Northern shortfin squid (*Illex illecebrosus*) fishery footprint on the Northeast US continental shelf

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## Introduction

*Illex illecebrosus* (hereafter *Illex*) live less than one year, die soon after spawning, and have recruitment that is highly variable and largely influenced by environmental conditions (Dawe and Beck 1997; Hendrickson, 2004). Since 1996, NEFSC assessments of this squid stock have recommended in-season assessment and fishery management to ensure sufficient spawner escapement from the U.S. fishery each year to provide for adequate recruitment levels in the subsequent year (Hendrickson et al., 1996). Subsequent stock assessments have applied depletion-based models (using a weekly time-step) using tow-based *Illex* fishery CPUE data, reported electronically by *Illex* fishermen in real-time (Hendrickson et al., 2002), to demonstrate the utility of this type of management regime (NEFSC, 1999; NEFSC 2003; NEFSC 2006). The 1999 stock assessment also used fishing effort and a crude measure of *Illex* habitat in order to estimate a lower bound on population size and upper bound on fishing mortality (NEFSC 1999). Given the limited information available, U.S. management has set the Acceptable Biological Catch at the highest observed catches because catches in that range do not appear to have caused the fishery to decline in the past (MAFMC SSC 2018 report).

*Illex* range from south of Cape Hatteras to Labrador and occupy continental shelf to slope sea habitats which they use as spawning, nursery and feeding grounds (O'Dor and Dawe, 2013; Roper et al., 2010). In the spring, some proportion of the *Illex* stock migrate inshore from the shelf edge to occupy summer and fall feeding and spawning (Hendrickson, 2004) habitats on the US and Canadian continental shelf and in waters managed by the Northwest Atlantic Fisheries Organization (NAFO), while the remaining proportion of adults and juveniles remain in the shelf slope sea (e.g., Rathjen, 1981; Roper et al., 2010; Shea et al., 2017). In the fall, squid using the shelf migrate off-shelf to an unknown winter spawning grounds (Hendrickson and Holmes, 2004). Analyses of spatial patterns of sexual maturity using US and Canadian shelf-wide surveys and fisheries-dependent biosampling collections indicate that *Illex* squid migrate onto and off of the continental shelf at approximately the same maturity stages and sizes in US and Canadian waters at approximately the same time (NEFSC, 1999, pg 246). The US and Canadian fisheries are prosecuted exclusively on the continental shelf (Hendrickson and Showell, 2019). Thus, based on the pattern of wavelike migration and the distribution of fishing, the squid do not appear to be vulnerable to the fishery at a single chokepoint on the continental shelf (NEFSC, 1999).

Under the assumption that the squid move onto and off of the US shelf in waves, and not through chokepoints (NEFSC, 1999), the vulnerability of *Illex* to the fishery can be roughly approximated in two dimensions by the ratio of the area fished, $A_f$, to the area occupied by the species, $A_o$. This is a spatial estimate of the proportional availability $\rho=A_f/A_o$ of the stock to the fishery. This index of availability can be used as a proxy for estimating the order of magnitude of proportional fishing mortality $F_{proxy}$ if the assumption above holds. The complement of ρ (i.e. 1-ρ, or 1- $A_f/A_o$) is the proportion of the area occupied by the species that is not fished. This statistic can be viewed as a spatial index of proportional escapement of the species from the fishery.

*Illex* occupies an area much larger than the Northeast US continental shelf, but there are limited data from the entirety of the species range. Thus, we adopted a conservative approach to develop estimates of availability to the fishery (ρ), and proportional escapement (1-ρ) by confining analysis to fishery and fishery independent survey data collected in US continental shelf waters where the fishery is well monitored and routine bottom trawl surveys are conducted. The shelf slope sea is not routinely surveyed and although shelf-wide bottom trawl surveys are conducted in Canadian waters where *Illex* is abundant, effort data are not available for the Canadian inshore jig fishery (Hendrickson and Showell, 2019). We therefore did not include the shelf slope sea and Canadian shelf waters in our analysis. Thus, our estimates of availability to the fishery (ρ) are likely overestimated while estimates of proportional escapement (1-ρ) are underestimated.

**Data**

Bottom trawl surveys are conducted in the fall in offshore waters by the Northeast Fishery Science Center (NEFSC) and inshore waters by the Northeast Area Monitoring and Assessment Program (NEAMAP) and by state agencies of Maine and New Hampshire (Figure 1).

The NEFSC fall survey is conducted in September through November, and tows are made during both day and night. The survey follows a stratified random design, and used a standardized Yankee 36 trawl prior to 2009 and a three-bridle, four-seam trawl thereafter. The vessel used for conducting the survey transitioned from the Albatross to the Bigelow in 2009, following a calibration study in 2008 (Miller et al. 2010). The NEFSC bottom trawl survey gear and protocols are described in Politis et al. (2014). The NEAMAP fall survey is conducted in September through October, and tows are made during the day. The NEAMAP survey follows a stratified random design and uses a trawl with the same design as used in the surveys conducted by the H. B. Bigelow, but with a three-inch cookie sweep instead of a rockhopper sweep . Full details of the survey protocols are described in Bonzek et al. (2017). The ME/NH fall survey is conducted in October through November, and tows are made during the day. The survey follows a stratified random design, and uses a modified shrimp net design. For a complete description of the ME/NH survey sampling protocols, see Sherman et al. (2005). The surveys used for this analysis have limited spatial overlap, which could be problematic for teasing apart differences in spatial effects versus vessel effects on catch abundance. For this application, however, we are considering only presence and absence of *Illex*, so the impact of variable survey catchability is minimal.

All bottom trawl survey data were filtered to account for *Illex* catchability and ecological dynamics as described below. Each of the surveys are designed for multispecies sampling and, thus, use different gear than the *Illex* fishery. The survey gear likely has a low catchability for *Illex;* therefore, catch information was reclassified as presence/absence data for this analysis. Furthermore, *Illex* exhibit diel vertical migration and are typically associated with bottom water during the day. The fall survey is conducted near the end of the *Illex* fishing season. The spring survey occurs during the period of northward and onshore migration, and hence, the proportion of positive tows and relative abundance indices for the spring survey are much lower than for the fall survey (NEFSC, 2006). As a result, the fall surveys are used in assessments to estimate stock size (NEFSC, 1999). Consequently, we only used data from NEFSC fall survey tows from 2000-2019 during "daytime" hours, which we defined for filtering purposes as between the hours of 06:00 and 18:59 EST. After filtering the NEFSC survey data using these criteria, we were left with a data set of 3,213 tows from the NEFSC surveys, 3,561 NEAMAP tows, and 3,284 tows from the ME/NH survey (Table 1).

Vessel Trip Report (VTR) data were provided by the Greater Atlantic Regional Fisheries Office (GARFO) and used to characterize the area fished by the *Illex* fishery. Records of fishing locations for trips that reported any *Illex* landings were aggregated to five-minute squares for each year from 2000 through 2019 (Table 2). This approach is at a finer scale than the ten-minute square regularly used to characterize the spatial dynamics of the *Illex* fishery (Hendrickson 2019). Vessel Monitoring System (VMS) data were considered for this analysis, but complete years were only available from 2017-2019.

**Methods**

The shortfin squid habitat area was estimated based on a Vector Autoregressive Spatio-Temporal (VAST) model (Thorson 2019). The NEAMAP, ME/NH, and NEFSC fall survey data were used in the model to determine the area of the US shelf waters occupied by *Illex* squid based on probability of occupancy. Thus, this analysis produced $A_o$, the denominator used to compute proportional availability to the fishery (and its complement, the area of escapement). Area swept is accounted for directly and a vessel effect is included to account for efficiency differences. The spatial information from the survey data were used to determine the region used in the spatial component of the model (although a "Northwest Atlantic" region is available as a preset region in the VAST package, it is limited to the federal survey; therefore, we specified the region as "Other" to allow the program to determine an appropriate sampling region based on the input data).

The user specifies the number of "knots," which are used as the sampling locations for the VAST model. VAST uses a k-means clustering algorithm to minimize the distance between samples and knot (i.e. the knots are allocated over the spatial domain of the survey region relative to the density of observations. The knots are used to define a Voronoi tessellated surface, and the spatial component of each prediction point is assigned based on the value at the knot of its corresponding Voronoi tile (or when using the "fine scale" method, the values are based on averaging of the values of knots of surrounding tiles). The output of the model is then the predicted values at each location of the extrapolation/prediction grid (based on the habitat variable values assigned at each grid point and the spatial component values at each corresponding knot).

Based on the three surveys, we specified 100 knots as sampling locations for VAST and specified a prediction grid of 25 km per side (625 $km^2$ or 182 $nm^2$ or). For our initial estimate, we considered only spatial and temporal factors without habitat covariates. Year intercepts were treated as fixed effects, and spatio-temporal random effects were treated as independent among years. We allowed for overdispersion by turning on random effects of vessels on the catchability. We assumed a binomial distribution and logit link. For full model configuration please see the script available at [https://github.com/brookewright/Illex2020](https://github.com/brookewright/Illex2020). For model diagnostics, see Appendix A.

The output prediction points were converted to Voronoi polygons then joined to form polygons based on probability of occurrence (i.e. less than 20%, 20 to 39.9%, 40 to 59.9%, 60 to 79.9%, and greater than 80% probability of occurrence). We considered three different thresholds to represent habitat area: 40%, 60%, and 80%.

Raster files of *Illex* fishing effort were converted to polygons then intersected with the habitat areas. The intersection with fishing effort divided by the total habitat area (at each threshold) is the metric of availability of the *Illex* population to the fishery.

**Results**

The apparent habitat range occupied by *Illex* was broadly similar across time in the Mid Atlantic, but probability fluctuates in the Gulf of Maine and Georges Bank (Figure 2). Years with notably high landings (e.g. 2004, 2017, 2018, 2019) did not show a consistent pattern of probability of occurrence, and nor did years with notable low landings (e.g. 2001, 2002, 2013, 2015) (Figure 2). Much of the Gulf of Maine is characterized by relatively low probabilities of occurrence (mostly less than 50%) in 2000-2002, with probability increasing to about 70% in many areas through 2005. Concurrently, probability stays slightly higher on much of Georges Bank (except for the center of the bank which remains an area of low probability, probably due to lack of sampling). From 2007 to 2019, probability of occurrence is high in most of the Gulf of Maine and Georges Bank area in most years except for a decline in 2015-2017. The highest probabilities over the largest area occur in 2014, 2018, and 2019 (Figure 2).

The spatial distribution of effort is consistent at the shelf break in the Mid Atlantic (Figure 2 and 3). Effort was more widespread, covering more inshore areas in early years (2000-2004). From 2005 through 2019, effort is mostly confined to a narrow band along the shelf break. A few years show larger patches of effort inshore Gulf of Maine and on Georges Bank (e.g. 2012 and 2014).

The *Illex* habitat area ranged across years from 28,515 $km^2$ to 153,117 $km^2$ using the 80% probability threshold of habitat area and from 157,073 $km^2$ to 198,618 $km^2$ using the 40% threshold (Table 3). The wide range of habitat area reflects the highly variable nature of *Illex* catch in the multispecies bottom trawl surveys. The habitat area based on the 40% and 60% thresholds was nearly constant from 2005 to 2015 and more variable at the beginning and end of the time series, and the habitat area based on the 80% threshold is considerably more variable throughout the series (Figure 3).

The proportion of *Illex* available to the fishery (i.e. proportion of fished area overlapping with habitat area) each year varies slightly depending on the probability threshold used to define habitat area (the largest difference is approximately 6 percentage points, and the average difference is approximately 2 percentage points) (Table 3). Across years, the minimum estimate for the area occupied that was fished was 0.9% (2002 based on 40% threshold), and the maximum estimate of area occupied that was fished was 9.6% (2017 based on 80% threshold). The range of the estimates of proportional area of escapement was a maximum of 99.1% and a minimum of 90.4%.

**Discussion**

Despite the model being uninformed by habitat characteristics, the occupancy pattern is consistent with expectations. Results suggest that considering only the shelf habitat, a relatively small proportion of the resource (<10%) is exposed to the fishery regardless of the threshold chosen to indicate habitat. Given that 1) fishing effort is aggregated to a coarse scale representing a much larger area than the actual tow path and 2) *Illex* are known to occupy waters much deeper than those sampled in the available surveys as well as areas beyond the northern and southern extent considered here, the actual proportion of habitat exposed to fishing is likely to be substantially overestimated.

W*hy the results are conservative*

We developed estimates of *Illex* stock availability to the fishery (ρ) and proportional escapement (1-ρ) by confining our analysis to fishery and fishery independent survey data collected in US continental shelf waters where the fishery is well monitored and routine fishery independent bottom trawl surveys are conducted. This approach is conservative because it does not account for the a) distribution of squid over their entire geographic range and b) their habitat range which includes the water column. Thus, the statistics overestimate the availability of *Illex* to the fishery and underestimate the area of potential escapement from the fishery. Our estimate of the area occupied $A_o$ by *Illex illecebrosus* represents a small portion of the species range identified by the Food and Agricultural Organization of the United Nations (Figure 4).

The geographic range of *Illex illecebrosus* extends from South of Cape Hatteras, North Carolina in the Florida Straits, (Dawe and Beck, 1985; Hendrickson & Hart, 2006; Roper et al., 2010), northeast to Labradour, the Flemish cap, Baffin Island and southern Greenland. There are confirmed reports of *I. illecebrosus* farther east in Iceland, the Azores, and in the Bristol Channel, England (O'Dor and Lipinski, 1998; Roper et al., 1998; O'Dor and Dawe, 2013). In addition, the squid occupy shelf slope sea habitats as adults as well as in the juvenile and larval phases. Bottom and midwater trawl and submersible surveys of the shelf slope sea have documented high concentrations of juvenile and adult *Illex* squid to bottom depths of 4,800 meters far outside the domains of fishery independent bottom trawl surveys of the US continental shelf that we used in our analysis (max depth= 542m) (Politis *et al.,* 2014). Trawl surveys conducted in depths from 169 to 4,800 m in the slope sea off the Nova Scotian Shelf collected *I. illecebrosus* at depths greater than 500 meters, and the species was nearly twice as abundant as the 2nd most abundant species (Roper et al., 2010). Mature squid have also been collected at depths to 1,000 m in a fall bottom trawl survey of the continental slope from Georges Bank to Cape Canaveral (Rathjen, 1981), and the species was the most abundant organism captured in trawls to depths of 2,500 meters in the vicinity of the Bear Seamount in the shelf slope sea. (Vecchione M and G.; Harrop et al., 2014; Shea et al., 2017). Therefore, our estimate of the area occupied by *Illex* ($A_o$) confined to the shelf waters is considerably smaller than the actual species range during the fishing season.

*I. illecebrosus* is also a pelagic squid that spends significant amounts of time in water column habitats on the continental shelf and the shelf slope sea. Submersible as well as mid-water and surveys of the slope sea have observed large concentrations of adult *I. illecebrosus* in the water column (Vecchione M and G.; Harrop et al., 2014; Shea et al., 2017). The squid also spend significant amounts of time in the pelagic environment on the US and Canadian continental shelf (Froerman, 1981; Brodziak and Hendrickson, 1998; Roper et al., 2010). The pelagic lifestyle of *Illex* makes its space use volumetric rather than areal. However, this analysis used daytime data when *Illex* are more closely associated with the bottom. A volumetric calculation of the availability ($\rho$) of the squid to these fisheries may be different than the value we calculated using surface areas occupied by the fish and the fishery.

We chose to limit our analysis to US waters, despite the availability of Canadian fishery independent survey data because the Canadian commercial fishery and recreational fishery are not as well monitored as the US fishery (Hendrickson and Showell, 2019). Examination of available fishery statistics, however, indicates that the capacity of the Canadian commercial fishery is currently extremely small when compared with the US fishery (Table 4).

Since 1999 and the prohibition of foreign vessels in the Canadian Fishery, the US summer bottom trawl fishery has accounted for approximately 97% of the total landings of *Illex illecebrosus* in the Northwest Atlantic (Table 4). Fisheries operating in the Gulf of Saint Laurence, Scotian Shelf and Newfoundland have been responsible for approximately 3% of the landings. The Canadian fishery has been dominated by a small inshore commercial jig and recreational fishery and has achieved only about 1% of the Total Allowable Catch for NAFO areas 3 and 4 (range 0-21%) since 2000. Since 2016, 78-88% of Canadian catches were made in Newfoundland and Labrador (NAFO Area 3; Table 5). These catches represented 0-6% of the total *Illex* caught in US and Canadian waters. Since 2016, vessels less than 34 feet made 64-85% of the Canadian catches (Table 5). Canadian landings have been low even during recent years when fishery independent survey abundance indices for *Illex* have been high throughout the Northwest Atlantic (Hendrickson and Showell, 2019; Table 6). Processing capacity is limited in Newfoundland where snow crab, shrimp, herring, and other more valuable fisheries are given priority in shoreside cold storage facilities (James Barbera, Seafreeze LTD, Pers Comm). The relatively low level of current Canadian *Illex* landings appears to be the result of limited processing and cold storage and economic opportunity costs rather than the availability of the squid. Since the Canadian fishery has remained small in capacity even though squid have appeared to be more abundant in the region (Table 6), the northern stock area which is not included in our analysis provides an additional area of the species range that provide for escapement of potential spawners from the fishery.

US spatial fishery regulations that prevent fishing in areas on the outer continental shelf and slope sea also provide *Illex* with permanent regions of escapement from the fishery. These areas include the *Frank R. Lautenberg Deep-Sea Coral Protection Area*, the *Northeast Canyons and Seamounts National Monument*, the tilefish and lobster gear restricted areas, and other regulated mesh areas in Gulf of Maine and Georges Bank that prohibit the use of fine mesh trawls used by the squid fishery. The Coral Protection Area occurs along the shelf break at depths greater than 450 m (246 fathoms), covers 38,000 square nautical miles including a large area of the slope sea, and 15 canyon areas where the fishery cannot be prosecuted. Large concentrations of *Illex* squid have also been observed in the slope sea near seamounts within the 4,913 square mile Monument Area that is now closed to mobile gear fishing (Shea et al., 2017).

*Other indicators of stock condition*

Abundance indices in both mean weight and number for *Illex* collected from fishery independent bottom trawl surveys conducted by US, Canadian and the EU throughout the northwest Atlantic have been relatively high over the past 3 years when compared to median values since 1999 (Table 4). This follows the recent trends in landings in both US and Canadian Waters (Tables 5 and 6).

*Relevance to Management*

Our findings support the MAFMC SSC's conclusion that the northern shortfin squid has been lightly exploited because a small portion of the species range falls within the area where the US fishery operates. The overlap of fishing area with areas where *Illex* are likely to be does not account for the variations in density where fishing takes place. Fishing is concentrated on the shelf break because this is where squid are concentrated prior to their subsequent use of shoreward habitats. In some years these areas may have had sufficient densities or detectabilities by the fishing fleets to support commercial harvest. In view of our nearly complete lack of understanding of recruitment dynamics of *Illex*, the potential impacts of harvests on spawning stock escapement are not known. By the same measure there is no direct evidence of recruitment overfishing for *Illex* squid.

However, several lines of evidence suggest low potential effects of fishing activity. The near absence of fishing activity in the known historical range of *Illex* in the US and Canada and the occurrence of *Illex* at depths and distances well offshore suggest a large region of unfished resource. A high fishing mortality on the entire resource would be possible only if a large fraction of the resource passed through the actual fishing areas of the US. Oceanographic data, although not fully evaluated for this purpose, suggest such a process is unlikely. A more detailed examination of the overlap of fishing activity and areas where the probability of occurrence exceeds 90 or even 95% may provide evidence of areas where high rates of fishing mortality are possible. Thus, it is unlikely that the US fishery has had a substantial impact on the northern shortfin squid stock.

**Next Steps**

Moving forward, there are several planned refinements to the model. We will incorporate data from several additional inshore surveys (MA, NY, NJ). Additionally, we will revise the habitat model by including habitat covariates such as depth and temperature. The region currently used for extrapolation is automatically detected by the VAST package, but performance should improve by manually adjusting the region. We will also explore methods to refine the area fished estimate, using VMS and fine-scale fishery dependent data generated by the NEFSC Study Fleet. These additional research efforts will improve estimates of the availability of the *Illex* stock to the fishery and escapement of *Illex* from the fishery.

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Table 1. Fishery independent surveys used for building *Illex* habitat map. Only fall surveys were used, and tows were filtered for daylight hours based on start times between 0600 and 1859 EST.

| Survey | Years | Months | Maximum Depth (m) | Number of hauls | Number of Illex Positive Hauls |
|---|---|---|---|---|---|
| NMFS fall bottom trawl | 2000 - 2018 | Sept – Nov | >183 | 3,213 | 1,660 |
| NEAMAP | 2007 - 2019 | Sept – Oct | >36.6 | 3,561 | 96 |
| ME/NH | 2000 - 2019 | Oct – Nov | >102 | 3,284 | 747 |

Table 2. Approximate fishing area covered based on Vessel Trip Reports (VTR). Area is based on fishing effort aggregated to 5 minute squares.

| Year | Area Fished ($km^2$) |
|---|---|
| 2000 | 14,361 |
| 2001 | 11,095 |
| 2002 | 6,130 |
| 2003 | 8,742 |
| 2004 | 12,681 |
| 2005 | 9,405 |
| 2006 | 6,949 |
| 2007 | 6,128 |
| 2008 | 7,572 |
| 2009 | 8,706 |
| 2010 | 9,415 |
| 2011 | 11,791 |
| 2012 | 11,094 |
| 2013 | 10,004 |
| 2014 | 12,279 |
| 2015 | 9,080 |
| 2016 | 10,926 |
| 2017 | 12,993 |
| 2018 | 15,313 |
| 2019 | 14,640 |

Table 3. *Illex* shelf habitat area and availability defined at three levels of probability of occurrence. Availability is the proportion of the habitat area that overlaps spatially with fishing effort.

| | Probability Threshold for Habitat Definition | | | | | |
|---|---|---|---|---|---|---|
| | 40% | | 60% | | 80% | |
| **Year** | **Habitat Area ($km^2$)** | **Availability** | **Habitat Area ($km^2$)** | **Availability** | **Habitat Area ($km^2$)** | **Availability** |
| **2000** | 166,416 | 2.9% | 103,823 | 3.8% | 43,310 | 6.6% |
| **2001** | 160,214 | 3.3% | 109,961 | 4.4% | 37,429 | 9.6% |
| **2002** | 157,073 | 0.9% | 83,195 | 1.2% | 28,515 | 2.2% |
| **2003** | 181,697 | 1.7% | 140,690 | 1.9% | 63,248 | 3.7% |
| **2004** | 162,110 | 2.8% | 108,912 | 3.9% | 47,127 | 8.2% |
| **2005** | 178,968 | 2.4% | 155,832 | 2.5% | 67,746 | 5.4% |
| **2006** | 181,919 | 2.0% | 163,030 | 2.1% | 91,915 | 3.1% |
| **2007** | 183,567 | 1.3% | 170,972 | 1.3% | 129,013 | 1.5% |
| **2008** | 180,219 | 2.2% | 166,860 | 2.1% | 102,846 | 2.8% |
| **2009** | 181,091 | 2.9% | 158,132 | 3.3% | 99,583 | 4.5% |
| **2010** | 175,202 | 2.5% | 158,530 | 2.4% | 72,815 | 4.3% |
| **2011** | 179,628 | 3.9% | 163,363 | 4.0% | 89,405 | 5.6% |
| **2012** | 178,801 | 4.3% | 155,062 | 4.3% | 92,136 | 5.4% |
| **2013** | 180,839 | 3.6% | 161,988 | 3.8% | 100,217 | 4.6% |
| **2014** | 180,119 | 4.3% | 166,640 | 4.4% | 129,793 | 4.7% |
| **2015** | 181,175 | 3.0% | 155,970 | 3.3% | 86,570 | 5.2% |
| **2016** | 171,287 | 3.9% | 127,850 | 4.5% | 57,946 | 8.7% |
| **2017** | 184,231 | 4.4% | 159,123 | 4.7% | 70,081 | 9.6% |
| **2018** | 198,618 | 5.0% | 184,913 | 5.1% | 153,117 | 4.9% |
| **2019** | 189,264 | 5.4% | 176,171 | 5.6% | 121,092 | 6.8% |
| **Min** | 157,073 | 0.9% | 83,195 | 1.2% | 28,515 | 1.5% |
| **Max** | 198,618 | 5.4% | 184,913 | 5.6% | 153,117 | 9.6% |
| **Mean** | 177,622 | 3.1% | 148,551 | 3.4% | 84,195 | 5.4% |

Table 4. *Illex* landings (in metric tons, MT) and Percent of Total Landings in US (NAFO 5&6), and Canadian waters (NAFO 3&4) since 1999 when Canadians ceased licensing foreign fishing on the Nova Scotia Shelf.

| | Total Landings | US waters NAFO 5&6 | | Gulf St Lawrence/ Scotian Shelf NAFO 4 | | Newfoundland-Flemish Cap NAFO 3 | | Total Allowable Catch MT | |
|---|---|---|---|---|---|---|---|---|---|
| Year | MT | MT | % Total | MT | % | MT | % | CAN (NAFO 3+4) | US (NAFO 5-6) |
| 1999 | 7693 | 7388 | 96 | 286 | 4 | 19 | 0 | 75000 | 19000 |
| 2000 | 9377 | 9011 | 96 | 38 | 0 | 328 | 3 | 34000 | 24000 |
| 2001 | 4066 | 4009 | 99 | 34 | 1 | 23 | 1 | 34000 | 24000 |
| 2002 | 3010 | 2750 | 91 | 30 | 1 | 230 | 8 | 34000 | 24000 |
| 2003 | 7524 | 6391 | 85 | 46 | 1 | 1087 | 14 | 34000 | 24000 |
| 2004 | 28671 | 26097 | 91 | 34 | 0 | 2540 | 9 | 34000 | 24000 |
| 2005 | 12591 | 12013 | 95 | 30 | 0 | 548 | 4 | 34000 | 24000 |
| 2006 | 20924 | 13943 | 67 | 24 | 0 | 6957 | 33 | 34000 | 24000 |
| 2007 | 9268 | 9022 | 97 | 16 | 0 | 230 | 2 | 34000 | 24000 |
| 2008 | 16434 | 15900 | 97 | 11 | 0 | 523 | 3 | 34000 | 24000 |
| 2009 | 19136 | 18418 | 96 | 42 | 0 | 676 | 4 | 34000 | 24000 |
| 2010 | 15945 | 15825 | 99 | 18 | 0 | 102 | 1 | 34000 | 24000 |
| 2011 | 18935 | 18797 | 99 | 50 | 0 | 88 | 0 | 34000 | 23328 |
| 2012 | 11756 | 11709 | 100 | 29 | 0 | 18 | 0 | 34000 | 22915 |
| 2013 | 3819 | 3792 | 99 | 27 | 1 | 0 | 0 | 34000 | 22915 |
| 2014 | 8788 | 8767 | 100 | 21 | 0 | 0 | 0 | 34000 | 22915 |
| 2015 | 2437 | 2422 | 99 | 14 | 1 | 0 | 0 | 34000 | 22915 |
| 2016 | 6836 | 6682 | 98 | 18 | 0 | 134 | 2 | 34000 | 22915 |
| 2017 | 22881 | 22516 | 98 | 52 | 0 | 313 | 1 | 34000 | 22915 |
| 2018 | 25663 | 24117 | 94 | 70 | 0 | 1476 | 6 | 34000 | 22915 |
| 2019 | | 26922 | | | | | | 34000 | 24825 |

Table 5. Since 2016, most landings (metric tons, MT) of *Illex illecebrosus* in Canadian Waters occurred in Newfoundland and Labrador (NAFO 3) and most of these were made by small vessels less than 34 ft in length http://www.nfl.dfo-mpo.gc.ca/NL/Landings-Values

| | | | Vessel Lengths (Feet) Landings in MT | | | |
|---|---|---|---|---|---|---|
| Year | Canadian Landings NAFO 3 & 4 (MT) | NAFO 3 Landings (MT) | < 34' | 35-64'11" | 65'-99'11" | > 100 ' |
| 2016 | 152 | 134 | 130 | None | None | None |
| 2017 | 364 | 313 | 281 | 32 | None | None |
| 2018 | 1546 | 1,205 | 982 | 223 | None | None |
| 2019 | | 2,527 | 2,179 | 348 | None | None |

Table 6. Over the last few years indices *of Illex illecebrosus* abundance (Mean Kilogram per Tow, Mean Number per Tow) have been trending upward throughout the Northwest Atlantic based on US, Canadian and EU-Spain/Portugal fishery independent bottom trawls surveys. Fall North East Fisheries Science Center (US NEFSC. Fall), Fall southern Gulf of St. Lawrence (Div4t StLau Sep), July Scotian Shelf and Bay of Fundy (July DFO SS), Fall Grand Banks, (3LNO GB), July Flemish Cap. Data from (Hendrickson and Showell, 2019)

| Year | Fall US NEFSC | Fall Div4t StLau | July DFO SS | Fall 3LNO GB | July Flemmish Cap |
|---|---|---|---|---|---|
| 2010 | 0.05, 8.70 | 0.18, 0.88 | 1.08, 19.60 | 0.00, 0.00 | 43, NA |
| 2011 | 0.50, 10.00 | 0.10, 0.86 | 1.90, 23.00 | 0.00, 0.00 | 89, NA |
| 2012 | 0.05, 6.30 | 0.12, 0.88 | 1.50, 16.90 | 0.03, 0.22 | 38, NA |
| 2013 | 0.40, 8.00 | 0.01, 0.11 | 0.10, 1.4 | 0.00, 0.01 | 0, NA |
| 2014 | 0.60, 8.30 | 0.06, 0.28 | 1.10, 10.10 | | 3, NA |
| 2015 | 0.50, 9.50 | 0.00, 0.00 | 0.20, 2.40 | 0.01, 0.09 | 0.001, NA |
| 2016 | 0.66, 7.60 | 0.03, 0.39 | 0.40, 10.90 | 0.0185, 0.117 | 3, NA |
| 2017 | | 0.28, 1.35 | 16.10, 119.90 | 0.162, 0.907 | 2359, NA |
| 2018 | 1.30, 15.80 | 0.89, 5.07 | | 0.2794, 1.648 | 49, NA |
| 2019 | | | 32.10, 196.00 | | 363, NA |
| Median: 2000-present | 0.60, 8.7 | 0.10, 0.495 | 1.5, 16.15 | 0.03, 0.117 | 79, NA |

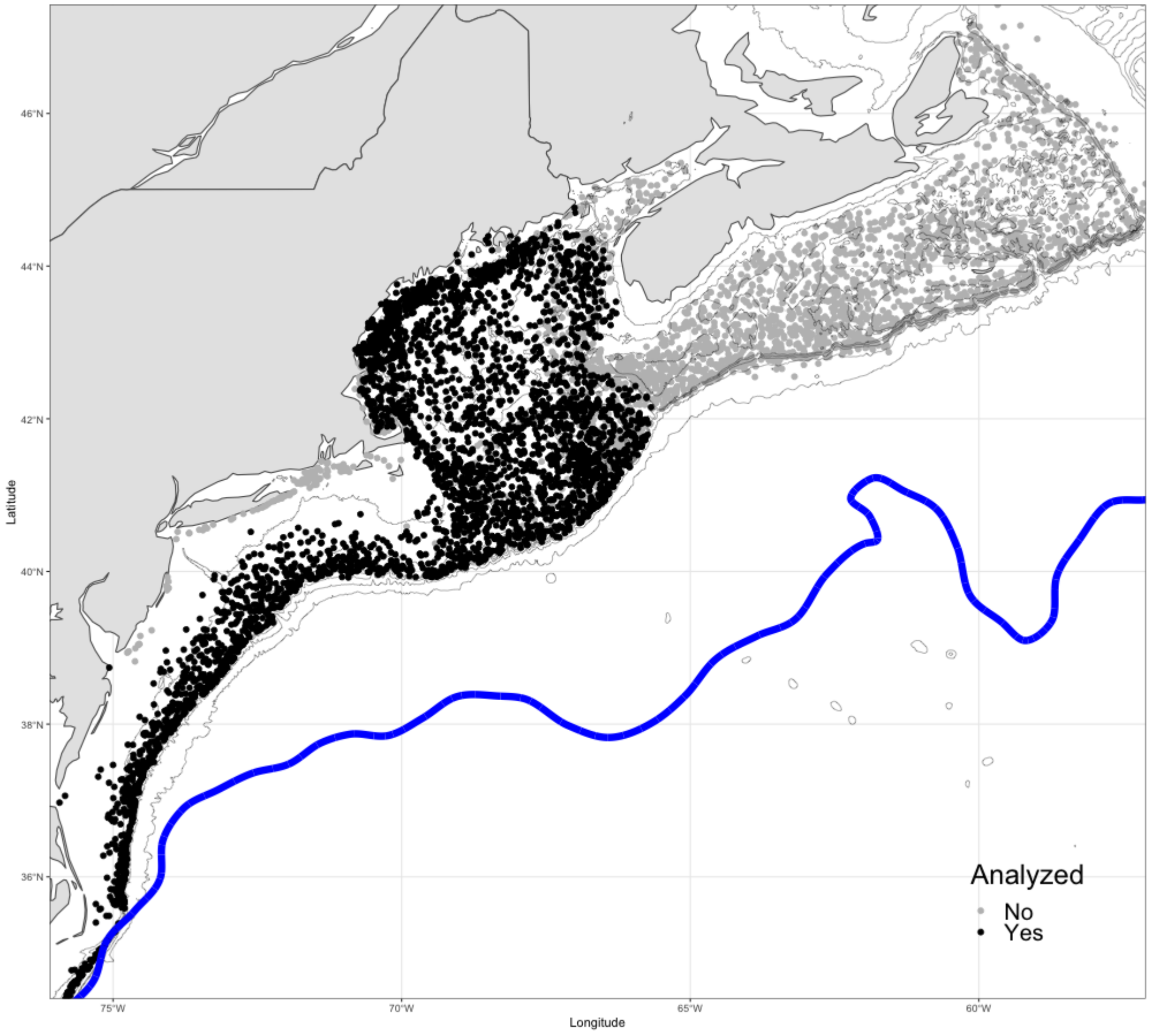



Figure 1. Map of survey coverage where *Illex illecebrosus* were caught 2000-2019. The Black points are from surveys that were included in our analyses, and the gray points were not included. Gray contours show 30 to 150 fathom isobaths. The thick blue outline shows the north wall of the Gulf Stream as of 2020-03-12 and is included for illustrative purposes.

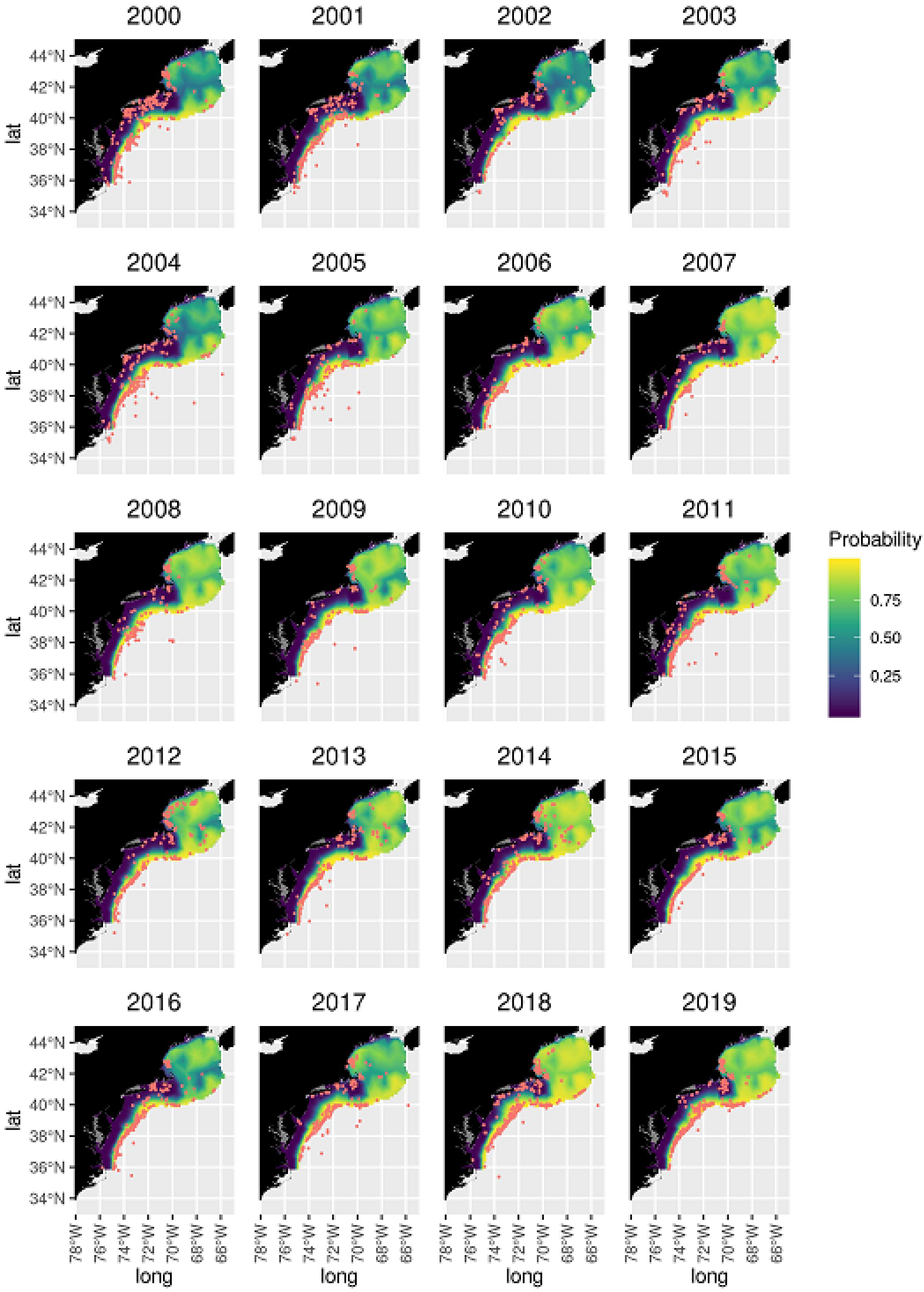



Figure 2. Probability of *I. illecebrosus* occurrence (gradient). Effort (VTR locations that reported shortfin squid, aggregated to 5 minute squares) is shown in red.

A)

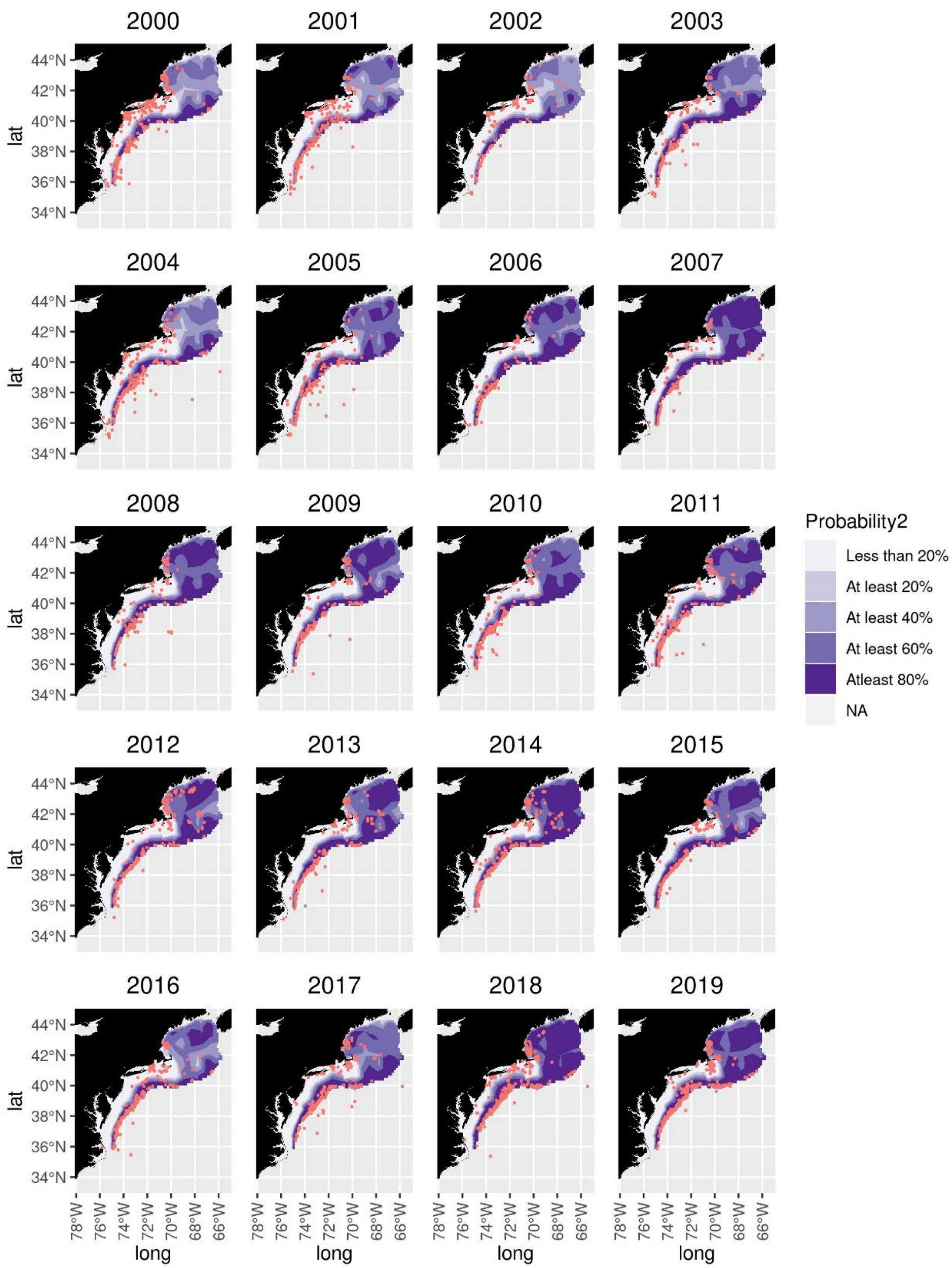
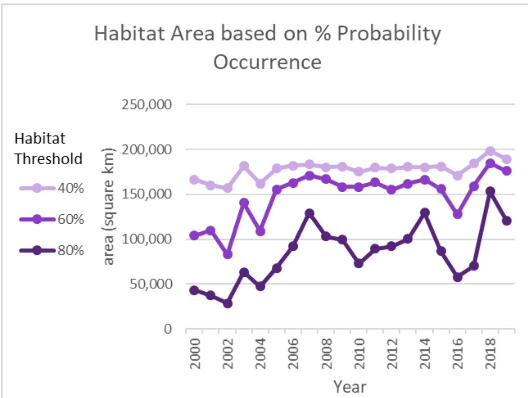


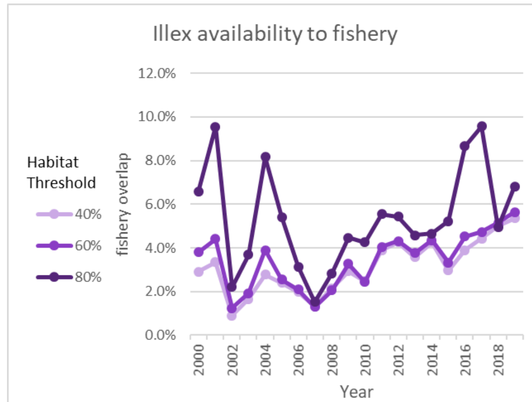

Figure 3. *Illex* fishery effort (red) overlain on binned probability of occurrence map (A). *Illex* habitat area (B) and availability to fishery (C) based on 40%, 60%, and 80% probability threshold definitions of habitat.

Figure 3 continued

B)




C)



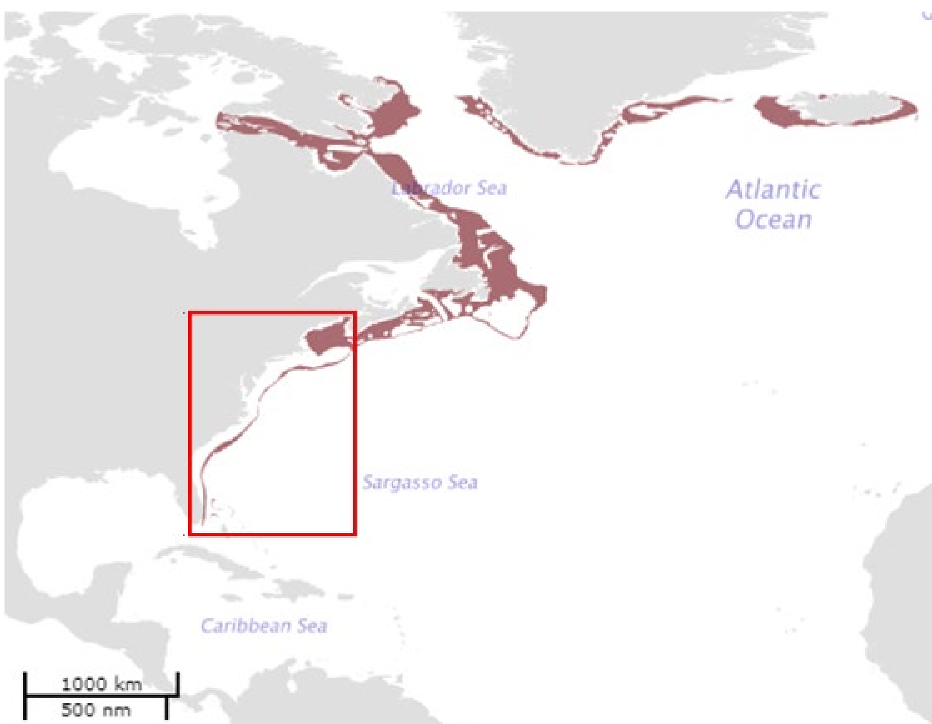




Figure 4. Known geographic range of *Illex illecebrosus* (maroon) identified by the UN FAO (http://www.fao.org/fishery/species/2720/en). Continental shelf habitat falling within the red box is the domain of analysis for computing area occupied.

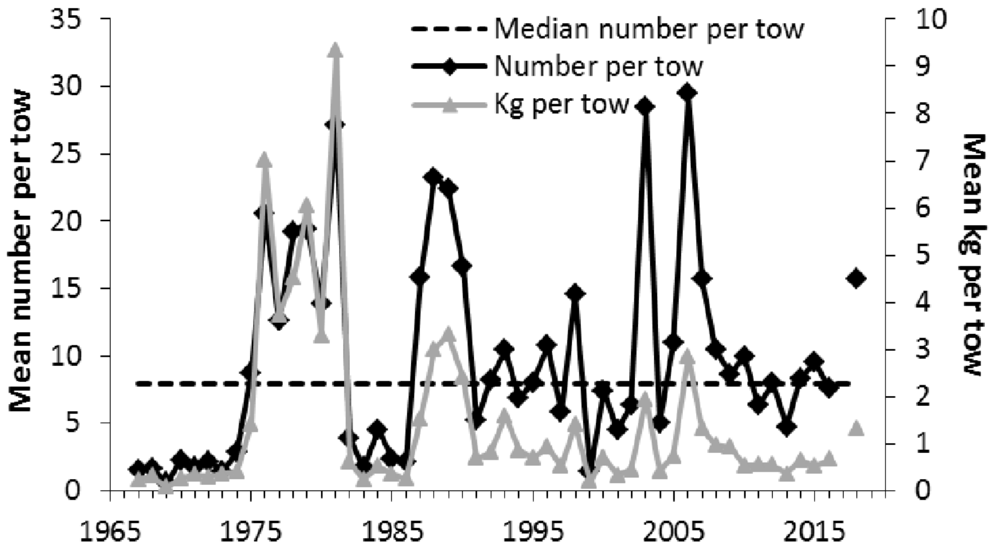



Figure 5. Indices of relative abundance of *Illex illecebrosus* from the Northeast Fisheries Science Center fall bottom trawl survey. Fall 2017 survey indices were not included due to lack of sampling in the primary *Illex* habitat region. Figure from Hendrickson (2019).

Appendix A. VAST model diagnostics

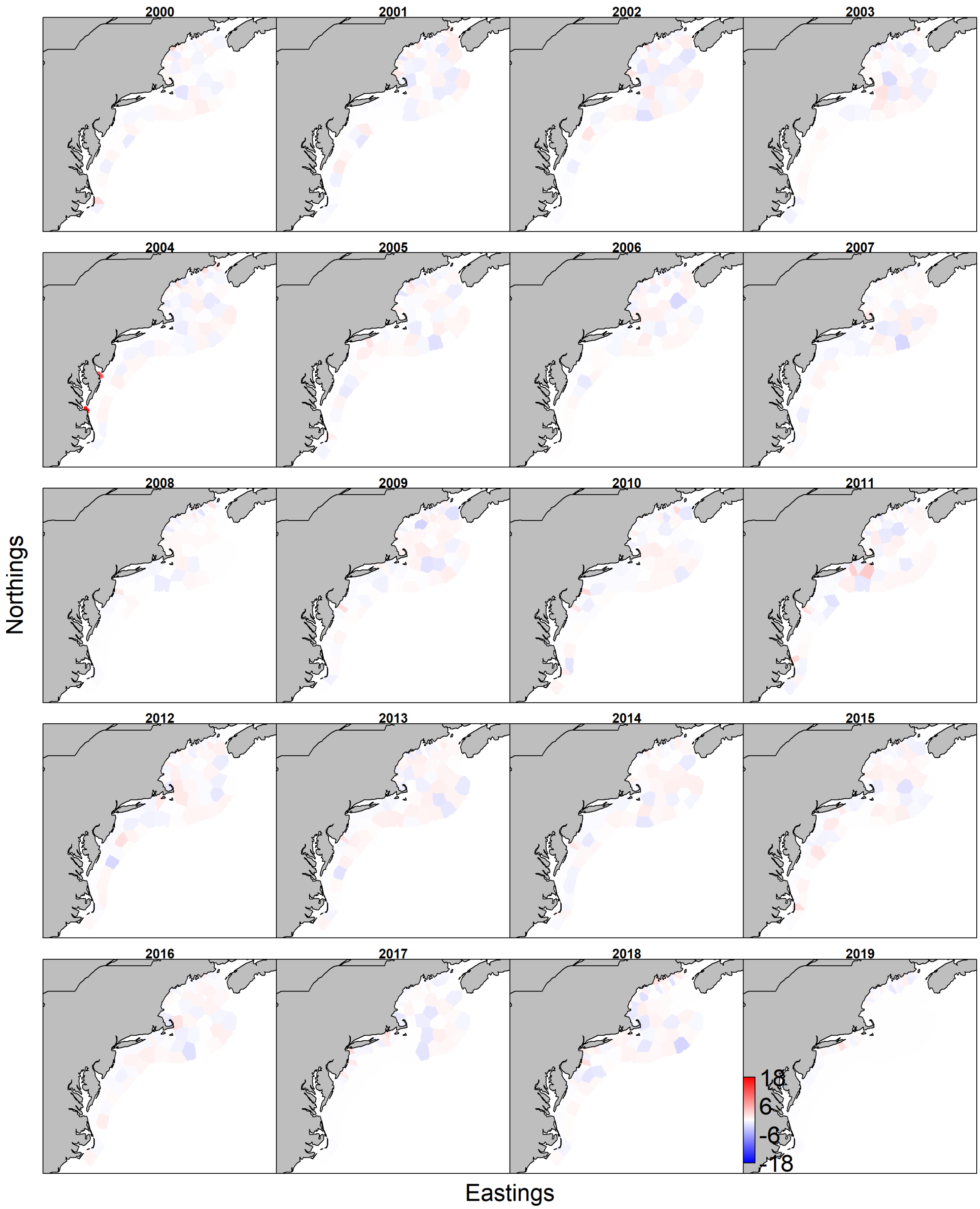



Figure A1. Residual plot for probability of occurrence.

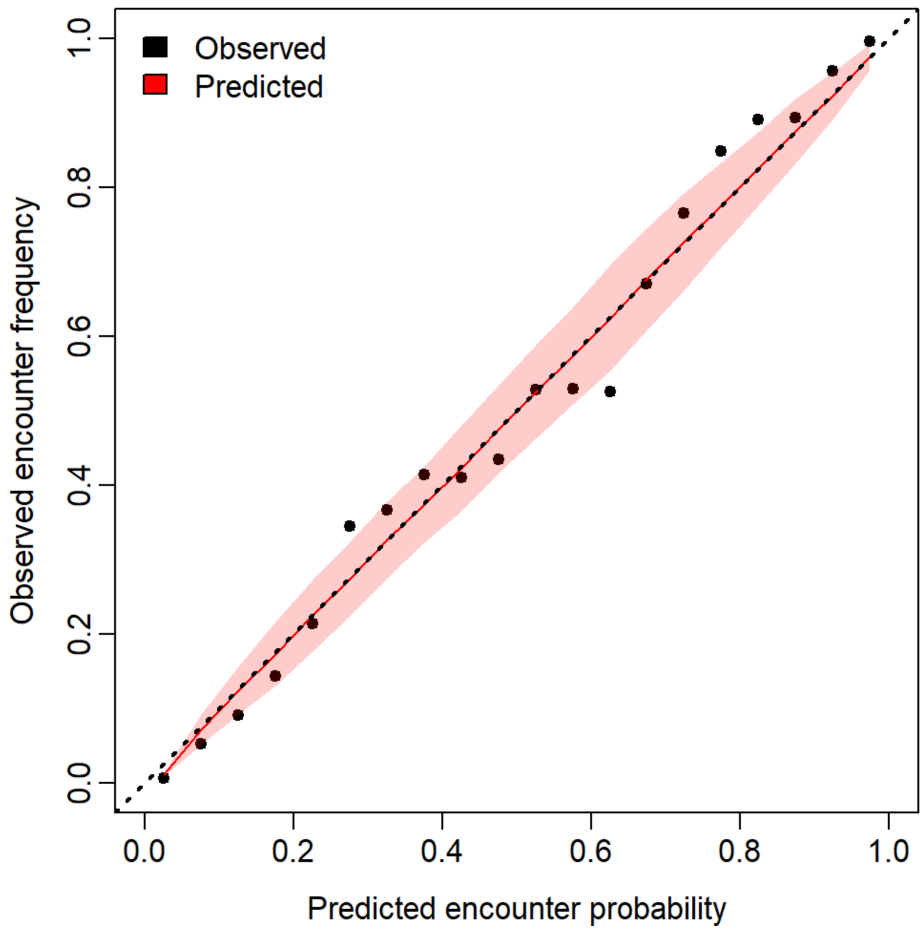



Figure A2. Observed encounter frequency plotted against the predicted counter probability.