A. ASSESSMENT OF NORTHERN SHRIMP

A1.0 CONTRIBUTORS

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A2.0 TERMS OF REFERENCE (TOR) FOR NORTHERN SHRIMP

1. Characterize the Gulf of Maine northern shrimp commercial catch, effort, and CPUE, including descriptions of landings and discards of that species.

2. Estimate fishing mortality and exploitable stock biomass in 2006 and characterize the uncertainty of those estimates. Also include estimates for earlier years.

3. Comment on the scientific adequacy of existing biological reference points (BRPs).

4. Evaluate current stock status with respect to the existing BRPs.

5. Perform sensitivity analyses to determine the impact of uncertainty in the data on the assessment results.

6. Analyze food habits data and existing estimates of finfish stock biomass to estimate annual biomass of northern shrimp consumed by cod and other major predators. Compare consumption estimates with removals implied by currently assumed measures of natural mortality for shrimp.

7. Review, evaluate and report on the status of the 2002 SARC/Working Group Research Recommendations.

A3.0 EXECUTIVE SUMMARY

A3.1 Major findings for TOR 1 – Gulf of Maine northern shrimp commercial catch, effort, and CPUE, with descriptions of landings and discards

Landings in the Gulf of Maine northern shrimp fishery declined since the mid 1990s (with 182-day seasons), from a high for the decade of 9,166 mt (20 million lbs) in 1996 to a low of 424 mt (0.9 million lbs) in 2002, the result of low abundances of shrimp and reductions in fishing effort. Since then, landings have increased to 2,553 mt (5.6 million lbs) in the 70-day 2005 season (preliminary) and 1,877 mt (4.1 million lbs) in the 140-day 2006 season (preliminary). The 2006 season was characterized by very high catch rates, low participation, and poor market demand. The numbers of fishing vessels and trawl trips have dropped from about 310 and 10,734 respectively in 1997 to 119 and 1,646 in 2006 (preliminary). Discard rates for northern shrimp have been low, except in the 1995 and 1996 whiting fisheries. See Section A5 for details.

A3.2 Major findings for TOR 2 – Estimate fishing mortality and exploitable stock biomass in 2006 and characterize the uncertainty of those estimates. Also include estimates for earlier years

The estimate of fishing mortality from CSA modeling (preferred method) for 2006 was F=0.03 (3% exploitation), based on preliminary 2006 landings data. Annual estimates for 1985 to 2005 range from 0.08 to 1.06. Exploitable stock biomass estimates vary from a low of 4,400 mt (9.7 million lbs) in 2001 to a high of 71,500 mt (158 million lbs) at the beginning of the 2007 fishing season. ASPIC modeling in general confirms the CSA trends, and provides fishing mortality and biomass estimates back to 1968. Bootstrap results suggest that estimates of abundance, biomass and fishing mortality were relatively precise, with the greatest uncertainty about the most recent biomass estimate. See Section A6 for details.

A3.3 Major findings for TOR 3 – Comment on the scientific adequacy of existing biological reference points (BRPs)

The current biological reference points for Gulf of Maine northern shrimp are:

$B_{Threshold}$ = 9,000 mt or 19.8 million lbs
B_{Limit} = 6,000 mt or 13.2 million lbs
$F_{Target/Threshold}$ = 0.22
F_{Limit} = 0.60

(ASMFC 2004) and are based on historical abundance estimates and responses to fishing pressure, as shown in Figure A6-12. The BRPs provide adequate guidance to managers in a timely fashion. It is also noted that, unlike many managed species, the northern shrimp management process provides the ability for responses to changes in stock status in a short time period (annually). See Section A7 for details.

A3.4 Major findings for TOR 4 – Evaluate current stock status with respect to the existing BRPs

The Gulf of Maine northern shrimp stock is in good condition; the stock is not overfished, nor is overfishing occurring. Recent fishing mortality rates were well below the BRPs, and biomass is well above. See section A8 for details.

A3.5 Major findings for TOR 5 – Perform sensitivity analyses to determine the impact of uncertainty in the data on the assessment results

Sensitivity analyses on underreporting of landings in terminal years showed that CSA abundance and biomass estimates were not affected, but F values were sensitive. Starting biomass values from ASPIC runs were also affected. CSA abundance and biomass were sensitive sensitive to changes in the mean weight of a landed shrimp, while F was not. CSA abundance and biomass estimates were increased by a factor of 4 to 5 when values of M were increased from 0.25 to 0.60, while values of F were reduced. See section A9 for details.

A3.6 Major findings for TOR 6 – Analyze food habits data and existing estimates of finfish stock biomass to estimate annual biomass of northern shrimp consumed by cod and other major predators. Compare consumption estimates with removals implied by currently assumed measures of natural mortality for shrimp

Food habits data (stomach contents) from NEFSC bottom trawl surveys conducted in the western Gulf of Maine were analyzed, and 18 major predators of pandalid shrimp were identified. Their annual rates of consuming pandalid shrimp were calculated, then multiplied by predator stock abundance estimates, and then summed over all the predator species to estimate the total pandalid abundance removed. The total amount of pandalid shrimp removed was finally multiplied by the ratio of *Pandalus borealus* to all pandalid shrimps, as estimated from the shrimp surveys and bottom trawl survey ratios, to estimate the total *P. borealis* removal. Consumptive removals of *P. borealis* were compared with survey abundance indices and model biomass estimates. Consumptive removals were generally the same order of magnitude, but usually higher, than model exploitable biomass estimates. Consumption exhibited some of the same trends as survey and model indices. The results suggest that there is more *P. borealis* biomass in the system than the models estimate, and that a value of M higher than 0.25 may be appropriate. See Section A10 for details.

A3.7 Major findings for TOR 7 – Status of the 2002 SARC Research Recommendations

The stock assessment review committee (SARC), which met during the 36th Stock Assessment Workshop (SAW) in December 2002, made nine recommendations for further research (NEFSC 2003). Each recommendation was discussed and its status listed here. There has been significant progress made in improving estimates of natural mortality, M, based on predation data and sex-stage abundance ratios. Some other recommended items still await further work. See section A11 for details.

A4.0 INTRODUCTION

A4.1 Management history

The Gulf of Maine fishery for northern shrimp (*Pandalus borealis* Krøyer) is managed through interstate agreement between the states of Maine, New Hampshire and Massachusetts. The management framework evolved during 1972-1979 under the auspices of the State/Federal Fisheries Management Program. In 1980, this program was restructured as the Interstate Fisheries Management Program (ISFMP) of the Atlantic States Marine Fisheries Commission (ASMFC). The Fishery Management Plan (FMP) for Northern Shrimp was approved under the ISFMP in October 1986 (McInnes 1986). The full Commission in May 2004 approved Amendment 1 to the FMP (ASMFC 2004). Amendment 1, which entirely replaces the original FMP, establishes biological reference points (BRPs) for the first time in the shrimp fishery and expands the tools available to manage the fishery. Any new tools proposed to manage the shrimp fishery must be implemented through the ASMFC addendum process.

Within the ISFMP structure, the Northern Shrimp Technical Committee (NSTC) provides annual stock assessments and related information to the ASMFC Northern Shrimp Section. Annually, the Section decides on management regimes after thorough consideration of the NSTC stock assessment, input from the Northern Shrimp Advisory Panel, and comment from others knowledgeable about the shrimp fishing industry. In the first five years (1987 – 1991) after the passage of the 1986 FMP, the NSTC generally recommended full fishing seasons (182 days) and the Section followed the committee's recommendations (Table A4-1). Nearly every year from 1992 to 1999, the NSTC recommended restricted seasons. The managers set seasons that were less than the full 182 days but more than the seasons recommended by its scientific advisors. With the exception of 2001, the NSTC recommended no fishery from 2000 to 2004. The managers set limited fishing seasons during that time, with the shortest (25 days) in 2002. The NSTC has taken a new approach to its recommendation to the Section since 2005. It recommends a maximum landings amount for the fishing season. The Section used that number and recommendations from the Advisory Panel to establish recent seasons. In the past two years the Section has tentatively set both the upcoming and the following year's season length, provided triggers for number of fishing trips, landings, and fishing mortality in the first year are not exceeded.

A4.2 History of past assessments and approach taken in this one

A4.2.1 Past Assessments

Stock assessments initially consisted of total landings estimates, indices of abundance from Northeast Fisheries Science Center (NEFSC) groundfish surveys, fishing mortality estimates from the application of cohort slicing of length frequencies from the State of Maine survey, and yield per recruit modeling (Clark and Anthony 1980; Clark 1981, 1982).

The NSTC unified individual state port sampling programs in the early 1980s to better characterize catch at length and developmental stage (sex and maturity), and established a dedicated research trawl survey for the species in the summer of 1983 to monitor relative abundance, biomass, size structure and demographics of the stock annually. Subsequent stock assessments provided more detailed description of landings, size composition of catch, patterns in fishing effort, catch per unit effort, relative year class strength and survey indices of total abundance and biomass. Length distributions from the summer shrimp survey have been used for size composition analysis to estimate mortality rates, but did not fit length-based models well because of variable recruitment and growth (Terceiro and Idoine 1990, Fournier et al. 1991).

Beginning in 1997, the northern shrimp stock in the Gulf of Maine has been evaluated more quantitatively using three analytical models that incorporate much of the available data (Cadrin et al. 1999):

- Preferred: Collie-Sissenwine analysis (CSA) that tracks removals of shrimp using summer survey indices of recruits and fully-recruited shrimp scaled to total catch in numbers, and provides estimates of F (instantaneous fishing mortality rate) and B (exploitable biomass) – see Section A6.3;
- Supportive: A surplus production analysis (ASPIC) that models the biomass dynamics of the stock with a longer times series of total landings and three survey indices of stock abundance – see Section A6.3;
- A yield-per-recruit (YPR) model and an eggs-per-recruit (EPR) model that simulate the life history of northern shrimp (including growth rates, transition rates, natural mortality, and fecundity) and fishing mortality on recruited shrimp. It uses estimates of trawl selectivity to estimate yield and egg production at various levels of fishing mortality, providing guidance on the selection of biological reference points (Cadrin et al. 1999).

In 2004, Amendment 1 to the ASMFC Interstate Fishery Management Plan for Northern Shrimp was adopted. This was the first time formal biological reference points were defined for this fishery (see Section A7).

A4.2.2 Current Assessment and Changes from Past Assessments

Assessments are made annually in October, using the above methods, last reviewed by SARC 36 in 2002.

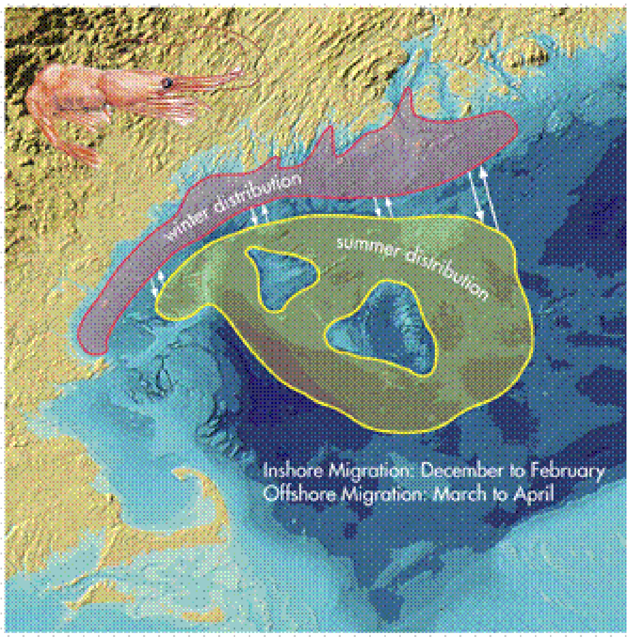
In 2002 the NSTC began using a new method of calculating the instantaneous rate of fishing mortality, F, based on CSA harvest rates instead of the log-ratio method (Collie and Kruse, 1998).

In the current assessment, results of using an instantaneous rate of natural mortality, M, of 0.25, which was used in past assessments, is compared with results using a value of 0.60. See Sections A6.3, A7, and A10 for discussion.

A4.3 Biology

A4.3.1 Life History

Northern shrimp (*Pandalus borealis* Krøyer) are protandric hermaphrodites, usually maturing first as males at roughly 2½ years of age and then transforming to females at roughly 3½ years of age in the Gulf of Maine (Figure A4-1). Spawning takes place in offshore waters beginning in late July. By early fall, most adult females extrude their eggs onto the abdomen. Egg-bearing females move inshore in late autumn and winter, where the eggs hatch. The planktonic larvae pass through six larval stages and settle to the bottom in inshore waters after metamorphosing to a juvenile state (Berkeley 1930; Haynes and Wigley, 1969; Apollonio and Dunton 1969; Stickney and Perkins 1977; Stickney 1980). Juveniles remain in coastal waters for a year or more before migrating to deeper offshore waters, where they mature as males. The males pass through a series of transitional stages before maturing as females. Some females may survive their first egg hatch to repeat the spawning process. Females that have never extruded eggs are referred to here as "female I". Non-ovigerous females that have carried eggs in the past are "female II". Female Is and IIs can be distinguished by the presence or absence of sternal spines (McCrary 1971). The females are the individuals targeted in the Gulf of Maine fishery. It is believed that most *P. borealis* in the Gulf of Maine do not live past age 5 (Haynes and Wigley 1969; Apollonio and Dunton 1969).



Distribution of adult female northern shrimp, from *Ecosystem Relationships in the Gulf of Maine-Combined Expert Knowledge of Fishermen and Scientists*. **NAMA collaborative report 1:1-16, 2006.**

The extent, location, and timing of these transitions and migrations are variable. Several factors may influence the size and age at sex transition (see Bergström 2000 for review). Several year classes in recent decades show some percentage of 2½ year old shrimp maturing first as females instead of males (early-maturing females) (Figure A6.7). This presents both sexes in the same year class and may be a reaction to stress in the population as predicted by sex allocation theory (Charnov et al. 1978), or may be temperature (Apollonio et al. 1986; Hansen and Aschan 2000) or density dependent growth driven (Koeller et al. 2000), or may be the result of fishery removals of larger females selecting for smaller females (Marliave et al. 1993; Bergström 2000). Other year classes have exhibited some late sex transition. In the 2001 year class, there was evidence of both very early- and late-maturing females, with early-maturing females appearing at assumed age 1½, but also males remaining as males at assumed age 3½ (Figure A6.7).

Growth, as in other crustaceans, is a discontinuous process associated with molting of the exoskeleton (Hartnoll 1982). Information on growth of Gulf of Maine northern shrimp has been reported by Haynes and Wigley 1969; Apollonio et al. 1986; Terceiro and Idoine 1990; and Fournier at al. 1991. Differences in size at age by area and season can be ascribed in part to temperature effects, with more rapid growth rates at higher temperatures (Apollonio et al. 1986).

Instantaneous natural mortality (M) for northern shrimp stocks has been estimated between 0.2 and 1.0 (Shumway et al. 1985). See sections A6.3 and A10 for further discussion of M.

4.3.2 Habitat

Pandalus borealis, and its northeast Pacific relative *Pandalus eous,* have a discontinuous distribution throughout the North Atlantic, North Pacific, and Arctic Oceans. In the Gulf of Maine, northern shrimp populations comprise a single stock (Clark and Anthony 1981), which is concentrated in the southwestern region of the Gulf (Haynes and Wigley 1969; Clark et al. 1999). Water temperature, salinity, depth, and substrate type have all been cited as important factors governing shrimp distribution in the Gulf of Maine (Haynes and Wigley 1969; Apollonio et al. 1986; Shumway et al. 1985).

A4.3.2.1 Temperature

The most common temperature range for this species is 0-5 °C (Shumway et al. 1985). The Gulf of Maine marks the southern-most extent of this species' range in the Atlantic Ocean, and seasonal water temperatures in many areas regularly exceed the upper physiological limit for northern shrimp. This environmental limitation restricts the amount of available habitat occupied by this species to the western region of the Gulf (west of 680 W) where bottom topography and oceanographic conditions create submarine basins protected from seasonal warming by thermal stratification. The deep basins act as cold water refuges for adult shrimp populations (Apollonio et al. 1986). In the northeastern region of the Gulf, large shrimp populations do not persist because bottom waters are not protected from seasonal warming, due to continual mixing from intense tidal currents nearer to the Bay of Fundy (Apollonio et al. 1986).

Several studies have found a significant negative correlation between annual mean temperatures and recruitment of northern shrimp (Dow, 1977; Richards et al. 1996). While the manner by which temperature affects recruitment and abundance trends has not been precisely determined, record high sea surface temperatures during the early 1950s correlate with complete failure of the fishery from 1954-1957; and conversely, the cold temperature years of the early to mid-1960s appear to have been very favorable for recruitment, with rapid increases in abundance and record landings from 1969-1972. The collapse of the fishery during the 1970s was more problematic as it occurred during a period of warming temperatures, and high and increasing levels of F; overfishing has been strongly implicated for the collapse. During the last two decades, significant recruitment events have coincided with normal to below normal spring sea surface temperature anomalies (ASMFC 2004).

A4.3.2.2 Depth

In the Gulf of Maine, northern shrimp are most frequently found from about 10 m to over 300 m (30-1000 ft) (Haynes and Wigley 1969), with juveniles and immature males occupying shallower, inshore waters and mature males and females occupying cooler, deeper offshore waters for most of the year (Apollonio and Dunton 1969, Haynes and Wigley 1969, Apollonio et al. 1986). During the summer months, adult shrimp inhabit water from 93-183 m (300-600 ft) (Clark et al. 1999); ovigerous female shrimp are found in shallower near-shore waters during the late winter and spring (Apollonio and Dunton 1969, Clark et al. 1999) when their eggs are hatching.

A4.3.2.3 Substrate

Northern shrimp most commonly inhabit organic-rich, mud bottoms or near-bottom waters (Hjort and Ruud 1938; Bigelow and Schroeder 1939; Wigley 1960; Haynes and Wigley 1969), where they prey on benthic invertebrates; however, shrimp are not limited to this habitat and have been observed on rocky substrates (Schick 1991). Shrimp distribution in relation to substrate type determined by trawl surveys clearly show northern shrimp primarily occupy areas with fine sediments (sand, silt, and clay) (ASMFC 2004). Shrimp are often associated with biotic or abiotic structures such as cerianthid anemone (Langton and Uzmann 1989) and occasional boulders in these fine sediment habitats (Daniel Schick, Maine Department of Marine Resources, pers. comm.).

A4.3.3 Predators and Prey

Northern shrimp are an important component of marine food chains, preying on both plankton and benthic invertebrates, and being consumed by many commercially important fish species, such as cod, redfish and silver and white hake (ASMFC 2004). *P. borealis* diet was documented by Wienberg (1981) and Apollonio and Dunton (1969). Species that include P. borealis in their diet are documented by many authors (see Synopsis: Shumway et al. 1985.) See section 10.0 for further discussion of predation.

A4.3.4 Migration

The migrations of juvenile northern shrimp from inshore to offshore areas in the western Gulf of Maine, and the subsequent movement of ovigerous females from offshore to inshore, are discussed above.

A4.3.4.1 Vertical migration

Male and non-ovigerous female shrimp exhibit diurnal vertical migration, from bottom and near-bottom during the day, up into the water column to feed at night. Egg-bearing females are less likely to exhibit vertical diurnal migration, and are more likely to stay on the bottom (Apollonio and Dunton 1969; Apollonio et al. 1986).

A4.3.5 Other Pandalid Species

The striped shrimp, *Pandalus montagui*, and the bristled long-beak shrimp, *Dichelopandalus leptocerus*, both smaller and less abundant than *Pandalus borealis*, are also common in Gulf of Maine commercial and survey catches, but are not targeted by the fishery.

See ASMFC (2004) for more information on the biology of *Pandalus borealis*.

A4.4 Fishery Description

Northern shrimp occur in boreal and sub-arctic waters throughout the North Atlantic and North Pacific, where they support important commercial fisheries. In the western North Atlantic, commercial concentrations occur off Greenland, Labrador, and Newfoundland, in the Gulf of St. Lawrence, and on the Scotian Shelf. The Gulf of Maine marks the southernmost extent of its Atlantic range (Parsons and Fréchette, 1989). In the Gulf of Maine, primary concentrations occur in the western Gulf where bottom temperatures are coldest. In summer, adults are most common at depths of 90-180 meters (Clark et al. 2000).

The fishery has been seasonal in nature, peaking in late winter when egg-bearing females move into inshore waters and terminating in spring under regulatory closure (ASMFC 2004). Northern shrimp have been an accessible and important resource to fishermen working inshore areas in smaller vessels who otherwise have few winter options due to seasonal changes in availability of groundfish, lobsters and other species (Clark et al. 2000).

A summer fishery, which existed in the 1970s, caught shrimp of all ages, including age 1 and 2. These immature and male shrimp made up 40-50% of the catch by numbers in April-June, increasing to 70-80% for July-September, during 1973-1974 (Clark et al. 2000). Since 1976, fishing has been restricted to months within a December to May timeframe. (Throughout this document, references to a particular fishing year will include the previous December unless otherwise indicated – *e.g.* the 2006 season includes December 2005 but not December 2006, which will belong to the 2007 season.)

The fishery formally began in 1938, and during the 1940s and 1950s almost all of the landings were by Maine vessels from Portland and smaller Maine ports further east. This was an inshore winter trawl fishery, directed towards egg-bearing females (presumably age 4 and 5) in inshore waters (Scattergood 1952). New Hampshire vessels entered the fishery in 1966, but throughout the 1960s and 1970s New Hampshire landings were minor. In contrast to the historical wintertime Maine fishery, New Hampshire and Massachusetts vessels fished continually throughout the year and made significant catches during summer months in the 1970s. New Hampshire currently accounts for about 10% of the total catch for the Gulf of Maine.

Landings by Massachusetts vessels were insignificant until 1969, but in the early 1970s the fishery developed rapidly, with Massachusetts landings increasing from 14% of the Gulf of Maine total in 1969 to over 40% in 1974-1975. Massachusetts landings have declined to 1-6 % of total during the past 10 years, while Maine vessels have accounted for 80-90% (Tables A5-1 and A5-2).

A map of the areas fished in 2006 is shown in Figure A4-2 (preliminary data).

A wide variety of vessels have been used in the fishery (Bruce 1971; Wigley 1973). The predominant type during the 1960s and 1970s appears to have been side-rigged trawlers in the 14-23 m (45-75 ft) range. During the 1980s and 1990s, side trawlers either re-rigged to stern trawling, or retired from the fleet. Currently, the shrimp fleet is comprised of lobster vessels in the 9-14 m (30-45 ft) range that re-rig for shrimping, small to mid-sized stern trawlers in the 12-17 m (40-55 ft) range, and larger trawlers primarily in the 17-24 m (55-80 ft) range. The otter trawl remains the primary gear employed and is typically chain or roller rigged, depending on area and bottom fished. There has been a trend in recent years towards the use of heavier, larger roller and/or rockhopper gear. These innovations, in concert with substantial improvements in electronic equipment, have allowed for much more accurate positioning and towing in formerly unfishable grounds, thus greatly increasing the fishing power of the Gulf of Maine fleet. The number of vessels participating in the fishery in recent years varied from a high of 310 in 1997 to a low of 119 in 2006 (preliminary data).

A small pot fishery has also existed in mid-coastal Maine since the 1970s, where in many areas bottom topography provides favorable shrimp habitat that is too rough or restricted for trawling. The trapped product is of good quality, as the traps target only female shrimp once they have migrated inshore. According to vessel trip reports (VTRs), trappers accounted for 12% of Maine's landings in 2001-2006 (Table A5-3). There is some indication that trap fishing for shrimp has grown in a few areas such as South Bristol (mid-coast Maine) and would continue to grow if market conditions were more favorable. Since the trap fishery is dependent on the inshore availability of shrimp in a specific area, there is apparently a shorter season for traps than for draggers. Most shrimp trappers also trap lobsters at other times of the year.

Management measures currently in place include season length (varying from year to year within a December 1 through May 31 timeframe), gear restrictions, licensing, and mandatory reporting. Maine and New Hampshire have open-access shrimp fisheries. Legal restrictions on trawl gear require a minimum 44.5 mm (1.75 inch) stretch mesh net and the use of a finfish separator device known as the "Nordmore grate" with a maximum grate spacing of 25.4 mm (1 inch) (ASMFC 2004).

A5.0 GULF OF MAINE NORTHERN SHRIMP COMMERCIAL CATCH, EFFORT, AND CPUE, WITH DESCRIPTIONS OF LANDINGS AND DISCARDS (TOR#1)

A5.1 Data sources

Commercial landings by state and month have been compiled by NMFS port agents from dealer reports. It is likely that catches sold to the small "peddler" market were unreported, as well as some of those sold to those dealers (non-federally permitted) who are not required to report. These data were used for annual stock assessments until 2001, when vessel trip reports (VTRs) were found to be more complete. Small Maine vessels that did not have federal permits were not required to fill out VTRs until 2000. Landings (quantity kept, not discarded) and numbers of vessels and trips have been calculated from VTRs for use in assessments since 2001. However, the data for latter years (eg. 2005 and 2006 fishing seasons) are preliminary. Data used here for 2006 were compiled from VTRs received and entered as of September 2006. We expect final landings for 2006 to be as much as 20% higher than reported here.

Prior to 1994, effort (numbers of trips by state and month) was estimated from landings data collected from dealers, and landings per trip information (LPUE) from dockside interviews of vessel captains:

$$Effort = \frac{Landings}{LPUE}$$

Beginning in the spring of 1994, a vessel trip reporting system (VTR) supplemented the collection of effort information from interviews. From 1995 to 2000, landings per trip (LPUE) from these logbooks were expanded to total landings from the dealer weighouts to estimate the total trips:

$$Total.Trips = VTR.Trips\frac{Total.Landings}{VTR.Landings}$$

Since 2000, VTR landings have exceeded dealer weighout landings, and the above expansion is not necessary. The 1996 assessment report (Schick et al. 1996) provides a comparison of 1995 shrimp catch and effort data from both the NEFSC interview and logbook systems and addresses the differences between the systems at that time. It showed a slightly larger estimate from the logbook system than from the interview system. Thus effort statistics reported through 1994 are not directly comparable to those collected after 1994. However, patterns in effort can be examined if the difference between the systems is taken into account. An additional complication of the logbook system is that one portion of the shrimp fishery may not be adequately represented by the logbook system during 1994-1999. Smaller vessels fishing exclusively in Maine coastal waters are not required to have federal groundfish permits and were not required to submit shrimp vessel trip reports until 2000. In the 1994-2000 assessments, effort from unpermitted vessels was characterized by catch per unit effort of permitted vessels.

Beginning in 2001, landings, vessels, and trips are calculated from vessel trip reports (VTRs) only.

A port sampling program was established in the early 1980s to characterize catch at length and developmental stage, as well as to collect effort and fishing depth and location data. Samplers strive to achieve representative sampling by maintaining up-to-date lists of active buyers and visiting ports in proportion to their landings activity. Sampling consists of interviewing boat captains and collecting a 1 kg (2.2 lbs) sample of shrimp from each catch. The samples are separated and weighed in the lab by species, sex and development stage. Measurements are made of all shrimp dorsal carapace lengths to the nearest 0.01 mm. The numbers of shrimp measured each season are shown in Table A5-6.

A5.2 Commercial Landings

A5.2.1 Total Landings

Small quantities of northern shrimp have been incidentally caught in New England otter trawl fisheries since 1905 (Scattergood 1952). A directed winter fishery in coastal waters developed in the late 1930s, which landed an annual average of 63 mt (139,000 lbs) from 1938 to 1953, but no shrimp were landed from 1954 to 1957 due to low inshore availability (Wigley 1973). The fishery resumed in 1958, and landings increased steadily to a peak of 12,824 mt (28,272,000 lbs) in 1969 as an offshore, year-round fishery expanded (Table A5-1). After 1972, landings declined rapidly, and the fishery was closed in 1978. The fishery reopened in 1979 and seasonal landings increased gradually to 5,253 mt (11,581,000 lbs) by 1987 and averaged 3,300 mt (7,275,000 lbs) from 1988 to 1994 (Tables A5-1 and A5-2). Seasonal landings increased to 6,466 mt (14,255,000 lbs) in 1995 and to 9,166 mt (20,208,000 lbs) in 1996, which was only exceeded by the five years of landings prior to the late 1970s stock collapse. Landings declined between 1996 and 1999 to 1,816 mt (4,004,000 lbs). This was followed by a slight increase to 2,390 mt (5,269,000 lbs) in the 2000 season. Landings dropped during 2001 to 1,329 mt (2,930,000 lbs) and in 2002 to a low of 424 mt (935,000 lbs) for the 25-day 2002 season. The 2002 landings were the lowest northern shrimp landings since the fishery was closed in 1978 (Table A5-1, Figure A5-1). Total landings increased in 2003 to 1,211 mt (2,670,000 lbs) and in 2004 to 1,949 mt (4,297,000 lbs). The 2005 northern shrimp landings increased to 2,553 mt (5,628,000 lbs) (preliminary), the highest since the 1998 season (Table A5-1). The fishing season for 2006 reached 1,877 mt (4,138,000 lbs) (preliminary) with poor market conditions.

A5.2.2 Landings by State

Maine landings comprised 75% of season totals during 1984-1996. The proportional distribution of landings among the states has shifted gradually since the 1980's when Massachusetts accounted for about 30% of the catch. In 2005 and 2006, the proportional distribution of landings was still greatest for Maine, followed by NH with 12% (2005) and 5% (2006). Massachusetts landings made up 2% of the 2005 landings and 1% of the landings in 2006 (Tables A5-1 and A5-2, and Figure A5-1).

A5.2.3 Landings by Time of Year

The distribution of landings throughout the season, during years which had full 6-month seasons (December to May, and some longer), is shown in Figure A5-2. The majority of landings generally occur in January and February (Table A5-2, Figure A5-2). See Clark et al. (2000) for a discussion of the distribution in the 1970s when fishing was allowed during summer months.

A5.2.4 Landings Size and Sex Composition and Year Class Strength

Size composition data, collected from catches since the early 1980s, indicate that trends in landings have been determined primarily by recruitment of strong (dominant) year classes (Figures A5-1 and A5-7). Landings more than tripled with recruitment of a strong 1982 year class in 1985 – 1987 and then declined sharply in 1988. A strong 1987 year class was a major contributor to the 1990-1992 fisheries. A strong 1992 year class, supplemented by a moderate 1993 year class, partially supported large annual landings in 1995 – 1998 (Figure A5-7). Low landings in 1999 – 2003 were due in part to poor 1994, 1995, 1997, 1998, and 2000 year classes with only moderate 1996 and 1999 year classes. The 2003 catches were composed primarily of assumed 4-year old females from the 1999 year class, and early-maturing two-year-old females and two-year-old juveniles, males and transitionals from the strong 2001 year class. Catches in 2004 were composed primarily of egg bearing, early maturing, presumed three-year-old females from the 2001 year class and a few larger females from the 1999 year-class. In 2005, catches were composed of egg bearing females and female II's from the presumed 2001 year class and males from the 2003 year class. 2006 catches were composed of egg bearing and female IIs, probably from the strong 2001 year class. Catches in March and April had significant numbers of smaller shrimp, presumably from the 2003 (transitionals and female I's) and 2004 (juveniles and males) year classes (Figures A5-5 and A5-6).

Maine trappers produced a smaller proportion of small shrimp in the landed catch than trawls, and generally were more apt to catch large females after egg hatch, as in previous years (Figure A5-5). See the table below for average counts per pound by month and gear.

2006 commercial shrimp fishery average counts per pound, from port samples. 1 lb=0.45kg

	Pandalus borealis only					All shrimp species				
	Dec.	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**
Maine trawls	40	38	36	56	60	41	40	38	58	58
Maine traps	no samples	33	35	36	35	no samples	35	37	37	59
Maine total	40	37	36	48	57	41	39	37	50	58
Massachusetts	no samples	48	50	50	44	no samples	48	50	49	43
New Hampshire	38	47	50	61	62	38	48	50	60	62

In the 2007 fishery it is expected (from the 2006 summer survey size distributions; see Figure A6-7) that the strong 2001 year class (assumed 6-year-old females) may still be present, the 2002 year class (assumed 5-year-old females) will be very weak, the strong 2003 year class (4-year-old females) will contribute most to landings, and the exceptionally strong 2004 year class and moderate 2005 year class will be transitionals, males and juveniles.

Landings from January to March consist primarily of mature female shrimp (presumably ages 3 and older) and December, April, and May landings have included higher proportions of males (assumed ages 1 and 2; Figure A5-4b, A5-5, and A5-6). These patterns reflect shifts in distribution of fishing effort in response to seasonal movements of mature females: inshore in mid-winter and offshore after their eggs hatch.

A5.2.5 Landings in Numbers

Catch in numbers for the CSA model (see section 6.0) was derived by dividing landed weight (Table A5-2) by mean individual weights from port samples by year, state and month -- see the example in the table below. Individual weights are calculated by dividing the total weight of a sample by the number of *P. borealis* in the sample. Mean weight for non-sampled landings was estimated (in past years) by a general linear model of mean weight incorporating year, month and state effects, or (in recent years) by using samples from a nearby state or month within the same year.

The general patterns in size composition of landings are reflected in mean weight of individual shrimp landed by year, state, and month: the size of landed shrimp generally increases from December to January, peaks in February, and decreases through the spring, and is often larger in Maine landings than in those of the other states, and larger in Maine trap catches than trawl catches.

Mean weights of individuals (and numbers of samples) of *P. borealis* in 2006 catches 1 g = 0.0022 lb				
		Maine	**New Hampshire**	**Massachusetts**
December	Trawls Traps	11.49g (14) No samples, use Jan.	11.97g (3)	No samples, use NH Dec.
January	Trawls Traps	12.36g (29) 13.69g (6)	9.68g (4)	10.01g (1)
February	Trawls Traps	12.97g (26) 13.76g (13)	9.41g (4)	9.28g (5)
March	Trawls Traps	8.63g (21) 12.90g (13)	7.62g (5)	9.45g (5)
April	Trawls Traps	7.99g (9) 29.71g*(1)	7.45g (3)	10.58g (1)

*From one sample that was more than half *P. montagui*.

A5.3 Commercial Discards

Sea sampling observations aboard trips using a shrimp trawl from 1989 to 1997 and 2001 to 2006 in the Gulf of Maine (NMFS statistical areas 511, 512, 513, and 514) indicate that the mean weight of shrimp discards is less than 1% of total catch for all years except 1997, when it was 1.36% (Table A5-7).

From examination of the observer database for 1989 to 2006, the only other fisheries which had trips with significant shrimp discards were the small-mesh herring and whiting fisheries. Industry representatives reported substantial discards of shrimp in the small-mesh whiting fishery east of Jeffreys Ledge in the mid 1990s. Sea sampling observations from finfish trawl fisheries in the Gulf of Maine suggest that bycatch of northern shrimp was inconsequential from 1984-1994. However, in 1995 and 1996 the amount of discarded shrimp per trip increased considerably, and the increase was from small-mesh (whiting) trips sampled in the area of Jeffreys Ledge. The mean shrimp discarded per observed whiting trip was 62 kg (137 lbs) in 1996. Unfortunately, no shrimp lengths were measured during sea sampling, and estimating the total number discarded would be difficult. Shrimp discards in observed small-mesh trips have averaged less than 1 kg (2.2 lbs) since 1996 (Table A5-7).

Shrimp discards were considered, but not included in this assessment.

A5.4 Commercial Catch Rates and Fishing Effort

A5.4.1 Trips

Since the late 1970's, effort in the fishery (measured by numbers of trips in which shrimp gear is used) has increased and then declined on three occasions. The total number of trawl trips in the fishery peaked at 12,285 during the 1987 season (Table A5-4, Figure A5-8a). Increases in season length, shrimp abundance and record ex-vessel prices coupled with reduced abundance of groundfish all contributed to this increase. Effort subsequently fell to 5,990 trips in the 1994 season. Effort nearly doubled between 1994 and 1996 and then declined again from the 1996 level of 11,791 to 1,010 trips in 2002, a year with only a 25-day open season. The number of trips increased during 2003-2005 as the seasons were lengthened, to 3,091 trawl trips in 2005. Trips in 2006 dropped to 1,646 (preliminary), likely due to poor market conditions.

Maine trapping operations accounted for 18%, 25%, and 30% of Maine shrimp fishing trips in 2004, 2005, and 2006 respectively, but only 4%, 18%, and 11% of landings, according to 2004-2006 Vessel Trip Report (VTR) data (preliminary) (Table A5-3 and A5-5).

A5.4.2 Vessels

The number of vessels participating in the fishery in recent years has varied from a high of 310 in 1997 to a low of 119 in 2006 (preliminary). In the 2006 fishery, there were 6 vessels from Massachusetts, 102 from Maine, and 11 from New Hampshire (preliminary data).

Year	Vessels	Year	Vessels
1997	310	2003	248
1998	260	2004	190
1999	238	*2005	197
2000	285	*2006	119
2001	288	*preliminary	
2002	200		

A5.4.3 Seasonal Spatial Distribution of Effort

Seasonal spatial trends in distribution of effort have been evaluated from port interview data. The relative magnitude of offshore fishing effort (deeper than 100 m (55 fathoms)) has varied, reflecting seasonal movements of mature females (inshore in early winter and offshore following larval hatching), but also reflecting harvesters' choices for fishing on concentrations of shrimp. During the 2005 season, 56% of the 25 sampled trips from Massachusetts and New Hampshire were inshore, while in Maine, most trips in December were offshore (90%) but increasingly inshore through the season, with 89% inshore in March. In the 2006 season, trips were generally offshore in December and April, inshore during January and February, and about 59% inshore in March, based on a total of 130 interviews. In years with a May fishing season, trips have been almost entirely offshore in that month.

A5.4.4 Catch Rates

Catch per unit effort (CPUE) indices have been developed from NMFS interview data (1983-1994) and logbook data (1995-2006) and are measures of resource abundance and availability (Figure A5-8b). They are typically measured in catch per hour or catch per trip. A trip is a less precise measure of effort, because trips from interviews and logbooks include both single day trips and multiple day trips (in the spring), and the proportion of such trips can vary from season to season.

Higher catch rates (per hour) may reflect increased biomass or denser aggregations of shrimp, which make them more available to the gear. For example, denser aggregations probably caused high catch rates during 2000, rather than high biomass. Another possible cause for an increase in catch rate is an increase in vessel fishing power. Higher catch rates per trip may also indicate a higher than average incidence of multiple-day trips.

In 2004 to 2006, only 0.24% of trips were multiple-day trips – and these were all two days – probably because shortened seasons limited the fishery to the times of year when shrimp are generally inshore and multiple-day trips are not necessary (from VTR data; 2005 and 2006 are preliminary).

Landings per trip increased from 383 kg (844 lbs) in 1983 to 602 kg (1,328 lbs) in 1985 when the strong 1982 year class entered the fishery. CPUE subsequently dropped to 328 kg (723 lbs/trip) in 1988 but increased to 478 kg (1,053 lbs) in 1990 with entry of the strong 1987 year class. This index averaged 445 kg (981 lbs) between 1991-1992, declined to 348 kg (767 lbs) in 1993, and increased in 1994 to 487 kg (1,073 lbs). The 1995-2000 CPUEs, from logbooks, averaged 632 kg (1,393 lbs). In 2001, the catch per trip dropped to 336 kg (740 lbs) per trip, the lowest since 1988, and remained low, at 377 kg (831 lbs), in 2002. In 2003, the catch per trip was 467 kg (1,029 lbs), and in 2004 it was 826 kg (1,821 lbs) per trip, one of the highest values in the past 30 years. In 2005 it was 699 kg (1,541 lbs) (preliminary) and in 2006 it was 1,022 kg (2,252 lbs) per trip (preliminary), the highest in the time series (Figure A5-8b and Table A5-8).

More precise CPUE indices (pounds landed per hour fished) have also been developed for both inshore (depth less than 100 m (55 fathoms)) and offshore (depth more than 100 m (55 fathoms)) areas using information collected by Maine's port sampling program, and agree well with the (less precise) catch per trip data from logbooks (see Table A5-8 and Figure A5-8b). Inshore CPUE for 2006 was 259 kg (572 lbs) per hour, offshore was 156 kg (345 lbs) per hour, and the season average was 226 kg (499 lbs) per hour, all time-series highs. Catch per trip, though high, did not increase as much as catch per hour, probably because trips were short. Port samplers report that shrimp trawlers sometimes came in after one good tow (usually about two hours), because of poor market demand.

A5.5 Recreational Catch

A very limited recreational fishery exists for northern shrimp. This fishery, using traps, has been for personal use and has not been licensed (ASMFC, 2004).

A6.0 FISHING MORTALITY AND EXPLOITABLE STOCK BIOMASS AND THE UNCERTAINTY OF THOSE ESTIMATES (TOR #2)

A6.1 Data Sources

A6.1.1 Fishery data

Landings data and numbers of shrimp caught by fishing season are compiled and calculated as described in Sections A5.1 and A5.2.5 above, and displayed in Table A5-1 and Figure A6-9.

A6.1.2 Fishery-independent survey data

A6.1.2.1 Maine Shrimp Survey

Maine conducted summer shrimp surveys in the Gulf of Maine from 1967 to 1983. Fixed stations were sampled with an otter trawl during daylight at locations where shrimp abundance was historically high (Schick et al. 1981; Figure A6-1). The Maine survey biomass index began declining in about 1970, and depicts the stock collapse in the late 1970s (Figure A6-5b, Table A6-3) (Clark 1981, 1982; Schick et al. 1981).

A6.1.2.2 NEFSC Groundfish Surveys

NEFSC autumn bottom trawl surveys have been conducted since 1963, and spring bottom trawl surveys have been conducted since 1968. Stations are sampled from Cape Hatteras to Nova Scotia according to a stratified random design (Figure A6-2; Despres et al. 1988). Although the groundfish surveys catch relatively few northern shrimp and have more measurement error, they represent a longer time series. Correspondence among research surveys and fishery indices of abundance suggests that the autumn survey tracks resource conditions more closely than the spring survey (Clark and Anthony 1980; Clark 1981, 1982). The autumn survey indicates a precipitous decline from peak biomass in the 1960's and early 1970's (averaging 3.2 kg/tow in 1967 - 1971) to a low of 0.2 kg/tow in 1976. The index subsequently increased, and fluctuated about a mean of 1.5 kg/tow from 1979 to 1999. It then dropped again to 0.2 kg/tow in 2001 but has increased to 2.8 kg/tow in 2005 (Figure A6-5a; Table A6-3).

A6.1.2.3 NSTC Shrimp Survey

The NSTC shrimp survey has been conducted offshore (depths > 50 m) each summer since 1983 aboard the R/V Gloria Michelle employing a stratified random sampling design and gear specifically designed for Gulf of Maine conditions (Blott et al. 1983, Clark 1989). The summer survey is considered to provide the most reliable information available on abundance, distribution, age and size structure and other biological parameters of the Gulf of Maine northern shrimp resource. Indices of abundance and biomass are based on catches in the strata that have been sampled most intensively and consistently over time (strata 1, 3, 5, 6, 7, and 8; Figure A6-3). Survey catches have been highest in strata 1, 3, 6, and 8 – the region from Jeffreys Ledge and Scantum Basin eastward to Penobscot Bay. The 1983 survey did not sample strata 6-8 and is not used in the assessment.

The statistical distribution of the summer survey catch per tow (in numbers) was investigated to determine the best estimator of relative abundance. Catches within strata were distributed with significant positive skew, and arithmetic stratum means were correlated to stratum variances. Log-transformed catches (Ln[n+1]) were more normally distributed. Log transformation is a common practice for estimating relative abundance from trawl surveys, because stratum means and variances are seldom independent, and log transformation generally normalizes observations, renders the variance independent, and reduces anomalous fluctuations (Grosslein 1971). Geometric means were estimated with more precision (mean CV=2.4%) than arithmetic means (mean CV=13.5%). Therefore, stratified geometric mean catch per tow was used to estimate relative abundance (Cadrin et al. 1999).

Shrimp summer survey catches by length and developmental stage (Figure A6-7) reflect the predominance of the strong 1982, 1987, 1992, and 2001 cohorts in the stock. Although size at age-1.5 varies from year to year, discrete length modes indicate the relative abundance of age-1.5 shrimp (generally around 12-18 mm CL) and age-2.5 shrimp (generally 18.5-23 mm CL). Length modes for older cohorts overlap extensively. Age 1.5 shrimp are not fully recruited to the survey, probably because of variation in the timing of their migration from inshore to offshore, and also because they are not fully retained by the survey net.

A6.1.2.4 Fishery Selectivity

Relative abundance indices are estimated using NSTC shrimp survey stratified geometric mean catch per tow (Cadrin et al. 1999). Mean number per tow at length is classified as one of three components, based on growth and the selectivity to commercial gear (Schick and Brown 1997). The process is illustrated in Figure A6-4. Shrimp which are large enough to be caught by the fishery at the time of the survey are considered post-recruits. The sizes of the remaining shrimp by the end of one year (i.e., growth between surveys) are modeled using a von Bertalanffy growth curve:

$$CL_{t+1} = CL_t + (CL_{\equiv} - CL_t)\,(1-e^{-K}))$$

where $CL_{\equiv}$=35.2 and K=0.36 (McInnes 1986). The length frequency of those shrimp which were not fully recruited at the time of the survey are then multiplied by the same selectivity at length to obtain an index of recruits. The remaining shrimp are pre-recruits, and will not be selected by the fishery during the year following the survey. Using this selectivity method, age-classes recruit to the fishery over several years, and recruitment in each year is composed of several cohorts. Therefore, the definition of recruitment used in this assessment is not synonymous with year-class strength.

Mean weight of recruits and fully recruited shrimp are estimated according to length-weight equations for each developmental stage from Haynes and Wigley (1969), and 1990 northern shrimp survey observations.

A6.2 Biomass Indices

A6.2.1 NEFSC Fall Trawl Survey

There has generally been good agreement (r = 0.62) between the NEFSC autumn survey index (Figure A6-5a and Table A6-3, stratified mean catch per tow, kg) and landings trends

(Figure A6-5a). This index was at all time highs at the beginning of the time series in the late 1960's and early 1970's when the Gulf of Maine Northern shrimp stock was at or near virgin levels. In the late 1970's the index declined precipitously as the fishery collapsed; this was followed by a substantial increase in the middle 1980's to early 1990's, with peaks in 1986, 1990 and 1994. This reflects recruitment and growth of the strong 1982, 1987 and 1992 year classes and the above average 1993 year class. After declining to 1.1 kg/tow in 1996, the index rose sharply in 1998 and 1999 to 2.30 and 2.54 kg per tow respectively, both well above the time series mean of 1.51 kg/tow. This is likely due to recruitment of the 1996 year class to the survey gear at age 2 in 1998 and age 3 in 1999. Beginning in 2000, the fall survey index declined precipitously for three consecutive years, reaching a time series low of 0.17 kg/tow in 2002, indicating very poor 1997, 1998, and 2000 year classes. Since 2002, the index has generally increased, reaching 2.77 kg/tow in 2005, the highest value observed since 1971. The improved fall survey indices observed since 2002 are indicative of robust 2001, 2003, and 2004 year classes.

A6.2.2 NSTC State/Federal Summer Survey

Abundance and biomass indices (stratified mean catch per tow in numbers and weight) for the state-federal summer survey for 1984-2006 are given in Table A6-1 and Figures A6-5 and A6-6, and length-frequencies by year are provided in Figure A6-7. The $\log_e$-transformed mean weight per tow averaged 15.8 kg/tow between 1984 and 1990. Beginning in 1991 this index began to decline and averaged 10.2 kg/tow between 1991 and 1996. The index then declined further, averaging 6.1 kg/tow from 1997 to 2001, and reaching a time series low of 4.3 kg/tow in 2001. In 2002 the index increased to 9.2 kg/tow, and then declined to the second lowest value in the time series (5.5 kg/tow) in 2003. Since 2003, the index has increased markedly, reaching new time series highs in both 2005 (23.3 kg/tow) and 2006 (66.0 kg/tow) respectively. The total mean number per tow demonstrated the same general trends over the time series.

The stratified mean catch per tow in numbers of 1.5-year old shrimp (Table A6-1; Figure A6-6, and graphically represented as the total number in the first size modes in Figure A6-7) represents a recruitment index. Although these shrimp are not fully recruited to the survey gear, this index appears sufficient as a preliminary estimate of year class strength. This survey index indicated strong year classes in 1987, 1992, 2001, and 2004, and moderately strong year classes in 1990, 1993, 1996, 1999, and 2003.

The strong 1992 year class observed at (assumed) age 1.5 in the 1993 summer survey (Figures A6-6 and A6-7) was smaller than the dominant 1982 and 1987 year classes, but was followed by the above-average 1993 year class. These two year classes supported the fishery in 1995-1998. The 1996 year class appeared comparable to the moderately strong 1993 year class (Table A6-1; Figures A6-6 and A6-7). The 1997 and 1998 age classes were very weak, both well below the time series mean of 410 individuals per tow. The above-average 1999 year class was comparable to the 1996 year class. In 2001 the age 1.5 recruitment index was at its lowest level since 1984, with a stratified mean of 18 individuals per tow on the transformed scale, representing recruitment failure of the 2000 year class. In 2002 the age 1.5 recruitment index increased dramatically to 1,164, which was the time series high and represents an extremely strong 2001 year class. It is interesting to note that, in the 2002 summer survey, more small, early-maturing females (< 19 mm CL, assumed 1.5 years old) were caught than at any other time in the history of the survey (Figure A6-7). The index subsequently dropped to 11 individuals per tow in 2003, indicating a very poor 2002 year class, the worst in the time series. The index increased in 2004 to 286 individuals per tow, and reached a time series high in 2005 (1,753 individuals per tow). This is indicative of a moderate 2003 year class and a very strong 2004 year class. The 2006 index dropped to (423 individuals per tow) indicating a moderate 2005 year class.

The record 2001 year class appeared in a greatly diminished state in the 2003 survey, yet stabilized in the 2004 and 2005 surveys. The re-appearance of the 2001 year class, as indicated by the increased abundance of presumed 3.5 year old shrimp in the 2004 summer survey, is evidence that the distribution of shrimp in the summer of 2003 made them largely unavailable to the summer survey that year. This supports anecdotal reports that shrimp stayed "inshore" in 2003, in areas not visited by the survey. It is not so clear why the 2001 year class appeared to increase again in abundance between 2004 and 2005 (Figure A6-7, rightmost mode in 2004 and 2005 surveys). The virtually absent 2002 year class first observed in the 2003 survey remained very weak in the 2004 and 2005 surveys, however.

Individuals >22 mm will be fully recruited to the upcoming winter fishery (primarily age 3 and older) and thus survey catches of shrimp in this size category provide indices of harvestable numbers and biomass for the coming season. (Table A6-1 and Figure A6-6). The harvestable biomass index exhibited large peaks in 1985 and 1990, reflecting the very strong 1982 and 1987 year classes respectively. This index has varied from year to year but generally trended down until 2004. The 2001 index of 1.5 kg/tow represented a time series low, and is indicative of poor 1997 and 1998 year classes. In 2002 the index increased slightly to 2.9 kg/tow, reflecting recruitment of the moderate 1999 year class to the index. The index subsequently dropped to the second lowest value in the time series (1.7 kg/tow) in 2003. Since 2003, the fully recruited index has increased dramatically reaching a time series high in 2006 (28.8 kg/tow). This increase may be related to the continued dominance of the record 2001 year class, some of which may have survived into the summer of 2006, and to an unexplained increase in the number of female stage 1 shrimp (Figure A6-7), probably the 2003 year class.

Note that the 2006 summer survey indices (Table A6-1), which are almost all well above historical norms for this survey, are based on 29 tows, compared with about 40 tows in previous years.

A6.3 Analytical Stock Assessment

A6.3.1 CSA Model – Preferred

A6.3.1.1 Methods

Descriptive information for the Gulf of Maine shrimp fishery (total catch, port sampling, trawl selectivity, survey catches, and life history studies) were modeled to estimate fishing mortality, stock abundance, and candidate target fishing levels. The Collie-Sissenwine Analysis (CSA) (Collie and Sissenwine 1983; Collie and Kruse 1998) tracks the removals of shrimp using summer survey indices of recruits and fully-recruited shrimp scaled to total catch in numbers. The estimation of these indices is described above in Section A6.1.2.4.

This modified DeLury model was applied to the Gulf of Maine northern shrimp fishery:

$$N_{t+1} = (N_t + R_t - C_t)\, e^{-M} \qquad (1)$$

where fully-recruited abundance at the end of the year (N_{t+1}) equals fully-recruited abundance at the beginning of the year (N_t), plus recruitment (R_t), minus catch (C_t), all reduced by one year of natural mortality (e^{-M}).

Natural mortality (M) was assumed to be 0.25 (but see Sections A9 and A10), as approximated from the intercept of a regression of total mortality on effort (Rinaldo 1973, Shumway et al. 1985). Estimates of Z for age-2+ shrimp from visual inspection of length modes from the Maine summer survey was 0.17 from 1977 to 1978, when the fishery was closed (Clark 1981, 1982), suggesting, for the population as a whole, M is low relative to estimates for other *Pandalus* stocks, which range from 0.2 to 1.0 (ICES 1977, Abramson 1980, Frechette and Labonte 1980, Shumway et al. 1985).

Catch was assumed to be taken at mid-year, whereby the summer survey marks the beginning of the "survey year" (August 1), and catch was taken on February 1 of the next calendar year (which was based on the time of 50% cumulative seasonal catch for 1985-1996 (Figure A5-2):

$$N_{t+1} = [(N_t + R_t)\boldsymbol{e}^{\mathbf{-0.5M}} - C_t]\, \boldsymbol{e}^{\mathbf{-0.5M}} \qquad (2)$$

so that recruited shrimp ($N_t + R_t$) experience a half-year of natural mortality ($e^{-0.5M}$), catch is removed, then the survivors $[(N_t + R_t)e^{-0.5M} - C_t]$ experience another half-year of natural mortality.

Abundance is related to survey indices of relative abundance:

$$n_t' = q_n N_t\, e^{\eta t} \qquad (3)$$

and

$$r_t' = q_r R_t\, e^{\delta t} \qquad (4)$$

where r_t' and n_t' are observed survey indices of recruits and fully-recruited shrimp, q is catchability of the survey gear, and $e^{\eta t}$ and $e^{\delta t}$ are lognormally distributed measurement errors. The process equation is derived by substituting survey indices into equation 3:

$$\boldsymbol{n}_{t+1} = [(\boldsymbol{n}_t + \boldsymbol{r_t}/\mathbf{s_r})e^{-0.5M} - \boldsymbol{q}_{\mathbf{n}}C_t]\, e^{-0.5M} \qquad (5)$$

where

$$s_r = q_r / q_n \qquad (6)$$

is the relative selectivity of recruits to fully-recruited shrimp. Selectivity studies (Blott et al. 1983) and survey catch at length suggest that age-1.5 sized shrimp are sampled less efficiently than age-2+ shrimp, because total catch per tow is greater at age-2.5 than at age-1.5 for some cohorts (Figure A6-7). For the shrimp survey, there are two components to s_r: selectivity and availability of age-1.5 shrimp. The 32mm codend mesh in the survey trawl may not retain some small shrimp, and in some years, age-1.5 males may not completely migrate from inshore areas to the survey strata (Figure A6-3). Precise estimation of survey selectivity at size was not possible due to high variability in catch at size and few comparative experimental tows (Blott et al. 1983). For the present analysis, s_r was approximated from the relative sampling efficiency of <19mm CL shrimp to that of larger shrimp, and the relative proportions of those sizes comprising total recruits and fully recruited indices.

The parameters n_t, r_t, and q_n were estimated by iteratively minimizing the sum of measurement errors for the entire time series.

In assessments from 2003 to 2006, fishing mortality was based on the CSA harvest rates (Collie and Kruse 1998). The harvest rate is defined as:

$$Ui = \frac{Li + Di}{(Ri + Ni) * e^{-Mi*(Tf - Ts)}} \quad (7)$$

where:

U_i = Harvest Rate
L_i = Landings
D_i = Discards (For northern shrimp, discards are assumed to be zero)
R_i = Recruiting Stock
N_i = Fully Recruited Stock
M_i = Natural Mortality
T_s = Time of Survey during year
T_f = Time of Catch during year
i = year

Since this expresses exploitation, F may be iteratively solved based on:

$$U = \frac{F * (1 - e^{-Z})}{Z} \quad (8)$$

where $Z = F + M$.

The northern shrimp fishery occurs primarily in January-February (Figure A5-2), so an estimate of T_f-T_s = 0.5 is reasonable.

The current analysis differs from that presented during SAW 36 (NEFSC 2003) in two aspects. The first is in the way fishing mortality is calculated. The problems associated with the log/ratio estimation of F and the formulation on the CSA software used was resolved by the use of the harvest rate approach described above. Since that time, the CSA software has been modified to calculate mortality using “exact” exponential mortality calculations. The harvest rate and “exact” approach provide the same estimates. Additionally, it has been determined to be appropriate to set the process error term to zero (0) that formerly appeared in equation 5. See the 2006 American lobster assessment (ASMFC 2006a) for the rationale for both of these changes in the most recent northern shrimp assessment.

A6.3.1.2 Results

CSA results are summarized in Table A6-2 and Figures A6-8 and A6-9. Abundance and catchability were relatively well estimated, and the model fit the data well. Total exploitable stock biomass estimates averaged about 14,000 mt (31 million lbs), with a peak at 16,000 mt (35 million lbs) before the 1991 season, and decreased to a time series low of 4,400 mt (9.7 million lbs) in 2001. Total stock biomass has increased over recent years to its current value of 71,500 mt (158 million lbs) (32,100 mt or 71 million lbs in 2006) mt (Table A6-2 and Figure A6-8).

The recent two years of high abundance and low F are due, in part, to the same years of observed very high survey catches and very low reported landings that have leveraged those estimates to account for those observations. Since 2002, both fall and summer survey indices have been increasing, and the reported landings have declined steadily since the mid-1990s.

Annual estimates of fishing mortality (F) averaged 0.25 (19% exploitation) for the 1985 to 1994 fishing seasons, peaked at 1.06 (57% exploitation) in the 1997 season and decreased to 0.30 (22% exploitation) in the 2001 season (Table A6-2 and Figures A6-8 and A6-9). In 2002 F dropped to 0.08 (7% exploitation), due in part to a short season and poor stock conditions. Continued poor stock conditions (in terms of exploitable shrimp) along with an exceptional recruitment pulse resulted in F rising to 0.23 (18% exploitation) in 2004. The 2006 estimate of F is 0.03 (3% exploitation) (Table A6-2 and Figure A6-8). Recent patterns in F reflect the pattern in nominal fishing effort (Figure A5-8a).

Precision of CSA estimates was assessed by "bootstrap" analysis, in which survey measurement errors were randomly shuffled 2000 times to provide simulated replications of the model (Figure A6-8). Bootstrap results suggest that estimates of abundance, biomass and mortality were relatively precise.

Because of a lack of detailed information about discards (see Section A5.3), there were no analyses of discarding for this assessment.

A6.3.1.3 Retrospective Analyses

Comparison of results from 5 retrospective CSA runs to the results reported above was investigated to assess the stability of estimates in the last year of the analysis and the possibility that terminal mortality estimates are systematically inconsistent. The analysis was performed by sequentially deleting the last year of survey and catch data (for five years) to create a retrospective series of CSA estimates of abundance, biomass and fishing mortality. In the most recent assessment (ASMFC 2006b) the scale of terminal and previous year estimates of abundance, biomass and fishing mortality had larger than average confidence intervals. This, however, had little effect on terminal year estimates, and the pattern shows minimal retrospective differences and no pattern in terms of F (Figure A6-13). Similar stability was seen in estimates of abundance and biomass (Figure A6-13). The NLSS estimate of q was also very stable for the series of retrospective analyses.

A6.3.2 ASPIC Model – Confirmatory Analysis

A6.3.2.1 Methods

An alternative method of estimating stock size and F was explored to corroborate results from CSA. A nonequilibrium surplus production model (Prager 1994, 1995) was fit to seasonal catch and survey biomass indices from 1968 to 2006 (summarized in Table A6-3). The model assumes logistic population growth, in which the change in stock biomass over time (dB_t/dt) is a quadratic function of biomass (B_t):

$$dB_t/dt = rB_t - (r/K)B_t^2$$

where r is intrinsic rate of population growth, and K is carrying capacity. For a fished stock, the rate of change is also a function of F:

$$dB_t/dt = (r\text{-}F_t)B_t - (r/K)B_t^2$$

For discrete time increments, such as annual fishing seasons, the difference equation is:

$$B_{t+1} = B_t + (r\text{-}F_t)B_t - (r/K)B_t^2$$

Initial biomass (B_1), r, and K were estimated using nonlinear least squares. The fall groundfish survey catch per unit effort (CPUE) contributed to the total sum of squares as a series of observed effort (E=CPUE/C); the Maine summer survey and the NSTC shrimp surveys contributed as independent indices of biomass at the start of the fishing season. Note that no assumption about M is needed for the biomass dynamics analysis.

6.3.2.2 Results

Two observations from the NMFS fall survey (1982 and 2002) and one observation from the summer shrimp survey (2006) appear to be outliers. The pattern of residuals from the Maine and NSTC surveys suggest autocorrelation (Figure A6-10). A fair portion of the variance in the fall and Maine surveys was explained by the model (R^2=0.49 and 0.63, respectively); however the majority of the variation in the NSTC summer survey was not resolved (R^2=0.15). The model did not account for peaks in biomass from strong recruitment that occurred in 2005 and 2006.

Estimates of F and B from the biomass dynamics model generally confirm the pattern and magnitude of estimates from the CSA model (Figure A6-11). Recruitment of the strong 1982, 1987, 1992, 2001, and 2005 cohorts is not as pronounced in the biomass trajectory from the production model, because dynamic recruitment is not explicitly estimated, as it is in the CSA. The biomass dynamics model suggests that a maximum sustainable yield (MSY) of 5,395 mt can be produced when stock biomass is approximately 30,110 mt (B_{MSY}) and F is approximately 0.18 (F_{MSY}). However, estimated biomass was only above B_{MSY} during the first three years in the analysis, which are not reliable (Prager 1994, 1995).

Survey residuals were randomly resampled 1000 times to estimate precision and model bias. Bootstrap results suggest that B_1/ B_{MSY}, K, r, MSY, B_{MSY} and F_{MSY} were relatively well estimated (relative interquartile ranges were <14%, and bias was ≤1%). Estimates of the survey q's were moderately precise (relative IQs were 21-26%, bias was <1%). The ratio of F/F_{MSY} in 2006 was estimated with moderate precision (relative IQ = 26%, bias = 2.29%.). Similarly, B/B_{MSY} in 2006 was estimated with moderate precision (relative IQ =25%, bias = 1.18%).

A6.3.2.3 Retrospective Analysis

A total of 5 retrospective ASPIC runs were completed and examined to assess the stability of model estimates of biomass and fishing mortality in the terminal year, and to assess the sensitivity of time series trends of biomass and fishing mortality to terminal values of survey and catch time series. The analysis was performed by sequentially removing the last year of survey and catch data (for five years) to create retrospective time series of surplus production fishing mortality and biomass estimates.

Terminal fishing mortality estimates were very stable in most years with minimal retrospective differences in F observed (Figure A6-14a). Biomass estimates exhibited slightly more retrospective bias than F estimates, especially between 1982 and 1993 (Figure A6-14b). Despite the retrospective bias observed in the surplus production biomass estimate, stock status determination would not be affected because of the relative nature of the biomass threshold used for Northern shrimp.

A7.0 SCIENTIFIC ADEQUACY OF EXISTING BIOLOGICAL REFERENCE POINTS (BRPs) (TOR #3)

Biological reference points for US Gulf of Maine northern shrimp were developed for and adopted by the ASMFC Northern Shrimp Section for Amendment 1 (ASMFC 2004) to the ASMFC Northern Shrimp FMP. The Section chose a fishing mortality target and limit based on Spawning Potential Ratio (SPR). The fishing mortality target of F50%=0.22 was based on a level of the fishing mortality rate in the mid-1980s through mid-1990s when biomass and landings were “stable”. The fishing mortality limit of F20% = 0.6 is based on the limit that was exceed in the early to mid-1970s when the stock collapsed (see Table A6-3).

The Section chose a stock biomass threshold and limit based on historical patterns. Amendment 1 does not employ a biomass target because the Section did not want to set unlikely goals for a species whose biomass can easily be affected by environmental conditions. The stock biomass threshold of $B_{Threshold}$ = 9,000 mt (19.8 million lbs) and limit of B_{Limit} = 6,000 mt (13.2 million lbs) are based on historical abundance estimates and response to fishing pressure. The limit was set 2,000 metric tons higher than the lowest observed biomass – 4,000 mt in 1976 from ASPIC analysis (ASMFC 2001).

The absolute values of the other reference points are based on CSA estimates of stock status (ASMFC 2003) and on Egg per Recruit analyses (Cadrin et al. 1999). Although these reference points were not adopted in a formal manner until 2004, management decisions have tended to react to stock conditions that were between the now established thresholds and limits. Figure A6-12b shows the pattern of biomass and fishing mortality from 1985 to present. A similar pattern is seen when viewing the reference points scaled to estimates from a surplus production (ASPIC) analysis (Figure A6-12a). Although the CSA is used for absolute values for stock status and providing advice to management, the ASPIC runs have been used to corroborate that information, and in this case, provide a longer time period, including the late 1970s.

Observing these patterns, it appears that the BRPs provide adequate information to managers in a timely fashion. It is also noted that, unlike many managed species, the northern shrimp management process provides the ability for response to changes in stock status in a short time period. This is based, in part, on management review of northern shrimp assessments on an annual basis.

A8.0 CURRENT STOCK STATUS WITH RESPECT TO EXISTING BRPs (TOR #4)

The existing biological reference points (BRPs) for northern shrimp, as defined in the FMP (ASMFC 2004) are:

$B_{Threshold}$ = 9,000 mt or 19.8 million lbs
B_{Limit} = 6,000 mt or 13.2 million lbs

$F_{Target/Threshold}$ = 0.22
F_{Limit} = 0.60

[From the FMP wording, F=0.22 is both a target (as defined on page 23 of the FMP) and a threshold (as implied on page 24 of the FMP, ASMFC 2004). A target Biomass is not defined in the FMP.]

For the purposes of determining the stock status of northern shrimp relative to the BRPs, fishing mortality and biomass estimates derived from the CSA model (using M=0.25) are used (ASMFC 2004).

In 2006 the CSA fishing mortality rate (2006 F = 0.03) was well below the target/threshold fishing mortality (F = 0.22) and has been so since 2005 (Table A6-2).

The 2006 CSA biomass estimate of 32,100 mt (70.9 million lbs) (Table A6-2) is well above the biomass threshold ($B_{Threshold}$ = 9,000 mt or 19.8 million lbs), and was the highest value observed in the time series. The Gulf of Maine stock of northern shrimp is in good condition; the stock is not overfished, nor is overfishing occurring.

Although results of biomass dynamics modeling are not used for management purposes, estimates of fishing mortality and biomass from the ASPIC model confirm the stock status determination from the CSA model. The 2006 fishing mortality estimate from ASPIC was F = 0.09, which is well below the 1985 to 1994 stable period average fishing mortality of F = 0.24. Similarly, the 2006 biomass estimate from ASPIC was B = 19,620 mt (43.3 million lbs), which is well above the 1985 to 1994 stable period average biomass of B = 15,453 mt (34.1 million lbs) (Table A6-3).

Size composition data from both the fishery and summer surveys indicate that good landings have followed the recruitment of strong (dominant) year classes. Poor landings from 1998 to 2004, as well as low biomass estimates, can be attributed in part to the below-average recruitment of the 1994, 1995, 1997, 1998, 2000, and 2002 year classes.

During the 2007 fishing season, the strong 2001 year class (assumed 6-year-old females) may still be present in part, the 2002 year class (assumed 5-year-old females) will be very weak, the strong 2003 year class (4-year-old females) will contribute most to landings, and the exceptionally strong 2004 year class and moderate 2005 year class will consist of males and transitionals, and immature males respectively.

A9.0 SENSITIVITY ANALYSIS TO DETERMINE THE IMPACT OF UNCERTAINTY IN THE DATA ON ASSESSMENT RESULTS (TOR #5)

A9.1 CSA Model

Sources of uncertainty in CSA estimates of stock status identified and tested involve the estimation of the mean weight of a landed shrimp, and underreported landings in the most recent years of the assessment. Additional analyses were performed to examine different natural mortality rates.

A9.1.1 Mean weight of a landed shrimp

The estimation of the mean weight of a landed shrimp (see description of this process in Section A5.2.5) would result in an inverse estimation of the CSA inputs: numbers landed, as well as the mean weight. To examine this, the mean weights used in the baseline CSA (the values used in the most recent assessment) were adjusted by +/- 10 and 20%. The total landings in weight remained constant. Predictably, the effect on the CSA estimates of abundance (N) and biomass (B) were essentially the same as the % changes in the indices (Figure A9-1.1). Also predictably, there was no change in the estimates of F, since that is derived from survey indices.

A9.1.2 Underreported landings in terminal years

It has been noted that the reporting process for northern shrimp landings lags well behind the assessment cycle time constraints. Analysis of the last six years of data indicates that in the terminal year of an assessment, between 70 and 88% of landings for that year will be available. Landings for the previous year are 98 – 99% complete. Two CSA runs were done looking at a case where landings for the last year (2006) were 70% of the total, and where they were at 88%. In both cases, year t-1 (2005) landings were presumed to be 98% complete. The results of these runs (Figure A9-1.2) show no substantial changes in N or B estimates for any years including the terminal years. Estimates of F did show an increase equivalent to the magnitude of the change in landings, however an increase of 30% in an F = 0.03 is small.

A9.1.3 Natural Mortality

As noted above (Section A6.3.1.1) the natural mortality rate (M = 0.25) used in US Gulf of Maine northern shrimp assessments may be underestimated. Several higher values were examined in further CSA runs. The choice of M = 0.6 (an average of the range noted above) is presented here. The results are shown in Figure A9-1.5. In general, the results are relatively logical. The abundance and biomass estimates when M is increased from 0.25 to 0.6 also increase on average by a factor of 4 to 5 (compare Figure A9-1.5 with A6-8). Since landings remained constant, the catchability (q) decreased for the higher value of M and the abundance and biomass had to increase in order to provide the same level of catch. The retrospective patterns (Figure A9-1.3 and A9-1.4) are similar to those for M = 0.25 (Figure A6-13). The estimates of N, B and F were basically different only in scale. As a result, the use of a higher M should have little effect on management advice based on stock status. It is possible that a change in scale will be confusing (at best), but the overall process of maintaining biomass at a sustainable level through controlling F is the same. As mentioned before, it really is only a matter similar to using Fahrenheit vs Celsius scales to describe temperature.

These analyses are certainly far from exhaustive, but they point to the need for further examination of the values of rates of natural mortality used in the assessment. The US portion of the Gulf of Maine is marginal, in terms of environment, for *P.borealis*. It is clear that M = 0.25 is an underestimate for a species that has a life span of 5 to 6 years. The use of a higher M, as presented here, is supported by the following section (A10) on the effects of predation. It seems probable that the higher value used includes the M2 component of M.

A9.2 ASPIC Model

Estimates of fishing mortality and biomass derived from the biomass dynamics model (ASPIC) were examined for sensitivity to potential uncertainty and biases in reported shrimp landings. Three different sensitivity runs were completed; 1) Landings overestimated by 20%, 2) Landings underestimated by 20%, and 3) Landings underreported by 10% and 20% in the sub-terminal and terminal year respectively. The first two runs set an upper and lower bound on the impact of potential uncertainty in the landings data. The third run mimics an observed retrospective bias in Northern shrimp landings data related to late catch reporting that occurs after the assessment is completed on a annual basis.

Estimates of fishing mortality from ASPIC were not very sensitive to potential uncertainty in landings data (Figure A9-2.1). The average annual percent difference between fishing mortality estimates using the "true" landings and runs 1, 2, and 3 were 11%, 5% and 4% respectively.

Estimates of starting biomass from ASPIC were fairly sensitive to potential uncertainty in landings data (Figure A9-2.2). The average annual percent difference between starting biomass estimates using the "true" landings and runs 1, 2, and 3, were -9%, 23% and 2% respectively. In general landings "underreporting" would cause starting biomass estimates to be biased high, and landings "over-reporting" would cause starting biomass estimates to be biased low. Systematic bias in the terminal years of landings had little impact on starting biomass estimates.

A10.0 ANALYZE FOOD HABITS DATA AND EXISTING ESTIMATES OF FINFISH STOCK BIOMASS TO ESTIMATE ANNUAL BIOMASS OF NORTHERN SHRIMP CONSUMED BY COD AND OTHER MAJOR PREDATORS. COMPARE CONSUMPTION ESTIMATES WITH REMOVALS IMPLIED BY CURRENTLY ASSUMED MEASURES OF NATURAL MORTALITY FOR SHRIMP (TOR 6)

A10.1 Introduction

Food habits data from NEFSC bottom trawl surveys were evaluated for a wide range of pandalid shrimp predators. The total amount of food eaten and the type of food eaten were the primary food habits data examined. From these basic food habits data, diet composition of pandalids, per capita consumption, total consumption, and the amount of shrimp removed by these shrimp predators were calculated. Combined with abundance estimates of these predators, when summed the total amount of shrimp consumed was calculated. Contrasts to other estimates of biomass (see above) were conducted to place this source of mortality into context and to fully address the Term of Reference.

A10.2 Methods

Every predator that contained pandalid shrimps was identified. From that original list, a subset of predators was analyzed to elucidate which predators ate pandalids with a diet composition of >1% for any five year block. The predators were examined in typical size classes and were limited to the bottom trawl survey strata 01240-01400 (Azarovitz 1981, NEFC 1988), a geographic area largely coincident with the shrimp survey (see above). These size classes correspond to notable changes in diet and life history and also minimized low data density (i.e., number of stomachs sampled) for each size class. From this secondary list, predators that had <10 stomachs per three year block, had a period of non-zero pandalid diet percentages for more than five years in a row, and were not routinely sampled across the time period were excluded as non-consistent pandalid predators. The remaining 18 consistent pandalid predators (size-species combinations) were analyzed as described below (Table A10-1).

Estimates were calculated on a seasonal basis (two 6 month periods) for each species, summed for each annum. Although the food habits data collections started quantitatively in 1973, not all species of shrimp predators were sampled during the full extent of this sampling program. In such instances as long as the sampling was routine for that predator by 1985 we included them as 1985 was the initial year in the shrimp assessment based on the summer shrimp survey. For more details on the food habits sampling protocols and approaches, see Link and

Almeida (2000). This sampling program was a part of the NEFSC bottom trawl survey program; for background and context, further details of the survey program can be found in Azarovitz (1981) and NEFC (1988).

A10.2.1 Basic Food Habits

To estimate mean stomach contents (S_{it}), each shrimp predator had the total amount of food eaten (as observed from food habits sampling) calculated for each size class, temporal (*t,* fall or spring; year) and spatial (the selected strata) scheme. The denominator in the mean stomach contents (i.e., the number of stomachs sampled) was inclusive of empty stomachs. These means were weighted by the number of tows in a temporal and spatial scheme as part of a two-stage cluster design. Further particulars of these estimators can be found in Link and Almeida (2000). Units for this estimate are in grams (g).

To estimate diet composition (D_{ij}) that was pandalids, where j is the specific prey type (here pandalids) and the amount that was summed across for each predator set of stomachs. These estimates were then divided by the total amount of food eaten in a size class, temporal and spatial scheme, totaling 100%. These estimates are the proportions of the data comprised by pandalids for each size class, temporal and spatial scheme. Further particulars of these estimators can be found in Link and Almeida (2000).

A10.2.2 Consumption Rates

To estimate per capita consumption, the gastric evacuation rate method was used (Eggers 1977, Elliott and Persson 1978). There are several approaches used for estimating consumption, but this approach was chosen as it was not overly simplistic (as compared to % body weight; Bajkov 1935) or overly complex (as compared to highly parameterized bioenergetics models; Kitchell et al. 1977). Additionally, there has been copious experience in this region using these models (e.g., Durbin et al. 1983, Ursin et al. 1985, Pennington 1985, Overholtz et al. 1991, 1999, 2000, Tsou & Collie 2001a, 2001b, Link & Garrison 2002, Link et al. 2002, Overholtz & Link 2007). Units are in g year^{-1}.

Using the evacuation rate model to calculate consumption requires two variables and two parameters. The per capita consumption rate, C_{it} is calculated as:

$$C_{it} = 24 \cdot E_{it} \cdot \overline{S_{it}}^{\gamma} \quad ,$$

where 24 is the number of hours in a day and the evacuation rate E_{it} is:

$$E_{it} = \alpha e^{\beta T} \quad ;$$

and is formulated such that estimates of mean stomach contents (S_{it}) and ambient temperature (T; here used as bottom temperature from the NEFSC bottom trawl surveys for either season (Taylor & Bascuñán 2000, Taylor et al. 2005)) are the only data required. This was done for each predator i (size and species) for each time period t (season and year). The parameters α and β are set as values chosen from the literature (Tsou and Collie 2001a, 2001b, Overholtz 1999, 2000). The parameter γ is a shape function is almost always set to 1 (Gerking 1994).

To evaluate the performance of the evacuation rate method for calculating consumption, a simple sensitivity analysis had been previously executed (NEFSC 2007). The results of that sensitivity analysis indicate singly the most sensitive factor when well within normal ranges is the mean stomach contents of a predator. The ranges of α and β within those reported for the literature do not appreciably impact consumption estimates (< half an order of magnitude), nor do ranges of *T* which were well within observed values (<< quarter an order of magnitude). An order of magnitude change in the amount of food eaten linearly results in an order of magnitude change in per capita consumption. Variance about any particular species of predator stomach contents has a CV of ~50%. Thus, within any given species for each size class, temporal and spatial scheme, the variability of S_{it} is likely to only influence per capita consumption by half an order of magnitude or less. Estimates of abundance, and changes in estimates thereof, are likely going to dominate the scaling of total consumption by a broader range of magnitudes than the parameters and variables requisite for an evacuation method of estimating consumption. The parameters α and β were set as 0.04 and 0.11 respectively.

A10.2.3 Scaling Consumption

Once per capita consumption rates were estimated for each shrimp predator in a size class, temporal (*t*) and spatial scheme (these strata), those estimates were then scaled up to a seasonal estimate ($C'_{it} = C_{fall}$ or C_{spr}) by multiplying the number days in each half year:

$$C'_{it} = C_{it} \cdot 182.5 \qquad .$$

These were then multiplied by the diet composition D_{ijt} that was pandalids, to estimate the seasonal per capita consumption of pandalids C_{ijt}:

$$C_{ijt} = C'_{it} \cdot D_{ijt} \qquad .$$

These were then summed to provide an annual estimate, C'_{ij}:

$$C'_{ij} = C_{ij,fall} + C_{ij,spring} \qquad ,$$

and were then scaled by the total stock abundance to estimate a total amount of shrimp (*j)* removed by any predator *i*, C_{ij}:

$$C_{ij} = C'_{ij} \cdot N_i \qquad ,$$

where N_i is the swept area estimate of abundance for each predator (species-size class) for each year and spatial scheme.

These C_{ij} were then summed across all *i* predators to estimate a total amount of pandalid shrimp removed by all consistent pandalid predators, C_j:

$$C_j = \sum_i C_{ij} \qquad .$$

The total amount of pandalid shrimp removed was finally multiplied by the ratio of *Pandalus borealus* to all pandalid shrimps, as estimated from the shrimp surveys and bottom trawl survey ratios (see above). In practice, as this ratio exhibited a wide range of variability, we set this ratio to equal 0.5. The total consumption of shrimp per predator, total amount of pandalid shrimp removed by all predators, and total amount of *Pandalus borealus* removed by all predators are presented as metric tons year^{-1}.

To evaluate the consumptive removals of *P. borealis* shrimp as a biomass index relative to total shrimp biomass, one contrast was executed. Comparisons of consumptive removals of *P. borealis* shrimp relative to survey indices of shrimp abundance and the assessment model were executed. These track three items: first whether trends and major changes in shrimp biomass were consistent across multiple indices, second whether the predatory index of shrimp biomass consumed was consistent in magnitude with other indices and estimates, and third if parameters in the shrimp assessment model were consistent with these trends and magnitude.

Results from just one representative species is presented, namely as an example of major, consistent pandalid predators. For the full suite of consistent pandalid predator graphics, see Appendix A1.

A10.3 Results

The mean stomach contents for medium silver hake had a relatively stable amount of food eaten (Figure A10-1), averaging 3-4 g for the time series for both the fall (Figure A10-1a) and spring (Figure A10-1b). The per capita consumption for medium hake average 1-1.5 kg in the fall (Figure A10-2a) and 700g to 1 kg in the spring (Figure A10-2b), largely due to warmer fall temperatures. The per capita consumption of this shrimp predator generally tracks the amount of food eaten.

The diet composition of pandalid shrimps in medium silver hake averages approximately between 5-10% in both the fall (Figure A10-3a) and spring (Figure A10-3b), with both showing an increase in the late 1990s. The per capita consumption of pandalid shrimp by medium silver hake exhibits a notable increase in the mid 1990s, in both the fall (Figure A10-4a) and spring (Figure A10-4b) seasons.

The average per capita pandalid shrimp consumption by medium silver hake has averaged approximately 200 g yr^{-1} since the mid 1980s, with lower values prior to that time period (Figure A10-5). The minimum swept area abundance of medium silver hake for these strata has exhibited a consistent increase through the early 2000s, with an average of about 125 million individuals (Figure A10-6). Scaling these two estimates, medium silver hake have eaten an increasing amount of pandalid shrimp through the early 2000s, averaging on the order of 10-20,000 mt yr^{-1} (Figure A10-7).

Total consumptive removals by all 18 pandalid predators exhibits two increasing trends, one in the mid 1990s and another more recently (Figure A10.8a). These estimates have averaged around 50 mt yr^{-1} since 1985, with a lower value prior that time period. When examining only the amount of consumptive removals of solely *Pandalus borealis*, the same trends and patterns follow, averaging approximately 40 mt yr^{-1} since 1985 (Figure A10.8b).

When comparing the total amount of *Pandalus borealis* consumed by all predators to CSA runs using different levels of mortality (Figure A10.9a), some of the same patterns in the mid 1980s were coincident in both estimates. The mid 1990s show some departure of this trend, with the consumption estimates slightly higher than the model outputs, yet with both relatively stable during this period. Finally, the same increase in the early 2000s is tracked in both estimates.

The key observation is that those model runs with a higher mortality seem to be of a more consistent order of magnitude with the consumption estimates than runs with a lower mortality. When comparing the consumption estimates of *Pandalus borealis* to the shrimp survey, although different in magnitude and units, the same general trends and patterns are exhibited in both indices (Figure A10-9b).

A10.4 Summary

1. Total consumption of shrimp is on the same order of magnitude of independent estimates of stock biomass, but can be a bit higher.
2. Total consumption of shrimp exhibits similar trends as other biomass estimates.
3. The results suggests there is more shrimp biomass in the ecosystem than previously thought.
4. Total consumption of shrimp is suggestive of a higher M than the 0.25 previously used.

A10.5 Recommendations

1. At least, the consumption estimates of shrimp biomass should be able to be used as a qualitative index in the shrimp assessment, providing context.
2. More so, they serve as further justification, among other factors, for modifying (increasing) M in the assessment model.
3. Ultimately these estimates may prove to be useful as a scaling index in future efforts.

A10.6 Sources of Uncertainty

A10.6.1 Underestimating Consumption Index of Biomass relative to other estimates

1. Minimum swept area estimates of predator abundance; does not account for q
2. Dropped some predators that did not consistently eat Pandalids
3. 24 hour stomach sampling compared to shrimp survey sampling (just during day)
4. Spatial considerations

A10.6.2 Overestimating Consumption Index of Biomass relative to other estimates

1. *P borealis*/Pandalid ratio is hard to estimate; consumption of all shrimp is not just this species
2. Is the α too high compared to the literature?
3. Prey misidentification: e.g. assigning Pandalid to euphasiid, mysid or similar prey while processing stomachs
5. Spatial considerations

A11.0 STATUS OF THE 2002 SARC RESEARCH RECOMMENDATIONS (TOR 7)

The stock assessment review committee (SARC), which met during the 36th Stock Assessment Workshop (SAW) in December 2002, made the following nine recommendations for further research (NEFSC 2003). The NSTC agrees with the recommendations that it has yet to act on.

A11.1 Further exploration of natural mortality assumption

The SARC felt that a value for M of 0.25 seemed very low for such a short-lived species. M has been estimated between 0.2 and 1.0 for other northern shrimp stocks (Shumway et al. 1985 and others; see Section A6.3.1.1).

Scientists at NEFSC have recently looked at using predation rates and stock sizes of finfish to estimate the consumption of northern shrimp and to compare with natural mortality assumptions made in past shrimp assessments. See Section A10.6 for details.

The NSTC has also looked at ratios of assumed age class abundances for further insight. Although they are still preliminary, these analyses also suggest a higher value of M.

A11.2 Investigation of growth for improved calculation of YPR and SPR

Yield and eggs per recruit modeling for Gulf of Maine northern shrimp were reported by Cadrin et al., 1999. No new research on Gulf of Maine northern shrimp growth has been done since then.

A11.3 Consider alternative estimators of F

The NSTC and SARC (2002) concluded that "…determining F from the CSA harvest rate….is a more precise approximation than the log ratio method." (NEFSC 2003) The NSTC has adopted the harvest rate method since 2002, and no further work has been done on this issue.

A11.4 Consider a two- rather than a one-stage control rule

The SARC (2002) noted that "management advice based on the results of biomass dynamics models may not provide sufficient detail relative to the unique life history characteristics of the species. The SARC questioned the usefulness of a single reference point estimate…" (NEFSC 2003).

The NSTC has struggled to formulate appropriate management advice in certain situations: when the full recruit abundance (>22 mm) is moderate or high but the abundance of pre-recruits (age 1.5) is low (e.g., 1990 and 2004 in Table A6-1 and Figure A6-6), or conversely, when pre-recruits are high but full recruit abundance is low (e.g., 1993 and 2002 in Table A6-1 and Figure A6-6). In a stock with so few year classes, either situation can be reason for concern, even when total stock biomass is above the management threshold. Although the NSTC discusses these situations in its management advice, it has not proposed any two-stage BRPs or control rules.

A11.5 Investigate survey selectivity

Several factors influence the selectivity of both the NEFSC fall trawl survey and the NSTC state/federal summer survey – the size-selectivity of the survey gears for northern shrimp, the timing and location of the surveys relative to shrimp inshore-offshore migration and distribution, diurnal vertical migration, distribution relative to towable/untowable bottom, and net avoidance behavior could all effect the ability of surveys to adequately represent the stock.

There has been no new work looking specifically at these issues.

There is concern that the 2003 summer survey may have underestimated the stock because a portion of the stock may have stayed inshore (not in the survey strata) that summer. There is also concern that the 2006 survey may have overestimated the stock because of small sample size.

In 2002, an industry-based survey was conducted using similar gear, timeframe, locations (survey strata), and stratified random design as the NSTC state/federal summer survey. Size distributions and spatial trends in abundance were similar to the NSTC survey, although the abundance indices were not directly comparable (Schick et al. 2007).

A11.6 Explore alternative assessment models, especially statistical catch-at-length methods

Length distributions from the summer shrimp survey have been used for size composition analysis to estimate mortality rates, but did not fit length-based models well because of variable recruitment and growth (Terceiro and Idoine 1990, Fournier et al. 1991). No further work has been done on this issue.

A11.7 Consider the potential for using length-frequency distributions for developing management advice.

The NSTC always includes a discussion of relative year class strengths, derived from visual inspections of commercial catch and summer survey length-frequency distributions, in its annual assessments (e.g., end of Section A8 and ASMFC 2006a), and in its oral presentation during annual management public hearings. This discussion is usually an important component of the NSTC's management advice. No recommendations for BRPs or control rules based on size distributions have been made however.

A11.8 Explore utilizing the ratio of stage 2 to stage 1 females for estimating total mortality

The NSTC has recently explored this approach for estimating total mortality. Although they are still preliminary, these analyses suggest higher values of Z than those currently estimated by CSA using M=0.25.

A11.9 Investigate the appropriate weighting of port sample data for estimates of mean weight

The NSTC currently does not weight port samples by catch weight, that is, each sample is weighted equally in the calculation for the mean weight of a shrimp for that state and month. An alternative would be to weight samples from large catches more heavily than samples from small catches (by raising, or expanding the sample by the ratio of the sampled catch weight divided by the sample weight). This weighting would be appropriate if the mean size of individual shrimp tended to be larger or smaller in large vs. small catches.

No further work has been done on this issue.

A12.0 ACKNOWLEDGMENTS

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