Report of the *Illex* 2021
Research Track Assessment
Working Group

EXECUTIVE SUMMARY

The following Terms of Reference were addressed and are summarized below:

1. Estimate catches from all sources, including landings and discards, and characterize their uncertainty.

Landings from the U.S. commercial fishery on the northeastern U.S. shelf were updated through 2021. A new estimation method (SBRM approach) was used to estimate commercial fishery discards of *Illex* for 1989-2019. Landings from the commercial fisheries involving the northern stock component (Scotian Shelf and Newfoundland) were also updated. Data on recreational fishing for *invertebrates* are generally not collected, but it is believed that recreational catches are negligible.

2. Evaluate indices used in the assessment, including annual abundance and biomass indices based on research survey data and standardized industry CPUE data. Characterize the uncertainty of the abundance and biomass index estimates. Explore the relationship between fishing effort and economic factors (e.g., global market price) in order to determine whether the addition of an economic factor will improve the fit of the CPUE standardization model.

Fishery-independent research survey indices of abundance from all four seasons have been compiled through the most recent years available for consideration in this assessment. These include the winter, spring and fall Northeast Fisheries Science Center (NEFSC) bottom trawl surveys, the Canada Department of Fisheries and Oceans (CA DFO) Division 3LNO spring and fall surveys, the CA DFO Division 4VXW summer survey, the Maine-New Hampshire Division of Marine Resources (ME-NH DMR) spring and fall trawl surveys, the Atlantic States Marine Fisheries Commission (ASMFC) Gulf of Maine northern shrimp summer survey, the Massachusetts Division of Marine Fisheries (MA DMF) spring and fall trawl surveys, the New Jersey Department of Environmental Protection (NJ DEP) summer trawl survey, and the Virginia Institute of Marine Science (VIMS) Northeast Area Monitoring and Assessment Program (NEAMAP) bottom trawl surveys.

Multiple fishery-dependent indices of stock biomass were developed from the U.S. regional commercial fisheries databases. Hendrickson (2020, updated) used landings and effort data from the Dealer/Logbook (Vessel Trip Report; VTR) merged database to develop a directed fishery Landings Per Unit Effort (LPUE) index. The LPUE data for 1997-2019 were modeled using a General Linear Model that considered multiple error structure assumptions and classification variables. A negative binomial model that included year, week, vessel permit (a unique vessel identifier) and statistical area provided diagnostics indicating the best fit. The standardized fishery LPUE indices and the NEFSC fall survey biomass indices (stratified mean kg per tow) showed similar trends and were significantly correlated.

Lowman *et al.* (2022) used the Dealer/Logbook data, the Northeast Fishery Observer Program data (Observer), the Cooperative Research Branch Study Fleet data, and insights from *Illex* processors and harvesters to develop directed fishery LPUE indices by component fleets

('Freezer' and 'Wet' vessels) (Mercer *et al.* 2022). Specific effort was made to integrate economic covariates, including *Illex* price, global production of ommastrephids, and fuel price, which were identified by industry members as impactful on fishery dynamics (Mercer *et al.* 2022). Other covariates explored include year, week (when feasible), spatial smoother, distance from fishing grounds to landing port, trip duration, and landing port. The LPUE data were modeled using Generalized Additive Models that considered multiple error structure assumptions, classification variables, and covariates. Results indicated that several factors are important in driving *Illex* LPUE, including year, fishing location, *Illex* market price, trip length, and landing port. Year and fishing location are intuitive, as the *Illex* population has historically exhibited high inter-annual variability and a patchy distribution. Results reveal general synchrony in *Illex* LPUE trends over time, but differences in the scale of LPUE depending on the fleet and standardization approach. The Dealer/Logbook wet boat LPUE GAM standardization results are the most similar in trend and scale to the Hendrickson LPUE GLM standardization results. Insights on the technical and economic factors impacting the *Illex* fishery helped to steer the Lowman *et al.* (2022) LPUE standardization and highlighted the importance of considering socio-economic factors when analyzing and interpreting data from this fishery (Mercer *et al.* 2022).

Although the relationship between observed fishing effort and international market prices was not explicitly considered, both domestic *Illex* price and annual global ommastrephid production, which are tightly coupled with international market price, were directly integrated into the LPUE GAM standardization (Lowman *et al.* 2022).

Salois *et al.* (2022) investigated a suite of oceanographic features, including mesoscale eddies and fronts, to assess and characterize their relationships to *Illex* catch rates. As such, the work addresses aspects of both TOR 2 (indices of abundance) and TOR 4 (environmental factors that may influence body size and recruitment [and by extension stock size and availability]). GAM results identified ten covariates that were significant predictors of *Illex* CPUE, including temporal (year, week), spatial (latitude, longitude, and NAFO subareas) and environmental (bottom temperature, ring footprint index, ring orientation, salinity at the 222 meter isobath, chlorophyll frontal activity, and standard deviation in sea surface temperature) variables. The results suggest a suite of environmental variables which may serve as indicators of *Illex* habitat condition or areas of increased primary productivity. These indicators are of interest due to their implications for identifying potential areas of *Illex* aggregation and better understanding their distribution and availability to the fishery. In particular, bottom temperature and ring footprint index may be useful indicators for habitat conditions relevant to *Illex* juvenile/adult and pre-recruit/larval life stages, respectively, whereas the remaining covariates, ring orientation, salinity, and chlorophyll frontal dynamics are potential indicators of areas of high productivity.

3. Utilize the age, size and maturity dataset, collected from the 2019 landings, to identify the dominant intra-annual cohorts in the fishery and to estimate growth rates and maturity ogives for each cohort. Also use these data to identify fishery recruitment pulses.

The life history of *Illex illecebrosus* is very similar to that of other *Illex* species, such as the well-studied *Illex argentinus*. Both species have a sub-annual lifespan, semelparous reproduction and highly variable inter-annual abundance and rapid growth rates with high plasticity due to the strong influence of environmental factors on *Illex* species' life history traits. Age rather than length data must be used to identify intra-annual cohorts and determine growth rates of squid stocks because two individuals of the same size can be from different cohorts due to differential cohort growth rates. Temporally and spatially representative *I. illecebrosus* samples were randomly sampled from unculled catches of the directed fisheries during 2019 and 2020. Dorsal mantle length (DML), body weight (g), sex and sexual maturity were recorded for 951 and 1,269 individuals, respectively. Statoliths from 400 (2019) and 325 (2020) individuals were extracted and the time-consuming ageing work, two independent counts of the daily growth increments for each statolith, was conducted by two squid aging experts One of the agers experienced with conducting Trace Element Analysis (TEA) on squid statoliths used laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to sample strontium and 12 additional trace element concentrations, with Ca used as an internal standard to account for variation in ablation yield. Trace elements were sampled continuously along a transect of each of 252 statoliths. Due to COVID-19 project delays during 2020 and 2021, a considerable amount of the age-based analyses could not be completed in time for this report. Thus, we focused on cohort identification using Sr:Ca concentrations for this stock assessment and note that he remaining analyses will be completed and published following the *Illex* Management Track Assessment process. The Sr:Ca concentrations from the statolith samples were binned by the same hatch month ranges that the age frequency data identified as the winter and summer cohorts and the data for each cohort were modeled separately, a Gaussian GAMM (identity link, to ensure positive fitted values) to determine whether Sr:Ca ratios were distinct for each assigned cohort and how they changed throughout ontogeny.

The study results showed unimodal and bimodal age and length compositions for the 2019 and 2020 fishery catches, respectively. This difference was explained by the catch age frequencies binned by hatch month and which were used to identify the intra-annual cohorts. The first mode represented the winter cohort, hatch months November-April, and the second mode represented the summer cohort, hatch months May-July. The binned age frequency data also indicated that the summer cohort recruited to the fishery in low numbers during September, but dominated the catches in October. However, a September sample but no October sample was collected during 2019 and an October sample but no September sample was collected during 2020. Thus, the summer cohort mode could only be seen in the 2020 data. The catch age frequencies binned by hatch month confirmed the results of a May 2000 study that two cohorts support the U.S. fishery; a winter cohort that supports the early fishery period (during May-September, although September is a cohort transition month) and a summer cohort (previously inferred as the spring cohort) supports the fishery mainly from October onward. The study results also confirmed continuous spawning noted in the initial ageing study and determined that monthly fishery catches were comprised of two to four different hatch months.

The results of the 2020 TEA analysis confirmed the aged-based assignment of the winter and summer cohorts because the two cohorts have significantly different Sr:Ca ontogenetic signatures. Correct cohort assignment is crucial for the sustainable management of squid stocks because differences in growth and maturation rates between cohorts require each cohort to be assessed separately as if it were a separate stock. Thus, management of the U.S. fishery, should take into account the abundance of each of the two intra-annual cohorts identified for this resource. A good reminder of the need for cohort-specific management of squid stocks is the collapse of the northern stock component (NAFO Subareas 3+4) of *I. illecebrosus* in 1982, following record high catches during 1976-1981. The collapse subsequently led to a 36-year period of low productivity during 1982-2017 that could not support a fishery on this stock component.

The TEA of the 2020 data indicated that the winter and summer cohorts, which confirms the assignment. Future analysis of the 2020 trace element data may help elucidate migration patterns to and from the fishing grounds, but for now presents further evidence that the winter and summer cohort assignments presented at this Research Track Assessment are accurate.

4. Characterize annual and weekly, in-season spatio-temporal trends in body size based on length and weight samples collected from the landings by port samplers and provided by *Illex* processors. Consider the environmental factors that may influence trends in body size and recruitment. If possible, integrate these results into the stock assessment.

Both annual and weekly *Illex* body weight data were collected from the commercial fishery landings during 1997-2019. The body weight data for 1997-2003 was collected as part of a cooperative research study that involved real-time, fishery dependent data collection to evaluate changes in stock productivity. Body weight data for 2004-2006 and 2009-2018 were collected from landings of the directed fishery by staff from the two primary *Illex* processors. *Illex* body length samples were also collected by NEFSC port samplers, with body weight computed by dividing the sample weight by the number of lengths in the sample. Samples collected by port samplers included 100 squid per market category per month. Research survey trends in annual mean body weight are associated with annual trends in *Illex* relative abundance, such that stratified mean body weight is generally lower during years of low relative abundance, and vice versa, on the U.S. Shelf. When trends between the fishery mean body weight time series and the NEFSC fall survey stratified mean body weight time series are compared, the fishery time series does not show the gradual decrease exhibited by the survey time series. In addition to quantitatively exploring trends in *Illex* body size, Mercer *et al.* (2022) also synthesized industry observations on trends in body size within the fishing season and between years. Salois *et al.* (2022) addressed environmental factors that may affect the stock in TOR 2.

5. Develop a model that can be used for estimation of fishing mortality and stock biomass, for each dominant cohort that supports the fishery, and estimate the uncertainty of these estimates. Compare the results from model runs for years with low, medium and high biomass estimates.

Rago (2020, 2021) developed a suite of Indirect Estimation Methods, including Leslie-Davis Depletion, Mass Balance, Envelope of bounds, Escapement given fishing mortality, and the

analysis of Vessel Monitoring System catch and effort data to develop logical bounds on population biomass and fishing mortality rates and provide useful catch advice. A Leslie-Davis depletion model did not work very well for *Illex* because key assumptions for model application are violated. A Mass Balance Model shows the magnitude of migration, growth and recruitment effects necessary to offset the differences in relative abundance between the NEFSC spring and fall bottom trawl indices. An Envelope Model approach was 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 were used to establish potential ranges for an Escapement Model for existing and hypothesized ABC values. Vessel Monitoring System data were analyzed to estimate effective fishing mortality rates over the entire population. The WG concluded that when considered together, the Indirect Estimation Methods suggest that the overall *Illex* population is likely to be large and relatively low chances of high fishing mortality rates over a broad range of assumed parameter extremes. However, the point estimates of stock biomass and fishing mortality were not accepted as a basis for stock status determination.

Manderson & Mercer (2022) evaluated Generalized Depletion Modeling (GDM; Roa-Ureta 2012, 2015, 2020), a technique that can explicitly account for in-season pulses of animals onto and off of fishing grounds in the estimation of parameters useful for assessment. Specifically, GDM can be used to un-confound the effects of in-season migration on estimates of N_0, M, F and fishery escapement H. Manderson & Mercer (2022) reviewed the technique and applied intra-annual GDM to weekly landings and individual weights of squid measured by processors during 5 recent US *Illex* fishing seasons (2013, 2016-2019). GDM involves multi-model inference about the timing of in-season ingress and egress of animals onto the fishing ground based usually on fishery dependent indicators. Steps in development and evaluation of a 2 fleet GDM (freezer trawler and RSW + ICE Boats) for the 2016 fishing season were demonstrated in detail. The sample size was largest in 2016 (N=38) and "best" GDM produced plausible values and reasonable CVs (<57%) for most perimeter estimates. Caution is warranted in interpreting and applying the GDM results since high CVs were produced for some parameter estimates associated with the fishing process and catch perturbations due in part to relatively small sample sizes. Fleet specific parameters associated with the fishing process, and the timing and magnitudes of pulses detected in landings were particularly problematic. Moving to a time step of a day could produce sample sizes necessary for GDM to produce parameter estimates and derived quantities accurate and precise enough for operational assessment of the risk of overfishing in the US *Illex* fishery.

The WG believes GDM is promising but requires further research. The WG found that the GDM results suggest in a qualitative way that F was lower than M (from internal GDM F to M ratios results) and that stock biomass was lightly fished in 2019 (from comparison of the estimated range of annual biomass to the Rago (2021) Mass Balance bounds). The WG concluded that the GDM (as currently configured with weekly fishery landings data) does not provide an adequate quantitative basis for stock status determination using any of the candidate BRPs, including Mass Balance bounds, F to M ratios, or previously published estimates of biological reference points for the stock (i.e., Hendrickson and Hart 2006).

6. Describe the data that would be needed to conduct in-season stock assessments for adaptive management and identify whether the data already exist or if new data would need to be collected and at what frequency.

As *Illex* is a sub-annual species, assessments should be based on data from the current year. However, stock assessments are prepared for the previous year because data for the current year are unavailable at the time of the assessment. Consideration of the timing of the *Illex* assessment and the collection of in-season assessment data are needed to remedy these issues.

The data, analytical, and management needs for in-season assessment and management of *Illex* include: Precise fishing locations, precise catch and effort data (daily), individual *Illex* size, weight, and sex data throughout the fishing season by fleet (freezer and wet boat), operational oceanographic indicators of *Illex* biomass and availability, a functional depletion model, and an in-season management process.

Some of these data needs would require Council approval and a rule-making action which could take 18 months or more before implementation. It is recommended that sufficient data needs are met and in place and the assessments completed for at least 1 full fishing year before considering implementing measures that could make an in-season adjustment to the quota. Overall, additional research and resources are needed prior to pursuing in-season assessment or management for northern shortfin squid.

7. Update or redefine Biological Reference Points (BRP point estimates for B_{MSY}, $B_{THRESHOLD}$ and F_{MSY}) or BRP proxies, for each dominant cohort that supports the fishery, and provide estimates of their uncertainty. If analytical model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPs. Comment on the scientific adequacy of existing and recommended BRPs or their proxies.

Although new age and maturity data were collected during 2019 and 2020 for the current assessment, the number of mature females in the aged samples were too few to run the Hendrickson and Hart (2006) models to estimate updated values of natural mortality. Statolith-based ageing of squid samples is very expensive and there are few squid ageing experts available globally. These facts, combined with the need for an adequate number of mature females, suggest aged-based estimation methods for BRP proxies might not be practical for this southern stock component of the northern shortfin Illex stock managed by the U.S.

An extension (Rago 2022) of the Hendrickson and Hart (2006) was considered by the WG. The extended model recast the continuous time model as a discrete monthly time step model with a seasonal fishery. The model provided useful insights into the magnitude of population compensation necessary to offset the force of fishing mortality and the protective effects of seasonal (vs continuous) fisheries. However, it was not sufficient to redefine an alternative basis for a biological reference points or MSY proxies. The revised matrix model may have utility as a dynamic estimation model for future assessments.

8. Recommend a stock status determination (i.e., overfishing and overfished), for each dominant cohort supporting the fishery, based on new modeling approaches developed for this peer review.

The WG recommends that the stock status is unknown with respect to reference points-based definitions of overfishing and overfished.

9. Define the methodology for performing short-term projections of catch and biomass under alternative harvest scenarios, including the assumptions of fishery selectivity, weights at age, and maturity.

The WG does not consider the use of traditional multi-age projection methods commonly used in Northeast U.S. finfish assessments to be appropriate for the *Illex* stock on the U.S. shelf. The reason is the stock's life span of less than one year and subsequent lack of multiple age class 'inter-annual memory' in the population that makes such projections useful for multi-age finfish stocks. If some 'projection' approach is needed to satisfy management requirements, the Illex WG proposes the 'PlanBsmooth' approach (NEFSC IBMWG 2021) as a guide for forecast OFL/ABC advice.

10. Review, evaluate and report on the status of the Stock Assessment Review Committee (SARC) and Working Group research recommendations listed in the most recent SARC-reviewed assessment and review panel reports. Identify new research recommendations.

The WG provided updated responses to Research Recommendations from the previous benchmark assessments and MAFMC SSC 2020-2021 meetings. The WG developed 11 new prioritized Research Recommendations.

11. Develop a "Plan B" alternate assessment approach to providing scientific advice to managers if the analytical assessment does not pass review.

The WG recommends that the MAFMC and NMFS continue to use the current Indirect Estimation Methods approach (Rago 2021) to establish future ABC.