A. LONGFIN SQUID

TERMS OF REFERENCE

1. Update fishery dependent (including discards) and fishery independent data for longfin squid.

2. Provide estimates of fishing mortality and stock biomass and characterize stock status in 2000, in absolute or relative terms, and characterize uncertainties as appropriate.

3. Update estimates of biological reference points and uncertainties, as appropriate.

EXECUTIVE SUMMARY

1) The inshore longfin squid (*Loligo pealeii*) is distributed from the Caribbean to Newfoundland, depending on season and oceanographic conditions. The stock area for this assessment is defined as wherever longfin squid are found between the northern edge of Georges Bank and Cape Hatteras. More precisely, the northern and southern boundaries of the stock are defined by survey strata used in this assessment to calculate abundance indices based on Northeast Fisheries Science Center (NEFSC) autumn bottom trawl survey data. This stock definition includes the main range of commercial exploitation. The stock area assumed in previous assessments was similar, but did not include northern Georges Bank.

2) Longfin squid are short-lived (less than 11 months) and grow rapidly. Males grow faster and reach larger size. Spawning occurs year round. Substantial new information about life history and biology is available, particularly in the areas of age and growth, geographic distribution and reproductive biology. Much of the new information is used in this assessment.

3) In the northeast, longfin squid move offshore and probably south during late autumn and then inshore and probably north during the spring and early summer.

4) The peak length body size of longfin squid in landings is 12-15 cm dorsal mantle length (DML) but appreciable amounts are landed out to about 30 cm DML.

5) Abundance information used in this assessment include bottom trawl survey data for NEFSC autumn surveys during 1967-2001, NEFSC spring surveys during 1968-2001, NEFSC winter surveys during 1992-2001, and Massachusetts inshore spring surveys data during 1978-2001. Standardized commercial landings per unit effort (LPUE) for winter and summer fisheries during 1983-1993 are also used. None of the bottom trawl surveys cover the entire range of the stock although coverage is best during the NEFSC autumn survey.

6) Longfin squid generally move towards the bottom during the day. Survey data used in this assessment are adjusted to daytime equivalents based on estimated diel correction factors.

7) All surveys indicate relatively low longfin squid biomass during the mid- to late 1990's, increases to moderate or high levels by 2000 with modest declines in all but the autumn survey during 2000-2001. The autumn survey increased to near record levels during 2000-2001.

8) Trends in the autumn survey are generally most reliable for longfin squid because the autumn survey has the highest catch rates, lowest CV's, and best overlap between survey strata and squid distribution.

9) This is the first assessment for longfin squid where NEFSC autumn survey data were available for use in an assessment during the same year. NEFSC survey data were available more rapidly due to improvements in data recording and auditing at sea.

10) It is likely that environmental factors affect longfin squid catchability and catch rates in all of the bottom trawl surveys available. This hypothesis is a major topic of investigation in this assessment.

11) Bottom trawl survey data indicate increased recruitment of longfin squid since 1998.

12) Length based virtual population analysis (LVPA) for longfin squid in the winter and summer fisheries gave trends in relative biomass and fishing mortality that were similar to trend estimates by other methods. In particular, LVPA biomass estimates for longfin squid declined in the late 1990's then increased to intermediate recent levels. LVPA *F* estimates increased in the late 1990's and appear to have declined recently.

13) Feasible bounds and distributions measuring prior uncertainty for the NEFSC autumn trawl survey catchability coefficient are important parts of this assessment. Factors affecting uncertainty in catchability are the size of the effective area occupied by the squid stock, the average distance of a standard survey tow, the effective width of the survey bottom trawl, and the efficiency of the trawl for longfin squid above the ground swept by the trawl.

14) Scaled catch-survey fishing mortality estimates for longfin squid based on autumn trawl survey data were high in 1998 but declined to below average levels during 1999-2000. Trends in unscaled fishing mortality rates based on spring and winter survey data also indicate that fishing mortality rates for longfin squid declined during 1999-2001.

15) The new surplus production-modeling program (PDQ) used in this assessment has greater flexibility, and more options for characterizing uncertainty than programs used previously for longfin squid. Population dynamics calculations can be based on a conventional logistic surplus production model or a "simple" production model that does not assume a carrying capacity. In addition to survey measurement errors, PDQ accommodates process errors (natural variability) in surplus production rates and survey catchability.

16) Biomass trend data from length based virtual population analysis (LVPA) for longfin squid during winter and summer fisheries were used experimentally as abundance indices in PDQ. LVPA biomass trends are an almost independent source of information based on port sampling, growth, and longevity data that are not otherwise included in PDQ. In addition, LVPA data for longfin squid may be less affected by changes in oceanographic conditions that appear to affect catchability of longfin squid in bottom trawl surveys.

17) The most important characteristic of LVPA trend data in production modeling for longfin squid is relative stability from year to year. In the PDQ model, the stability of

LVPA information tends to counteract inter-annual variability in bottom trawl survey data in a way that makes estimates of biomass and B_{MSY} higher and more feasible.

18) A new hypothesis explains problems with infeasible low biomass estimates that have plagued production model estimates in stock assessments for longfin squid over the last decade. Based on experience with LVPA data and likelihood profile analysis, problems stem from the high year to year variability in bottom trawl survey data. Relatively high values in NEFSC autumn bottom trawl survey data for longfin squid in one time step, for example, tend to be followed by low values in the next time step and so on. In order to fit bottom trawl survey data, production rates have to change rapidly. To accomplish this, traditional production models (with surplus production always positive) estimate low biomass and carrying capacity for longfin squid so that moderate increases or decreases in biomass are followed by substantial decreases or increases in production rates. It is likely that high variability in bottom trawl survey data stems from oceanographic features that affect catchability.

19) Estimated production rates ρ_t for longfin squid in preliminary runs of the simple PDQ model that does not estimate carrying capacity were autocorrelated with production rates higher or lower than average for periods of 1-5 years. Some environmental variable, acting over periods of years, appears to effect either surplus production in the longfin squid stock or catchability of longfin squid in bottom trawl surveys.

20) Process errors in bottom trawl survey catchability for longfin squid, estimated in the basecase PDQ model run, were correlated across surveys and autocorrelated within surveys. Environmental variables affecting catchability or surplus production appear to act consistently on all surveys carried out within periods of 1-5 years. This suggests it may be possible to model catchability or production process errors for longfin squid in a more simple and parsimonious fashion based on variation in water temperatures or some other environmental variable.

21) Traditional per recruit models were run with updated estimates of natural mortality, growth, fishery selectivity, and maturity at age. Reference point *F*'s estimated in this assessment were lower than estimates in the last assessment.

22) It is unlikely that the overfishing is occurring in the longfin squid fishery based on a number of reference points and stock status measures.

23) It is unlikely that the longfin squid stock is overfished based on a number of reference points and stock status measures.

INTRODUCTION

The inshore longfin squid (*Loligo pealeii*) is a short lived (maximum observed age less than 11 months, Brodziak and Macy 1996, Macy and Brodziak 2001) squid distributed between the Caribbean in the south (Cohen 1976) and, depending on environmental conditions and season, as far north as Newfoundland (Dawe et al. 1990). In most years, however, they are not abundant in the Gulf of Maine and Canadian waters. South of Cape Hatteras, the geographic distribution of longfin squid overlaps with the distribution of the morphologically similar species *L. plei* (Cohen 1976). The distribution of longfin squid in the water column depends on time of day and, in most seasons, densities are highest on the bottom in the daytime (Hatfield and Cadrin in press).

The stock in this assessment is distributed at all depths were longfin squid are found between the northern edge of Georges Bank and Cape Hatteras. The northern and southern boundaries of the stock are defined more precisely by survey strata used in this assessment to calculate abundance indices based on Northeast Fisheries Science Center (NEFSC) autumn bottom trawl survey data. This stock definition includes the main range of commercial exploitation. The stock definition in all fut the previous assessments was similar, but did not include northern Georges Bank (NEFSC 1986, Cadrin and Hatfield 1999).

Relationships between the population dynamics of inshore-offshore, and northern-southern components of the longfin squid stock in this assessment are complex and not well understood. Longfin squid have complicated seasonal and annual distribution patterns (Brodziak and Macy 2001, Hatfield and Cadrin in press). Depending on season and water temperatures, they are distributed from relatively shallow near shore areas, across the continental shelf and on the upper continental slope with the largest individuals in relatively deep water (Cadrin and Hatfield in press).

In the northeast, longfin squid move offshore and probably south during late autumn, to over-winter in warmer waters along the continental shelf and possibly deeper water (Cadrin and Hatfield 1999, Brodziak and Macy 2001, Hatfield and Cadrin in press). They move inshore during the spring and early summer. Migratory patterns in deep water on the continental slope, and along the continental shelf are less well understood but probably occur.

Considerable progress has been made in characterizing average growth, maturity and other biological parameters for the longfin squid stock but the problem is a difficult one. Uncertainty is understandable and probably unavoidable because sampling is often opportunistic, the distribution of longfin squid is dynamic, schools are patchy and the stock is distributed nonrandomly with respect to size across a large area at unknown local densities.

Longfin squid grow rapidly and are sexually dimorphic with males growing faster and to larger size than females. Males may grow larger than 40 cm dorsal mantle length (DML). The largest individuals recorded in Northeast Fisheries Science Center (NEFSC) survey databases were larger than 50 cm DML. Longfin squid from the "summer hatch" (June-October) grow more rapidly than individuals from the "winter hatch" (November-May). Growth is highly variable among individuals (Brodziak and Macy 1996) and samples (Macy and Brodziak 2001). Variation among samples may be due to different sampling locations, environmental conditions in different years, seasonal effects, different hatch dates, or all of these factors (Macy and Brodziak 2001).

Female longfin squid reach 50% sexual maturity at about 21 cm DML and males reach 50% sexual maturity at about 20 cm DML (Hatfield and Cadrin, in press). Reproductive biology in longfin squid is complex (Maxwell and Hanlon 2000). Spawning occurs year round. Macy and Brodziak (2001) suggest that two spawning peaks are evident in samples from the northeast, one inshore during August-September and one elsewhere with a peak in November-December. Hatfield and Cadrin (in press) hypothesize that the majority of squid taken north of Cape Hatteras during the summer are spawned south of Cape Hatteras during the winter.

DATA

In this assessment, the "winter" quarter is January-March, "spring" is April-June, "summer" is July-September, and "autumn" is October-December. Following Cadrin and Hatfield (1999), the "summer fishery" is during the second and third quarters and the "winter fishery" is during the fourth and first quarters. In this assessment, for example, the 1998 winter fishery occurred during October 1998-April 1999. The last assessment used a different naming convention with, for example, the 1998 fishery during October 1997-April 1998. Following Macy and Brodziak (2001), the "winter hatch" for longfin squid includes individuals hatched during November-April and the "summer hatch" includes individuals hatched during May-October. All survey data are in units of either weight (kg) or numbers per standard survey tow. All survey data are adjusted to daytime equivalents using diel correction factors in Hatfield and Cadrin (in press, see below for details).

Landings

Landings data for longfin squid (Tables A1-A2 and Figure A1) during 1963-1997, with corrections for unspecified squid landings, are from Cadrin and Hatfield (1999). New landings data for 1998-2000 were from the National Marine Fisheries Service (NMFS), Northeast Region (NER) commercial fishery detail species (CFDETS) database with adjustments for unspecified squid described below. Landings data for longfin squid during January-June 2001 (without corrections for unspecified squid) were from the Interactive Voice Response (IVR) database used by NER to monitor landings of quota-managed species. IVR data probably underestimated actual landings during January-June 2001, but were the best data available. Landings data (without corrections for unspecified squid) for the second half of 2001 were assumed equal to quarterly quota allocations used to manage the longfin squid fishery (i.e. 2,941 mt total during July-September and 5,416 mt total during November-December).

Unspecified squid landings were less than 22-65 mt per year during 1998-2000 and were prorated into longfin squid and northern shortfin squid *(Illex illecebrosus)* portions based on ratios of squid landings that were identified to species during each month and year:

$$R_{m,y} = \frac{L_{Longfin,m,y}}{L_{Shortfin,m,y} + L_{Longfin,m,y}}$$

where, for example, $L_{Longfin,m,y}$ was longfin squid landings during month m of year y and $R_{m,y}$ was the ratio used to prorate unspecified squid landings.

According to Cadrin and Hatfield (1999), there is substantial uncertainty in estimates of foreign landings and historical domestic landings. Accuracy of landings estimates is better beginning in 1987 due to better reporting of landings by species and prohibitions on foreign fishing (Cadrin and Hatfield 1999). There was no observer coverage of foreign fleets before 1978, and observer coverage was low in the early 1980s (Cadrin and Hatfield 1999). The relative proportion of total landings from unspecified squid landings was substantial in some years (e.g., 20% in 1983), but has been generally low since 1985 (<5%; with the exception of 1996, when 10% of total landings estimates were from unspecified records). Some landings of L. plei may be included in longfin squid catches south of Cape Hatteras, because landings are categorized to genus, not species.

Port sample length composition data (Figure A2) show that the peak length of longfin squid in landings is about 12-15 cm DML. Appreciable amounts of longfin squid are landed out to about 30 cm DML.

Discarded catch

Discarded longfin squid are generally small (<10 cm DML; Figure A3) and difficult to market. Cadrin and Hatfield (1999) concluded that discard of longfin squid is currently minor but indicated that precise estimates of discard are difficult to obtain and that discard rates likely vary by fishery, season, time of day, location and target species. In addition to reviewing published reports, Cadrin and Hatfield (1999) used data from 915 otter trawl trips in the National Marine Fisheries Service (NMFS) observer database to calculate ratios of the weight of longfin squid discarded divided by the weight of all species landed during 1989-1998. The ratios ranged 1%-14% and averaged 6%. Mesh size regulations changed in 1996 when minimum mesh sizes increased. Changes in regulations since 1997 may have reduced discard rates for longfin squid to levels below 6% of total landings.

In this assessment, observer data were used to estimate discard rates for longfin squid during trips directed at key target species during 1997-2000 (while net size regulations were unchanged). Observers determined target species for each tow by asking the captain on the vessel after the tow was completed. Target species include longfin squid because small squid may be discarded following tows that target longfin squid.

Discard estimates were calculated as the product of average landings during 1997-2000 and discard rates from observer data for 1997-2001 (Table A3). The data were collected by NMFS observers on commercial fishing boats during 1997 to mid-2000, and by Rutgers University personnel aboard five commercial boats during13 trips targeting black sea bass and scup during January-February 2001 as described by Powell et al. (2001). In most cases, the number of trips and tows was small and possibly non-representative so that the estimated discard rates, like Cadrin and Hatfield's (1999), are imprecise and possibly biased.

All available discard information was used to estimate discard rates for each target species. Butterfish are typically taken in tows directed at other species. Tows with butterfish as target species may also have been identified as trips for other target species. Our calculations may therefore overestimate the discard rate for longfin squid in directed butterfish trips, to the extent that multiple target species were identified for the same tow. No observer data was available for trips targeting Atlantic herring so discard rates for Atlantic mackerel were used instead.

Results indicate that total longfin squid discards during fishing for key target species averaged about 600 mt per year during 1997-2000. By comparison, longfin squid landings averaged about 18,000 mt per year so that the ratio of discards of longfin squid to longfin squid landings was about 0.03. The bulk of average longfin squid discards (about 500 mt per year) were from tows and trips targeting longfin squid. Of course, longfin squid are taken in tows targeting many species, including target species not in this analysis. It seem reasonable, therefore, that the estimated 3% discard rate for key target species is less than Cadrin and Hatfield's (1999) estimate for the entire bottom trawl fishery.

Landings per unit of commercial fishing effort (LPUE)

Landings per unit commercial fishing effort (LPUE) data from NEFSC (1996, Table A4 and Figure A4) were for the domestic squid fishery during the winter (October-March) of 1983-1993 and the summer (April-September) of 1981-1993. Standardized LPUE was computed as the ratio of landings and standardized fishing effort for otter trawl trips that caught at least 10% longfin squid by weight. Effort was standardized using a general linear model (GLM) with years, seasons (summer or winter), catch areas and vessel ton-classes as explanatory factors. The original effort data were collected by port agent interviews. Standard LPUE data time series were not updated because of changes in data collection procedures starting in 1994 and associated problems in measuring fishing effort and catch location for longfin squid.

Bottom trawl survey data

Bottom trawl survey data for longfin squid used in this assessment were from: a) NEFSC autumn surveys during 1967-2001 (offshore strata 1-23, 25 and 61-76, Figure A5, 2001 data preliminary); b) NEFSC spring surveys during 1968-2001 (same strata as autumn survey, Figure A5); c) NEFSC winter surveys during 1992-2001 (offshore strata 1-17, 61-76, Figure A5); and c) Massachusetts inshore spring surveys data during 1978-2001 (Massachusetts bottom trawl survey strata 11-20, Figure A6). Strata sets used with bottom trawl survey data for longfin squid in this assessment were the same as in Cadrin and Hatfield (1999) and previous assessments. The traditional set for NEFSC strata for longfin squid consists of all consistently occupied offshore strata between Georges Bank and Cape Hatteras. However, longfin squid catch rates are relatively high during the autumn survey in many inshore strata along the Mid-Atlantic Bight (Figure A7). Strata sets used for longfin squid should be revaluated prior to the next assessment.

This assessment marks the first time NEFSC autumn survey data were available for an autumn assessment during the same year. Quicker availability of data is due to new procedures for electronic data entry and at-sea data auditing. Use of recent survey data is an important advantage in assessments for longfin squid, which are short-lived and highly dynamic.

Survey data used in this stock assessment for longfin squid are either mean numbers of "pre-recruit" squid ≤ 8.9 cm DML per standard tow (number/tow), or total catch weight (all sizes) per standard tow (KG/tow). The former is a measure of relative recruitment strength. The latter is a measure of total stock biomass and was computed by converting lengths (in 1 cm increments) to weights and multiplying the estimated weights by numbers per tow in the same length group.

NEFSC surveys

NEFSC surveys follow a stratified random design with stations allocated in rough proportion to stratum area. Standard tows in NEFSC surveys are 30 minutes in duration at a speed of 3.8 knots. The type of trawl door used in NEFSC spring and autumn surveys was changed in 1985 (NEFSC 1992) from the original "BMV" door to a newer polyvalent door (Tables A5-A6).

Autumn NEFSC survey data have been collected since 1964 (longfin squid identified starting in 1967) using a single type of trawl and the NOAA research vessels Albatross IV and Delaware II. The timing of the autumn survey changed during the late 1960's and early 1970's (Table A5) along with average water temperatures at tow stations (Table A9). Spring NEFSC survey data have been collected since 1968 with longfin squid identified starting in the first year. Two types of bottom trawls and both NOAA research vessels have been used in the spring survey (Table A6). In particular, the "high-rise" Yankee No. 41 trawl was used during 1974-1981 while the standard Yankee No. 36 trawl was used in 1968-1974, 1981 and subsequent years. The winter survey has been conducted with a single type of trawl and both NOAA research vessels (Table A7).

Survey data collected with polyvalent and BMV doors, by the NOAA research vessels Albatross IV and Delaware II, the No. 36 and No. 41 Yankee bottom trawls are used in this assessment without adjustment because catch rates in paired gear experiments did not differ significantly for longfin squid (NEFSC 1992, Sissenwine and Bowman 1978). There are no obvious discontinuities in average survey catch rates that correspond to changes in doors, vessels or bottom trawls. The autumn NEFSC bottom trawl survey time series was not adjusted for changes in survey timing (or associated changes in bottom temperatures). However, this issue was addressed indirectly in catchability process error models (see below).

Massachusetts inshore survey

The Massachusetts inshore spring bottom trawl survey has been conducted in state waters since 1978 from the borders of New Hampshire to Rhode Island (including Cape Cod Bay and Nantucket sound) (Table A8). Sampling is based on a stratified random design involving five geographic regions and depth zones. Standard survey tows are 20 minutes at 2.5 knots using a ¾ North Atlantic type two seam ('whiting') otter trawl (11.9 m head rope, 15.5 m footrope), rigged with a 19.2 m chain sweep and 7.6 cm rubber discs, 18.3 m bottom legs of 9.5 mm chain, 19.2 m wire top legs, 1.8 x 1.0 m 147 kg wooden trawl doors, and a 6.4 mm mesh cod end liner. Data for longfin squid data used in this assessment are from Massachusetts survey strata 11-20 (Figure A6).

Survey coverage

As pointed out in Cadrin and Hatfield (1999), the autumn NEFSC survey is carried out while longfin squid are distributed across the continental shelf at the northern end of their seasonal migration (Figure A7). In contrast, the spring and winter NEFSC surveys (Figures A8-A9) are carried out while longfin squid are along the shelf-edge and in water deeper than sampled by NEFSC surveys. The Massachusetts spring survey is carried out in inshore waters (within 3 miles of shore) exclusively (Figure A10). Although sampling and stock distribution overlap to the greatest degree during the autumn NEFSC survey, longfin squid are common along both the shallow (western) and deep (eastern) boundaries of the autumn survey and along the deep southeastern boundaries of the spring and winter surveys. Thus, none of the bottom trawls surveys cover the entire range of the longfin squid resource but overlap between the stock and the autumn survey is relatively high.

Adjustments for diel catchability differences

Longfin squid catch rates in bottom trawl surveys depend on time of day and season because longfin squid move towards the bottom during daylight hours and up into the water column during night, to a degree that depends on size of squid and season. Hatfield and Cadrin's (in press) diel correction factors (see below) were used to adjust all bottom trawl survey data used in this assessment for longfin squid to daytime equivalent (maximum) values. Adjustment factors for the Massachusetts spring survey were not available so corrections factors for the NEFSC spring survey were used for Massachusetts spring data. CV's for the adjusted and unadjusted series were assumed the same because variances were not available for the diel correction factors.

Diel connection factors for longfin squid (Hatfield and Cadrin, in press).

Time of Day	**≤80 mm DML**	**> 80 mm DML**
NEFSC autumn survey		
Night (8 PM-4 AM)	0.0873	0.3420
Dawn/Dusk (4 AM-8 AM or 4 PM-PM)	0.4654	0.8325
Day (8 AM-4 PM)	1.0000	1.0000
NEFSC spring survey		
Night	0.5102	0.7205
Dawn/Dusk	0.7872	0.9157
Day	1.0000	1.0000
NEFS winter survey		
Night	0.6519	1.3051
Dawn/Dusk	0.8098	1.1451
Day	1.0000	1.0000

Survey data computations

Mean total weight (all size classes) per standard tow (computed from numbers caught in 1 cm length groups and length-weight relationships[2]) and pre-recruit abundance (mean number of longfin squid ≤ 8.9 cm DML per standard tow), along with coefficients of variation (CV=standard error/mean), were computed for each survey and year using standard formulas (Tables A9-A12). Not all strata were sampled in all years during NEFSC surveys. Weights used in computing survey averages were adjusted in calculations to accommodate missing strata. CV's for NEFSC survey data underestimate the true variance in NEFSC survey data because some small strata are sampled only once. Variances for stratum means with only one station could not be calculated and were assumed to be zero. Mean surface and bottom temperatures were calculated as the simple average of temperatures recorded at each tow location used for longfin squid.

Survey results

Trends in weight per tow were generally similar except during 2001 (the most recent year). All of the surveys suggest relatively low squid biomass levels during the mid- to late 1990's and increases to moderate or high levels by 2000 with declines in all but the autumn survey during 2000-2001 (Tables A9-A12 and Figures A11-A14). The autumn survey during 2001 was at a near record level. Overall, catch rates for longfin squid were highest and CV's were lowest in the autumn survey. In contrast, the NEFSC spring survey had the lowest kg per tow values and the highest CV's.

[2] $W=0.249118\ L^{2.18390}$ for NEFSC surveys; $W=0.250206\ L^{2.14418}$ for Massachusetts surveys, DML in cm and W in grams.

Water temperatures may affect catchability of longfin squid i bottom trawl surveys (Hatfield and Cadrin, in press). Mean bottom temperatures increases in the NEFSC autumn survey after 1981 but bottom temperatures for the autumn survey, along with surface and bottom temperatures for other surveys, fluctuated without trend (Tables A9-A12 and Figures A15-A16). The trend in bottom temperature in the NEFSC autumn survey was likely due to changes in survey timing. Since the early 1960's, the average date of autumn bottom trawl tows has decreased by about six weeks (Table A5 and Figure A17). The timing of other surveys has varied but without trend (Tables A6-A8 and Figure A17).

The NEFSC autumn bottom trawl survey index was at a near record level in 2001 while other surveys showed some decline during 2000-2001 and longfin squid in the Massachusetts spring survey were quite low. However, trends in the autumn survey are generally most reliable for longfin squid because it has the highest catch rates, lowest CV's, and best overlap between survey strata and squid distribution. Other bottom trawl surveys for longfin squid have lower catch rates, higher CV's and low overlap between survey strata and squid distribution. Autumn survey data for longfin squid are the most recent information available. As discussed, it is likely that environmental factors affect longfin squid catchability and catch rates in all of the bottom trawl surveys available.

Trends in pre-recruit abundance were consistent among surveys. All surveys indicate a steady general increase in recruitment since the early 1990's (Tables A9-A12, Figure A18). Based on NEFSC and Massachusetts bottom trawl survey data, recent longfin squid recruitment has been at high to record high levels (Massachusetts survey data for longfin squid were low during 2001) but trends in the Massachusetts survey are highly variable.

Length composition data for NEFSC offshore surveys (Figure A19) show that smaller longfin squid are taken offshore during the autumn survey. The highest proportions of large squid are taken offshore in the winter survey. The widest range of lengths is taken in the Massachusetts inshore survey (Figure A19) where length distributions are bimodal. Bimodal length distributions in the Massachusetts survey are likely due to small mature males and large mature females on spawning grounds during May (Figure A19).

ASSESSMENT CALCULATIONS

In this assessment, longfin squid biomass is measured in units of mt. Body weights for individual squid are in units of kg whole wet weight. All instantaneous mortality rates are for quarterly time steps, although length based virtual population and reference point calculations used monthly time steps. Divide quarterly rates by three to get monthly values and multiply quarterly rates by four to get annual values. Use care in comparing results from this assessment to results in Cadrin and Hatfield (1999) who present mortality rates in both quarterly and monthly time steps.

Length-based virtual population analysis

Length-based virtual population analyses (LVPA, Jones 1974, 1981, 1986) were carried out for longfin squid in the winter and the summer fisheries of each year (Cadrin and Hatfield 1999). In this assessment, the 1991 "winter" fishery, for example, took place during the six-month period October 1990 to March 1991. Similarly, the 1991 "summer" fishery took place during the six-month period April 1991 to September 1991. Cadrin and Hatfield (1999) used a different naming convention. Two cm length groups were used in LVPA calculations for longfin squid (Table A13).

Growth and Δt_L values

The amount of time that longfin squid spend in each 2 cm size class (Δt_L, Table A13) is a key parameter in LVPA (Cadrin and Hatfield 1999). For this assessment, Δt_L values were calculated based on unpublished exponential growth curves fit by J. Brodziak (NEFSC, Woods Hole) to all of the length-age data available for longfin squid. Data used in fitting growth curves for this assessment include all observations used in Brodziak and Macy (1996) and Macy and Brodziak (2001). Curves were for males and females combined and with "summer hatch" dates (November-April, N=517, ages 1.6-9.2 months) and "winter hatch" dates (May-October, N=314, ages 2.6-9.7 months).

Based on the new curves, summer hatch squid appear to grow more rapidly and to larger sizes than winter hatch date squid (Figure A20). The new Δt_L values for winter hatch dates changed substantially (Figure A21) but there was little change in Δt_L values for summer hatch squid. Like Cadrin and Hatfield (1999), we used separate sets of Δt_L values for summer hatch and winter hatch squid, based on hatch date-specific growth curves for males and females combined.

Natural mortality rate

Cadrin and Hatfield (1999) assumed that the natural mortality rate for summer hatch and winter hatch longfin squid in LVPA calculations was M_L=0.3 month^{-1} (0.9 quarter^{1}). Longfin squid larger than 50 cm DML are unusual and 50 cm is a reasonable practical estimate of maximum size. The new growth curves (Figure A20) suggest that summer hatch squid reach 50 cm DML before age 10 months and that winter hatch squid reach 50 cm at about age 12 months. Using age at 50 cm DML as an estimate of maximum age, Gabriel et al's (1989) "3/M rule" suggests M=3/9=0.33 month^{-1} or M= 1.00 quarter^{-1} for summer hatch longfin squid and M=3/12=0.25 month^{-1} or M= 0.75 quarter^{1} for winter hatch date squid. These estimates of natural mortality were used in LVPA calculations for length groups (L) up to 27-28.9 cm. For the last length group (29-30.9 cm), the assumed natural mortality rate was doubled to further reduce survival at large sizes. Assumptions about natural mortality rates affected the scale but not trends in biomass and F estimates. The assumption of higher mortality in the last length group made selectivity curves more asymptotic in shape, but had little effect on trends in biomass or F estimates.

<u>LVPA calculations</u>

Length-based virtual population analysis estimates the length composition, abundance and biomass of a theoretical equilibrium population based on catch at length data and a number of simplifying assumptions (i.e. constant recruitment and constant mortality over time). As in traditional virtual population analysis (VPA), LVPA calculations for longfin squid were carried out "backwards" in time, from the largest length group towards the smallest.

Abundance in the largest length group in LVPA calculations for longfin squid (N_{29}) was calculated as

$$N_{29} = \frac{C_{29} Z_{29}}{F_{29}\left(1 - e^{-Z_{29}\Delta t_{29}}\right)}$$

where C_L was catch in length group L (length groups identified by the lower bound, e.g. "29" for 29-31.9 cm), F_L was the instantaneous fishing mortality rate (see below), and the total instantaneous mortality rate Z_L=F_L+M_L. Calculations did not include a plus group (the few squid surviving to grow larger than 30.9 cm were ignored).

The terminal fishing mortality rate F_{29} was chosen using an ad-hoc scheme that combined the method used in Cadrin and Hatfield (1999) with a smoothing penalty. Trends in biomass and fishing mortality rates were not sensitive to choice of terminal F but estimated selectivity patterns were more domed using the method in Cadrin and Hatfield (1999).

Fishing mortality rates for smaller size classes were calculated "exactly" by solving for F_t (Sims 1982) in the "backward" catch equation:

$$C_L = \frac{F_L\left(1 - e^{-Z_L \Delta t_L}\right) N_{L+2} e^{Z_{L=2}\Delta t_{L+2}}}{Z_L}$$

Abundance of squid in smaller sizes classes was calculated as

$$N_L = N_{L+2} e^{Z_{L+2}}$$

Biomass of squid in each size class (B_L) was calculated as

$$B_L = N_L W_L$$

where mean weights were calculated based on a length-weight relationship (W_L=0.2566 $L^{2.1518}$, with L the middle of the length group).

LVPA catch data

Catch at length of longfin squid in the winter and summer fisheries during 1987-2000 was estimated for each length group using quarterly length data from port samples as described by Cadrin and Hatfield (1999). Port sample length data were collected during every quarter after 1987, but sampling was not carried out during every month when landings occurred. In addition, some market categories were not sampled during some quarters (market categories are based on size: super small, small, medium, large, extra large, and unclassified). Quarterly landings for market categories with no port samples or length data were pooled with adjacent categories for calculation of catch at length (i.e., extra large were pooled with large; extra small were pooled with small; medium were pooled with unclassified, etc). When port samples and length composition data were not available for adjacent categories, landings were pooled with landings of unclassified squid. Mean individual body weight was estimated from length composition data for each pooled market category using the length weight relationship used in LVPA calculations (see above). Catch at length was computed for each pooled market category by multiplying proportions at each length (from port samples) by the ratio of total landings and mean individual weight. Total catch at length for each quarter was computed by summing catch at length for all pooled market categories.

LVPA results

LVPA results are affected by many factors and assumptions (Lai and Gallucci 1988). LVPA results for longfin squid may give useful information about trends in biomass and mortality based on fishery length composition data, but should not be used by managers as direct estimates of stock biomass or fishing mortality.

LVPA results were summarized in terms of the estimated total biomass of squid (all length groups, in relative terms to show trends only, Figure A22) and biomass weighted average *F* (in relative units to show trends only, Figure A23) for squid 13+ cm (13 cm is approximately the peak length taken in the commercial fishery). LVPA biomass and fishing mortality estimates for winter 2001 were affected by incomplete landings data for 2001 and are not presented. Length-based fishery selectivity was characterized for each fishery (Figure A24) by averaging F_L values across all years, and dividing by the largest average value.

Trends in biomass estimates from LVPA (Figure A22) were similar to trends in survey data and estimates from other models (see below). LVPA results indicate that biomass declined in the late 1990's then increased to intermediate current levels. Trends in biomass-weighted average *F* (Figure A23) from LVPA were also similar to trends in *F* estimates from other models (see below). LVPA biomass weighted average F estimates increased in the late 1990's and appear to have declined recently.

Fishery selectivity results from LVPA analyses (Figure A24) were almost asymptotic and indicate that fishing mortality rates for longfin squid generally increase with length. In contrast, fishery selectivity results in Cadrin and Hatfield (1999) from LVPA were more domed, indicating that fishing mortality rates for longfin squid decrease at the largest sizes. Sensitivity analyses (not shown) showed that differences in fishery selectivity results were due mostly to the scheme chosen to set F_L for the largest size groups and higher assumed M_L values for the largest length group. A single smooth average selectivity curve

$$s_L = e^{\eta_L} / \left(1 + e^{\eta_L}\right)$$

with

$$\eta_L = 0.343 \, \overline{L} - 6.08$$

($\overline{L}$ the midpoint of the 2 cm length intervals) fit by least squares adequately describes the selectivity curves for both winter and summer fisheries (Figure A24).

Bounds for Q in assessment models for longfin squid

Recent modeling efforts using surplus production models (NEFSC 1996, Cadrin and Hatfield 1999) estimated implausibly low biomass levels. As pointed out by Cadrin and Hatfield (1999), problems are evident in comparing biomass estimates from the model to minimum swept area biomass estimates which are computed from survey data under the assumption that survey bottom trawls are 100% percent efficient and capture 100% of the squid in the water column above the ground swept by the net. As shown below, this problem means that stock assessment models used recently for longfin squid tended to estimate implausibly high estimates of survey bottom trawl catchability (Q). Biomass is estimated as $B=I/Q$ were I is survey KG/tow and tends to be too low when Q is too large.

This assessment considers factors that determine survey bottom trawl efficiency for longfin squid individually, and upper and lower bounds for each. Using the bounds for each factor, upper and lower bounds for catchability in the NEFSC autumn bottom trawl survey are computed. Moreover, based on non-informative prior distributions for uncertainty in each underlying factor, we characterize uncertainty about survey catchability by means of a prior distribution. Our approach could be extended easily to accommodate informative prior distributions and may be useful for other species.

NEFSC autumn survey adjusted for diel catchability affects (Table A9 and Figure A11) are used exclusively in analysis of survey catchability because the geographic distribution of the autumn survey overlaps with the distribution of longfin squid to the greatest degree (Figures A7-A10). The autumn survey is highly variable from year to year for longfin squid but, based on survey CV's (Tables A9-A12 and Figures A11-A14), is most precise for longfin squid. The adjusted autumn bottom trawl survey for longfin squid series measures biomass per tow during the day when longfin squid are closest to the bottom and the efficiency of bottom trawl survey gear is highest. Other surveys were not used because uncertainties were too large to be readily characterized.

Factors affecting autumn survey catchability

The hypothetical relationship between survey data (I_y, e.g. mean biomass per tow) and longfin squid biomass is:

$$I_y = QB_y$$

where Q is the survey-specific catchability coefficient (here assumed constant over years). The catchability coefficient is:

$$Q = \frac{aeu}{A}$$

where $u=10^6$ changes weight from units for stock biomass (thousand mt in this assessment) to units of weight for survey data (kg), *a* is the area swept during one standard tow (all distances in km and all areas in km^2), *e* is the efficiency of the survey bottom trawl (the net captures the proportion *e* of the squid in the water column above the ground swept by the net) and *A* is the "effective" area of the stock.[3] Survey bottom trawl efficiency must be larger than zero if the survey takes at least one longfin squid and, by definition, must be smaller than or equal to one ($0 < e \leq 1$). Breaking area swept (*a*) into the product of average "effective" tow distance for the survey (*d*, assumed constant over time) and effective width (*w*) of the survey bottom trawl[4] for longfin squid gives:

$$Q=\frac{dweu}{A}$$

[3] The effective area *A* is a hypothetical area larger than the area covered by the survey but smaller than the geographic distribution of the stock, where the density of squid (measured in units of squid biomass per standard tow) is equivalent to density in the area surveyed. Mathematically, $S = 139{,}357\ km^2 \leq A \leq$ the total area of the stock. This abstraction is useful because the stock is distributed over a very large area that includes substantial grounds with low densities of squid, and because uncertainty about *A* is easier to characterize than uncertainty about the area of the stock (see below).

[4] The effective width of the survey bottom trawl *w* is a hypothetical measurement. For longfin squid, it is larger than the width of the wings and smaller than the width of the doors (see below). Mathematically, $w_{wings} \leq w \leq w_{doors}$. The notion of effective width is useful because w_{wings} and w_{doors} are upper and lower bounds for uncertainty about the effective width of the survey bottom trawl for squid

Uncertainties about effective stock area *A*, effective width of the survey bottom trawl *w*, effective tow distance *d*, and about the efficiency of the survey bottom trawl *e* for longfin squid under daytime conditions are substantial and the focus of this analysis.

Bounds for each of the key factors (*d, w*, *e*, and *A*) affecting catchability of longfin squid in the autumn NEFSC bottom trawl survey (Table A14) are explained below. Bounds are subjective but were based on common sense and available information. We made an effort to honest about uncertainties, and to include the whole range of potential values for each parameter, because there was neither modeling advantage nor technical justification for understating uncertainty.

Bounds for effective tow distance (d)

Variance in the length of individual tows probably contributes little uncertainty to estimates of average tow distance because tow distance used in calculations is a mean for all the tows in a survey, the number of tows is large (average 150, Table A9), and tow times are controlled carefully during the survey. However, the mean value is uncertain due to questions about when the survey trawl starts and stops fishing effectively for longfin squid during daytime tows. The nominal tow distance in the autumn survey is *d*=3.52 km/tow, based on a 0.5 hr standard tow time at 3.8 knots (7.04 km/hr).

Data measuring time on bottom were collected for 17 tows using inclinometers (bottom sensors) during the 1999 spring NEFSC bottom trawl survey (H. Milliken, NEFSC, Woods Hole, pers. comm.). Time on bottom ranged from 27.5-31.9 minutes with a median of 31.7 minutes and an average of 30.7 minutes and a standard error of 0.31

minutes. Tow distance depends on depth for the NEFSC survey clam dredge (Weinberg et al., in press, based on analysis of bottom contact sensor measurements). The same relationship likely exists for survey bottom trawl tows. However, tows in the bottom trawl survey are allocated in relatively constant numbers to depth strata, so uncertainty in tow distance due to variance in tow depth may be unimportant for longfin squid in the autumn bottom trawl survey.

Sensor data used for surfclam, ocean quahog and sea scallop shows that effective mean tow distances in NEFSC surveys using clam and scallop dredges may be different than the nominal value (NEFSC 2000a, NEFSC 2000b, NEFSC 2001). This is the most important area of uncertainty for longfin squid in the autumn bottom trawl survey as well. Squid are distributed near the bottom during the day but individuals off bottom may be taken before the survey trawl is on the bottom and the winches are locked or as the net is retrieved, so that effective tow distance may be greater than the nominal value. As described above, effective tow distance increases with depth for the NEFSC clam survey dredge and this may occur in bottom trawl surveys as well. It is also possible, but probably unlikely, that the survey bottom trawl does not begin to fish effectively until after the winches are locked so that tow distances are less than the nominal value.

In this analysis, the lower bound for effective tow distance d_{min}=0.95 x 3.52 = 3.34 km was 5% smaller than the normal tow distance. This assumption accommodates the hypothesis that the survey bottom trawl does not fish effectively until after the trawl contacts the bottom. The upper bound for effective tow distance d_{max}=1.1 x 3.52 = 3.87 km/tow in this analysis was 10% larger than the nominal tow distance. This accommodates the alternate hypothesis that the survey bottom trawl fishes a distance effectively greater than the nominal distance because squid are taken before the winches are locked, as the net is retrieved, or due to depth effects. The upper bound is farther from the nominal value (the uncertainty interval is asymmetric) because many factors seem likely to increase the effective tow distance.

<u>Bounds for effective trawl width (w)</u>

The lower bound for effective width of the survey bottom trawl (w_{min}, Table A14) in this analysis was 11.6 m (CV=1%), based on 51 door spread measurements (mean of three sensor measurements per tow, H. Milliken, NEFSC, Woods Hole, pers. comm.) that ranged from 9.67-13.0 m (median=11.7, CV 6%). Door spread measurements were for the NEFSC standard bottom trawl fished from the NOAA Research Vessel Albatross IV during the 2000 NEFSC bottom trawl survey (data provided by H. Milliken, NEFSC, Woods Hole, MA). The lower bound accommodates the hypothesis that no herding of longfin squid occurs during fishing by the NEFSC survey bottom trawl during daytime (herding means that squid originally beyond the sides of the wings of the net, move towards the mouth of the trawl and are captured). Uncertainty due to squid initially above the head rope is included in uncertainty about survey bottom trawl efficiency *e* (see below).

Squid in the path of the net may escape by moving up above, or out beyond the wings so that the effective width of the net could actually be less than the width of the wings. Average head rope height in 21 tows (mean of 1-3 three sensor measurements per tow, a subset of the tows used for door- and wingspread measurements) averaged 1.95 m

(CV 1%) and ranged from 1.7-2.1 m (median=1.93, CV 5%). However, the survey bottom trawl is towed rapidly (3.8 knots, roughly twice the speed of commercial bottom trawls) and survey data are adjusted to daytime equivalents when longfin squid are closest to the bottom so that escapement may be minimized. A bycatch reduction experiment (Glass et al. 1999) in Nantucket Sound and Vineyard Sound during May-June 1997-1999 aboard commercial vessels did not find substantial escapement of longfin squid with commercial small mesh bottom trawls towed in daytime.[5] Commercial bottom trawls in the study were relatively large and towed at about one-half or two-thirds the speeds used in the NEFSC autumn survey. The upper bound for effective width of the survey bottom trawl in this analysis is the mean w_{max}= 23.8 m (CV 1%, Table A14) of door spread measurements (mean of three sensor measurements per tow) for the same 51 tows (H. Milliken, NEFSC, Woods Hole, pers. comm.). Tow door spreads ranged from 19.5-27.0 m (median 24.3 m, CV=9%). The upper bound accommodates the alternate hypothesis that 100% of longfin squid between the wings and doors are herded into the mouth of the NEFSC survey bottom trawl and captured.

[5] According to Glass et al. (1997), "the behavior of *Loligo* squid towards trawl gear is very similar to that adopted by many fish species. That is, they react to the approaching ground-gear of the net by turning and swimming at the same speed as the net in the direction of the tow. . . While being herded in the mouth of the net, squid tend to move to the edges of the net close to the wing-ends and side panels and gradually rise up to a position close to the top of the net…On tiring, *Loligo* were also observed to rise upwards and turn so that the mantle faces directly towards the codend of the net. The squid cease to swim and allow the net to overtake them. The overall effect of these behavior patterns results in squid being distributed in the upper and upper-lateral parts of the net during herding and falling back through the main body of the net."

<u>Bounds for effective stock area (A)</u>

During the NEFSC autumn survey, longfin squid densities are relatively high (Figure A11) and squid are found throughout the area covered by the survey (Figure A7). Densities are high during the autumn survey because water temperatures are still relatively warm, squid are on the continental shelf and likely near the northern end of their seasonal migration pattern. Autumn survey catches are high around the border of strata used in tabulation of survey data for longfin squid, indicating that the survey does not cover the whole area of the stock. However, survey data (Figure A7) and Dawe et al. (1990) indicate longfin squid abundance is low north of Georges Bank in, in both US and Canadian waters.

Longfin squid are found south of Cape Hatteras during the autumn but the stock in this assessment is defined to be in the range of commercial exploitation from southern Georges Bank to Cape Hatteras. Squid south of Cape Hatteras during the autumn survey (when the stock is likely at the northern end of its seasonal distribution) are therefore irrelevant. Hatfield and Cadrin (in press) suggest that spawning south of Cape Hatteras during the winter and spring is important to fisheries north of Cape Hatteras, but the autumn survey would measure abundance of biomass and squid spawned south of Cape Hatteras when (and if) they recruit to the stock in northern waters.

Abundance of longfin squid outside the range of the autumn survey in shallow water near shore and deep water offshore is an important uncertainty. Depth increases rapidly offshore of the continental shelf and autumn survey strata for squid. It seems unlikely that high densities extend over very broad areas in deep water.

Considering all factors, bounds used in this assessment for the effective stock area of longfin squid (*A*) were 5% and 30% larger than the area of all survey strata (*S*, Table A14) used for autumn bottom trawl survey data for this assessment:

$$A_{\min} = S(1+\delta_{\min})$$

and

$$A_{\max} = S(1+\delta_{\max})$$

with $\delta_{min} = 5\%$

and $\delta_{max} = 30\%$

accommodates the hypothesis that there are only small additional areas during the autumn where average effective biomass densities of squid are as high as in the area surveyed. A_{max} accommodates the alternative hypothesis that longfin squid are distributed during the autumn over large areas outside the area surveyed, where average biomass densities are relatively high.

<u>Bounds for survey bottom trawl efficiency (e)</u>

If the autumn survey bottom trawl failed to catch a single longfin squid, then the efficiency of the trawl would be zero ($e = \phi$). However, longfin squid are caught at relatively high rates and in the majority of autumn survey tows in the survey strata used in this assessment. In addition, autumn survey data for longfin squid are adjusted for diel catchability patterns to daytime equivalents, which effectively increases *Q*. If the autumn survey bottom trawl caught all of the squid in the water column above the zone of effective net with (*w*), then its efficiency would be 100% (i.e. *e*=1.0).

Bounds used for the efficiency of NEFSC autumn bottom trawl survey tows for longfin squid during the daytime (*e*) were taken to be 0.1 and 0.9 (Table A14). The lower bound for *e* accommodates the hypothesis that the gear has low efficiency due, for example, to squid distributed above the trawl squid or squid that escape by moving into the water column above the head rope of the net. The upper bound for *e* accommodates the alternate hypothesis that the NEFSC autumn bottom trawl is very efficient for longfin squid during the daytime.

<u>Bounds for Q_{Fall}=dwe/A</u>

The lower bound, ${}^{min}Q_{Fall}$=0.02149 (Table A14), for catchability in the autumn NEFSC bottom trawl survey was calculated from the minimum values for *d, w* and *e* in the numerator, and maximum value for stock area *A* in the denominator:

$${}^{\min}Q_{Fall} = \frac{u\, d_{\min}\, w_{\min}\, e_{\min}}{A_{\max}}$$

Similarly, the upper bound ${}^{max}Q_{Fall}$=0.5669 (Table A14) was calculated using the maximum values for *d, w* and *e* in the numerator, and the minimum value for *A* in the denominator:

$${}^{\max}Q_{Fall} = \frac{u\, d_{\max} w_{\max} e_{\max}}{A_{\min}}$$

Statistical distributions for uncertainty

We characterized uncertainty in effective stock area *A*, effective tow distance, effective trawl width *w*, and trawl efficiency *e* with uniform distributions that had upper and lower bounds described above. This means, for example, that any value of *A* between the upper and lower bound seemed equally probable, *a priori*. Uniform distributions for these parameters are "non-informative" prior distributions that don't require knowing or guessing the most likely single value or most probable values (Gelman et al. 1995). Moreover, uniform distributions accurately characterized our uncertainties about factors affecting autumn survey catchability for longfin squid.

Uncertainties about *A*, *d*, *w* and *e* were independent in our analysis because of the definitions for each term and independently chosen bounds (uncertainty and bounds for efficiency *e* did not depend, for example, on bounds and uncertainty about effective width *w* of the net). Given independence, the statistical distribution for uncertainty in *Q* can be evaluated to any level of precision by simulation. The first step is to draw random numbers *d'*, *w'*, *e'* and *A'* from uniform probability distributions (where, for example, *A'* is drawn from the uniform distribution with upper and lower bounds for effective stock area *A*). The second step is to calculate simulated catchability values as $Q'=d'w'e'u/A'$.

We characterized the distribution of our uncertainty about *Q* using 100,000 simulated *Q'* values (Figure A25). The mean of the simulated distribution was 0.20 (CV 52%) with values ranging from 0.023-0.55. The distribution had a broad flat peak with a "modal range" of high and almost equally probable *Q'* values ranging from 0.05-0.22. The 2.5%, 5%, 50%, 95% and 97.5% percentiles were at *Q'*=0.044, 0.052, 0.19, 0.38, 0.41. Thus, (0.044, 0.41) and (0.052, 0.38) are non-parametric 90% and 95% uncertainty intervals for Q_{Fall}. The modal range (0.023-0.22) of simulations contained roughly 60% of the total probability mass of the distribution for Q'_{Fall} values. This means that 0.05-0.22 is the narrowest uncertainty interval with 60% coverage for Q_{Fall}.

The broad mode in simulated Q_{Fall} values at intermediate values may seem surprising given that the simulation was based on uniform distributions with no mode. However, large values of simulated Q_{Fall} near the maximum can only occur when *d'*, *w'*, and *e'* are large and *A'* is small. Similarly, small values of simulated Q_{Fall} near the minimum can only occur when *d'*, *w'* and *e'* are small and *A'* is large. These combinations of events occur infrequently in the simulations and reflect the fact that large and small values of Q_{Fall} seem unlikely in nature, if uncertainty about *d*, *w*, *e* and *A* is accurately characterized by uniform distributions. Another, more statistical approach to understanding the mode in simulated Q_{Fall} values involves the central limit theorem. Ignoring weight units and taking logs gives $\ln(Q_{Fall})=\ln(d)+\ln(w)+\ln(e)+\ln(1/A)$. Thus, $\ln(Q_{Fall})$ is a random number that is the sum of four independent random variables. By the central limit theorem, the distribution of $\ln(Q_{Fall})$ will tend towards a normal distribution with a single mode. If the distribution of $\ln(Q_{Fall})$ has a mode, then the distribution of Q_{Fall} will also, although the distribution of Q_{Fall} may be more skewed.

In addition to characterizing the distribution of uncertainty in Q_{Fall} values by simulation, we used the method of moments to find parameters for a beta distribution that approximated the distribution of simulated values.[6] The beta distribution had parameters α = 1.624, and β =3.293, k_{Mode} = 0.135 (the middle of the mode in simulated Q_{Fall} values, see above), the same upper and lower bounds as simulated Q_{Fall}, and the same mean and variance as the simulated distribution of Q_{Fall} values.

The beta distribution approximated uncertainty in Q values reasonably well. The peak of the beta distribution (based on 100,000 values from a random number distribution with the parameters given) was sharper at the peak than the original simulated distribution but the cumulative distributions were almost identical (Figure A25). Percentiles for 2.5%, 5%, 50%, 95% and 97.5% of cumulative probability in the beta distribution were at Q_{Fall} =0.043, 0.054, 0.18, 0.38 and 0.42 and generally similar to percentiles of the simulated Q_{Fall} values.

Scaled catch-survey model

Using catch and survey data, longfin squid stock biomass ($B_{Fall,t}$) was estimated as

$$\hat{B}_{Fall,t} = \frac{I_{Fall,t}}{Q_{Fall}}$$

where $I_{Fall,t}$ is an autumn bottom trawl survey datum for longfin squid (adjusted to daytime units). Autumn fishing mortality rates for longfin squid were estimated as

$$\hat{F}_{Fall,t} = \frac{C_{Fall,t}}{\hat{B}_{Fall,t}}$$

where $C_{Fall,t}$ is autumn catch (landings plus 6% discard after 1987).

In catch-survey biomass and fishing mortality calculations, Q_{Fall} was 0.050, 0.22 (the upper or lower bounds of the "most likely" simulated values) or 0.547 (the highest feasible bound for Q_{Fall} to get the lowest feasible biomass and the highest feasible fishing mortality estimates). The mean simulated Q_{Fall} was not used for scaled catch-survey calculations because the distribution of simulated Q_{Fall} values is skewed and the mean has relatively low probability (Figure A25). However, the mean at Q'_{Autumn} =0.20 and upper bound of the most likely range at Q'_{Autumn}=0.22 were close and can be used interchangeably.

Relative exploitation rates for other surveys

Crude estimates of unscaled relative fishing mortality rates were calculated using quarterly catch data and unadjusted NEFSC spring and winter bottom trawl survey data. Absolute estimates of biomass, F and variances were not estimated because there was no information about catchability or its uncertainty for the spring and winter bottom trawl surveys. Winter and spring survey data for 2001 were available and used, with preliminary landings data for 2001, to calculate relative trends in F through the spring of 2001. Thus, relative trends give the

[6] If k follows a beta distribution with $k_{Min}<k<k_{Max}$ and parameters $(\alpha>0,\beta>0)$, then $\kappa=(k-k_{Min})/(k_{Max}-k_{Min})$ is a standardized beta variate. The expected value (mean) of the standardized beta distribution is $Exp(\kappa)=\alpha/(\alpha+\beta)$, the variance is $Var(\kappa)=\alpha\beta/[(\alpha+\beta)^2 (\alpha+\beta+1)]$, and the mode is at $\kappa_{Mode} =(\alpha-1)/(\alpha+\beta-2)$. It follows that $Exp(k)= Exp(\kappa)(\alpha+\beta)+\alpha$, $Var(k)=Var(\kappa)(\alpha+\beta)^2$, and $k_{Mode}=\kappa_{Mode} (\alpha+\beta)+\alpha$.

most current catch-survey based information available for longfin squid during 2001.

Catch-survey results

Average autumn biomass estimates for longfin squid during 1967-2001 from scaled catch-survey calculations ranged from 14-90 (average 51) thousand mt at one end of the most likely interval for Q_{Fall} values (Table A15; Figure A26). At the other end of the most likely interval, biomass estimates ranged from 63-396 (average 226) thousand mt. The lowest feasible biomass estimates ranged from 6-36 (average 21) thousand mt. The scaled autumn catch-survey biomass estimate in 2001 based on autumn survey data was at nearly a record high. However, other surveys declined during 2000-2001 to moderate levels (Figures A12-A14).

Fishing mortality estimates for longfin squid during 1967-2000 ranged from 0.01-0.04 (average 0.03) quarter^{-1} at the low end of the most likely interval, and ranged from 0.05-0.20 quarter^{-1} (average 0.12) quarter^{-1} at the other end of the interval (Table A15; Figure A27). The maximum feasible fishing mortality estimates ranged from 0.11-0.49 (average 0.30) quarter^{-1}. Fishing mortality estimates were at maximum levels in 1998 but declined to below average levels during 1999-2000. Unscaled relative fishing mortality rates based on spring and winter survey (Table A16 and Figure A28) indicate that fishing mortality rates for squid declined during 1999-2001.

Production modeling

A new surplus production modeling program called PDQ (Pretty Darn Quick) was developed using AD Model Builder (ADMB, Otter Software, Ltd.) tools and libraries and used for longfin squid (source code and program files available from L. Jacobson, NEFSC, Woods Hole, MA). PDQ is an alternative to the ASPIC program (Prager 1994). Advantages of PDQ include faster parameter estimation, greater flexibility including many options for modeling production and catchability process errors, more options for characterizing uncertainty, and population dynamics calculations based on either of two types of surplus production models. The first type of surplus production model is the conventional Schaefer logistic surplus production model (Prager 1994). The second type is a production model that does not assume the existence or require estimation of carrying capacity. Either model can be fit assuming "measurement errors only", as in ASPIC (see Polacheck and Punt 1993), or with "process errors" in surplus production rates or survey catchability. In PDQ, it is not necessary to assume catches are known with out error.

Carrying capacity is difficult to estimate for many stocks in the northeast that have been heavily fished and at low biomass for many decades because little data are available for periods of relatively high stock biomass NEFSC (2001b). In such cases, and in estimating biomass and fishing mortality rates, it may be advantageous to avoid numerical and statistical problems by using a production model that does not involve an inestimable carrying capacity parameter.

Catch data in the PDQ model are landings plus discard, based on user supplied discard rates for each landings observation:

$$C_t = L_t \left(1 + D_t\right),$$

if $D_t \geq 0$ and

$$C_t = L_t + abs\left(D_t\right)$$

if D_t <0 and where C_t is catch in weight for time step t in the model and L_t is landings data. If the discard datum D_t ≥0, PDQ treats it as a discard rate (computed as the ratio of weight discarded and weight landed). If the discard datum D_t <0, PDQ treats the absolute value $abs(D_t)$ as discards in weight. This approach is flexible because discards in different time steps in the same model run can be specified as either discard rates or discard weights and discard information can be utilized in whatever form available.

<u>Logistic surplus production population dynamics</u>

Using notation in Prager (1994), the logistic surplus production model calculates the rate of surplus production *dBt/dt* as a function of stock biomass B_t:

$$\frac{dB_t}{dt} = r_t B_t - \frac{r_t}{K} B_t^2$$

where r_t is a parameter (potentially time varying) measuring the maximum instantaneous ("intrinsic") rate of increase for population biomass, and K is the equilibrium unfished biomass. With fishing, the rate of increase is

$$\frac{dB_t}{dt} = \left(r_t - F_t\right)B_t - \frac{r_t}{K} B_t^2$$

where F_t is the instantaneous rate of fishing mortality. All instantaneous rates in production model calculations for longfin squid were quarterly values, although PDQ will use any user specified time step.

For simplicity, Prager (1994) defined $\alpha_t = r_t - F_t$ and $\beta_t = r/K$ so that:

$$\frac{dB_t}{dt} = \alpha B_t - \beta B_t^2$$

If F_t is constant during time step t, the equation for dB_t/dt can be integrated and solved to obtain:

$$B_{t+1} = \frac{\alpha_t B_t e^{\alpha_t}}{\alpha_t + \beta B_t\left(e^{\alpha_t} - 1\right)}$$

when $\alpha_t \neq 0$. If $\alpha_t = 0$, then

$$B_{t+1} = \frac{B_t}{1 + \beta B_t}$$

We use B'_{t+1} for the special case where F_t is zero and $\alpha_t = r_t$. Maximum surplus production in year t, defined as the increment to biomass during one time step with no fishing (Jacobson et al. 2001) during time period t, is $P_t = B'_{t+1} - B_t$.

As described in Prager (1994), predicted catch c_t in the fishery is calculated as

$$c_t = \frac{F_t}{\beta} \ln\left[1 - \frac{\beta B_t\left(1 - e^{\alpha_t}\right)}{\alpha_t}\right]$$

when $\alpha_t = 0$. If $\alpha_t \neq 0$ then

$$c_t = \frac{F_t}{\beta} \ln\left(1 + \beta B_t\right)$$

Population dynamics parameters in PDQ with n time steps and logistic population dynamics include: r_t (one value if r_t is assumed constant, n values otherwise), F_t (one value if F_t is assumed constant, n values in most cases), B_f (biomass at the beginning of the first time step), and K. All naturally positive parameters in PDQ (e.g. r_t, F_t and B_f) are estimated as log transformed values.

Fishing mortality rates F_t are estimated as formal parameters in PDQ. Although not done for longfin squid in this assessment, an important advantage in this approach is that catches can be estimated if catch data include measurement errors. Conventional iterative approaches with catches assumed accurate (e.g. Sims 1982) are not applicable in production modeling because the realized instantaneous surplus production rates

$$r_t (1 - \frac{B_t}{K})$$

are not constant within a time step. In PDQ, fishing mortality rates were parameterized:

$$F_t = e^{\phi + \nu_t}$$

where ϕ is the log scale geometric mean fishing mortality rate parameter and the ν_t are time period specific deviations that average and sum to zero. Typically, the log-scale geometric mean fishing mortality for longfin squid ϕ was estimated with all ν_t=0 (i.e. $F_t=e^{\phi}$ constant at the geometric mean level) in a preliminary phase of parameter estimation. In a latter phase, once mean fishing mortality ϕ had been estimated to a "good" starting value, the geometric mean and deviation parameters ν_t for fishing mortality rates were estimated together.

<u>Simple production population dynamics (without K)</u>

Let ρ be the instantaneous surplus production rate during time step t and let $z_t = \rho - F_t$ with the rates ρ and F_t defined as positive numbers. If no fishing occurs $F_t = c_t = 0$, then

$$B'_{t+1} = B_t e^{\rho_t}$$

Maximum surplus production is

$$P_t = B'_{t+1} - B_t$$

If fishing occurs and $z_t \neq 0$, then

$$B_{t+1} = B_t e^{z_t}$$

and

$$c_{t+1} = -\frac{F_t}{z_t}\left(1 - e^{z_t}\right)B_t$$

If the rates of surplus production and fishing mortality rates exactly balance, then z_t=0 and:

$$B_{t+1} = B_t$$

with

$$c_t = F_t B_t$$

<u>Process errors and variability in r_t</u>

PDQ models with r_t or ρ_t values that vary are "process error" models because they include natural variability in a biological parameter. As described in Hilborn and Walters (1992) and Jacobson and Cadrin (in press), there is a natural continuum with "all measurement error" models (such as ASPIC and PDQ with constant r_t or ρ_t) at one extreme and "all process error" models on the other. All measurement error models assume that all variability in data is due to measurement error. All process error models assume that all variability in data is due to variability in underlying biological parameters. All measurement error approaches tend to be biased but in the context of simple surplus production models fit to catch and fishing effort data (Polacheck and Punt 1993), relatively robust. All process error models are more realistic and complex, and capable of representing relatively complex biological hypotheses and data patterns. The approach in PDQ allows the user to use a model configuration anywhere in the continuum between all measurement error and all process error approaches.

Production process errors in PDQ may be random and independent (no autocorrelation) or may follow a random walk that changes relatively slowly (autocorrelated), depending on goodness of fit calculations (see below). For process errors in the logistic model

$$r_t = e^{\eta + \varepsilon_t}$$

where η is the log scale geometric mean production parameter and the ε_t are time period specific deviations from the geometric mean that average zero. If process errors are excluded from the model configuration, then the r_t are constant because ε_t =0 and $r_t = e^{\eta}$ for all t. Similarly, with simple surplus production dynamics (no carrying capacity)

$$\rho_t = e^{\eta + \varepsilon_t}$$

For longfin squid, the log-scale geometric mean production rate η was typically estimated with all ε_t =0 (i.e. $r_t = e^{\phi}$ constant) in a preliminary phase of parameter estimation. In a latter phase, the geometric mean and time-specific parameters ε_t were estimated together. Process errors in survey catchabilities (see below) and process error in production rates should probably not be used in PDQ at the same time because effects of changes in catchability and changes in productivity may be confounded.

Abundance data

Expected values for abundance data are calculated as

$$\hat{I}_{w,t} = \hat{Q}_w \hat{B}_t$$

where $\hat{I}_{w,t}$ is the predicted value for survey datum of kind w in time step t (KG/tow for longfin squid), Q_w is a catchability coefficient for survey w, and $\hat{B}_t$ is estimated biomass. If the relationship between biomass and the abundance data is nonlinear, then

$$\hat{I}_{w,t} = \hat{Q}_w \hat{B}_t^{\hat{\Theta}_k}$$

where the exponent $\hat{\Theta}_w = e^{\hat{\theta}_w} > 0$. Parameters estimated in PDQ for abundance data include one catchability parameter Q_k for each index and one exponent parameter Θ_k for each nonlinear index.

Although catchability parameters can be estimated as formal model parameters, they are calculated in PDQ via an equivalent closed form maximum likelihood estimator that assumes lognormal survey measurement errors (NEFSC 2000b)

$$\hat{Q}_w = \exp\left\{ \frac{\sum_{t=1}^{N_w} \ln\left(I_{w,t} / \sigma^2_{w,t} \right)}{\sum_{j=1}^{Nw} 1 / \sigma^2_{w,t}} \right\}$$

where $I_{w,t}$ is an observed survey datum (Tables A9-A12) and N_w is the number of survey observations. The log-scale variance (due to measurement errors) σ_w^2 was calculated from the arithmetic-scale sampling-based CV (Tables A9-A12) using a formula in Jacobson et al. (1994):

$$\sigma_{k,t}^2 = \ln\left(1 + CV_{k,t}^2\right)$$

<u>Process errors in bottom trawl survey catchabilities</u>

Variability in catchabilities for abundance data is another type of process error that can be modeled in PDQ. Survey catchability coefficients for longfin squid in the NEFSC autumn bottom trawl survey may change from year to year due, for example, to changing oceanographic features that control the distribution of the stock and availability of squid to the survey. With process errors in catchability coefficients

$$\hat{I}_{w,t} = \hat{Q}_w e^{\chi_{w,t}} \hat{B}_t$$

where the survey- and year- specific process error terms $\chi_{w,t}$ are deviation parameters, and Q_w is the geometric mean catchability. In PDQ calculations, it is convenient to calculate

$$\hat{B}^a_{w,t} = \hat{B}_t e^{\chi_{w,t}}$$

where

$\hat{B}^a_{w,t}$ is the adjusted biomass in year t for survey w. Then, Q_w can be calculated using the closed form maximum likelihood expression given above.

<u>Goodness of fit for each component</u>

Goodness of fit for observed C_t and predicted c_t catch data was calculated as

$$L_C = 0.5\sum_{t=1}^{n}\left(\frac{c_t - C_t}{\sigma_t}\right)^2$$

where L_C is the kernel of the negative log-likelihood for the normal distribution with variances known.[7] The user supplies the assumed standard deviation for catch σ. For longfin squid in this assessment, σ = 0.2 but the standard deviation is not relevant for longfin squid in this assessment because a high weight was placed on goodness of fit for the catch data (see below) so that observed and predicted catches matched almost exactly. In effect, catch data for longfin squid were modeled as though measured without error (a common and relatively robust approach, Methot 1990).

Goodness of fit for observed and predicted survey data was calculated assuming lognormal measurement errors:

$$L_{Survey,w} = 0.5\sum_{t=1}^{Nw}\left[\frac{\ln\left(I_{w,t}/\hat{I}_{w,t}\right)}{\sigma_{w,t}}\right]^2$$

Goodness of fit for autumn survey catchability estimates was calculated based on a beta probability prior distribution. The first step was to calculate standard beta deviates

$$\hat{q} = \frac{\hat{Q} - {}^{Min}Q_{Fall}}{{}^{Max}Q_{Fall} - {}^{Min}Q_{Fall}}$$

---

7 The kernel of a negative log-likelihood L contains all components important in calculation of simple and partial derivatives $dL/d\theta_i$ and $dL/d\theta_i d\theta_j$ of the complete log-likelihood with respect to parameters in the model.

where ${}^{Min}Q_{Fall}$ and ${}^{Max}Q_{Fall}$ (Table A14). For $0< \hat{q}<1$, the standardized beta probability density function is

$$p(\kappa)=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\hat{q}^{\alpha-1}(1-\hat{q})^{\beta-1}$$

where $\Gamma()$ is the gamma function, $\alpha>0$ and $\beta>0$. Log transforming the probability density function, changing sign, and eliminating constants to obtain the kernel of the negative log-likelihood gives

$$L_k = (1-\alpha)\ln(\hat{q}) + (1-\beta)\ln(1-\hat{q})$$

In the beta distribution, the probability of

$\hat{Q}_{Fall} \leq Q_{Min}$ ($\hat{q} \leq 0$)

or

$\hat{Q}_{Fall} \geq Q_{Max}$ ($\hat{q} \geq 1$)

is zero and the negative log-likelihood is undefined. A goodness of fit penalty was used to prevent infeasible estimates and numerical problems when trial parameter values went out of bounds during parameter estimation:

$$\begin{aligned}&\mathit{If}\ \left(\hat{Q}_{Fall} \leq Q_{Min}\right)\\ &\quad \mathit{then}\ L_k = 1000\left(\hat{Q}_{Fall} - Q_{Miin}\right)^2\\ &\mathit{else\ if}\ \left(\hat{Q}_{Fall} \geq Q_{Max}\right)\\ &\quad \mathit{then}\ L_k = 1000\left(\hat{Q}_{Fall} - Q_{Max}\right)^2\end{aligned}$$

Goodness of fit for production process errors was computed assuming that process errors were either random or followed a random walk process. In the case of random process errors

$$L_r = 0.5\sum_{t=1}^{N}\left(\frac{\varepsilon_t}{\omega}\right)^2$$

where ω was a standard deviation for the independent log scale production process errors ε_t. In PDQ, the user specifies an assumed arithmetic scale CV for production process errors and the log scale standard deviation is calculated

$$\omega=\sqrt{\ln\left(CV^2+1\right)}.$$

In the case of process errors that follow a random walk

$$L_r = 0.5\sum_{t=2}^{N}\left(\frac{\varepsilon_t - \varepsilon_{t-1}}{\omega}\right)^2$$

where ω was a standard deviation for the autocorrelated log scale production process errors ε_t (also calculated from a user specified CV).

Goodness of fit for catchability process errors was computed assuming they were either random or followed a random walk process. In the case of random process errors

$$L_{Q_w} = 0.5\sum_{t=1}^{N_w}\left(\frac{\chi_{w,t}}{\xi}\right)^2$$

where ξ was a standard deviation from a user specified CV for the independent log scale process errors $\chi_{w,t}$. In the case of process errors that follow a random walk

$$L_{Q_w} = 0.5 \sum_{t=2}^{N_w} \left(\frac{\chi_{w,t} - \chi_{w,t-1}}{\xi} \right)^2$$

where ξ was a standard deviation from a user specified CV for the autocorrelated log scale production process errors $\chi_{w,t}$.

Forward simulation models such as PDQ may explore low biomass scenarios during parameter estimation that involve implausibly high exploitation rates. To prevent possible numerical problems and to avoid implausible solutions, another penalty strategy was used

$$If \left(\frac{C_t}{\hat{B}_t} \geq \tau \right) then\ L_{C/B} = 0.5 \left(\frac{C_t}{\hat{B}_t} - \tau \right)^2$$

For longfin squid, the threshold $\tau = 0.9$.

Objective function

The objective function in PDQ for longfin squid was a weighted sum of the log-likelihood kernels for each component:

$$\Xi = \lambda_C L_C + \sum_{k=1}^{N_{Surveys}} \left(\lambda_{Survey,k} L_{Survey,k} \right) + \sum_{j=1}^{N_{Surveys}} \left(\lambda_{Q_J} L_{Q_J} \right) + \lambda_k L_k + \lambda_r L_r + \lambda_{C/B} L_{C/B}$$

The weighting factors (λ) for longfin squid were generally one except during sensitivity analysis. The exceptions in the PDQ model for longfin squid were weighting factors λ=1000 for catch data and the penalty for low C_t/B_t levels. A large weighting factor (λ_C=1000) was used for catch data in the PDQ model so that the observed and estimated longfin squid catches would be almost equal (catches were assumed known without error).

Variance and confidence interval calculations

Variances, covariances and uncertainty intervals for parameters in the PDQ model for longfin squid can be estimated by:

1) Inverting the Hessian matrix to obtain asymptotic variance and covariance estimates and calculating confidence interval bounds as ±1.96σ;

2) Likelihood profiles;

3) Bootstrapping survey and catch data (see below); and

4) Integrating the posterior distribution for parameters using Markov Chain Monte Carlo (MCMC) techniques (Gelman et al. 1995).

Variances, covariances and confidence intervals for derived variables (e.g. biomass estimates) were obtained by the same methods except that asymptotic variances and covariances were by the delta method based on asymptotic variances for parameters (Seber 1982).

Software for calculation of asymptotic and delta method variances, likelihood profiles and MCMC is supplied with ADMB. Bootstrapping was carried out by extracting predicted values ($\hat{I}_{w,t}$) for active ($\sigma_{w,t}$>0) survey data and standardized residuals from a basecase PDQ model run:

$$r_{w,t} = \frac{\ln \left(\hat{I}_{w,t} \big/ \hat{I}_{w,t} \right)}{\sigma_{w,t}}$$

After fitted values and residuals were saved to a file, bootstrap calculations were carried out by a FORTRAN program that constructed data files and ran the PDQ model once for each bootstrap iteration.

For each bootstrap iteration and each active survey datum, the FORTRAN program constructed generated the simulated survey datum as:

$$I^j_{w,t} = \hat{I}_{w,t} \exp\left(r^j_{w,t}\sigma_{w,t}\right)$$

for the j^{th} bootstrap iteration and with the bootstrap residuals $r^j_{w,t}$ drawn randomly with replacement from the pool of original standardized survey residuals $r_{w,t}$. It is possible to include catch data in bootstrap calculations and this is a topic for future research.

PDQ model configuration for longfin squid

Model runs for longfin squid covered the period with quarterly landings data during 1987-2001 Table A2). Catch data were increased by 6% to account for discards based on the average discard rate during 1989-1998 in Cadrin and Hatfield (1999). Biomass estimates were for January 1, 1987 to January 1, 2002 but were not reliable for time steps after the first quarter of 2001 due to preliminary catches for 2001.

Some exploratory runs were conducted for 1963-2001. Annual landings data are available beginning in 1963 (Table A1) but data for years prior to 1987 may be less reliable (Cadrin and Hatfield 1999). For runs including years prior to 1987, hypothetical quarterly catches were calculated for 1963-1986 by dividing the historical annual catch into four equal portions. Actual quarterly catches were used for later years. This is a topic for future research.

All available abundance information was used in the model for longfin squid including bottom trawl survey data through 2001 from NEFSC autumn, winter and spring surveys, and the Massachusetts inshore spring survey. Standardized LPUE for summer and winter fisheries during 1982-1993 was included assuming CV's =20%. Preliminary runs with LPUE treated as a nonlinear index had exponent parameter estimates that were near zero and not statistically significant. LPUE was therefore modeled as a linear index of longfin squid biomass trends. Finally, as an experimental approach, we used trends in LVPA biomass estimates for longfin squid as an index of stock biomass in PDQ.

LVPA biomass "data"

LVPA biomass trends were used experimentally in PDQ because

1) Trends in LVPA biomass and fishing mortality estimates were similar to trends in survey data and relative catch-survey fishing mortality estimates. This suggests that commercial catch at length data based on port samples contain substantial information about dynamics of longfin squid (see also Cadrin and Hatfield 1999).

2) Port sampling data are expensive to collect. Substantial energy was involved in programming and carrying out LVPA calculations (Cadrin and Hatfield 1999). Catch at length data are not usually used in surplus production modeling although there are few technical barriers (Jacobson and Cadrin, in press). It would be advantageous,

therefore, to use port sample data (and LVPA calculations) to the fullest extent.

3) LVPA biomass estimates for longfin squid were based almost completely on data not otherwise used in PDQ so that "double-dipping" (using the same data twice) was not a problem. Data used for LVPA but not otherwise used in PDQ include length composition information from port samples, new growth curves and a notion of the natural mortality rate and lifespan. Both LVPA and PDQ use total landings to estimate biomass but, in casting LVPA biomass estimates as measures of relative trend in the PDQ model, double dipping is reduced to the extent possible.

4) LVPA data are less variable over time than bottom trawl survey data and may be less affected by oceanographic features that likely affect catchability of longfin squid in bottom trawl surveys.

LVPA biomass estimates for winter and summer longfin squid fisheries were used as separate measures of biomass trends in PDQ because they were based on different growth curves and because winter and summer calculations were not linked in the LVPA model. One series might be biased or affected by imprecise growth estimates. The "seesaw" summer-winter pattern in LVPA biomass estimates (Figure A22) may be due to imprecise estimates of seasonal growth rates. For comparison, we combined the LVPA summer and winter results into a single index as well. In model runs, likelihood weights (λ) were one for the both the separate summer and autumn LVPA series while the likelihood weight for the combined summer and winter series was set to a nil values so that LVPA trend data were never used twice for parameter estimation in the same PDQ model run.

Cadrin and Hatfield (1999) used Monte Carlo simulations to estimate a CV of 5% for LVPA biomass estimates but noted that the CV was underestimated because variance in total catch, port sampling, natural mortality and growth was not included in the simulations. In PDQ, we assumed a CV of 35% for LVPA biomass trend estimates. LVPA biomass information for the winter 2001 fishery was not used because catch data for the first quarter of 2001 may be incomplete and underestimated catches would affect LVPA trends.

Status variables

Surplus production models calculate biomass at the beginning of the next time step *after* the last time step in the model without resorting to projection. This means, for example, that a model with catch and abundance data for 20 time steps can be used to estimate biomass at the beginning of the 21st time step without projection. In most cases for longfin squid, PDQ was run in quarterly time steps from the first quarter of 1987 to the last quarter of 2001. Thus, the model produced abundance estimates current to January 1, 2002 and fishing mortality estimates through the fourth quarter of 2001

Estimates of average biomass and average fishing mortality during 2000 were used for comparison to reference points. Thus, status variable estimates from PDQ runs for longfin squid were comparable to scaled catch-survey biomass and fishing mortality estimates.

Gauging goodness of fit - how much is enough?

In a hypothetical "perfect" PDQ model for longfin squid, the variance of residuals for model fit to abundance data would equal the variance of the survey index due to measurement errors in collecting the survey data. In dealing with imperfect real models, we expect the variance of residuals to be larger than the variance for measurement errors in the abundance data because the model should not fit the data more precisely than the data were originally measured. We used a variant of this "rule of thumb" in specifying process error parameters in the PDQ model for longfin squid ("models with catchability process errors", see below). In particular, we configured the PDQ model so that the goodness of fit CV for residuals in each survey was be larger than the average data CV for each observation used in fitting the model (Tables A9-12). Goodness of fit CV's were computed as

$$CV = \sqrt{e^{\tau^2} + 1}$$

where τ^2 was the mean squared residual for log scale residuals from a particular abundance index and model run.

Pseudo-ASPIC runs

The first step was to run PDQ in an ASPIC-like mode with quarterly times steps, logistic dynamics (carrying capacity *K* estimated), all abundance information included, no constraints on Q_{FALL} and process errors turned off. Results were similar to those in Cadrin and Hatfield (1999) because the model estimated implausibly low biomass levels (with Q_{Fall} larger than the largest feasible value) and B_{MSY} and *K* levels that, depending on the run, were either implausibly high or low. Fit to abundance indices was "too good" because average CV's for abundance data were usually larger than goodness of fit CV's.

Additional model runs used simple surplus production calculations (no carrying capacity) in PDQ with other factors as in the pseudo-ASPIC runs. Results were generally similar to results from the pseudo-ASPIC run.

Problems in the pseudo-ASPIC and other preliminary runs suggest that bounds to constrain Q_{Fall} for the NEFSC autumn bottom trawl survey may be required and that capacity, *K*, may not be estimable for longfin squid. Problems estimating *K* could stem from limitations in the available data or inapplicability of the logistic surplus production model (NEFSC 2001).

Likelihood profile calculations with the simple model

The next step was a likelihood profile analysis with the simple model (no carrying capacity) for a series of runs covering the entire feasible range of autumn survey catchability and longfin squid biomass values. The purpose of the likelihood profile analysis was to determine how different kinds of data affected model estimates and to understand modeling problems. Results (not shown) indicated that, with the exception of LVPA biomass trend data, abundance indices generally fit best at high autumn catchability/low biomass values. LVPA biomass trend data, in contrast, fit best at low autumn catchability/high biomass values. These results and additional sensitivity analyses (not shown) suggest that the most important characteristic of LVPA trend was their relative stability from year to year. In preliminary PDQ model runs, the stability of LVPA trend data tended to counteract interannual variability in bottom trawl survey data. In effect, the LVPA data stabilized model results and increased biomass estimates by preventing a close fit to the highly variable survey data.

<u>The trouble with production models for longfin squid-a hypothesis</u>

Likelihood profile analysis and experience in this assessment with LVPA data suggest an explanation for problems with infeasible low biomass and carrying capacity estimates that have plagued production models in stock assessments for longfin squid over the last decade. Problems appear to stem from the high year to year variability in bottom trawl survey data. Relatively high values in NEFSC autumn bottom trawl survey data for longfin squid in one time step, for example, are often followed by low values in the next time step and vice versa. In order to fit bottom trawl survey data, production rates have to change rapidly. To accomplish this, production models estimate low biomass and carrying capacity for longfin squid so that moderate increases or decreases in biomass are followed by substantial decreases or increases in production rates. In other words, conventional production models for longfin squid tend to estimate production rates that turn "on" and "off" as trawl survey and biomass estimates become smaller and larger.

Conventional surplus production models assume that production is always larger than zero. This characteristic likely exacerbates problems with low biomass estimates for longfin squid. Even with estimated production as small as possible (i.e. near zero), biomass in a production model can decline only due to catch. In order to achieve relatively large decreases in biomass, the observed catch must be relatively large in comparison to biomass. Thus, substantial declines in biomass (indicated by survey data for longfin squid) are achieved in production models by estimating biomass estimates that are relatively small (i.e., slightly larger than catches).

It seems likely that some of the variability in bottom trawl survey data for longfin squid stems from survey catchability process errors caused by variation in environmental conditions. It is possible that longfin squid biomass is low relative to catches, but not as low as the infeasible estimates from conventional production models. Based on likelihood profile results, experience with LVPA data and the considerations described above, it appears that relatively complex process error models may be required to interpret survey data in production modeling for longfin squid.

Two process error approaches were used for longfin squid. The first assumed process errors in surplus production rates. This approach is parsimonious (one process error parameter per time step) but indirect because process errors in surplus production rates and process errors in survey catchabilities during the same time step might be confounded in the estimated parameters. The second approach assumed process errors in survey catchabilities over time only. This is a more realistic but relatively complex approach. If separate process errors affect each survey, for example, then the number of parameters estimated is potentially as large as the number of survey observations.

Simple model with independent production process errors

We used the simple model without carrying capacity to explore production process error models. The simple surplus production model was run assuming independent production process errors with CV=0.1 (a modest level of variability). Fit to survey data was better than with the simple production model and no production process errors. Goodness of fit CV's were closer to average sampling CV's (see below). Autumn survey catchability was near its upper bound.

Estimated production rates, ρ_t, from the simple model with independent surplus production process errors were strongly autocorrelated with production rates higher or lower than average for periods of 1-5 years. Log scale production process errors ε_t had a lag 1 autocorrelation of 0.88 and the CV for variability in log scale production process errors ε_t was about 3%. This suggests that some environmental variable, acting over periods of years, effects either production or catchability in a variety of surveys during different seasons.

Models with catchability process errors

To parameterize catchability process errors for longfin squid we ran the simple version (no carrying capacity) of PDQ repeatedly with production process errors turned off and independent catchability process errors turned on for all surveys, while increasing the assumed CV for the variance of log scale catchability process errors ξ. In each subsequent run, the assumed CV's for catchability process errors were adjusted manually until the goodness of fit CV's for all abundance indices were larger, but within 0.1, of the average measurement CV. The final assumed CV's for catchability process errors in the basecase model run ranged from zero (for LPUE indices) to 0.35 for the Massachusetts spring bottom trawl survey (Table A17). Likelihood profile analysis (Table A18) showed that two abundance indices fit best at the higher boundary for feasible Q_{Fall} values, one fit best at the lower boundary, and three fit best at intermediate values.

The final PDQ model with catchability process errors, which was adopted by the Stock Assessment Review Committee (SARC) at the 34th Stock Assessment Workshop (SAW) as a basecase model, converged to feasible estimates of Q_{Fall} and biomass with no additional constraints (Table A18, Figures A29-A30). The model fit abundance data reasonably well although there was serial correlation in residuals for several abundance indices (Figure A31-A38). There was substantial variation in estimated catchability for the NEFSC autumn and Massachusetts spring bottom trawl surveys (Figure A39). Catchability process errors appear random for all abundance indices except the Massachusetts spring survey, where catchability decreased after 1990 and remained low (Figure A39).

To facilitate comparison of temporal variability in catchability, estimated catchabilities were rescaled and plotted as log scale anomalies (i.e. take logs, subtract mean log scale value and divide by the log scale standard deviation assumed in fitting the model). Results indicate that catchability process errors were strongly correlated (Figure A40). An attempt to estimate carrying capacity for longfin squid by fitting a logistic surplus production model with similar catchability process error assumptions gave unfeasible results with implausibly high estimates of carrying capacity.

Preliminary retrospective analyses with the basecase model showed that terminal biomass estimates for longfin squid from the PDQ model with catchability process errors were unstable, particularly when the terminal time step in the model was summer (probably because no abundance index data are collected during the summer). The same preliminary analysis showed that average estimates for the year prior to the terminal year (e.g. average biomass or fishing mortality for 2000 from a model including data for 2001) were more stable and probably useful for status determination purposes. Model stability and retrospective patterns are important topics for future research.

Managers are advised to ignore PDQ biomass estimates for 2001, the most recent year. According to the best-fit catchability process error model, estimated longfin squid biomass reached a record high of about 50,000 mt at the end of 2001 and beginning of 2002 (Table A19 and Figure A29). Record high biomass estimates in 2001 were driven primarily by the NEFSC autumn bottom trawl survey (Figure A11) which was at a near record level in 2000, while other abundance indices were at more moderate levels (Figures A12-A14 and A22). Terminal year estimates are the least precise in most stock assessment models because estimates for the last year are not constrained by data in subsequent years. As described above, the catchability process error version of the PDQ model suffered from instability in the terminal year.

Bootstrap and asymptotic delta method CV's for biomass and F estimates were similar for 1987-1998 (Table A19). However, asymptotic and bootstrap CV's began to diverge after 1998. By 1990, bootstrap CV's were substantially larger. The relatively large bootstrap CV's were due to very low biomass estimates and high *F* estimates for recent years in some bootstrap runs.

The estimated instantaneous surplus production rate was 0.24 quarter^{-1} and estimated longfin squid biomass in 2000 averaged 24 thousand mt. During 2000, estimated average fishing mortality and catch were 0.2 quarter^{-1} and 4.8 thousand mt quarter^{-1}. Average catch was less than average surplus production (6.3 thousand mt quarter^{-1}) during the same period.

Bootstrap confidence intervals (500 iterations for average biomass of *Loligo* during 2001 and average fishing mortality during 2000 were substantially wider than likelihood profile confidence intervals (see below). In contrast, the bootstrap confidence interval for the instantaneous production rate ρ was narrower.

<u>Traditional per recruit calculations</u>

Yield and spawning biomass per recruit calculations were carried out by age-structured simulation in monthly time steps (Thompson and Bell 1934, input data in Table A20 and Figure A41). Calculations used squid ages 1-12 months for winter hatch squid in the summer fishery and ages 1-10 for summer hatch squid in the winter fishery. The last age group was not a plus group (the few survivors to ages older than the last were ignored). Fishing mortality rates are given both as traditional fully recruited fishing mortality rates and as the corresponding biomass weighted average fishing mortality rates. The latter are more comparable to results from biomass dynamic models like PDQ (NEFSC 2001).

	Likelihood Profile 95% Lower Bound	Likelihood Profile 95% Upper Bound	Bootstrap 95% Lower Bound	Bootstrap 95% Upper Bound
Production rate ρ	0.16	0.30	0.16	0.28
Average 2000 *F* (per quarter)	0.12	0.26	0.12	0.41
Average 2001 *B*	23.75	52.00	7.9	59.6

Maximum ages for per recruit modeling were chosen based on the predicted age at 50 cm DML (see LVPA, above). To mimic assumptions used in LVPA that natural mortality was higher at sizes above 30 cm DML (see above), the natural mortality rate for winter hatch squid was M=0.75 quarter^{-1} for ages 1-10 months and M=1.5^{-1} quarter (doubled) for ages 11-12. Similarly, the natural mortality rate for summer hatch squid was M=1.00 quarter^{-1} for ages 1-8 months and M=2.00 quarter^{-1} for ages 9-10. In the context of per recruit modeling, these assumptions about natural mortality mean that natural mortality increases at about the time 100% of squid become sexually mature.

Fishery selectivity at age was calculated by converting the length based selectivity curve fit to LVPA results (Figure A24) to age, using inverted growth curves used to calculate $\underline{\Delta t}_L$ values for LVPA. Maturity at age was calculated as

$$s_L = e^{\eta_L} / \left(1 + e^{\eta_L}\right)$$

where

$$\eta_L = 0.303 \; L - 6.20$$

(Table A13) based on Hatfield and Cadrin's (in press) report that females were 25%, 50% and 75% mature at 16.6, 20.7 and 23.8 cm DML respectively. Weight at age in the summer fishery (winter hatch dates) and selectivity estimates used for per recruit modeling in this assessment were substantially different that those used by Cadrin and Hatfield (1999, compare Figures A41-A42 in this report). Changes to data, and selectivity estimates in particular, caused substantial changes in *F* estimates for per recruit reference points (see below).

F's for per recruit based biological reference points (Table A21, Figure A43-A44, and see below), particularly those based on yield, were lower than in Cadrin and Hatfield (1999). Spawning biomass per recruit calculations for Loligo squid appear less sensitive to uncertainty about growth, natural mortality, maturity and fishery selectivity than yield per recruit calculations. Reference points expressed as biomass weighted mean F's were smaller than the equivalent and corresponding fully recruited F's (Table A21 and Figures A43-A44). The relationship between biomass weighted and fully recruited F's for longfin squid was nonlinear with fully recruited values much higher than biomass weighted values (Figure A45).

Cohort	Source	Fully Recruited F_{MAX} (quarter^{-1})	Biomass Weighted F_{MAX} (quarter^{-1})	Fully Recruited $F_{0.1}$ (quarter^{-1})	Biomass Weighted $F_{0.1}$ (quarter^{-1})	Fully Recruited $F_{50\%}$ (quarter^{-1})	Biomass Weighted $F_{50\%}$ (quarter^{-1})
Winter hatch / Summer fishery	This assessment	1.4	0.77	0.94	0.58	0.69	0.45
Winter hatch / Summer fishery	Cadrin and Hatfield (1999)	2.6	Not available	1.5	Not available	0.82	Not available
Summer hatch / Winter fishery	This assessment	1.6	1.1	1.1	0.82	0.82	0.64
Summer hatch / Winter fishery	Cadrin and Hatfield (1999)	5.0	Not available	2.4	Not available	1.3	Not available

Yield maximizing reference points like F_{MAX} and $F_{0.1}$ should be viewed with caution for longfin squid and probably not used for management purposes. Technical problems stem from their sensitivity to input parameters, short lifespan and lack of age structure (dependence of future recruitment and stock biomass on current standing stock), uncertainties about growth, uncertainties about spatial variability and seasonal variability in biological parameters.

OVERFISHING DETERMINATION

It is unlikely that the overfishing is occurring in the longfin squid fishery. The largest feasible scaled catch-survey F estimates for 2000-2001 ranged from 0.11-0.17 quarter^{-1} (Table A15 and Figure A27). F estimates from the PDQ surplus production model for 2000-2001 ranged from 0.12-0.31 quarter^{-1} (Table A19 and Figure A30). Thus, all recent F estimates are less than the biomass weighed F_{MAX} values for longfin squid (0.77-1.1 quarter^{-1}). LVPA results (Figures A23), and unscaled catch-survey biomass estimates for winter and spring surveys (Table 16 and Figure A28) generally indicate that fishing mortality rates for longfin squid declined to relatively low levels during 2000 and 2001.

It is unlikely that the longfin squid stock is overfished. Survey data (with the exception of the Massachusetts inshore spring survey, Tables A9-12 and Figures A11-A14), LVPA results (Figure A22), scaled catch-survey biomass estimates (Table A15 and Figure A26), and PDQ model estimates (Figure A29) all indicate that longfin squid biomass was moderate to high during 2000 and 2001. The smallest feasible catch-survey biomass estimate for 2001 was 34,000 mt (Table A15), which is less than the best available estimate of $B_{MSY}/2$ (40,000 MT, NEFSC 1999). However, the probability of the lowest feasible biomass level is small for longfin squid.

SARC COMMENTS

The SARC review of the *Loligo* assessment focused on the results on a new surplus production model (PDQ model) presented by the working group. The recommended model run indicated a significant increase in biomass since 1998. The model results were driven by the increased biomass indices in the NEFSC autumn survey since 1999. The SARC questioned the trend given some conflicting patterns in other indices, such as the Massachusetts spring inshore survey. However, the higher precision of the autumn survey weighted the results toward that biomass trend.

Concerns about the model configuration were discussed. The PDQ model did not account for density dependent factors. Without estimation of a K parameter, the biomass estimate is not constrained but estimation of K confounds the estimation of other parameters. The results from this model changed the conclusions about the stock status since the previous assessment. The SARC requested a list of the changes in population models since the last assessment and the resulting differences in biomass and F estimates. The SARC also requested some additional analyses to evaluate the influence of catch estimates in 2001. It was suggested that the model outputs be limited to catch through 2000. A retrospective analysis was also requested to examine how robust the model estimates were to terminal catch inputs for the last five years.

The SARC concluded that the stock was not subjected to overfishing. However, the absolute values of F_{MSY} and B_{MSY} were not estimated in the model. The reference points in the current plan were based on F_{MAX} as a proxy for F_{MSY}. The SARC did not endorse a new estimate of F_{MSY} to replace the current estimate of F_{MAX}, but suggested a new threshold value.

In addition to the assessment results presented by the SAW Invertebrate Working Group, the SARC examined a new approach to analysis of the survey indices. A general additive model (GAM) was developed to account for the influence of factors such as time of day and area differences in the calculation of a survey index. This approach would adjust for influential factors prior to use in a model as opposed to an inclusive modeling approach adopted in the PDQ model. The GAM adjustments produced much different conclusions about the trend in the NEFSC autumn survey. The results suggested the biomass trend has been relatively stable over the past several decades and the changes in the indices are due to environmental effects. The SARC provided several suggestions for future GAM work, such as an increase in the number of size groups and standardization of the weeks the survey is conducted. The SARC noted the relative stability of the indices despite changes in landings and the possibility that it is the result of tremendous flexibility in life history patterns of *Loligo*.

Finally, the SARC examined some additional work on development of new estimates of F_{MAX} using model inputs specific to monthly cohorts. The SARC recommended an update in *Loligo* weight at age information. Growth differences between monthly cohorts had a noticeable effect on the monthly yield per recruit estimates. The SARC noted that the model provided some useful insight into the dynamics of *Loligo* but it was not appropriate for management use until the relative recruitment strength of each monthly cohort can be incorporated.

The SARC reviewed analyses of retrospective patterns of terminal year estimates of fishing mortality and biomass from the PDQ model. Model results suggested wide variation in the terminal year values but some stability in the penultimate year values for both F and B. It was recommended that the SARC focus on the biomass and F values for 2000 as measures of stock status. It was asserted that the biomass values generated by the model had greater utility than previous estimates because the constraints on the catchability coefficients ensured feasible upper and lower bounds.

Members of the SARC asked for comparison with results of GAM analyses and noted that these results provided a similar pattern of smoothing. Apparent convergence of these results suggested that the resource had been stable for years but that it was difficult to identify the absolute level of biomass. As a result, the SARC proposed and considered issues related to a heuristic assessment of the resource. Biomass appears to be stable given current annual harvest levels, but currently available information is insufficient to determine either the absolute level of biomass or the desired level with respect to long-term sustainability.

The SARC noted that this heuristic perspective on the status of the stock represented a marked change from previous assessments and that it would be necessary to build a bridge between this and earlier analyses.

RESEARCH RECOMMENDATIONS

1. Based on this assessment, it appears that traditional per-recruit reference points like F_{MAX} may be poor proxies for F_{MSY} in *L. pealeii* because they may not permit a sufficient level of escapement. There appears to be no satisfactory biomass based reference points for *L. pealeii* at this time. Fishing mortality and biomass reference points for use as targets and thresholds are an important area for research.

2. It is important to carry out further research on standardizing and modeling survey data for *L. pealeii*. A preliminary GAM model analysis of survey data should serve as a good starting point in developing standardization approaches that adjust for diel and other factors affecting catchability. PDQ model results show that survey catchability processes errors follow similar trends in different surveys and are auto-correlated within surveys. Survey catchabilities probably vary in response to water temperatures. These circumstances suggest that survey catchability processes errors might be modeled robustly and parsimoniously as a simple function of water temperatures in the PDQ model.

3. Growth information, particularly for older *L. pealeii*, is still uncertain. Additional age and growth studies are required to better estimate average growth patterns and to discern seasonal patterns. The latter are potentially important in more realistic, seasonally explicit population and reference point models like the preliminary multi-cohort reference point model.

4. The potential for fuller use of catch data prior to 1987 from foreign fishing

should be investigated for *L. pealeii*. Current assessment approaches use seasonal time steps but historical catch data are currently available only by calendar year. The working group should consult historical NAFO reports and determine if monthly or quarterly catches can be estimated. Alternatively, the PDQ model could be modified to use annual time steps prior to 1987 and quarterly time steps later. Another approach would be to use an annual surplus production model including years before and after 1987.

5. Results from this assessment demonstrate that retrospective analyses are a useful part of an assessment involving surplus production models because they provide an estimate of the stability of model estimates. However, retrospective patterns for estimates in production models may have a different meaning and origin than in traditional age structured models. This is a topic for analysis by the Methods Working Group.
6. Available logbook data are not adequate to measure fishing effort after 1993, or to prorate landings and effort data by area. It is not currently possible to measure commercial catch rates after 1993, to track trends in fishing effort, or to investigate relationships between catches and abundance in near shore, offshore, northern and southern areas. The spatial resolution, coverage and accuracy of commercial catch data for *L. pealeii* should be improved.
7. Information about the population biology of *L. pealeii* has improved in recent years but relationships between seasonal migrations, environmental conditions and temporal and spatial variability in sex ratios, maturity and growth rates are still not clear. It may be useful to carryout additional studies that collect sex and maturity data from *L. pealeii* taken during NEFSC surveys.

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