago.pdf

   b. SSC Link-Presentation
      https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ec2b57257350760ab500630/1589818739101/Illex12_Envelope+method.pdf

3. VMS Spatial Model
   a. SSC Link-Paper
      https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ea6f5c7f8f1a5492d21452b/1588000200506/k_Spatial_Patterns_VMS_and_Mortality_Rago.pdf

b. SSC Link-Presentation
https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ec2b56af3aa4c5b4febfa15/1589818732057/Illex11_Working+Paper_VMS.pdf

4. Overlap of fishery and Illex habitat
    a. Link to Wright et al. paper
    https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5ea6f4549aac8c314b30c13d/1587999830750/i_Illex-fishery-footrpint-CRB-Wright+et+al.pdf

    b. Link to Manderson paper 2021

5. Report of the May 11-12, 2020 Scientific and Statistical Committee of the MidAtlantic Fishery Management Council
    a. Link
    https://static1.squarespace.com/static/511cdc7fe4b00307a2628ac6/t/5eecd7f853421321c13863c6/1592580090989/Final+May+2020+SSC+Meeting+Report.pdf