Plausible bounds for availability of and net efficiency for northern shortfin squid in the US fishery and Northeast Fishery Science Center Bottom Trawl Survey

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Abstract

Rago (2020, 2001) has developed methods that use NEFC bottom trawl survey indices and fishery catch to develop feasible bounds for population size and fishery escapement for *Illex illecebrosus.* These methods rely on estimates of availability of and net efficiency for *Illex* to the NEFSC survey and the fishery to scale indices to population level statistics and to bound estimates of F and escapement. Here we update the work on Availability of Lowman et al (2021), using statistical species distribution modeling (SDM) of 4 surveys of US and Canadian continental shelf waters from 2008 to 2019, to developed plausible bounds for the availability of squid to the US fishery (v_f) and the NEFSC survey (v_s). We solicited expert opinion from the fishing industry to develop bounds for net efficiency in the fishery (q_f) and the NEFSC survey (q_s).

Analysis of availability using species distribution area developed with the SDM indicated that the US fishery (directed trips + incidental catches) accessed less than 1.14% ($v_f$max=0.011) of the modeled species range in summer and fall. On average the US fishery accessed 0.6% (v_f=0.006)of the modeled range.

In the fall NEFSC bottom trawl survey strata used in Illex abundance index development overlapped with ~37% (v_s=0.37)of the modeled species range (31-73%; v_s=0.37, 0.73). In the spring, a median of 22% (2%-38%; v_s=0.22; 0.02, 0.38) of the projected species distribution was accessed by the survey. It is important to note that *Illex* are known to be abundant outside the range of the 4 surveys of the continental shelf we used to develop the SDM. As a result, the availability of the squid population to both the fIshery and the survey are overestimated here.

Experts in the fishery (N=12) estimated their net efficiency to be approximately 25% (95% CI, 12.50, 32.50%; Range 2-80%; q_f=0.25, 0.125, 0.325). Five experts with experience in the Illex fishery who also participated in field evaluations of the “Bigelow” net were of the opinion that survey net efficiency is approximately 8% (range 2-20%; q_s=0.08, 0.02, 0.20) for the squid.

Introduction/rational

Illex illecebrosus is a data poor pelagic species and notoriously difficult to assess because of its broad geographic range, diversity of habitat use and extreme r-selected life history strategy. Rago (2020, 2021) has developed data poor methods to estimate feasible bounds for population size productivity (+ migration into the fishery) as well as fishery escapement for *Illex* based upon indices of abundance from the Northeast Fisheries Science Center (NEFSC) bottom trawl surveys and ranges of values for fishing and natural mortality. Availability of the *Illex* population to the survey (v_s) and survey net efficiency (q_s) are important terms scaling abundance indices to population size estimates in Rago’s (2021) Biomass Mass Balance and Envelope approaches. Estimates of population availability to the fishery (v_f), and net efficiency (q_f) can inform Rago’s estimates of fishing mortality (F) , fishery escapement and analysis of vessel monitoring system (VMS) data.

In this working paper, we update the work of Lowman et al (2021) to develop plausible bounds for the availability of the Illex population to the fishery (v_f) and to the NEFSC trawl survey (v_s) and summarize expert opinion about net efficiency for nets used in the fishery (q_f) and the NEFSC survey (q_s) .

We made 4 changes to the approach taken by Lowman et al. 2021. 1) Lowman et al. 2021 used the VAST model to develop probabilities of occupancy based on presence/absence of squid in US surveys during the Fall. VAST uses a complex delta modeling approach to predict both occupancy and density. We chose to apply a simpler approach of binomial Generalized Additive Mixed Modeling (GAMM), following the method of Moriarty et al. 2020, to model just occupancy probability. 2) The shift from the VAST to GAMM allowed us to easily perform Receiver Operator Characteristic (ROC) analysis of 10 fold cross validated predictions from the final GAM. We used ROC to evaluate model prediction accuracy and to develop objective threshold probabilities for developing classified species range maps. 3) Lowman et al. 2021 analyzed *Illex* presence and absence data in US surveys, exclusively. In our effort we train and evaluate the GAMM using data from Canadian as well as US bottom trawl surveys . We note that Illex ranges from the Florida Straits northeast to Southern Greenland (Trites 1983; Jereb & Roper 2010 ; Dawe & Beck, 1985) where it also occupies shelf slope sea habitats as adults as well as larvae and juveniles. As a result, a significant portion of the species range including the shelf slope sea is outside the domain of routine fishery independent bottom trawl surveys of the US and Canadian continental shelves. Thus even with the inclusion of the Canadian data our results overestimate of v_f and v_s . Finally 4) we report on ranges net efficiency for the fishery (q_f) and the NEFSC bottom trawl survey (q_s) developed from the expert opinion of individuals active in the fishery.

2. Methods

2.1 Availability Estimates ($v_{f,}$ v_s)

2.1.1 Species distribution model

2.1.1.1 Data used for model training and testing

We used shortfin squid catches in bottom trawl surveys conducted by the Northeast Fishery Science Center (NEFSC), the Northeast Area Monitoring and Assessment Program (NEAMAP), the Massachusetts Division of Marine Fisheries Resource Assessment Project Bottom Trawl Survey (MASSBAY) and the Maine and New Hampshire Inshore Groundfish Trawl Survey (MENH). We also included the Canadian Department of Fisheries and Oceans Maritimes Research Vessel Trawl Survey data (DFOCAN) in the analysis (Figure 1). All of the surveys have stratified random designs. We developed the SDM using survey data for the years 2008-2019 for the following reasons. All 4 surveys were conducted in full beginning in 2008. In 2020 the surveys were cancelled, curtailed or delayed due to the Covid 19 Pandemic. The NEFSC, NEAMAP and MENH surveys are conducted during the spring and the fall. DFOCAN is conducted during winter and summer. Sampling on the NEFSC and DFOCAN surveys occurs throughout the 24 hour day. Sampling on the inshore surveys NEAMAP, MASSBAY, MENH is conducted mainly during daylight hours

Several independent variables were developed for survey tow for use in generalized additive mixed modeling (GAMM). Wing swept area for each trawl survey tow in meters^2 was calculated from published wing spreads, tow distances, or tow speeds and durations if the variable was not included in the dataset provided. Geopositions and times of tows (UTC) were used to compute solar elevations during sampling with the “oce” library in R (Kelly 2018) . The “Rgdal” library in R (Bivand et al., 2019) was used to convert the Latitudes and Longitudes of tows to Universal Transverse Mercator coordinates in meters so the coordinates were on the same scale in the modeling. Finally, survey samples were allocated to two “seasonal” periods (Winter + Spring =Spring; Summer+Fall=Fall). “Spring” surveys were conducted before day of the year 178; June 27 in non leap years. Samples collected from June 28 through November were allocated to the “fall” season. No annual seasonal survey had samples allocated to two seasons.

2.1.1.2 Species distribution modeling

We followed the generalized additive mixed modeling (GAMM) framework of Moriarty et al. 2020 who combined 19 surveys in the ICES “Database of Trawl Surveys” to develop SDMs for many northeast Atlantic fish species. We used the “mgcv” package in R for model development (Wood, 2011). The final binomial GAMM had the following form.

$$\log(p/1\text{-}p) = S_i + \mathrm{Log}(E_i) + s(\text{solar elevation}_i, \text{by=Survey}_i) + s(X_i, Y_i, \text{year}_i, \text{by=Season}_i)$$

where S_i is a normally distributed random effect for survey associated with each tow$_I$ and $\mathrm{Log}(E_i)$ is the log of the swept area of tow$_I$ included as an offset to account for variable fishing effort. We included solar elevation as an independent variable to account for variation in *Illex* catchability in trawl tows associated with diel vertical migration (Brodziak & Hendrickson 1998; Bochenek & Powell, 2021). Finally patterns of occupancy in time and space were captured with a multivariate smoother that included geoposition in meters east and north, year and season. We used a ridge penalty for random effects as the basis of the survey effect (bs="re"). and a cyclic cubic regression spline (bs="cc") as the basis for the effects of solar altitude. For the smoothing space and time dimensions we used cubic splines with shrinkage (bs="cs") to accommodate differences in the scales of year and the spatial coordinates and year. GAMMs were fit using the method of restricted maximum likelihood “REML”. We developed models of varying complexity in a stepwise manner and evaluated them using the technique of multimodel inference (Burnham and Anderson, 2002).

We evaluated the prediction accuracy of the final SDM using Receiver Operator Characteristic (ROC) analysis of summary confusion matrices developed from a 10-fold cross validation of the final model (Fielding and Bell, 1997; Refaeilzadeh et al., 2009). We used the results of ROC to define two probability thresholds with which we developed classified species distribution maps from predictions projected onto an analysis grid. We used the minimum difference threshold; the probability at which the sensitivity (the true positive rate) and specificity (the true negative rate) of the model are equivalent. Jimenez-Valverde and Lobo, (2007) and Lobo et al., (2008) suggested this threshold, which minimizes the overall error rate, is preferred for species distribution modeling. We also developed classified species distribution maps using the probability that minimized the difference between the negative predictive value, (the proportion of negative predictions that are actually negative) and positive predictive value (the proportion of predicted positives that are actually positive). Predictive values account for prevalence (how oftenTrue positives, False Positives, True negatives, False negatives occur in test date sets) along with sensitivity and specificity in calculation. This threshold that minimized the frequency of false negatives provided the most conservative estimates of v_f and v_s, but potentially failed to capture some true positives.

2.1.1.3 Estimates of availability to the fishery and NEFSC survey

We developed analyses of availability using a gridded domain that matched the domain of the survey data used to train the model (76.09W, 34.40N, 56.75W, 47.43N). The squid were not uncommon in samples taken at depths from 1000M (present in 7 of 23 samples) to 1610 M in the Canadian DFO survey. As a result we limited the analysis grid to cells with bottom depths ranging from 0 to 1610 meters. We used GEBCO's gridded bathymetric data set to estimate the depths of cells in the analysis grid. Finally the resolution of the grid was 62.4 km^2 (~7.89 * 7.89 km), the same as the fishery dependent data made available to us.

The final GAMM=SDM was used to project probabilities of occupancy onto the analysis grid for each season and year fixing effects for log swept area and solar elevation values to the combined survey median values (3.219, 23, respectively) and the survey effect to the NEFSC survey. We also developed probability of occupancy grids for predictions +/- standard errors . Species distribution maps were developed by classifying predicted probabilities of occupancy (+/-SE) using the sensitivity-specificity threshold and the positive-negative predicted value threshold.

We used Vessel Trip Report (VTR) data to define the fishing areas in each year from 2008-2019. Records of fishing locations for trips that reported any shortfin squid landings in a year were aggregated (~7.89 * 9.25 km = 62.4 km^2) on the analysis grid. Each cell with a trip was scored as fished. Thus our analysis of availability to the fishery included both directed fishing and incidental catch in US fisheries. Analysis of availability to the fishery (v_s) which occurs during the summer months used fall species distribution maps.

NEFSC survey indices of Illex abundance are developed using survey data collected in NEFSC offshore strata 1-30, 350, 351, 36-40 and 61-76. Polygons representing these strata were projected onto the analysis grid and rasterized for to develop estimates of population availability to the NEFSC survey (v_s) . The area of the NEFSC strata on the analysis grid was estimated to be 209,670km^2. Analysis of availability to the spring and fall survey (v_s) used species distribution maps for the spring and fall.

Raster operations (Raster package in R. Robert J. Hijmans, 2019) were used to identify regions of overlap for areas fished or surveyed and species distribution developed using predictions (+/-SE) classified using sensitivity-specificity threshold and the positive-negative predicted value threshold. Area calculations were made using the analysis grid and the *area* function in the Raster package.

2.2 Net efficiency (q_f, q_s)

We solicited expert opinions from *Illex* fisherman to develop bounds for net efficiencies for the fishery and the NEFSC survey. Fishers participating in the *Illex* fishery (Total N=12) were asked to estimate minimum, maximum, and average percentages of squid under the vessel they believed were captured in net cod ends. In addition 5 industry experts were asked to provide opinions about the minimum, maximum, and average efficiency of the NEFSC survey bottom trawl. These 5 experts a) had all worked in the Illex fishery, b) were members of the Northeast Trawl Advisory Panel (NTAP) to the mid Atlantic and New England councils and, c) all had participated in field surveys and evaluations of the NEFSC bottom trawl. We developed ranges of net efficiency (q_f, q_s) for the fishery by bootstrapping 95% confidence intervals from the values provided by the experts.

We note that nets used in the fishery are much larger than the survey net. Fishing vessels use bottom trawls that have a maximum net height of 18 meters and ~3 meter mesh in the wings of the nets. Door spreads are 125-146 meters on large vessels. Nets on medium size fishing vessels have net heights of ~10 meters and doors spreads of 54 to 65 meters. The nets used by the industry are designed to maximize herding of the squid while simultaneously minimizing the incidental catch of other species. All dimensions of the NEFSC survey net are smaller than in the fishery The door spread of the survey net is 33 m, the wingspread is 12.76 m, headrope height is 3.69M, and the mesh in the wings is 12 cm.

Results and Discussion:

3.1 Availability Estimates ($v_{f,}$ v_s)

3.1.1 Species distribution model & model performance

3.1.1.1 Generalized additive mixed model

The final species distribution (SDM) model developed with generalized additive mixed modeling included a random survey effect, a survey dependent effect of solar altitude on catchability, and a seasonally dependent spatial effect that varied by year (Table 1a,b). This SDM explained 40% of the deviance. The residuals were well behaved (Fig. 2). The results of the diagnostic test of basis dimension indicated that the smoother was sufficiently complex for the space-time interaction but could perhaps have been more complex (Table 1c). Models failed to converge when the k parameter was manually increased in the space-time smoother.

The independent effects of the space-time interaction term accounted for 29% of the explained deviance. In the spring probabilities of occupancy were highest offshore (eg Fig. 4a). Before 2011 the occupancy probabilities were high south of Georges bank. After 2011 occupancy probabilities were also high offshore in the northern part of the surveyed area. In the summer and fall occupancy probabilities were highest along the shelfbreak in southern New England and the mid-Atlantic Bight and in the Gulf of Maine (eg Fig. 4b). In more recent years probabilities were also high in Canadian waters. The independent random survey effect accounted for 2% of the deviance while the independent effects of solar elevation accounted for 0.25% deviance. The impacts solar elevation on catches were marginal on the MENH and NEFSC surveys. The remaining 15% of the explained deviance was related to intercorrelated effects amongst the independent variables.

3.1.1.2 Evaluation of model prediction accuracy and thresholds for presence

The SDM produced relatively high classification accuracy. The ROC curve derived from the 10 fold cross validated test sets was displaced towards the top left corner of the plot, well away from the 45 degree line that indicates little to no prediction accuracy (Fig. 3 top). The difference between the sensitivity (the true positive predictions; i.e. presences) and specificity (the true negative predictions; i.e. absences) was minimized at a predicted probability of 0.29 (Fig. 3, middle). At this value the sensitivity was 0.850 (0.849-0.873) and specificity was 0.851 (0.844-0.880). Differences in the negative predictive value and positive predictive values were minimized at a predicted probability of 0.7 (Fig. 3 bottom). We developed species distribution maps from predicted probabilities of occupancy using both the sensitivity-specificity threshold and the predictive value threshold.

3.1.2 Area calculations from SDM projections of species distributions

During the winter and spring the median distribution area for *Illex* classified on the basis of the specificity-sensitivity threshold was 54,821 km^2 (35, 801 km^2 $^-$318,845km^2) and 13,693 km^2(2468 km^2 -140356 km^2) when the predictive value threshhold was used (Fig. 5 top; Table 2). This represented 6 to 56% of the analysis domain (573,594.3 km^2) when the specificity-sensitivity threshold was used and 0.4 to 24% of the domain when the predictive value threshold was used. Species distribution areas for the winter and spring were low from 2008 to 2016 and then increased.

During summer and fall the median distribution area for *Illex* classified on the basis of the specificity-sensitivity threshold was 421,079km^2 (334,468-483,185km^2) and 264,413 km^2 (115957-418723 km^2) when the predictive value was used (Fig. 5 bottom; Table 2). Species distribution areas were 58% to 80% of the analysis grid domain when the specificity-sensitivity threshold was used and 20% to 73% the domain when the predictive value threshold was used. Distribution area peaked in the summer and fall of 2010-2011 and again in 2017-2019. Interestingly, these were also periods of peak catch in the US fishery. When predictive value was used for classification the distribution area was smallest in 2014; 52% of the maximum area which occurred in 2019.

3.1.3 Availability estimates for the fishery v_f

From 2008 to 2019 the median area over which directed and incidental catches of Illex occurred in US waters was 1309 km (382 nm), based on the VTR data and the resolution of the analysis grid (Fig. 6; Table 2). The area of the fishery footprint varied around the median until 2017. From 2017 through 2019 the area fished doubled to approximately 3065 km^2 (894 nm^2).

The US fishery accessed less than 1.14% of the species distribution area developed using the SDM during the fall (Fig. 7; Table 2). The percentage of the Illex distributional area falling within the US fishing area ranged from 0.17% (0.16%-0.18%) to 0.80% (0.77%-0.84%) when the sensitivity-specificity threshold was used and from 0.31% (0.25%-0.39%) to 1.04% (0.88%-1.14%) when the predictive value threshold was used. The percentage of the distribution area fished increased from 2008 and peaked in 2017 and 2018.

As expected availability estimates to the US fishery developed here by including the Canadian survey data are lower than Lowman (2020). Lowman's estimates of availability to the fishery developed using VAST and data exclusively from US waters was 4% (1.4-6%) when a probability of 40% (3.5-35.3%) was used to threshold predictions and 15% when 80% was used as the threshold probability for occupancy.

3.1.4 Availability estimates for the NEFSC survey v_s

Estimates of the availability of the Illex population to NEFSC survey (v_s) strata used in the development of abundance indices during the fall ranged from 34.5% to 46% (median = 37%) when the sensitivity-specificity threshold was used to classify distribution area and 31 to 73% (35%) when the predictive threshold value was used (Fig. 8 bottom; Table 2). Availability was typically between 25% and 30% except from 2012 to 2017 when it was higher.

During spring, the survey strata fell within from 19% to 64% (median=52%) of the estimated species distribution area when the sensitivity-specificity threshold was used for classification and 2% to 38% (median=22%) when the predictive threshold value was used (Fig. 8 top; Table 2).

3.2 Net efficiency (q_f, q_s)

According to the 12 experts interviewed, the efficiency of the nets used by the fishery was approximately 25% (95% CI, 12.50, 32.50 %; Range 2-80%). Several experts were of the opinion that larger vessels with larger nets caught a greater percentage of Illex.

The five experts who had participated in the Illex fishery and also had field experience with the NEFSC bottom trawl believed the average efficiency the survey net to be 7.8% for Ilex with a range of 2-20%.

4. *Additional comments*

We felt justified in changing from a VAST to a GAMM modeling framework for this update. VAST is complex delta modelling approach that provides estimates of densities as well as probabilities of occupancy. The use of VAST for predicting just occupancy is overkill. Further shifting to the GAMM approach made 10 fold cross validation and the development of objective probability thresholds for classifying species distribution maps with Receiver Operator Characteristic (ROC) analysis tractable. We acknowledge that other methods exist that could have been applied to develop projections of species distributions. However we chose to follow the approach of Moriarty et. al. (2020) recently published in the fisheries literature.

We also felt justified to include data from Canadian DFO survey along with the US surveys of the continental shelf in the analysis of Illex population availability to the fishery and the NEFSC survey. The species ranges from the Florida Straits northeast to Southern Greenland (Trites, 1983; Jereb, 2010; Dawe & Beck, 1985. See also https://www.aquamaps.org/preMap.php?cache=1&SpecID=W-Msc-153087&from=premap&map=cached&type_of_map=regular). Adult squid use middle and inner continental shelf habitats including in the nearshore persistently during the summer months north of a latitude of ~ 40N and occupy shelf slope sea habitats as deep as 4800 meters throughout its range (Rathjen, 1981; Vecchione & Pohle, 2002; Harrop et al, 2014; Shea et al, 2017). Including Canadian data provided estimates of species range nearer the true range but still underestimated the range and thus overestimated availability (v_f & v_s) because the pelagic squid occupy habitat outside the domains fishery independent bottom trawl surveys of US and Canadian continental shelves.

We computed availability to the fishery (v_f) using only US fishery data because the Canadian fishery is not well monitored. However, the US bottom trawl fishery has accounted for a median of 96.5% (range 46-1005) of the total landings of *Illex* in the NAFO region since 1997. The Canadian fishery for *Illex* appears to be small and artisanal. The Canadian Fishery has accounted for a median of 3.5% of NAFO landings since 1997 (range 0-54%; see Hendrickson and Showell, 2019; Table 1). Fishing in Canada is primarily limited to an inshore, artisanal, jig fishery prosecuted on small boats (<35 ft) in Newfoundland as a result of regulation, technical constraints and opportunity costs associated with shoreside processing other more valuable fisheries (primarily snow crab) during the summer when Illex are available (see http://www.nfl.dfo- mpo.gc.ca/NL/Landings-Values).

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