Application of Envelope Method to Illex Squid: 1967-2019

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Concept

Stock assessment models typically incorporate two primary sources of information: estimates of total catch (landings plus discards), and fishery-independent indices of abundance. The former quantities provide estimates of population scale, the latter quantities provide measures of trend. Total catch provides some insight into the scale of the population but without additional information it is impossible to determine if total catch is the result of a low fishing mortality rate applied to a large population or a high fishing mortality rate applied to a small population. Fishery independent stock size estimates from trawl surveys, expressed in terms of average catch per tow, approximate the true population size subject to an arbitrary scalar that reflects gear efficiency, availability, and the variability in the realization of the sampling design. Collectively these factors are called catchability and denoted as the parameter **q**.

The following is a simple approach to reconcile these perspectives on stock size that provides a feasible range or "envelope" of population sizes. The purpose of this exercise is not to replace future analytic models that may be developed for Illex. Instead, the purpose is to demonstrate plausible simpler measures of stock size that are consistent with our knowledge of Illex dynamics and other stock assessments.. Coherence between the various approaches to stock size within the envelope may allow us to draw some general conclusions about the implications of recent catches for the probability of overfishing.

The Envelope Method was proposed and reviewed by the SSC in 2012 for the butterfish assessment. In this report the methodology is modified slightly to address the unique life history and fishery for Illex squid, and the timing of the NEFSC fall bottom trawl survey.

Methodology

Envelope Method

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

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

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

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

The NEFSC fall bottom trawl survey occurs after most of the fishery 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

$$B_0 = B_t \; e^{M\,t} + C_t \, e^{\frac{M}{2}t} \qquad (3)$$

Where **$\mathbf{B_t}$** is defined by Eq. 2.

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

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

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

$$\begin{aligned} \hat{B}_{1,t} &= B(I_t, q_{Low}, v_{Low}, M_{High}) \\ \hat{B}_{2,t} &= B(I_t, q_{High}, v_{High}, M_{Low}) \\ \hat{B}_{3,t} &= B^{'}(C_t, F_{Low}, M_{High}) \\ \hat{B}_{4,t} &= B^{'}(C_t, F_{High}, M_{Low}). \end{aligned} \qquad (5)$$

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. Results of the VMS analyses in WP xx were also used to inform a potential 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

$$\begin{aligned} \hat{B}_{upper,t} &= \min(B_{1,t}, B_{3,t}) \\ \hat{B}_{lower,t} &= \max(B_{2,t}, B_{4,t}) \end{aligned}. \qquad (6)$$

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.

Developing Bounds for Illex Squid

Illex squid do not constitute a closed population on the shelf. Instead it is thought that only part of the population is available at any given time. To develop extreme estimates of upper and lower bounds based on swept area analyses, the following assumptions were made:

- LOWER Bound on Swept Area Abundance
  - Availability of Illex is 100%. ($\mathbf{v_{High}}$=1.0). The survey overlaps the population entirely.
  - Efficiency of the NEFSC Bottom trawl adjusted to R/V Albatross units is 100% ($\mathbf{q_{High}}$=1.0)
  - Natural Mortality is at the lowest assumed value $\mathbf{M_{Low}}$=0.87.

- UPPER Bound on Swept Area Abundance
  - Availability of Illex is 20%. The survey overlaps only 20% of the population area ($\mathbf{v_{Low}}$=0.2)
  - Efficiency of the NEFSC Bottom trawl adjusted to R/V Albatross units is 20% ($\mathbf{q_{Low}}$=0.2)
  - Natural Mortality is at the highest assumed value ($\mathbf{M_{High}}$ **=3.92**)

- LOWER Bound on Catch-based Biomass Estimate
  - Fishing mortality is at a high value $\mathbf{F_{High}}$=1.2 (from VMS WP #xx) F
  - Natural Mortality is at the lowest assumed value ($\mathbf{M_{Low}}$=0.87)

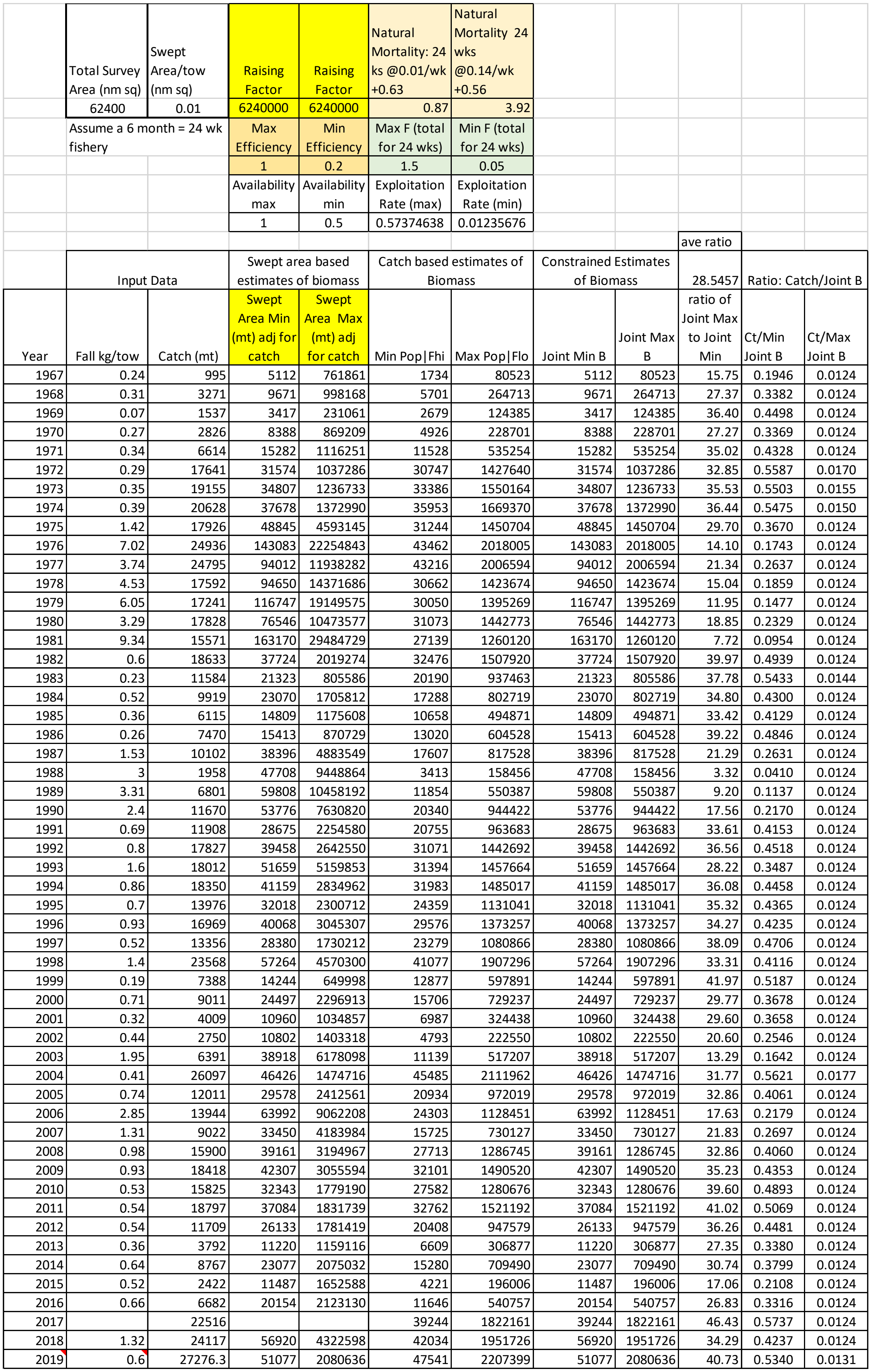
- UPPER Bound on Catch-based Biomass Estimate
  - Fishing mortality is at a low value $\mathbf{F_{Low}}$=0.05 (from VMS WP #xx).
  - Natural Mortality is at the highest assumed value ($\mathbf{M_{High}}$=3.92)

Given a feasible range of biomass estimates and the observed catch, it is now possible to estimate the fishing mortality rate consistent with this range. The upper bound of biomass estimates will generate a lower bound of fishing mortality. The lower bound of biomass will generate an upper bound of fishing mortality.

Results

The effect of the joint constraints on abundance are shown in Figure 1. Note the compression in the of biomass estimates as the constraint is applied. The average ratio of the max biomass to min biomass for the survey-based estimate is 96.2. The average ratio for the catch-based estimate is 41.0, but ratio for the constrained ratio is 28.1. Despite this reduction on the average ratio of maximum to minimum values the potential range of populations sizes remains very large. The average minimum population size was about 42,000 mt whereas the average maximum size was just over 1,000,000 mt. It is almost certain that any future potential model will lie within this range. Nonetheless it is instructive to examine the implications of these bounds and the assumptions that generated them, on the likely fishing mortality rates. An estimate of F was solved numerically by finding F such that $\mathbf{C_{obs}} - \mathbf{C_{pred}} = 0$ where $\mathbf{C_{pred}}$ is given by the Baranov catch equation. Results are presented in Fig. 2. The very large estimates of biomass (ie those around 1,000,000) give estimates of F near zero. Estimates of F from the constrained lower bound of biomass reach a maximum of F=0.061 per week. This is slightly less than the maximum assumed rate of F=1.5 for the entire 24 week period (i.e., 1.5/24=0.0625). In the following section, the relationship between these estimates and biological reference points will be examined.

Table1. Summary of model inputs, assumptions and results for Envelope Method for Illex squid, 1967-2019.



	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	6240000	6240000	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)					
			1	0.2	1.5	0.05					
			Availability max	Availability min	Exploitation Rate (max)	Exploitation Rate (min)					
			1	0.5	0.57374638	0.01235676					
									ave ratio		
	Input Data		Swept area based estimates of biomass		Catch based estimates of Biomass		Constrained Estimates of Biomass		28.5457	Ratio: Catch/Joint B	
Year	Fall kg/tow	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	Ct/Min Joint B	Ct/Max Joint B
1967	0.24	995	5112	761861	1734	80523	5112	80523	15.75	0.1946	0.0124
1968	0.31	3271	9671	998168	5701	264713	9671	264713	27.37	0.3382	0.0124
1969	0.07	1537	3417	231061	2679	124385	3417	124385	36.40	0.4498	0.0124
1970	0.27	2826	8388	869209	4926	228701	8388	228701	27.27	0.3369	0.0124
1971	0.34	6614	15282	1116251	11528	535254	15282	535254	35.02	0.4328	0.0124
1972	0.29	17641	31574	1037286	30747	1427640	31574	1037286	32.85	0.5587	0.0170
1973	0.35	19155	34807	1236733	33386	1550164	34807	1236733	35.53	0.5503	0.0155
1974	0.39	20628	37678	1372990	35953	1669370	37678	1372990	36.44	0.5475	0.0150
1975	1.42	17926	48845	4593145	31244	1450704	48845	1450704	29.70	0.3670	0.0124
1976	7.02	24936	143083	22254843	43462	2018005	143083	2018005	14.10	0.1743	0.0124
1977	3.74	24795	94012	11938282	43216	2006594	94012	2006594	21.34	0.2637	0.0124
1978	4.53	17592	94650	14371686	30662	1423674	94650	1423674	15.04	0.1859	0.0124
1979	6.05	17241	116747	19149575	30050	1395269	116747	1395269	11.95	0.1477	0.0124
1980	3.29	17828	76546	10473577	31073	1442773	76546	1442773	18.85	0.2329	0.0124
1981	9.34	15571	163170	29484729	27139	1260120	163170	1260120	7.72	0.0954	0.0124
1982	0.6	18633	37724	2019274	32476	1507920	37724	1507920	39.97	0.4939	0.0124
1983	0.23	11584	21323	805586	20190	937463	21323	805586	37.78	0.5433	0.0144
1984	0.52	9919	23070	1705812	17288	802719	23070	802719	34.80	0.4300	0.0124
1985	0.36	6115	14809	1175608	10658	494871	14809	494871	33.42	0.4129	0.0124
1986	0.26	7470	15413	870729	13020	604528	15413	604528	39.22	0.4846	0.0124
1987	1.53	10102	38396	4883549	17607	817528	38396	817528	21.29	0.2631	0.0124
1988	3	1958	47708	9448864	3413	158456	47708	158456	3.32	0.0410	0.0124
1989	3.31	6801	59808	10458192	11854	550387	59808	550387	9.20	0.1137	0.0124
1990	2.4	11670	53776	7630820	20340	944422	53776	944422	17.56	0.2170	0.0124
1991	0.69	11908	28675	2254580	20755	963683	28675	963683	33.61	0.4153	0.0124
1992	0.8	17827	39458	2642550	31071	1442692	39458	1442692	36.56	0.4518	0.0124
1993	1.6	18012	51659	5159853	31394	1457664	51659	1457664	28.22	0.3487	0.0124
1994	0.86	18350	41159	2834962	31983	1485017	41159	1485017	36.08	0.4458	0.0124
1995	0.7	13976	32018	2300712	24359	1131041	32018	1131041	35.32	0.4365	0.0124
1996	0.93	16969	40068	3045307	29576	1373257	40068	1373257	34.27	0.4235	0.0124
1997	0.52	13356	28380	1730212	23279	1080866	28380	1080866	38.09	0.4706	0.0124
1998	1.4	23568	57264	4570300	41077	1907296	57264	1907296	33.31	0.4116	0.0124
1999	0.19	7388	14244	649998	12877	597891	14244	597891	41.97	0.5187	0.0124
2000	0.71	9011	24497	2296913	15706	729237	24497	729237	29.77	0.3678	0.0124
2001	0.32	4009	10960	1034857	6987	324438	10960	324438	29.60	0.3658	0.0124
2002	0.44	2750	10802	1403318	4793	222550	10802	222550	20.60	0.2546	0.0124
2003	1.95	6391	38918	6178098	11139	517207	38918	517207	13.29	0.1642	0.0124
2004	0.41	26097	46426	1474716	45485	2111962	46426	1474716	31.77	0.5621	0.0177
2005	0.74	12011	29578	2412561	20934	972019	29578	972019	32.86	0.4061	0.0124
2006	2.85	13944	63992	9062208	24303	1128451	63992	1128451	17.63	0.2179	0.0124
2007	1.31	9022	33450	4183984	15725	730127	33450	730127	21.83	0.2697	0.0124
2008	0.98	15900	39161	3194967	27713	1286745	39161	1286745	32.86	0.4060	0.0124
2009	0.93	18418	42307	3055594	32101	1490520	42307	1490520	35.23	0.4353	0.0124
2010	0.53	15825	32343	1779190	27582	1280676	32343	1280676	39.60	0.4893	0.0124
2011	0.54	18797	37084	1831739	32762	1521192	37084	1521192	41.02	0.5069	0.0124
2012	0.54	11709	26133	1781419	20408	947579	26133	947579	36.26	0.4481	0.0124
2013	0.36	3792	11220	1159116	6609	306877	11220	306877	27.35	0.3380	0.0124
2014	0.64	8767	23077	2075032	15280	709490	23077	709490	30.74	0.3799	0.0124
2015	0.52	2422	11487	1652588	4221	196006	11487	196006	17.06	0.2108	0.0124
2016	0.66	6682	20154	2123130	11646	540757	20154	540757	26.83	0.3316	0.0124
2017		22516			39244	1822161	39244	1822161	46.43	0.5737	0.0124
2018	1.32	24117	56920	4322598	42034	1951726	56920	1951726	34.29	0.4237	0.0124
2019	0.6	27276.3	51077	2080636	47541	2207399	51077	2080636	40.73	0.5340	0.0131

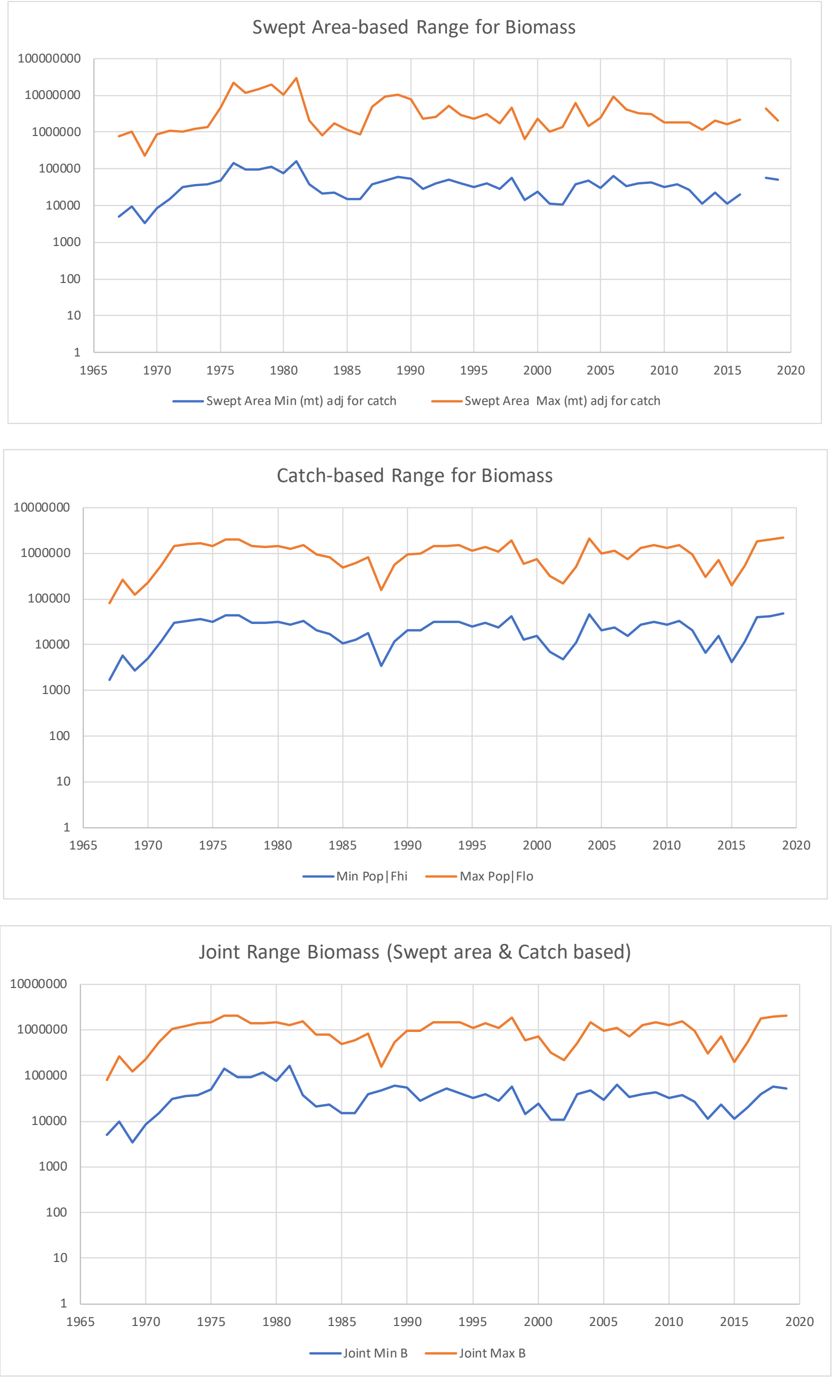


Figure 1. Comparison of the biomass estimates based on swept area biomass (top), catch (middle), and the constrained Envelope method (bottom).

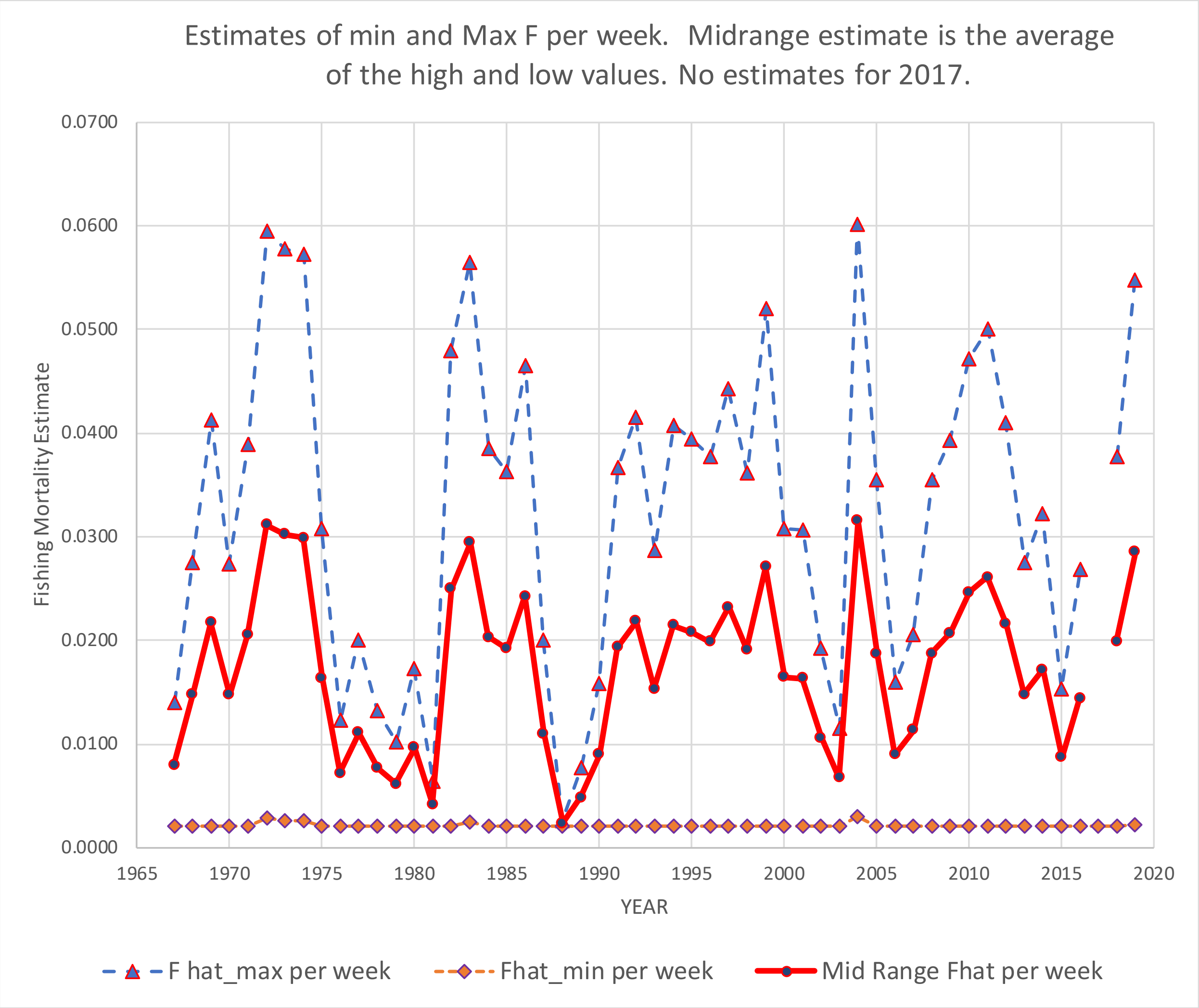


Figure 2. Range of fishing mortality rates derived from constrained bounds on population biomass using the envelope method.

Biological Reference Points

New methodology for biological reference points were developed by Hendrickson and Hart (2006). Their major advance was to incorporate the effects of post spawning mortality on abundance trends. One of the key factors incorporated into their model was the dependency of natural mortality on maturation rates. Resulting estimates of both weekly and post spawning mortality are roughly 10 times higher than past estimates in the literature. However, it should be noted that their rates represent a maximum value applied primarily to the fully mature squid. The force of natural mortality varies over a wide range of ages. In contrast to most other stock assessments in the Northeast US, the spawning stock biomass is expressed in terms of eggs per recruit as opposed to weight per recruit. Results of their paper (their Figure 5) are reproduced herein.

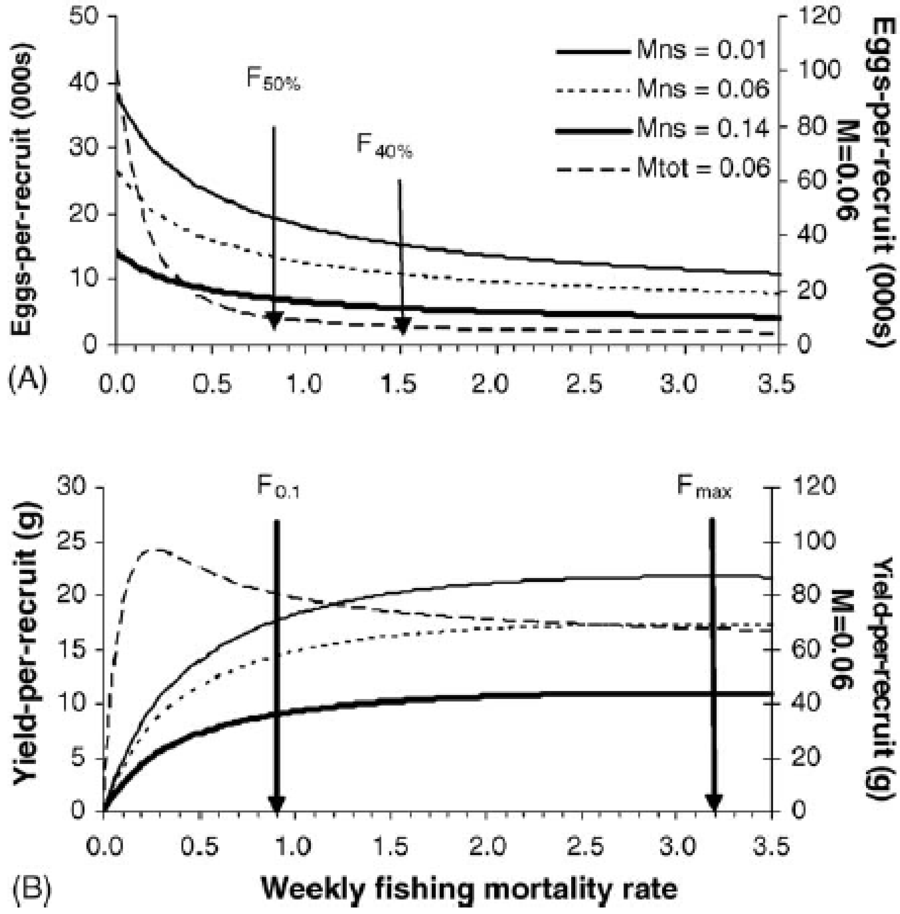


Fig. 5. Estimated number of eggs-per-recruit (000s) (A) and yield-per-recruit (g) (B) vs. weekly fishing mortality rate, for *Illex illecebrosus* at fixed non-spawning natural mortality rates (M_{ns}) of 0.01, 0.06, and 0.14 and estimated spawning mortality rates (M_{sp}) of 0.63, 0.55, and 0.42, respectively. Biological reference point estimates are shown for the model run where $M_{ns} = 0.14$. The curves shown for $M_{tot} = 0.06$ represent a constant total natural mortality rate with no spawning mortality included.

The following table is also taken from Hendrickson and Hart 2006.

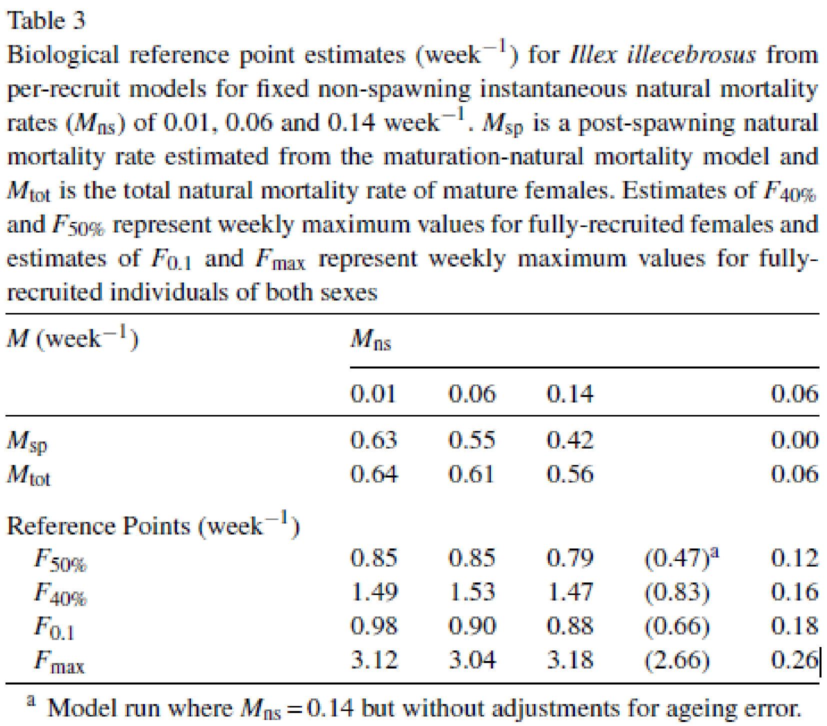


Table 3

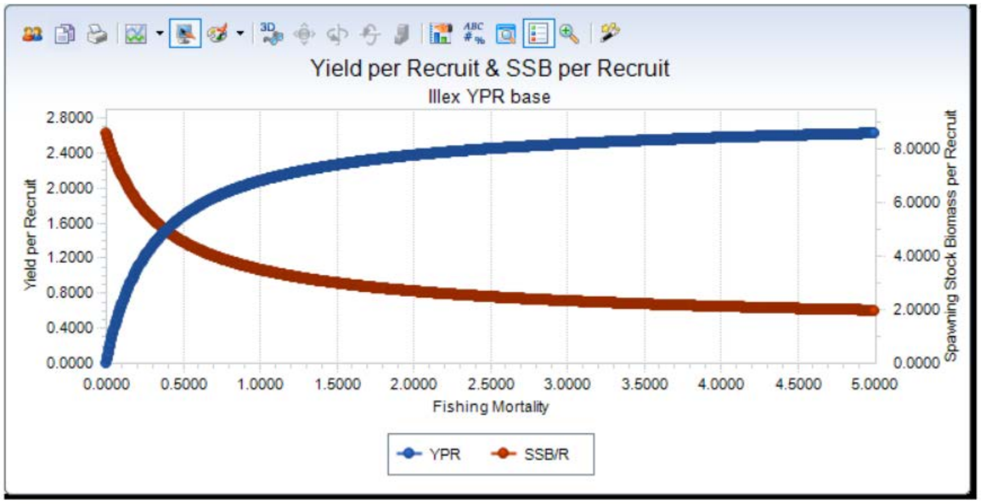
Biological reference point estimates ($week^{-1}$) for *Illex illecebrosus* from per-recruit models for fixed non-spawning instantaneous natural mortality rates (M_{ns}) of 0.01, 0.06 and 0.14 $week^{-1}$. M_{sp} is a post-spawning natural mortality rate estimated from the maturation-natural mortality model and M_{tot} is the total natural mortality rate of mature females. Estimates of $F_{40\%}$ and $F_{50\%}$ represent weekly maximum values for fully-recruited females and estimates of $F_{0.1}$ and F_{max} represent weekly maximum values for fully-recruited individuals of both sexes

M ($week^{-1}$)	M_{ns}				
	0.01	0.06	0.14		0.06
M_{sp}	0.63	0.55	0.42		0.00
M_{tot}	0.64	0.61	0.56		0.06
Reference Points ($week^{-1}$)					
$F_{50\%}$	0.85	0.85	0.79	(0.47)[a]	0.12
$F_{40\%}$	1.49	1.53	1.47	(0.83)	0.16
$F_{0.1}$	0.98	0.90	0.88	(0.66)	0.18
F_{max}	3.12	3.04	3.18	(2.66)	0.26

[a] Model run where $M_{ns} = 0.14$ but without adjustments for ageing error.

Below I compare the more sophisticated biological reference points for Illex from Hendrickson and Hart with those more commonly used in the Northeast. Using the parameters from their paper I used the NOAA Fishery Toolbox program YPR to derive estimates of $F_{0.1}$, F_{max} and $F_{50\%MSP}$. The base M was set to 0.14/wk and the post spawning M= Mps was set to 0.42/wk. M increased from 0.14 to 0.56 over a lifespan of 32 weeks, ramping from 0.14 in week 12 to 0.56 in week 32. The derived reference points and graph of YPR and SSB/R are shown below.

Reference Point	F	YPR	SSB/R
▶ F-Zero	0.000000	0.000000	8.579359
F-01	0.705000	1.885039	3.994796
F-Max	5.000000	2.619789	1.966275
F at 50% of MSP	0.580000	1.767857	4.299988



Preliminary Conclusions

Only under the most extreme assumptions, i.e., the lowest possible swept area estimates (100% efficiency, 100% of stock is in the survey area, natural mortality is one sixth the standard rate of 0.06/wk, does the estimated **F** approach any of the $F_{50\%MSP}$ thresholds in Table 3 of Hendrickson and Hart (See column 5 where $\mathbf{F_{50\%}}$ =0.12 when Mps is assumed equal to 0). Further, it should be noted that the reference points given in Hendrickson and Hart 2006 when Mps is estimated are much higher than maximum Y value in Figure 2. See Table 3 of Hendrickson and Hart). All reference points, regardless of the assumptions are greater than 0.58.

Acknowledgements

Lisa Hendrickson provided me with the time series of catch data and the estimated average weight per tow for the NEFSC fall bottom trawl survey. Any potential misinterpretations of the results of Hendrickson and Hart 2006 rest with the author.

References

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NEFSC 2010