22. Assessment of the Octopus Stock Complex in the Bering Sea and Aleutian Islands

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Executive Summary

Through 2010, octopuses were managed as part of the BSAI "other species" complex, along with sharks, skates, and sculpins. Historically, catches of the other species complex were well below TAC and retention of other species was small. Due to increasing market values, retention of some of the other species complex members increased. Beginning in 2011, the BSAI fisheries management plan was amended to provide separate management for sharks, skates, sculpins, and octopus and set separate catch limits for each species group. Catch limits for octopus for 2011 were set using Tier 6 methods based on the maximum historical incidental catch rate. In 2012, a new methodology based on consumption of octopus by Pacific cod was introduced; this method has been in use since 2012 and is recommended for 2017 and 2018. The consumption estimates have been updated this year with additional diet data for 2007-2015. The new estimates show an increase in consumption of octopus in recent years, due to both an increasing cod population and increases in the proportion of octopus in cod diets.

In this assessment, all octopus species are grouped into one assemblage. At least seven species of octopus are found in the BSAI. The species composition of the octopus community is not well documented, but data indicate that the giant Pacific octopus *Enteroctopus dofleini* is most abundant in shelf waters and predominates in commercial catch. Octopuses are taken as incidental catch in trawl, longline, and pot fisheries throughout the BSAI; a portion of the catch is retained or sold for human consumption or bait. The highest octopus catch rates are from Pacific cod fisheries in the three reporting areas around Unimak Pass. The Bering Sea and Aleutian Island trawl surveys produce estimates of biomass for octopus, but these estimates are highly variable and do not reflect the same sizes of octopus caught by industry. Examination of size frequency from survey and fishery data shows that both commercial and survey trawls catch predominantly small animals (<5 kg), while commercial pot gear catches or retains only large animals (10-20 kg). In general, the state of knowledge about octopus in the BSAI is increasing, but there is still no reliable estimate of octopus biomass.

Summary of Changes in Assessment Inputs

This assessment methodology has not changed from previous assessments, but the calculation of annual and long-term average consumption rates has been updated this year, using additional Pacific cod diet data from 2007-2015. Over 9,000 stomach samples were added to the data set. The more recent data and estimates are used to derive updated catch limits. The detailed methodology for these calculations is unchanged from previous years and has been moved to an appendix (Appendix 22.A1).

The table of incidental catch rates has been updated to include estimated catch for the entirety of 2015 and preliminary catch for 2016 (catch through October 2016). Catch in 2014-2016 has stayed consistent just below the 500 t TAC.

AFSC survey data for 2016 includes results from all three bottom trawl surveys in the BSAI: the EBS shelf survey, the EBS slope survey, and the Aleutian Islands survey. Shelf survey biomass increased substantially in 2015 and 1016 surveys; shelf biomass for 2016 was estimated at 7,513 t. The estimated total biomass from the 2016 slope survey was double the 2012 catch at 2,263 t. The 2016 estimate of biomass in the Aleutian Islands was also high, at 3,833 t. Overall, there appears to have been a substantial recent increase in octopus biomass in 2015 and 2016, which has also appeared in the Gulf of Alaska.

A number of research studies have been completed in the last few years and are in the process of publication; main results are summarized in an appendix to this document (Appendix 22.A2). A new theoretical octopus population model has been developed and can be used to examine different scenarios, but it is not a quantitative stock assessment model. A description of the octopus model is also included as an appendix (Appendix 22.A3).

Summary of Results

The SSC and BSAI Plan Team have approved an alternative methodology for setting octopus catch limits in the BSAI under Tier 6. This method uses a predation-based estimate of total natural mortality and the logistic fisheries model to set the OFL equal to a highly conservative estimate of total natural mortality; the OFL and ABC from this approach are much higher than the historical incidental catch. This year the calculation of annual consumption rates was updated with Pacific cod diet data through 2015. The annual consumption estimates for recent years have noticeably increased over the early part of the time series, both due to increasing numbers of Pacific cod and due to increased proportion of octopus in cod diets. The long-term average consumption has increased in the updated calculation from 3,452 t to 4,769 t. A small adjustment to the calculation algorithm and new data from 2007 and 2008 has also produced slight changes to some older annual estimates.

Quantity	As estimated or *specified last* year for: 2016	2017	As estimated or *recommended this* year for: 2017	2018
Tier 6 (consumption estimate)				
OFL (t)	3,452	3,452	4,769	4,769
ABC (t)	2,589	2,589	3,576	3,576
Status	As determined *last* year for: 2014	2015	As determined *this* year for: 2015	2016
Overfishing	n/a	n/a	n/a	n/a

Responses to SSC and Plan Team Comments on Assessments in General

At their October 2015 meeting, the SSC made two general requests of all assessment authors:

"The SSC reminds groundfish and crab stock assessment authors to follow their respective guidelines for SAFE preparation." This document has been reviewed for consistency with the 2016 SAFE guidelines for Tier 6 stocks.

"The "SSC requests that stock assessment authors bookmark their assessment documents and commends those that have already adopted this practice."
The requested bookmarks have been added.

Responses to SSC and Plan Team Comments Specific to this Assessment

There were no comments specific to this assessment from the October 2016 SSC meeting.
At their December 2015 meeting, the SSC approved the continued use of the Alternative Tier 6 consumption estimate.

Introduction

Description and General Distribution

Octopuses are marine mollusks in the class Cephalopoda. The cephalopods, whose name literally means head foot, have their appendages attached to the head and include octopuses, squids, and nautiluses. The octopuses (order Octopoda) have only eight appendages or arms and unlike other cephalopods, they lack shells, pens, and tentacles. There are two groups of Octopoda, the cirrate and the incirrate. The cirrate have cirri (cilia-like strands on the suckers) and possess paddle-shaped fins suitable for swimming in their deep ocean pelagic and epibenthic habitats (Boyle and Rodhouse 2005) and are much less common than the incirrate which contain the more traditional forms of octopus. Octopuses are found in every ocean in the world and range in size from less than 20 cm (total length) to over 3 m (total length); the latter is a record held by *Enteroctopus dofleini* (Wülker 1910). *E. dofleini* is one of at least nine species of octopus (Table 22.1) found in the Bering Sea, including one newly identified species. Members of these nine species represent seven genera and can be found from less than 10 m to greater than 1500 m depth. All but two, *Japetella diaphana* and *Vampyroteuthis infernalis*, are benthic octopuses. The state of knowledge of octopuses in the BSAI, including the true species composition, is very limited.

In the Bering Sea octopuses are found from subtidal waters to deep areas near the outer slope (Figure 22.1). The highest species diversity is along the shelf break region between 200 – 750 m. The observed catches of octopus from both commercial fisheries and AFSC RACE surveys indicates few octopus occupy federal waters of Bristol Bay and the inner front region. Some octopuses have been observed in the middle front, especially in the region south of the Pribilof Islands. The majority of observed commercial and survey hauls containing octopus are concentrated in the outer front region and along the shelf break, from the horseshoe at Unimak Pass to the northern limit of the federal regulatory area. Octopus have also been observed throughout the western GOA and Aleutian Island chain. The spatial distribution of commercial octopus catch is dependent primarily on the use of pot gear for Pacific cod, and is concentrated in the three statistical areas near Unimak Pass.

Life History and Stock Structure

In general, octopus life spans are either 1-2 years or 3-5 years depending on the species. Life histories of six of the seven species in the Bering Sea are largely unknown. *Enteroctopus dofleini* has been studied extensively, and its life history will be reviewed here. General life histories of the other six species are inferred from what is known about other members of the genus.

Giant Pacific Octopus

Enteroctopus dofleini samples collected during research in the Bering Sea indicate that *E. dofleini* are reproductively active in the fall with peak spawning occurring in the winter to early spring months (Brewer 2016). Like most species of octopods, *E. dofleini* are terminal spawners, dying after mating (males) and the hatching of eggs (females) (Jorgensen 2009). *Enteroctopus dofleini* within the Bering Sea have been found to mature between 10 to 13 kg with 50% maturity values of 12.8 kg for females and 10.8 kg for males (Brewer and Norcross 2012). *Enteroctopus dofleini* are problematic to age due to a documented lack of beak growth checks and soft chalky statoliths (Robinson and Hartwick 1986). Therefore the determination of age at maturity is difficult for this species. In Japan this species is estimated to mature at 1.5 to 3 years and at similar size ranges (Kanamaru and Yamashita 1967, Mottet1975). Within the Bering Sea, female *E. dofleini* show significantly larger gonad weight and maturity in the fall months (Brewer and Norcross 2012). Due to differences in the timing of peak gonad development between males and females it is likely that females have the capability to store sperm. This phenomenon has been documented in aquarium studies of octopus in Alaska and British Columbia (Gabe 1975). Fecundity for this species in the Gulf of Alaska ranges from 40,000 to 240,000 eggs per female with an average fecundity of 106,800 eggs per female (Conrath and Conners 2014). Fecundity was significantly and positively related to the size of the female. The fecundity of *E. dofleini* within this region is higher than that reported for other regions. The fecundity of this species in Japanese waters has been estimated at 30,000 to 100,000 eggs per female (Kanamaru 1964, Mottet 1975, Sato 1996). Gabe (1975) estimated that a female in captivity in British Columbia laid 35,000 eggs. Hatchlings are approximately 3.5 mm. Mottet (1975) estimated survival to 6 mm at 4% while survival to 10 mm was estimated to be 1%; mortality at the 1 to 2 year stage is also estimated to be high (Hartwick, 1983). Large numbers of planktonic paralarvae of this species have been captured in offshore waters of the Aleutian Islands during June through August. These juveniles were assumed have hatched in the coastal waters along the Aleutian Islands and been transported by the Alaska Stream (Kubodera 1991). Since the highest mortality occurs during the larval stage it is likely that ocean conditions have the largest effect on the number of *E. dofleini* in the Bering Sea and large interannual fluctuations in numbers of E. dofleini should be expected. Based on larval data, *E. dofleini* is the only octopus in the Bering Sea with a planktonic larval stage.

Other Octopus Species

Sasakiopus salebrosus is a small benthic octopus recently identified from the Bering Sea slope in depths ranging from 200 to1200 m (Jorgensen 2010). It was previously identified in surveys as *Benthoctopus sp*. or as *Octopus sp. n.* In recent groundfish surveys of the Bering Sea slope this was the most abundant octopus collected; multiple specimens were collected in over 50% of the tows. *Sasakiopus salebrosus* is a small-sized species with a maximum total length < 25 cm. Mature females collected in the Bering Sea carried 100 to 120 eggs (Laptikhovsky 1999). Hatchlings and paralarvae have not been collected or described (Jorgensen 2009).

Benthoctopus leioderma is a medium sized species, with a maximum total length of approximately 60 cm and a maximum weight of approximately 3 kg. Its life span is unknown. It occurs from 250 to 1,400 m and is found throughout the shelf break region. It is a common octopus and often occurs in the same areas where *E. dofleini* are found. The eggs are brooded by the female but mating and spawning times are unknown. Members of this genus in the North Pacific Ocean have been found to attach their eggs to hard substrate under rock ledges and crevices (Voight and Grehan 2000). *Benthoctopus* tend to have small numbers of eggs (< 200) that develop into benthic hatchlings.

Benthoctopus oregonensis is larger than *B. leioderma*, with a maximum total length of approximately 1 m. This is the second largest octopus in the Bering Sea and based on size could be confused with *E. dofleini*. We know very little about this species of octopus. Other members of this genus brood their eggs and we would assume the same for this species. The hatchlings are demersal and likely much larger than those of *E. dofleini*. The samples of *B. oregonensis* all come from deeper than 500 m. This species is the least collected incirrate octopus in the Bering Sea and may occur in depths largely outside of the sampling range of AFSC surveys.

Graneledone boreopacifica is a deep water octopus with only a single row of suckers on each arm (the other benthic incirrate octopuses have two rows of suckers). It is most commonly collected north of the Pribilof Islands but occasionally is found in the southern portion of the shelf break region. This species has been shown to occur at hydrothermal vent habitats and prey on vent fauna (Voight 2000). Samples of *G. boreopacifica* all come from deeper than 650 m and this deep water species has not been found on the continental shelf. *Graneledone* species have also been shown to individually attach eggs to hard substrate and brood their eggs throughout development. Recently collected hatchlings of this species were found to be very large (55 mm long) and advanced (Voight 2004) and this species has been shown to employ multiple paternity (Voight and Feldheim 2009).

Opisthoteuthis californiana is a cirrate octopus with fins and cirri (on the arms). It is common in the Bering Sea but would not be confused with *E. dofleini*. It is found from 300 to 1,100 m and likely common over the abyssal plain. *Opisthoteuthis californiana* in the northwestern Bering Sea have been found to have a protracted spawning period with multiple small batch spawning events. Potential fecundity of this species was found to range from 1,200 to 2,400 oocytes (Laptikhovsky 1999). There is evidence that *Opisthoteuthis* species in the Atlantic undergo ‘continuous spawning’ with a single, extended period of egg maturation and a protracted period of spawning (Villanueva 1992). Other details of its life history remain unknown.

Japetella diaphana is a small pelagic octopus. Little is known about members of this family. In Hawaiian waters gravid females are found near 1,000 m and brooding females near 800 m. Hatchlings have been observed to be about 3 mm mantle length (Young 2008). This is not a common octopus in the Bering Sea and would not be confused with *E. dofleini*.

Vampyroteuthis infernalis is a cirrate octopus. It is not common in the BSAI, being reported only from the slope immediately north of the easternmost Aleutian Islands (Jorgensen 2009). It is easily distinguishable from other species of octopus by its black coloration. Very little is known about its reproduction or early life history. An 8 mm hatchling with yolk was captured near the Hawaiian Islands indicating an egg size of around 8 mm for this species (Young and Vecchione 1999).

In summary, there are eight species of octopus present in the BSAI, and the species composition of natural communities is not well known. It is likely that some species, particularly *G. boreopacifica*, are primarily distributed at greater depths than are commonly fished. At depths less than 200 meters *E. dofleini* appears to be the most abundant species, but could be found with *S. salebrosus*, or *B. leioderma.*

Stock structure

The giant Pacific octopus is found throughout the northern Pacific Ocean from northern Japanese waters, throughout the Aleutian Islands, the Bering Sea and the Gulf of Alaska and along the Pacific Coast as far south as northern California (Kubodera, 1991). The stock structure and phylogenetic relationships of this species throughout its range have not been well studied. Three sub-species have been identified based on large geographic ranges and morphological characteristics including *E. dofleini dofleini* (far western North Pacific), *E. dofleini apollyon* (waters near Japan, Bering Sea, Gulf of Alaska), and *E. dofleini martini* (eastern part of their range, Pickford 1964). A recent genetic study (Toussaint et al. 2012) indicated the presence of a cryptic species of *E. dofleini* in Prince William Sound, Alaska, but did not find substantial genetic differences between specimens from Dutch Harbor and Kodiak. There is little information available about the migration and movements of this species in Alaska waters. Kanamaru (1964) proposed that *E. dofleini* move to deeper waters to mate during July through October and then move to shallower waters to spawn during October through January in waters off of the coast of Hokkaido, Japan. Studies of movement in British Columbia (Hartwick et al. 1984) and south central Alaska (Scheel and Bisson 2012) found no evidence of a seasonal or directed migration for this species, but longer term tagging studies may be necessary to obtain a complete understanding of the migratory patterns of this species.

Fishery

Management History

Through 2010, octopuses were managed as part of the BSAI "other species" complex, with catch reported only in the aggregate with sharks, skates, and sculpins. In the BSAI, the Total Allowable Catch (TAC) of other species was based on an Allowable Biological Catch (ABC) estimated by summing estimates for several subgroups (Gaichas 2004). Historically, catches of "other species" were well below TAC and retention of other species was small. Due to increasing market value of skates and octopuses, retention of other species complex members began to increase in the early 2000's. In 2004, the TAC established for the other species complex was close to historical catch levels, so all members of the complex were placed on "bycatch only" status, with retention limited to 20% of the weight of the target species. This status continued each year through 2009. In several years, the "other species" complex TAC was reached and all members of the complex were then placed on discard-only status, with no retention allowed, for the remainder of the year.

In October 2009, the North Pacific Fishery Management Council amended both the BSAI and GOA Fishery Management Plans to eliminate the "other species" category. Plan amendments moved species groups formerly included in "other species" into the "in the fishery" category and provide for management of these groups with separate catch quotas under the 2007 reauthorization of the Magnuson-Stevens Act and National Standard One guidelines. These amendments also created an 'Ecosystem Component' category for species not retained commercially.

Separate catch limits for groups from the former "other species" category, including octopus, were implemented in January 2011. Octopus remained on "bycatch only" status, with a TAC of 150 tons. As it happened, 2011 turned out to be an unusually high catch year for octopus in the BSAI. The TAC was reached in August 2011, and retention of octopus was prohibited for the remainder of the year. The OFL of 528 tons was reached in mid-October, 2011. To prevent further incidental catch of octopus, NMFS Alaska Regional Office closed directed fishing for Pacific cod with pots in the BSAI effective October 24, 2011. Since 2012, octopus TAC has been kept under 500 t to accommodate other species in the overall catch cap. Total catch of octopus in the BSAI has remained under this TAC.

Draft revisions to guidelines for National Standard One instruct managers to identify core species and species assemblages. Species assemblages should include species that share similar regions and life history characteristics. The BSAI octopus assemblage does not fully meet these criteria. All octopus species have been grouped into a species assemblage for practical reasons, as it is unlikely that fishers will identify octopus to species. Octopus are currently recorded by fisheries observers as either "octopus unidentified" or "pelagic octopus unidentified". *E. dofleini* is the key species in the assemblage, is the best known, and is most likely to be encountered at shallower depths. The seven species in the assemblage, however, do not necessarily share common patterns of distribution, growth, and life history. One avenue for possible future use is to split this assemblage by size, allowing retention of only larger animals. This would act to restrict harvest to the larger *E. dofleini* and minimize impact to the smaller animals which may be other octopus species. Under current fishery conditions, this size-based split is not needed, since commercial pot gear does not capture or retain small octopus.

Directed Fishery

There is no federally-managed directed fishery for octopus in the BSAI. The State of Alaska allows directed fishing for octopus in state waters under a special commissioner's permit. A small directed fishery in state waters around Unimak Pass and in the Aleutian Islands existed from 1988-1995; catches from this fishery were reportedly less than 8 t per year (Fritz 1997). In 2004, commissioner's permits were given for directed harvest of Bering Sea octopus on an experimental basis (Karla Bush, ADF&G, personal communication). Nineteen vessels registered for this fishery, and 13 vessels made landings of 4,977 octopus totaling 84.6 t. The majority of this catch was from larger pot boats during the fall season cod fishery (Sept.-Nov.). Average weight of sampled octopus from this harvest was 14.1 kg. The sampled catch was 68% males. Only one vessel was registered for octopus in 2005. Since 2006, few permits have been requested and catch of octopus in state waters has been incidental to other fisheries (Bowers et al. 2010, Sagalkin and Spalinger, 2011).

Incidental Catch

Octopus are caught incidentally throughout the BSAI in both state and federally-managed bottom trawl, longline, and pot fisheries. Until around 2003, retention of octopus when caught was minor, because of a lack of commercial market. Retained octopus were used and sold primarily for bait. In 2004-2007 a commercial market for human consumption of octopus developed in Dutch Harbor, with ex-vessel prices running as high as $0.90/lb. The main processor marketing food-grade octopus went out of business in 2009, decreasing demand; other processors continue to buy octopus for bait at ex-vessel prices in the $0.40 - $0.60/lb range. The worldwide demand for food-grade octopus remains high (www.fao.org), so the possibility of increased future marketing effort for octopus exists.

From 1992-2002 total incidental catch of octopus in federal waters was estimated from observed hauls (Gaichas 2004). Since 2003 the total octopus catch in federal waters (including discards) has been estimated using the NMFS Alaska Regional Office catch accounting system. Incidental catch rates are presented in the data section. The majority of both federal and state incidental catch of octopus continues to come from Pacific cod fisheries, primarily pot fisheries (Table 22.2; Bowers et al. 2010, Sagalkin and Spalinger, 2011). Some catch is also taken in bottom trawl fisheries for cod, flatfish, and pollock. The overwhelming majority of catch in federal waters occurs around Unimak Pass in statistical reporting areas 519, 517, and 509. The species of octopus taken is not known, although size distributions suggest that the majority of the catch from pots is *E. dofleini* (see below).

Data

Incidental Catch Data

Prior to 2003, there was little market for octopus and no directed fishery in federal waters; historical rates of incidental catch (prior to 2003) do not necessarily reflect fishing patterns where octopus are part of retained market catch. Estimates of incidental catch (Table 22.2) suggest substantial year-to-year variation in harvest, some of which is due to changing regulations and market forces in the Pacific cod fishery. A large interannual variability in octopus abundance is also consistent with anecdotal reports (Paust 1988, 1997) and with life-history patterns for *E. dofleini*.

Reported harvest of octopus from incidental catch in state fisheries in the BSAI ranged from 18-69 t between 1996 and 2002, but was 100-300 t in 2003-2006 (Sagalkin and Spalinger 2011). From 1992-2002 total incidental catch of octopus in federal waters, estimated from observed hauls, was generally between 100 and 400 t (Table 22.2). Since 2003 the total octopus catch in both state and federal waters (including discards) has been estimated using the NMFS Alaska Regional Office catch accounting system. Total incidental catch during this period has continued to be 200-400 tons in most years, with very high year-to year variation from 2006 - 2016. Total catch was generally high (300-500 tons) in 2003-2006 and low (<200 tons) in 2007-2010, with only 72 tons caught in 2009. The low octopus catch during this period may be a result of a decline in processor demand and a drop in cod pot-fishing effort due to a decline in the market price of cod and increased fuel prices. Catch in 2011 was the highest ever observed, reaching 534 tons by mid-October. On September 1, 2011 the NMFS Regional Office prohibited retention of octopus because the TAC of 150 tons had been reached. Catch rates for Pacific cod and incidental catch rates for octopus were both very high during fall 2011 and the octopus OFL of 428 t was reached; the NMFS closed directed fishing for Pacific cod with pot gear in the BSAI on October 21, 2011. As in previous years, the majority of the 2011 catch came from Pacific cod fisheries, primarily pot fisheries in statistical reporting areas 519, 517, and 509.

Incidental catch rates were low for 2012 and 2013, but were over 400 t in 2014 through 2016. All catches were still nearly an order of magnitude below the recommended ABC. The percentage of BSAI octopus retained has dropped from its high of over 50% in 2005-2006 to only 17% in the last two years.

AFSC Survey Data

Catches of octopus are recorded during the annual NMFS bottom trawl survey of the Eastern Bering Sea shelf and biennial surveys of the Bering Sea slope and Aleutian Islands. In older survey data (prior to 2002), octopus were often not identified to species; other species may also have been sometimes misidentified as *E. dofleini*. Since 2002, increased effort has been put into cephalopod identification and species composition data are considered more reliable. Species composition data from the summer Bering Sea shelf surveys in 2010-2016and from the three most recent Bering Sea slope and Aleutian Island surveys are shown in Tables 22.3 and 22.4. These catches are our only source of species-specific information within the assemblage. In general, the shelf survey rarely encounters octopus (less than 15% of the tows contain octopus), while the slope survey finds octopus in over half the tows. The dominant species on the shelf is *E. dofleini*, accounting for over 80% of the estimated shelf octopus biomass. The slope survey, which covers deeper waters, encounters a much wider variety of octopus species. The species most abundant numerically in the slope survey are *Sasakiopus salebrosus, E. dofleini,* and *Benthoctopus leioderma.* Because of their large body size, the estimated biomass of the slope is still dominated by *E. dofleini* (Table 22.4). The Aleutian Islands survey encounters octopus in about a quarter of the tows, primarily *E. dofleini.*

Survey data are beginning to provide information on the spatial and depth distribution of octopus species. Octopuses are rarely caught in Bristol Bay and the inner front. Survey catches of octopus in the Bering Sea shelf are most frequent on the outer shelf adjacent to the slope and in the northernmost portions of the survey. The majority of survey-caught octopuses are caught at depths greater than 60 fathoms (110 meters), with roughly a third of all survey-caught octopuses coming from depths greater than 250 fathoms (450 meters). Biomass estimates from the slope surveys suggest that *Opisthoteuthis californiana,* and *Benthoctopus leioderma* are distributed primarily toward the southern portion of the slope, while *Granoledone boreopacifica* and *Benthoctopus oregonensis* are found primarily at the northern end. *E. dofleini* were found throughout the slope survey.

Species are stratified by size and depth with larger (and fewer) animals living deeper and smaller animals living shallower. *Enteroctopus. dofleini* have a peak frequency of occurence at 250 m, *Sasakiopus salebrosus* peaks at 450 m, *B. leioderma* peaks at 450 and 650 m, and *G. boreopacifica* peaks at 1,050 m. At depths less than 200 m, *E. dofleini* is the most common species. The Aleutian Island survey catches octopus throughout the Aleutian Island chain, primarily at depths of 75-200 m. It is important to note that survey data only reflect summer spatial distributions and that seasonal migrations may result in different spatial distribution in other seasons.

The size distribution by weight of individual octopus collected by the Bering Sea shelf bottom trawl surveys from 2008 through 2011 is shown in Figure 22.2 (compared to size frequencies in commercial catch in Figure 22.3). Survey-caught octopus ranged in weight from less than 5 g up to 25 kg; 50% of all individuals captured in the shelf survey were <0.5 Kg. This pattern continues into the most recent shelf survey data. The slope survey captures more *E. dofleini* in the 0.5-3 kg range than the shelf survey; both surveys collect the occasional animal over 10 kg. In the 2008 surveys, the largest octopus caught were 4.5 kg for the shelf survey and 16.6 kg for the slope survey, both of which were *E. dofleini*. Data from the 2008 - 2016 slope survey show the marked difference in size distributions between the three most common species: *E. dofleini*, *B. leioderma*, and *S. salebrosus.* While E. dofelini ranges for <1 kg to > 20 kg, the other species generally do not exceed 3 kg. In general, the large individuals of *E. dofleini* typically seen in pot gear may be under-represented in trawl survey data because of increased ability to avoid the trawl.

Biomass estimates for the octopus species complex based on bottom trawl surveys are shown in Table 22.5 and Figure 22.4. These estimates show high year-to-year variability, ranging over two orders of magnitude. There is a large sampling variance associated with estimates from the shelf survey because of a large number of tows that have no octopus. It is impossible to determine how much of the year to year variability in estimated biomass reflects true variation in abundance and how much is due to sampling variation. In 1997, the biomass estimate from the shelf survey was only 211 t, approximately equal to the estimated BS commercial catch (Table 22.2). This suggests that the 1997 biomass estimate was unreasonably low. In general, shelf survey biomass was low in 1993-1999; high in 1990-1992 and in 2003-2005, and low again in 2006 -2010 (Figure 22.4). Shelf survey biomass increased to 3,554 t in 2011 and increased substantially in 2015 and 1016 surveys. The estimated total biomass from the 2016 slope survey was double the 2012 catch at 2,263 t , The 2016 estimate of biomass in the Aleutian Islands was also high, at 3,833 t . Overall, there appears to have been a substantial recent increase in octopus biomass in 2015 and 2016, which has also appeared in the Gulf of Alaska.

Federal Groundfish Observer Program Data

Groundfish observers record octopus in commercial catches as either “octopus unidentified” or “pelagic octopus unidentified”. Therefore, we do not know which species of octopus are in the catch. Observer records do, however, provide a substantial record of catch of the octopus species complex. Figure 22.1 shows the spatial distribution of observed octopus catch in the BSAI. The majority of octopus caught in the fishery come from depths of 40-80 fathoms (70-150 m). This is in direct contrast to the depth distribution of octopus caught by the survey. This difference is probably reflective of the fact that octopus are generally taken as incidental catch at preferred depths for Pacific cod. The size distribution of octopus caught by different gears is very different (Figure 22.3); commercial cod pot gear clearly selects for larger individuals. Over 86% of octopus with individual weights from observed pot hauls weighed more than 5 kg. Based on size alone, these larger individuals are probably *E. dofleini*. Commercial trawls and longlines show size distributions more similar to that of the survey, with a wide range in sizes and a large fraction of octopus weighing less than 2 kg. These smaller octopuses may be juvenile *E. dofleini* or may be any of several species, including *Sasakiopus salebrosus*.

Temporal catch patterns in the pot fishery are primarily determined by seasonal timing of pot fishing for Pacific cod; the overwhelming majority of octopus incidental catch comes during the primary cod seasons January-March and September-October. There is very little pot fishing effort, and very little octopus catch, during May-August and November-December. Spatial patterns in octopus catch are primarily determined by gear conflict considerations and proximity to processors. The majority of pot boats are catcher boats with a 72-hour limit for delivery of Pacific cod, so the pot effort is concentrated close to processing ports in the southeast Bering Sea and the Pribilov Islands. Most pot fishing and most octopus catch is concentrated in the regulatory no-trawl zones around Unimak Pass, where gear conflict with trawlers is avoided and trip duration is brief. It is unlikely that either of the predominant temporal or spatial patterns represents significant seasonal or spatial trends of the octopus population. What is apparent from the available data is that octopus catch rates are often notably higher in the fall cod season than in the winter; this may reflect seasonal movements of octopus related to mating. Both pot effort and octopus catch rates are consistently highest in NMFS statistical reporting area 519, on the north side of

Akutan and Akun Islands, just west of Unimak Pass. This area is heavily fished in part because the regulatory no-trawl zones around Steller sea lion rookeries and haulouts make it easy to avoid conflicts with trawlers, and cod catches are consistent. Since octopus are an item in Steller sea lion prey in the BSAI, however, the proximity of the major incidental catch to rookeries is a factor that should be noted (see discussion under "Ecosystem Considerations").

Analytic Approach

General Model Structure

The available data do not support quantitative catch-at-age modeling for either individual species of octopus in the BSAI or for the multi-species complex. Parameters for Tier 5 catch limits can be estimated from available data, but these estimates are not considered reliable. The alternative Tier 6 method, based on a predation-based estimate of total natural mortality (*N*), has been approved by the SSC and is recommended for use in 2017-2018.

The 2011 BSAI octopus assessment introduced a new methodology for examining population trends in octopus. This approach uses the underlying model from Tier 5, where MSY is obtained at ½ the total natural mortality (in tons). For Tier 5 stocks, the total natural mortality is usually estimated as the product of biomass (*B*) and an instantaneous mortality rate (*M*) $N=MB$. We use the letter *N* for the total natural mortality in tons to distinguish it from the *M* (continuous individual mortality rate) that is used widely in other stock assessment models. The new method uses a different approach to estimate total natural mortality that does not rely on being able to estimate biomass. The new method uses data from the AFSC's food habits database to estimate the total amount of octopus consumed by their main predator in the BSAI: Pacific cod. Because Pacific cod is an important commercial species, the AFSC food habits group collects a large number of Pacific cod stomachs for diet analysis. The amount of octopus consumed by Pacific cod is a conservative estimate of the total natural mortality *N* for octopus, since it does not include mortality from other predators (*i.e*. marine mammals) or non-predation mortality. This approach has been reviewed by the Science and Statistical Committee, and has been selected by the Bering Sea and Aleutian Islands Plan Team to set octopus catch limits for the BSAI fishery since 2012. This novel approach for setting annual catch limits for data-poor prey species has been presented at scientific conferences and is expected to be published next year.

This analysis was originally performed in 2011 using stomach data through 2008 (Conners et al. 2011). The consumption estimator has been updated this year after analysis of additional stomach samples through 2015. The new data include additional samples for 2005 – 2007 (Table 22.6). Details of the methodology are supplied in Appendix 22.A1.

Parameter Estimates

Total Natural Mortality (N)

The consumption estimator has been updated this year after analysis of additional stomach samples through 2015. The new data include additional samples for 2005 – 2007 (Table 22.6). The methodology used for this updated estimate is the same as used previously, with some minor changes to improve the way diets were binned into cod size strata.

The total consumption of octopus (t/year) estimated for the EBS is shown in Figure 22.5 (both old and new consumption calculations). In both calculations, we used the geometric mean of the posterior distribution to estimate annual predation for each year in the time series. The geometric mean is used rather than the arithmetic mean because the posterior distribution is right-skewed (higher values have higher uncertainty). Uncertainty of each annual estimate obtained by bootstrapping is also shown. Estimates of annual predation mortality by Bering Sea cod on octopus range from <200 to over 20,000 tons; the larger values have a higher level of uncertainty. The majority of the annual estimates prior to 2004 are in the range of 3,000 to 6,000 tons. The estimates for 2005 – 2015, however, show much higher levels of consumption, with several years in the 10,000-20,000 t range. This upward trend was initially assumed to be due to increasing abundance of Pacific cod, but there has also been an increase in the proportion of octopus in the diet of cod (Figure 22.6). Over the entire time series, this proportion shows large year-to year variability and some periods of high consumption for several years followed by low consumption. Thus, it is unclear whether the recent upward trend is a permanent change (perhaps due to climate factors) or the peak of a periodic cycle.

We use a geometric mean of all the annual values to calculate a conservative long-term average predation rate over the 30 years of annual estimates. The use of the geometric mean is recommended because the distribution of the annual estimates is strongly right-skewed, with annual variance increasing in proportion to the annual mean. The geometric mean of all of the annual estimates in the updated data set is 4,770 tons, a substantial increase over the old estimate of 3,452 tons**.** Both estimates are a full order of magnitude higher than the current rate of fishery catch of octopus. The BSAI Plan Team requested clarification in September 2016 on whether the arithmetic mean, geometric mean, harmonic mean, or median of the annual values should be used to calculate the long-term average. These different approaches are shown in Table 22.7. At the November 2016 plan team meetings, use of the geometric mean was agreed upon.

Harvest Recommendations

We recommend that octopus be managed conservatively due to the poor state of knowledge of the abundance of octopus in the BSAI, and their important role in the diet of Steller sea lions. Continued monitoring and catch accounting for the octopus complex is essential. Efforts to set appropriate overfishing limits for octopus will continue to be limited by poor information on octopus abundance. Further research is needed in several areas before octopus could managed by the stock assessment models used for commercial groundfish species.

The recent reauthorization of the Magnuson-Stevens act mandates that annual catch limits be set for all species and species complexes within the fishery management plan, even those that are not targets. Several possible methods for setting catch limits for octopus have been proposed in previous assessments (Conners and Conrath 2009, 2010). It would be possible to form a Tier 5 estimate based on survey biomass (an average of the most recent 3 surveys from Table 22.5 is 6,999 t) and a mortality rate of 0.53 as described above; this estimate would set OFL at 3,709 tons. The BSAI plan team and SSC have previously rejected this option because of the high uncertainty associated with the estimates of both *B* and *M*.

Since 2011, the Plan Team and SSC have used an alternative method based on biological reference points derived from consumption estimates for Pacific cod. This estimate of natural mortality (*N*) can then be combined with the general logistic fisheries model that forms the basis of Tier 5 assessments (Alverson and Petreyra 1969, Francis 1974) to set OFL = *N* and ABC = 0.75*OFL. **When this method is used, the resulting catch limits are OFL = 4,769 t and ABC = 3,546 t which are our recommended 2017 (and 2018) ABCs and OFLs.**

We do not recommend a directed fishery for octopus in federal waters at this time, because data are insufficient for adequate management. We anticipate that octopus harvest in federal waters of the BSAI will continue to be largely an issue of incidental catch in existing groundfish fisheries.

Ecosystem Considerations

Little is known about the role of octopus in North Pacific ecosystems. In Japan, *E. dofleini* prey upon crustaceans, fish, bivalves, and other octopuses (Mottet 1975). Food habits data and ecosystem modeling of the Bering Sea and AI (Livingston et al 2003, Aydin et al 2008) indicate that octopus diets in the BSAI are dominated by other benthic invertebrates such as mollusks, hermit crabs (particularly in the AI), starfish, and snow crabs (*Chinoecetes sp.*). The Ecopath model (Figures 22.7 and 22.8) uses diet information on all predators in the ecosystem to estimate what proportion octopus mortality is caused by which predators and fisheries. Results from the early 1990s indicate that octopus mortality in the Bering Sea comes primarily from Pacific cod, resident seals (primarily harbor seal, *Phoca vitulina richardsi*), walrus and bearded seals, and sculpins; in the AI principal predators are Pacific cod, Pacific halibut, and Atka mackerel. Adult and juvenile Steller sea lions account for approximately 7% of the total mortality of octopus in the Bering Sea, but cause insignificant octopus mortality in the GOA and AI. Modeling suggests that fluctuations in octopus abundance could affect resident seals, Pacific halibut, Pacific cod, and snow crab populations. Modeling suggests that primary and secondary productivity and abundance of hermit crabs, snow crabs, resident seals, Pacific cod, and Pacific halibut affect octopus production.

While Steller sea lions (*Eumetopias jubatus*) are not a dominant predator of octopus, however, octopus are important prey item in the diet of Stellers in the Bering Sea. According to diet information from Perez (1990; Fig. 22.8) octopus are the second most important species by weight in the sea lion diet, contributing 18% of adult and juvenile diets in the Bering Sea. Diet information from Merrick et al (1997) for the AI, however, do not show octopus as a significant item in sea lion diets. Analysis of scat data (Sinclair and Zeppelin 2002) shows unidentified cephalopods are a frequent item in Steller sea lion diets in both the Bering Sea and Aleutians, although this analysis does not distinguish between octopus and squids. The frequency of cephalopods in sea lion scats averaged 8.8% overall, and was highest (11.5-18.2%) in the Aleutian Islands and lowest (<1 – 2.5%) in the western GOA. Based on ecosystem models, octopus are not significant components of the diet of northern fur seals (*Callorhinus ursinus*). Proximate composition analyses from Prince William Sound in the GOA (Iverson et al 2002) show that squid had among the highest high fat contents (5 to 13%), but that the octopus was among the lowest (1%).

Little is known about habitat use and requirements of octopus in Alaska (Table 22.8). In trawl survey data, sizes are depth stratified with larger (and fewer) animals living deeper and smaller animals living shallower. However, the trawl survey does not include coastal waters less than 30 m deep, which may include large octopus populations. Hartwick and Barriga (1997) reported increased trap catch rates in offshore areas during winter months. Octopus require secure dens in rocky bottom or boulders to brood its young until hatching, which may be disrupted by fishing effort. Activity is believed to be primarily at night, with octopus staying close to their dens during daylight hours. Hartwick and Barriga (1997) suggest that natural den sites may be more abundant in shallow waters but may become limiting in offshore areas. In inshore areas of Prince William Sound, Scheel (2002), noted highest abundance of octopus in areas of sandy bottom with scattered boulders or in areas adjacent to kelp beds.

Ecosystem Effects on the Stock

Distributions of octopus along the shelf break are related to water temperature, so it is probable that changing climate and ice cover in the Bering Sea is having some effect on octopus, but data are not adequate to evaluate these effects. A recent paper (Scheel, 2015) showed a negative correlation between annual beach counts of juvenile octopus in Prince William Sound and surface water temperatures in the eastern GOA during the preceding winter. Unusually warm surface temperatures have been occurring in the eastern North Pacific and appear to be causing some shifts in groundfish distributions. It is not clear whether these climate shifts are related to trends in octopus populations.

Fishery Effects on the Ecosystem

There is no directed fishery for octopus in the BSAI, but the majority of the incidental catch is taken in pot gear fished for Pacific cod. Catcher vessels have a limited time to deliver cod to processors (72-hour trip limit), so much of the cod pot effort in the BSAI is focused on areas near processors in Dutch Harbor and Akutan. To avoid gear conflicts with trawlers, cod pots are usually deployed inside of no-trawl zones or in rocky areas unsuitable for trawling. This results in most of the incidental octopus catch in the BSAI coming from specific areas near Unimak Pass. The effects of removal of Pacific cod and octopus from these specific areas is unknown. The low retention rate of octopus in the BSAI, and the high survival rate of discarded octopus (see Appendix 22.A2), suggest that effects on the octopus population is minor.

Data Gaps and Research Priorities

Recent efforts have improved collection of basic data on octopus, including catch accounting of retained and discarded octopus, full species identification of octopus during research surveys, and direct data on the life-history of *E. dofleini* in Alaskan waters. Both survey and observer efforts provide a growing amount of data on octopus size distributions by species and sex and spatial separation of species. Studies currently underway may lead to development of octopus-specific field methods for capture, tagging, and index surveys. The AFSC has kept in communication with the state of Alaska regarding directed fisheries in state waters, gear development, octopus biology, and management concerns.

Aging methods for octopus are not in common use but have been developed for some species based on daily ring structure in beaks, stylets, or statoliths (Perales-Raya eta l 2010, Lepoarti 2015). Preliminary investigation confirmed that the statoliths of *E. dofleini* are too soft and chalky for use in aging analysis, but showed definite structure in sections of beaks and stylets (Conners et al. 2012). Further research would be needed to examine these structures further and validate correlation between age and rings. If this research could develop a reliable aging protocol for *E. dofleini*, our understanding of its life cycle and growth patterns would be vastly improved.

We do not expect that either fishing industry employees or observers will be able to record accurate identification of octopus species on a routine basis. A publication on cephalopod taxonomy and identification in Alaska is available (Jorgensen 2009). Efforts to improve octopus identification during AFSC trawl surveys will continue, but because of seasonal differences between the survey and most fisheries, questions of species composition of octopus incidental catch may still be difficult to resolve. Special projects and collections in octopus identification and biology will be pursued as funding permits.

Because octopuses are semelparous (breeding only once), a better understanding of reproductive seasons and habits is needed to determine the best strategies for protecting reproductive output. *E. dofleini* in Japan and off the US west coast reportedly undergo seasonal movements, but the timing and extent of migrations in Alaska is unknown. While many octopus move into shallower coastal waters for egg-laying, it is probable that at least some BSAI octopus reproduction occurs within federal waters. The distribution of octopus biomass and extent of movement between federal and state waters is unknown and could become important if a directed state fishery develops. If feasible, it would be desirable to avoid harvest of adult females following mating and during egg development. Larger females, in particular, may have the highest reproductive output (Hartwick 1983).

Factors determining year-to year patterns in octopus abundance are poorly understood. Octopus abundance is probably controlled primarily by survival at the planktonic paralarval stage; substantial year-to-year variations in abundance due to climate and oceanographic factors are expected. The high variability in trawl survey estimates of octopus biomass make it difficult to depend on these estimates for time-series trends; trends in CPUE from observed cod fisheries may be more useful.

Fishery-independent methods for assessing biomass of the harvested size group of octopus are feasible, but would be species-specific and could not be carried out as part of existing multi-species surveys. Pot surveys are effective both for collecting biological and distribution data and as an index of abundance; mark-recapture methods have been used with octopus both to document seasonal movements and to estimate biomass and mortality rates. These methods would require either extensive industry cooperation or funding for directed field research.

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Table 22.1. Species of Octopodae found in the BSAI.

	Scientific Name	Common Name	General Distribution	Age at Maturity	Size at Maturity
Class	Cephalopoda				
Order	Vampyromorpha				
Genus	*Vampyroteuthis*				
Specie	***Vampyroteuthis infernalis***	vampire squid	Southeast BS Slope >300 m	unknown	unknown
Order	Octopoda				
Group	Cirrata				
Family	Opisthoteuthidae				
Genus	*Opisthoteuthis*				
Species	***Opisthoteuthis*** cf ***californiana***	flapjack devilfish	BS deeper than 200 m	unknown	unknown
Group	Incirrata				
	Bolitaenidae				
	Japetella				
	Japetella diaphana	pelagic octopus	Pelagic	unknown	< 300 g
Family	Octopodidae				
Genus	*Benthoctopus*				
Species	***Benthoctopus leioderma***	smooth octopus	Southern BS deeper than 250 m	unknown	< 500 g
	Benthoctopus oregonensis	none	BS shelf break	unknown	> 2 kg
Genus	*Enteroctopus*				
Species	***Enteroctopus dofleini***	giant octopus	all BSAI, from 50 - 1400 m	3 - 5 yr	>10 kg
Genus	*Graneledone*				
Species	***Graneledone boreopacifica***	none	BS shelf break 650 - 1550 m	unknown	unknown
Genus	*Sasakiopus*				
	Sasakiopus salebrosus	stubby octopus	BS shelf break, 200 - 1200 m	unknown	75 - 150 g

Table 22.2. Estimated catch (t) of all octopus species in state and federal waters. 1997-2002 estimated from blend data. 2003-2016 data from AK region catch accounting, as provided in October 2016. Catch is shown separately for the two target fisheries that have the highest rate of incidental octopus catch, Pacific cod and flatfish. The estimated percentage of total catch retained is shown for 2003-2016. *2016 data includes only part of the year, January –October 15, 2016.

	Target Species				
Year	**P cod**	**FlatFish**	**Other**	**Total**	**% Retained**
1997	160	86	3	248	
1998	168	13	9	190	
1999	310	14	2	326	
2000	359	57	3	418	
2001	211	9	7	227	
2002	334	21	19	374	
2003	211	34	19	269	38%
2004	279	45	246	338	24%
2005	311	17	10	338	64%
2006	332	5	14	351	55%
2007	156	7	9	178	39%
2008	196	11	8	214	37%
2009	58	10	6	73	23%
2010	162	11	6	177	33%
2011	565	9	14	587	6%
2012	127	4	8	137	17%
2013	218	2	4	224	21%
2014	405	21	7	432	25%
2015	410	24	12	446	17%
2016*	392	13	27	433	17%

Table 22.3. Species composition of octopus from recent AFSC Bering Sea shelf, slope, and Aleutian Islands bottom trawl surveys: numbers of hauls containing octopus and numbers of octopus caught by species.

	Bering Sea Shelf Survey							**Slope Survey**				**A.I. Survey**			
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2008**	**2010**	**2012**	**2016**	**2010**	**2012**	**2014**	**2016**
Number of Hauls	376	422	376	376	376	376	376	200	200	187	175	418	420	410	419
No. Hauls w/ Octopus	47	43	39	28	17	39	38	113	110	114		99	80	84	81
Species															
Enteroctopus dofleini	124	69	48	29	26	68	44	57	63	76	40	162	69	84	81
Sasakiopus salebrosus	17				1		11	73	94	72	47		3		
Benthoctopus leioderma	4	14	29	16	12	20	15	89	62	66	27		3		
Graneledone boreopacifica								41	33	57	11				
Opisthoteuthis californiana								39	39	190	40		1		
Benthoctopus oregonensis								8	3		18				
Japetella diaphana								16	1	3	5				
Octopus sp.								1		3					
Benthoctopus sp.								1	18			1			
octopus unident.		11	1	20	7	3	1		1		4	6	4	12	8
All species	145	94	78	65	46	91	71	325	315	467	192	169	162	96	89

Table 22.4. Species composition of octopus from recent AFSC Bering Sea bottom trawl surveys: biomass estimates by species.

	Estimated Biomass (t)										
	EBS Slope Survey				**EBS Shelf Survey**						
Species	**2008**	**2010**	**2012**	**2016**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Enteroctopus dofleini	356.8	216.3	659.2	565.7	650.0	2,844	2,087	1,654	2,095	5,248	6,997
Graneledone boreopacifica	84.0	96.1	248.1	142.7							
Benthoctopus leioderma	155.8	86.6	134.7	132.5	27.0	250.0	479	97	157	113	328
Benthoctopus sp.	0.44	76.9						1.5			
Benthoctopus sibiricus								39.9			
Opisthoteuthis californiana	156.1	70.4	342.4	1205.9							
Sasakiopus salebrosus	23.6	32.2	28.6	51.1	142.5				3.6		188.2
Benthoctopus oregonensis	28.1	27.8		150.9				13.0	93.4		
Opisthoteuthis sp.		14.6									
Japetella diaphana	10.0	0.5	6.4	8.6							
Vampyroteuthis infernalis		0.1									
octopus unident.	0.01	0.0	1.3	5.3	0.2	460	0.1	4.4	2.0	1.7	0.8
All species	814.9	621.4	1,421	2,263	823	3,554	2,567	1,769	2,351	5,636	7,513
Pecentage *E. dofleini*	44%	35%	46%	25%	79%	80%	81%	94%	89%	93%	93%

Table 22.5. Biomass estimates in tons for octopus (all species) and coefficients of variation (CV) of the estimates from AFSC bottom trawl surveys.

	EBS Shelf		EBS Slope		AI		BSAI
Year	Survey Biomass	CV	Survey Biomass	CV	Survey Biomass	CV	Total Biomass
1982	13,076		180				
1983	3,517				260	(0.22)	
1984	2,647						
1985	2,582		152				
1986	510				250	(0.33)	
1987	7,813	(0.52)					
1988	9,935	(0.29)	138				
1989	4,910	(0.33)					
1990	11,619	(0.48)					
1991	8,114	(0.34)	61		1,159	(0.20)	9,334
1992	5,611	(0.42)					
1993	1,588	(0.34)					
1994	2,479	(0.39)			1,727	(0.20)	
1995	2,928	(0.59)					
1996	1,804	(0.68)					
1997	255	(0.40)			1,219	(0.25)	
1998	1,285	(0.51)					
1999	832	(0.52)					
2000	2,031	(0.41)			790	(0.31)	
2001	5,908	(0.32)					
2002	2,525	(0.44)	979	(0.18)	1,393	(0.26)	4,897
2003	8,244	(0.46)					
2004	4,957	(0.31)	1,957	(0.14)	4,096	(0.35)	11,010
2005	10,219	(0.28)					
2006	1,903	(0.34)			3,062	(0.18)	
2007	2,278	(0.29)					
2008	1,174	(0.43)	781	(0.17)			
2009	1,028	(0.54)					
2010	820	(0.48)	621	(0.15)	3,075	(0.33)	4,516
2011	3,554	(0.30)					
2012	2,567	(0.32)	1,419	(0.21)	2,779	(0.44)	6,765
2013	1,810	(0.50)					
2014	2,351	(0.49)			2,845	(0.22)	
2015	5,363	(0.30)					
2016	7,513	(0.44)	2,263	(0.13)	3,833	(0.29)	13,608

Table 22.6. Numbers of Pacific cod stomach samples analyzed for octopus consumption estimates. New data for the current update of consumptions calculations are highlighted.

Year	Stomach Samples
1984	636
1985	952
1986	1,338
1987	747
1988	551
1989	1,662
1990	1,121
1991	1,546
1992	1,876
1993	2,303
1994	2,381
1995	2,395
1996	1,314
1997	1,155
1998	1,262
1999	1,049
2000	1,101
2001	1,304
2002	1,334
2003	1,770
2005	408
2006	671
2007	578
2008	1,204
2009	1,312
2010	1,169
2011	1,511
2014	1,617
2015	1,893

Table 22.7. Results of different approaches for calculating a long-term mean value from annual consumption estimates. The geometric mean is recommended by the authors and accepted by the plan team.

Method:		**Value (t)**
Median		5,055
Arithmetic Mean		6,842
Geometric Mean		**4,769**
Harmonic Mean		2,653

Table 22.8. Analysis of ecosystem considerations for the octopus complex.

Ecosystem effects on *BSAI octopus*			
Indicator	Observation	Interpretation	Evaluation
Prey availability or abundance trends			
Zooplankton	Stomach contents, ichthyoplankton surveys, changes mean wt-at-age	Stable, data limited	Unknown
Non-pandalid shrimp and other benthic organism	Trends are not currently measured directly, only short time series of food habits data exist for potential retrospective measurement	Benthic bivalves and crustaceans principal prey for all sizes	Unknown
Sandlance, capelin, other forage fish	Trends are not currently measured directly, only short time series of food habits data exist for potential retrospective measurement	Prey of larger octopus	Unknown
Salmon	Populations are stable or slightly decreasing in some areas	Unlikely to be important in octopus diet	No concern
Flatfish	Increasing to steady populations currently at high biomass levels	May be part of adult diet	No concern
Pollock	High population levels in early 1980's, declined to stable low level at present	Unlikely to be important in octopus diet	No concern
Other Groundfish	Stable to low populations	May be part of adult diet	No concern
Predator population trends			
Marine mammals	Fur seals declining, Steller sea lions increasing slightly	Both prey on octopus; importance unknown	Unknown
Birds	Stable, some increasing some decreasing	Unlikely to affect octopus	Unknown
Fish (Pollock, Pacific cod, halibut)	Stable to increasing	Possible increases to mortality	Unknown
Sharks	Stable to increasing	Predation on octopus unknown	Unknown
Changes in habitat quality			
Temperature regime	Warm and cold regimes	May shift distribution, depth selection, or growth rates	Unknown

***BSAI octopus* effects on ecosystem**			
Indicator	Observation	Interpretation	Evaluation
Fishery contribution to bycatch			
Not Targeted	Some market value, retention of incidental catch. Current level of fishery catch small in relation to estimated predation mortality.	No concern	No concern
Fishery concentration in space and time	Octopus catch concentrated in areas of Pacific cod pot fishing, esp. around Unimak pass.	Possible overlap of fishery with two SSL rookeries	Unknown
Fishery effects on amount of large size target fish	Pot fishing catches predominantly large males, unknown seasonal timing of fishing vs. mating	No concern at this time	Unknown
Fishery contribution to discards and offal production	None. Discards from pot vessels have low immediate and short-term mortality.	No concern	No concern
Fishery effects on age-at-maturity and fecundity	Unknown	No concern at this time	Unknown

Figure 22.1. Distribution of octopus (all species) in the BSAI, based on octopus occurring in observed hauls during the period 1990-1996.

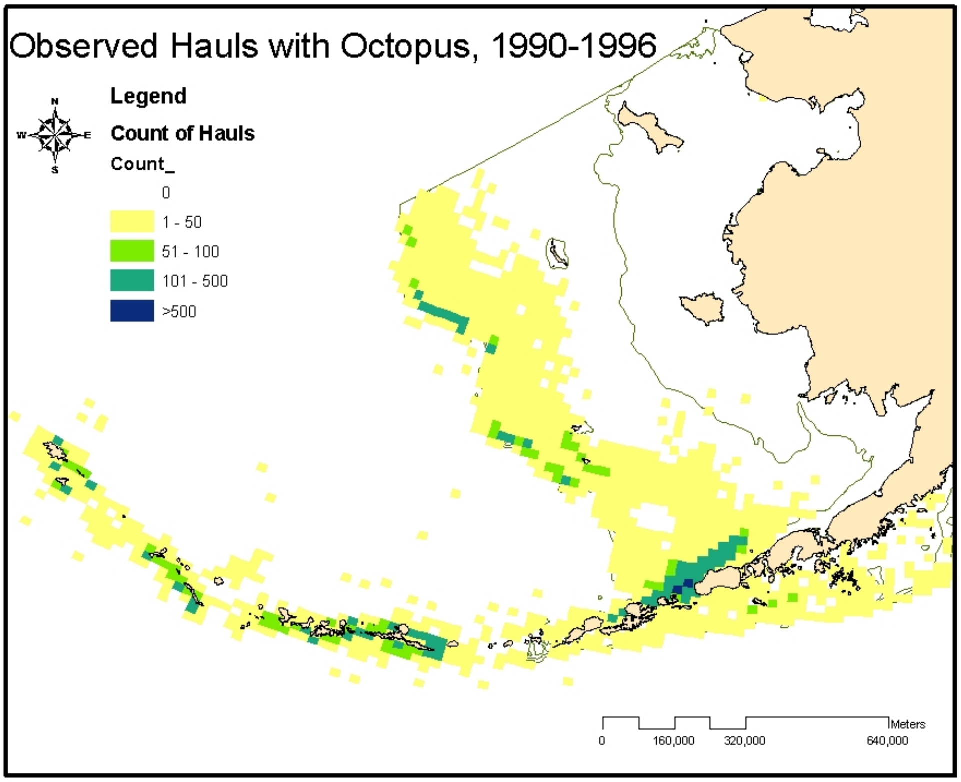


Figure 22.2. Size frequency of individual octopus (all species) from Bering Sea shelf bottom trawl surveys 2009 - 2011.

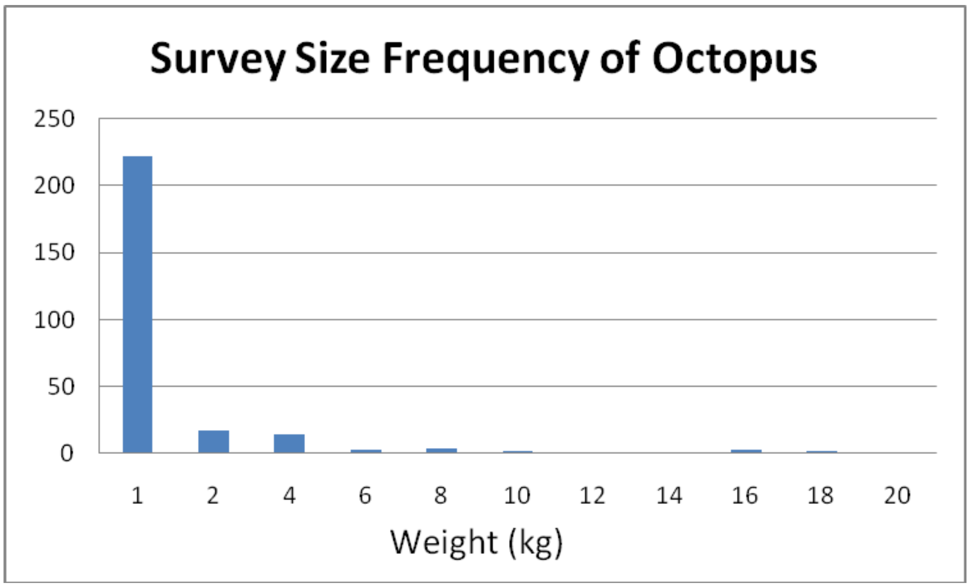
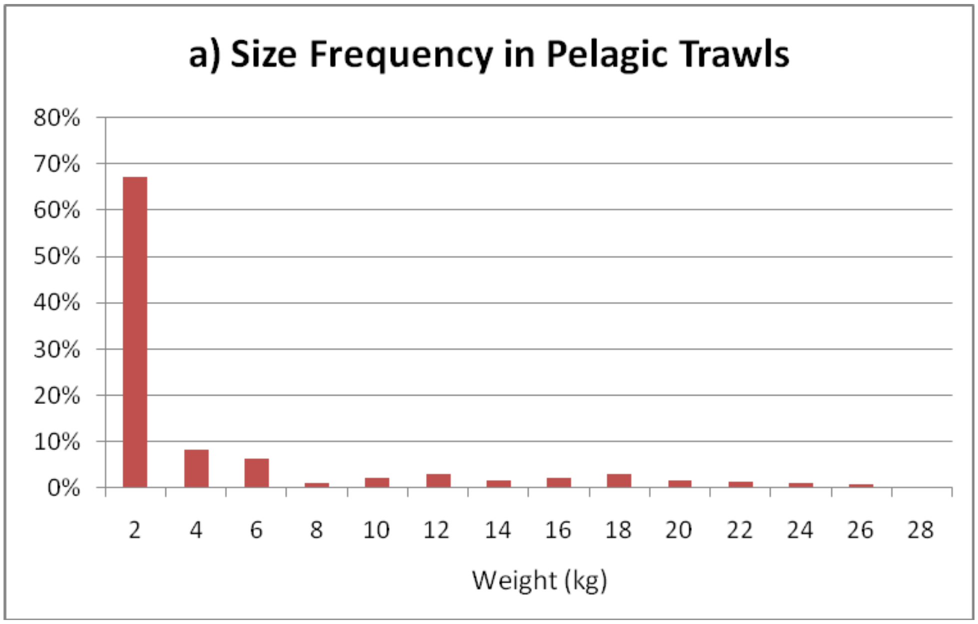


Figure 22.3. Size frequency of individual octopus from observer special project 2006-2011 by gear type: a) pelagic trawl, b) bottom trawl, c) pots, d) longline.



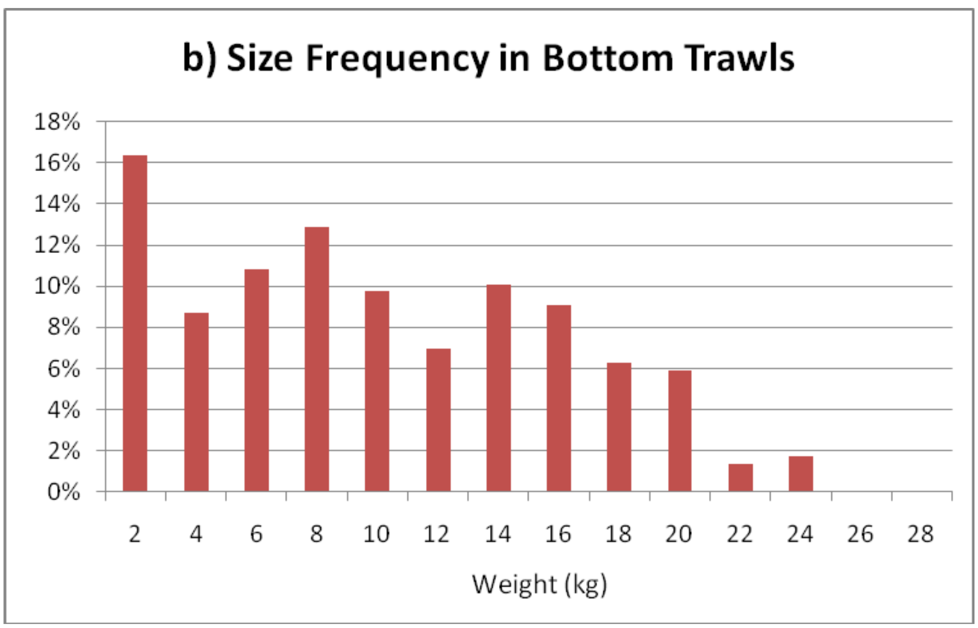
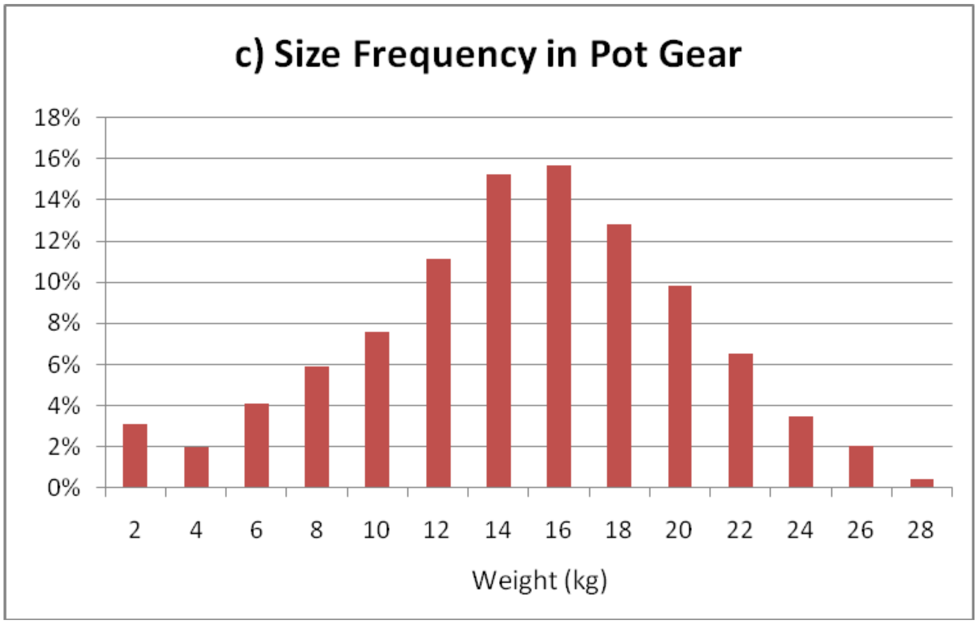


Figure 22.3. Continued.



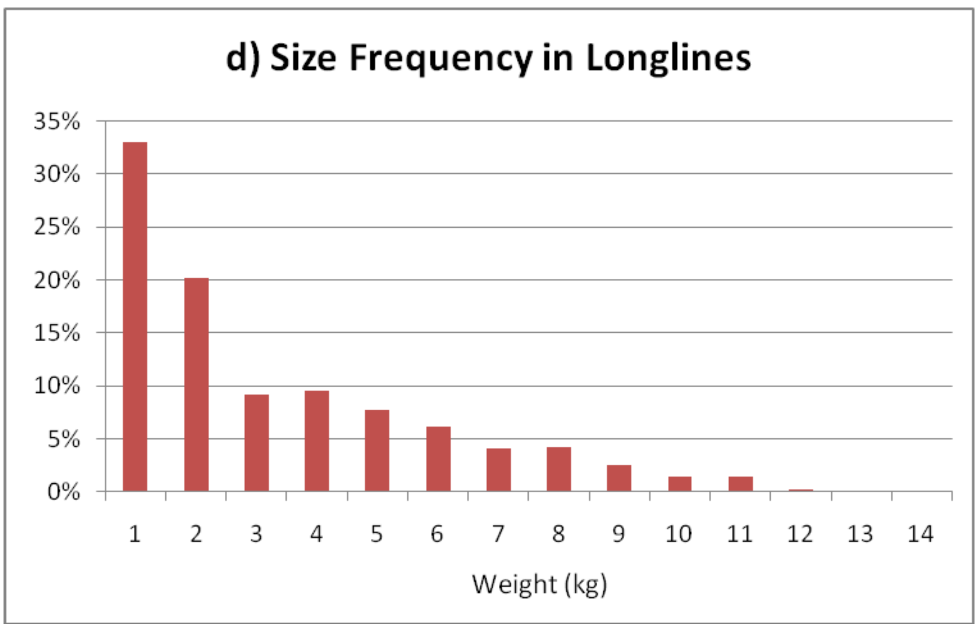


Figure 22.4. Biomass estimates (t) of octopus (all species) from the Bering Sea shelf survey, with 95% confidence intervals shown.

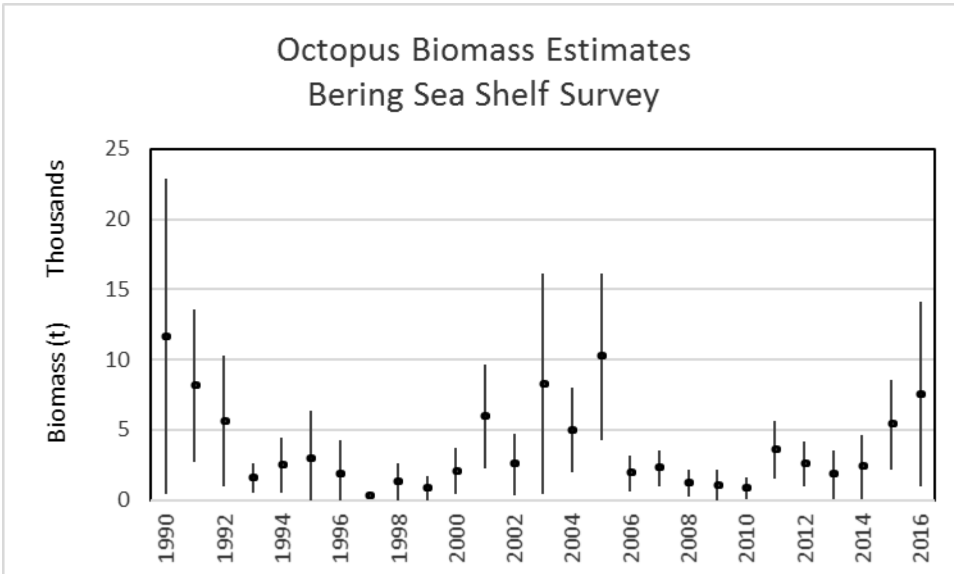
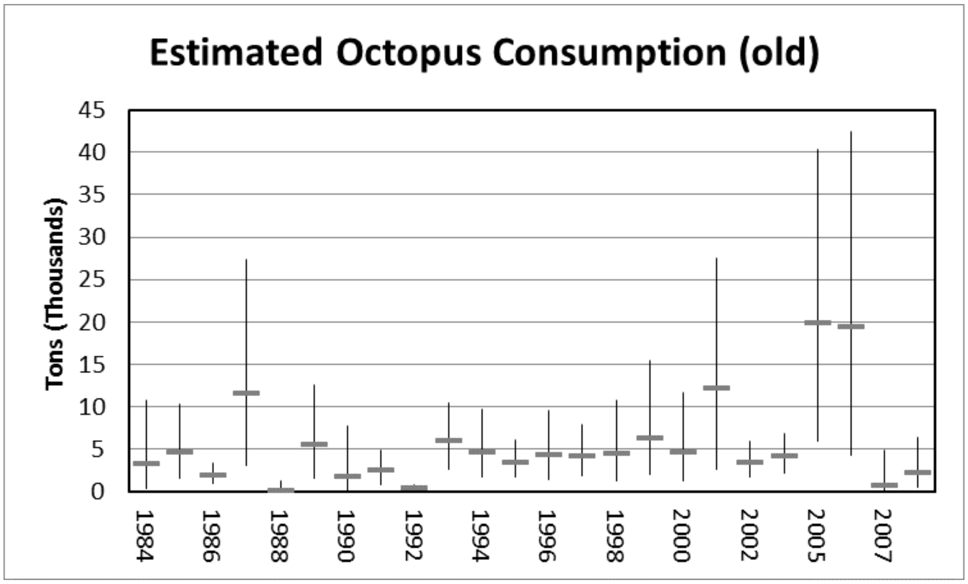


Figure 22.5. Estimated consumption of octopus by Bering Sea Pacific cod, 1984-2008. Error bars show 95% confidence intervals of posterior distribution; solid bars are annual hyperbolic means. The top chart shows estimates made in 2011, the bottom chart shows new estimates from updated data set.



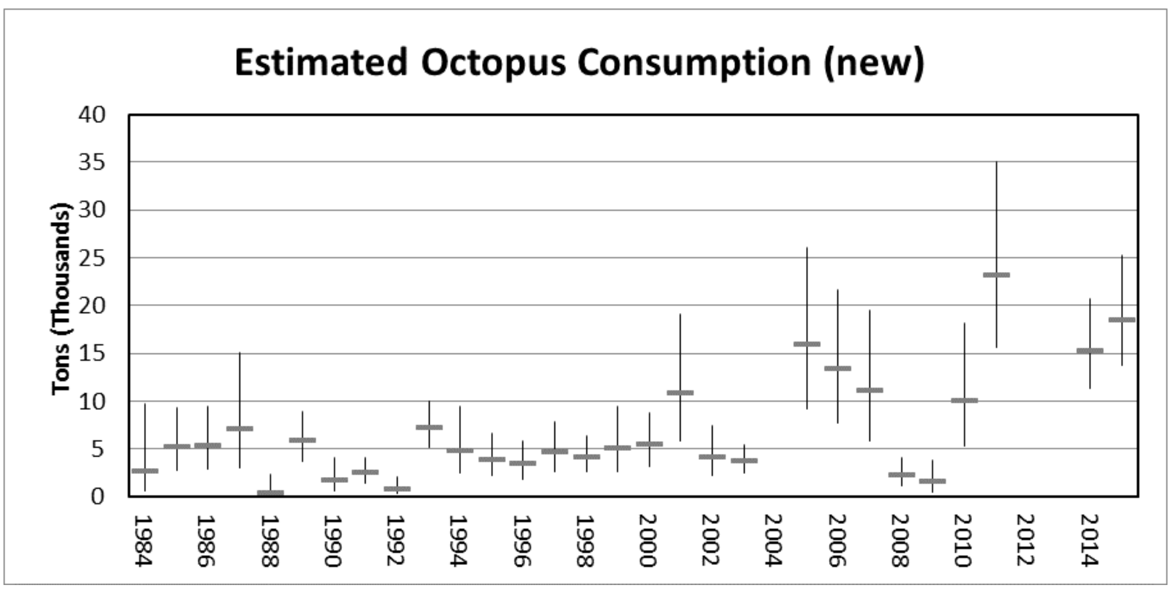
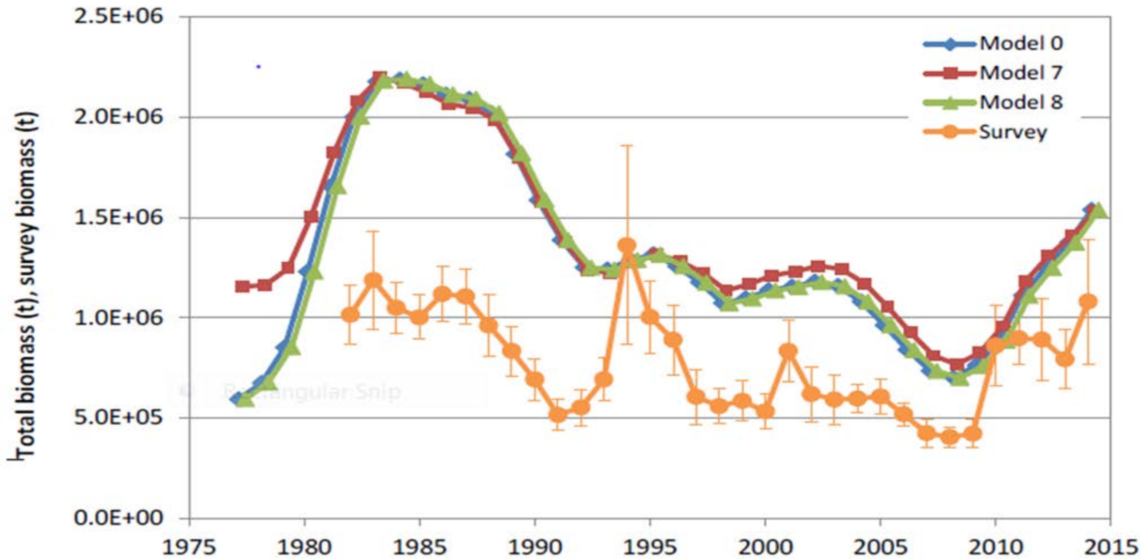


Figure 22.6 Time series trends in a) the biomass of Bering Sea Pacific cod and b) the proportion of octopus in cod diets.



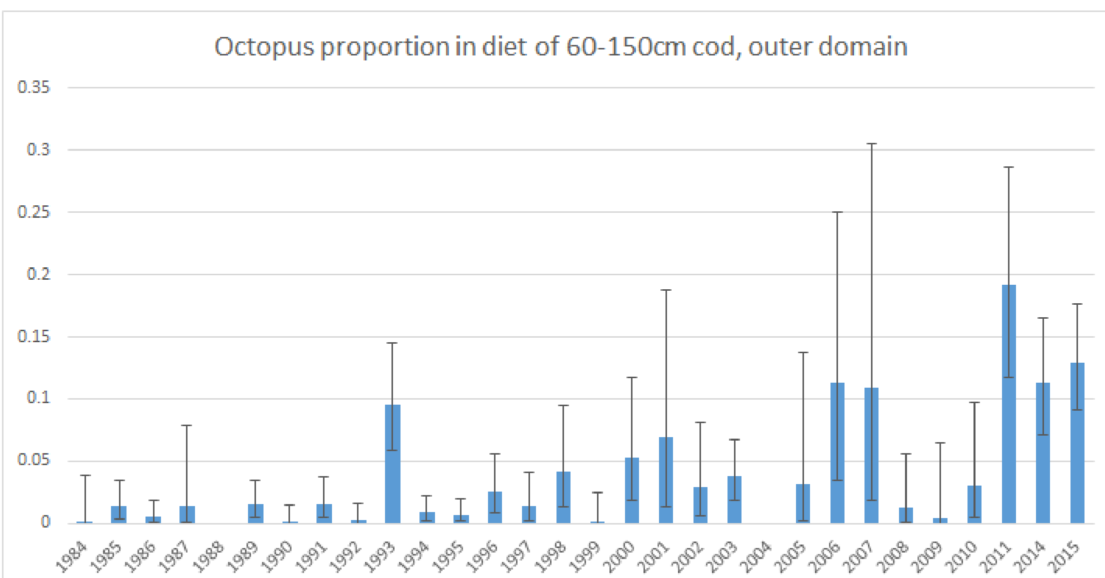
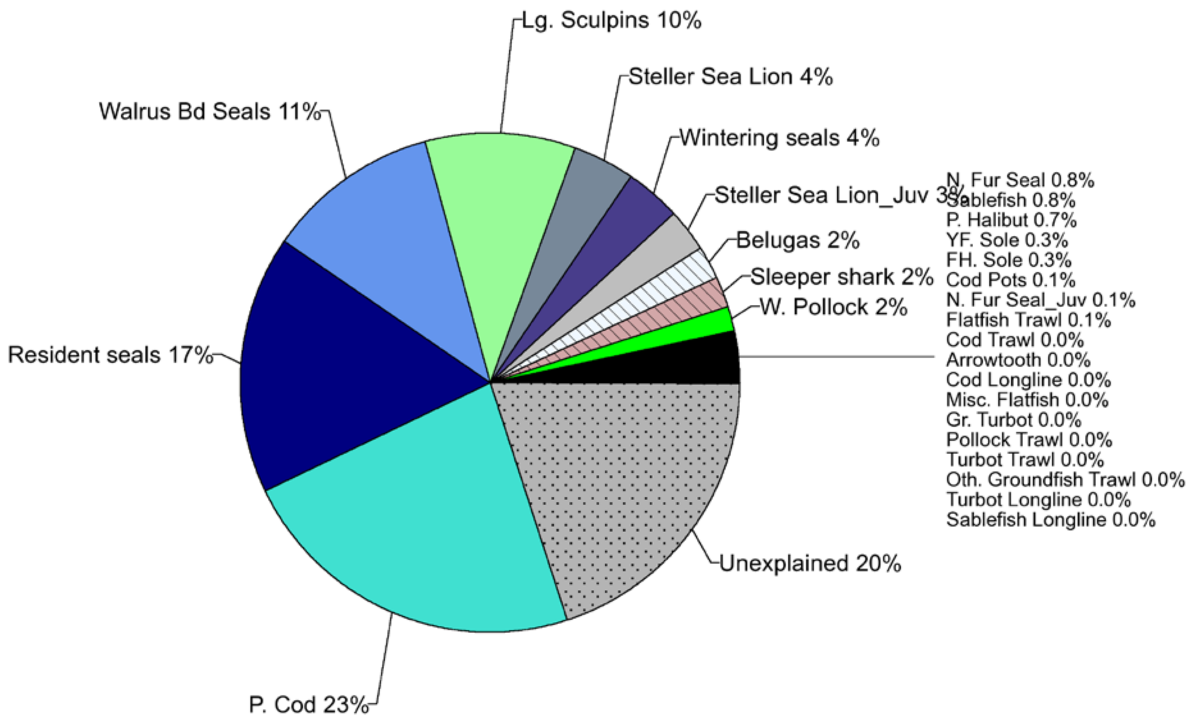


Figure 22.7. Ecopath model estimates of mortality sources of octopus in the BSAI.

a) Bering Sea Ecosystem



b) Aleutian Islands Ecosystem

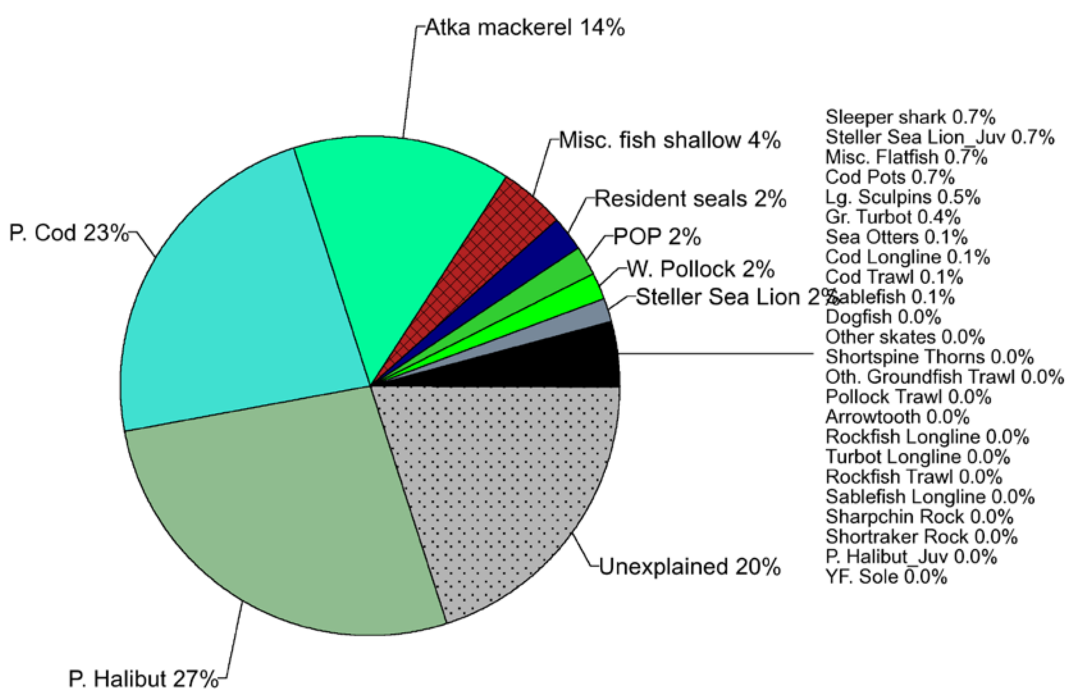
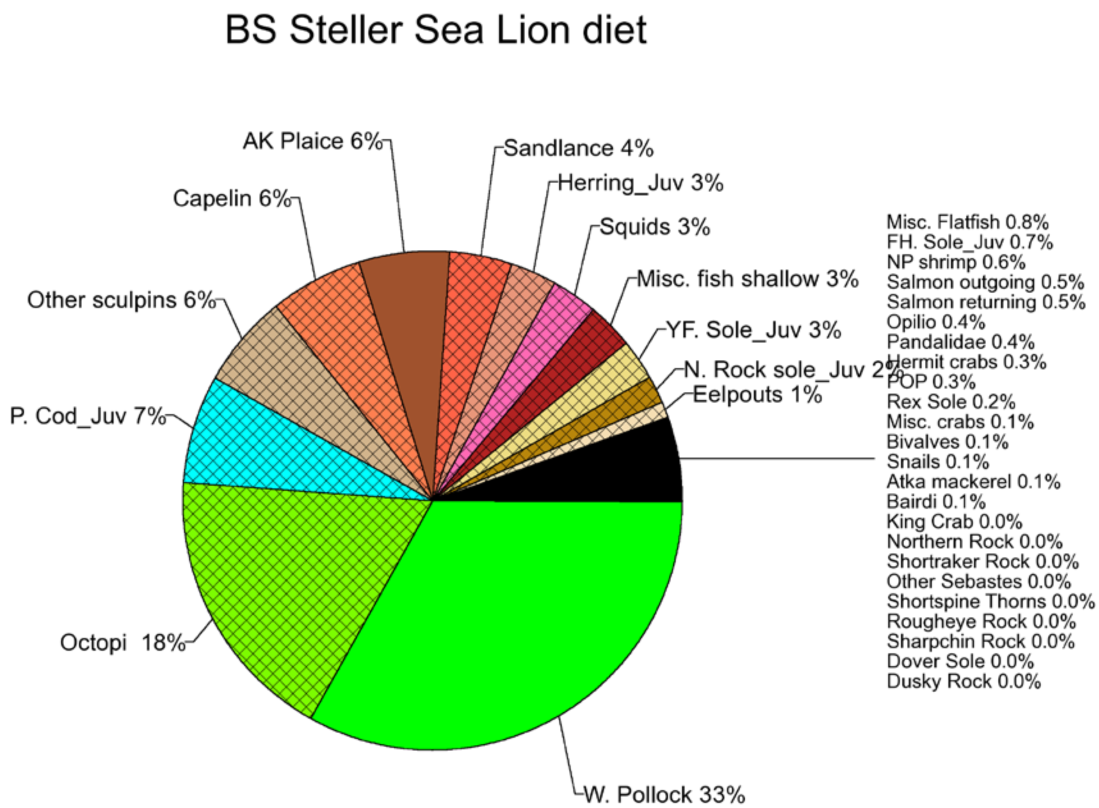
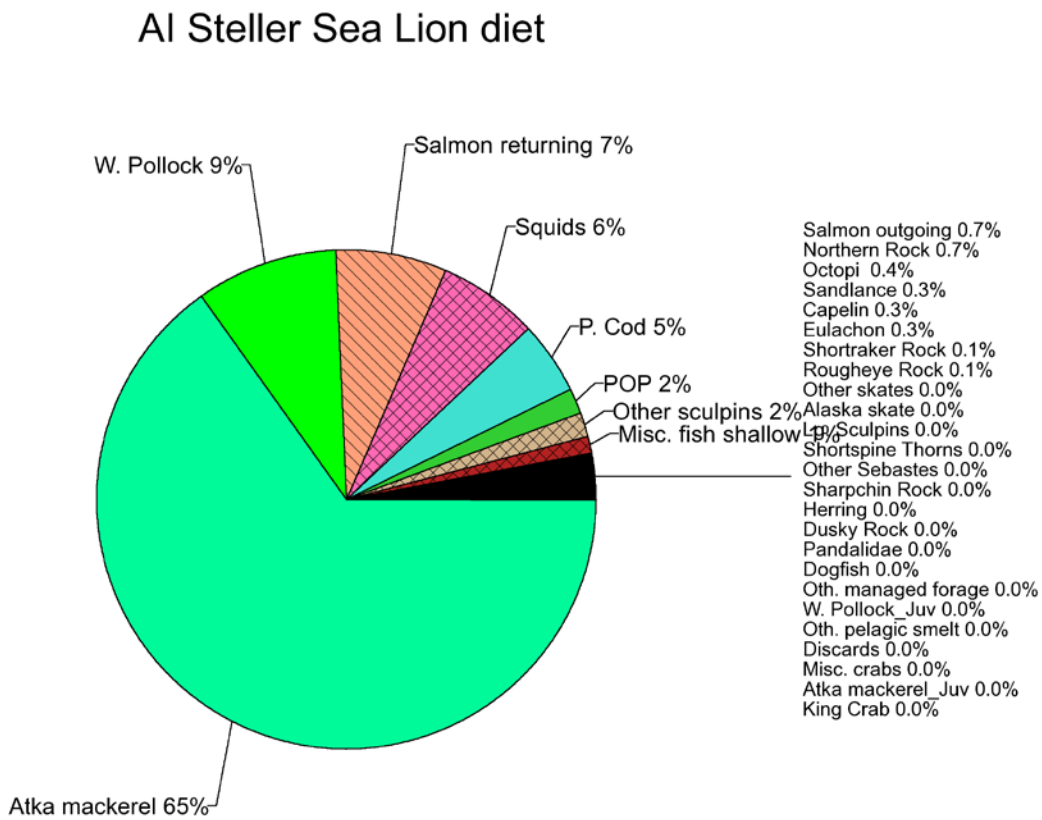


Figure 22.8. Literature-derived diets of Steller sea lions in the BS and AI.




AI Steller Sea Lion diet
W. Pollock 9%
Salmon returning 7%
Squids 6%
P. Cod 5%
POP 2%
Other sculpins 2%
Misc. fish shallow 1%
Atka mackerel 65%
Salmon outgoing 0.7%
Northern Rock 0.7%
Octopi 0.4%
Sandlance 0.3%
Capelin 0.3%
Eulachon 0.3%
Shortraker Rock 0.1%
Rougheye Rock 0.1%
Other skates 0.0%
Alaska skate 0.0%
Lg. Sculpins 0.0%
Shortspine Thorns 0.0%
Other Sebastes 0.0%
Sharpchin Rock 0.0%
Herring 0.0%
Dusky Rock 0.0%
Pandalidae 0.0%
Dogfish 0.0%
Oth. managed forage 0.0%
W. Pollock_Juv 0.0%
Oth. pelagic smelt 0.0%
Discards 0.0%
Misc. crabs 0.0%
Atka mackerel_Juv 0.0%
King Crab 0.0%

Appendix 22.A1 Methods for Estimation of total natural mortality of BSAI octopus

Pacific cod food habits analysis

Since 1982, the Alaska Fisheries Science Center has collected and analyzed the stomachs of Pacific cod (*Gadus macrocephalus*) from the Bering Sea, the Gulf of Alaska, and the Aleutian Islands. For the descriptive work in this section, the total sample size was 48,665 from the Bering Sea, 9,200 from the Gulf of Alaska, and 4,528 from the Aleutian Islands. For the final sample sizes used in the Bering Sea assessment, see Table 22.6. Stomachs are primarily collected on RACE groundfish surveys during the summer, but substantial additional samples have been collected by fisheries observers throughout the winter (Figure 22.A1.1). For these estimates, we have used samples collected during the summer groundfish survey only, as winter samples, associated with observed fishing operations, do not provide full geographic coverage for making population-level estimates (Figure 22.A1.1, bottom panel).

Stomachs are analyzed on shipboard or preserved in a buffered neutral, 10% formalin and seawater solution and analyzed in the lab. Stomach content analysis in the laboratory provides data on the composition of the contents in an individual stomach. Total stomach content weight is recorded to the decagram (0.01g) and wet weight, exact count, and weight (0.001g) is recorded for all individual prey types. Fish and crabs are identified to species whenever possible; other prey items such as zooplankton are generally identified to family. Octopus are identifiable as "octopus" and not generally identified to species.

Octopus occur in cod stomachs in both the summer and the winter (red circles, Figure 22.A1.1) and so represent a regular, but not majority diet item for Pacific cod. Pooling across all years and regions, octopus is considerably lower in diets in water shallower than 75m, increasing to approximately 10% occurrence in cod captured between 100-250m depth (Figure 22.A1.2, top). Octopus consumption also shows a strong relationship with Pacific cod length, being rare in cod with fork lengths less than 40cm, increasing to 7% for 60cm+ cod (Figure 22.A2, bottom). Initial exploration with Generalized Additive Models (GAMs) suggests that the depth and length relationships are relatively independent and not a function of season or year.

The diets of Pacific cod for all years and seasons combined, broken out by region (AI, BS, and GOA) and depth (<100m and ≥100m) are shown in Figures 22.A1.3-22.A1.4. Generally, small cod feed on zooplankton, transitioning to benthos and shrimp, and finally to fish, primarily pollock in the BS and GOA and Atka mackerel (part of "other fish") in the AI. Octopus are nearly absent from the diet of cod in shallower water (Figure 22.A1.3). In deeper water, for larger size classes of cod, octopus are up to 10% of prey by weight (Figure 22.A1.4).

The weight (and therefore age or life stage) of octopus consumption is an important consideration when comparing to fisheries data. Octopus specimens recovered from Pacific cod stomachs are not directly measureable to individual weight, due to digestion. However octopus beaks are hard parts that are frequently recovered whole. To measure the size of consumed octopus, in 2012 we worked to obtain data to calibrate regressions between octopus weight and octopus beak hood length (both the upper and lower beaks). This year, we obtained whole octopus from fisheries samples and developed an initial regression between beak size and octopus weight (Figure 22.A1.5, top); the regressions showed a strong relationship. Further, we are currently measuring all octopus beaks found in Pacific cod stomachs, the initial data (from 2011 samples) are shown in Figure 22.A1.5, bottom).

Results of these measurements indicate that the largest beaks eaten by cod generally correspond with the smallest (1-2kg) octopus in the commercial samples, with the majority of octopus eaten by cod being smaller (Figure 22.A1.6, compare top and bottom graphs). However, an exact weight frequency is not obtainable at this time, both due to limited sampling to date, and the lack of smaller octopus in the regression set. We have obtained samples of smaller whole octopus to extend the regression, and expect to develop better weight frequency over the next 1-2 years.

However, it is also important to note that there is a strong relationship between size of octopus beak and size of cod, with larger cod feeding on larger octopus (Figure 22.A1.6); the larger cod, with higher ration and larger percentage of octopus in diet, do overlap in size composition with the smaller octopus in the fisheries, although insufficient data exists for a quantitative weight frequency or weight-specific mortality calculation.

Estimation of annual consumption of octopus by Pacific cod

Cod predation on octopus was estimated using the following formula: $C_y = \sum_{s,l} N_{y,s,l} \cdot R_l \cdot DC_{y,s,l}$, where C_y is the total consumption (t/year) of octopus by cod in a given year y; $N_{y,s,l}$ is the number of cod in the bottom trawl survey for year y, survey stratum s, and length l; R_l is the annual ration for a cod (t prey/cod), and $DC_{y,s,l}$ is the proportion by weight of octopus in the diet of cod by year, stratum, and cod length. Therefore, the units of t/year octopus are the same as the units of the combined **M·B** caused by cod, while not relying on separate estimates of M or B for octopus. **It is important to note that, while this combined estimate of C_y (octopus consumed by cod) replaces the usual Tier 5 M·B reference point, it is neither possible nor necessary for this method to provide separate estimates for either of M or B.** Further, it should be noted that the quantity **M·B is an equilibrium reference quantity, so multiple years of estimates should be treated as improving the single reference point, rather than used as a moving average for catch.** This is especially important to the extent interannual variation is driven by predator fluctuations (cod); changing the reference point to track changing annual estimates would have the effect of increasing catch limits when predation is higher overall, leading in theory to greater fluctuations in the stock.

The EBS was divided into a total of 6 (standard areas 1-6) survey strata based on NW/NE orientation and depth. For diet composition calculations, cod were divided into 3 length classes based on the ontogenetic shifts in diet as shown in Figure 22.A1.2: 10-40cm, 40-60cm, and 60+cm. Numbers and ration for cod were calculated for 10cm size bins, then summed into the larger bins before being applied to diet compositions for the final estimates.

Each of the quantities N, R, and DC were estimated as follows:

1. Predator numbers $N_{y,s,l}$ were directly estimated from trawl survey numbers of Pacific cod for 10 cm increments of cod, including 95% confidence intervals from the survey for each stratum and length bin. Since a comparison between survey biomass and stock assessment biomass of Pacific cod indicates that survey catchability is less than 1, using survey numbers therefore leads to a conservative estimate of overall cod numbers, and therefore a conservative estimate for predation.

2. Ration R_l for each 10cm size bin was estimating following the methods of Essington et al. (2001) by fitting the generalized von Bertalanffy growth equation to weight-at-age data for GOA Pacific cod,as described in Holsman and Aydin (2015). The generalized Von Bertalanffy growth equation assumes that both consumption and respiration scale allometrically with body weight, and change in body weight over time (dW/dT) is calculated as follows:

$$\frac{dW_t}{dt} = H \cdot W_t^d - k \cdot W_t^n \qquad (1)$$

Here, W_t is body mass, t is the age of the fish (in years), and H, d, k, and n are allometric parameters. The term $H \cdot W_t^d$ is an allometric term for "useable" consumption over a year, in other words, the consumption (in wet weight) by the predator after indigestible portions of the prey have been removed and assuming constant caloric density between predator and prey. Total consumption is calculated as $(1/A) \cdot H \cdot W_t^d$, where A is a scaling fraction between predator and prey wet weights that accounts for indigestible portions of the prey and differences in caloric density. While A=0.6 is appropriate for bony fishes (40% indigestible loss), efficiency of conversion of octopus would be expected to by higher due to fewer hard parts, but measurements of digestibility are not available; therefore, to provide the most conservative estimate of consumption, an A=1.0 was used. The term $k \cdot W_t^n$ is an allometric term for the amount of biomass lost yearly as respiration.

Based on an analysis performed across a range of fish species, Essington et al. (2001) suggested that it is reasonable to assume that the respiration exponent n is equal to 1 (respiration linearly proportional to body weight). In this case, the differential equation above can be integrated to give the following solution for weight-at-age:

$$W_t = W_\infty \cdot \left(1 - e^{-k(1-d)(t-t_0)}\right)^{\frac{1}{1-d}} \qquad (2)$$

Where W_∞ (asymptotic body mass) is equal to $(H/k)^{\frac{1}{1-d}}$, and t_0 is the weight of the organism at time=0. From measurements of body weight and age, equation 2 can be used to fit four parameters (W_∞, d, k, and t_0) and the relationship between W_∞ and the H, k, and d parameters can then be used to determine the consumption rate $H \cdot W_t^d$ for any given length class of fish.
For these calculations, weight-at-age data available and specific to the modeled regions were fit by minimizing the difference between log(observed) and log(predicted) body weights from Pacific cod survey weight-at-age data. Separate estimates were performed for the GOA and EBS using AD Model Builder; estimates included MCMC-generated confidence intervals for ration (Figure 22.A1.7). Interannual differences in consumption were not calculated.

2. Diet Composition $DC_{y,s,l}$ was calculated for each year and stratum for three size classes of Pacific cod: (0-40cm, 40-60cm, and 60cm+). **If a stratum, year, and size class combination contained less than 10 stomach samples, the consumption of octopus in that stratum was assumed to be 0.** This was done to represent a conservative effort; methods of smoothing from neighboring strata were attempted but the noise of the data led to low confidence in such smoothed estimates.
For each fish in the sample, stomach content weight was normalized by predator body weight as calculated through a length/weight regression; the total normalized octopus weight for all the fish in that stratum, and the normalized sum of all prey items, was converted into a percentage by weight. To calculate confidence intervals, this sample set was used to bootstrap 10,000 sample sets with replacement, and following the methods outlined in Ainsworth et al. (2010), a Dirchlet distribution was estimated from the resampled data using the estimation method in the VGAM R package. This allowed for the calculation of confidence intervals for octopus diet proportion from the resulting fit Dirichlet distribution.

Figure 22.A1.1. Locations of all sampled Pacific cod stomachs (black circles; N=62,393) and stomachs containing octopus (red circles), 1982-2011, for May-September (top panel) and October-April (bottom panel).

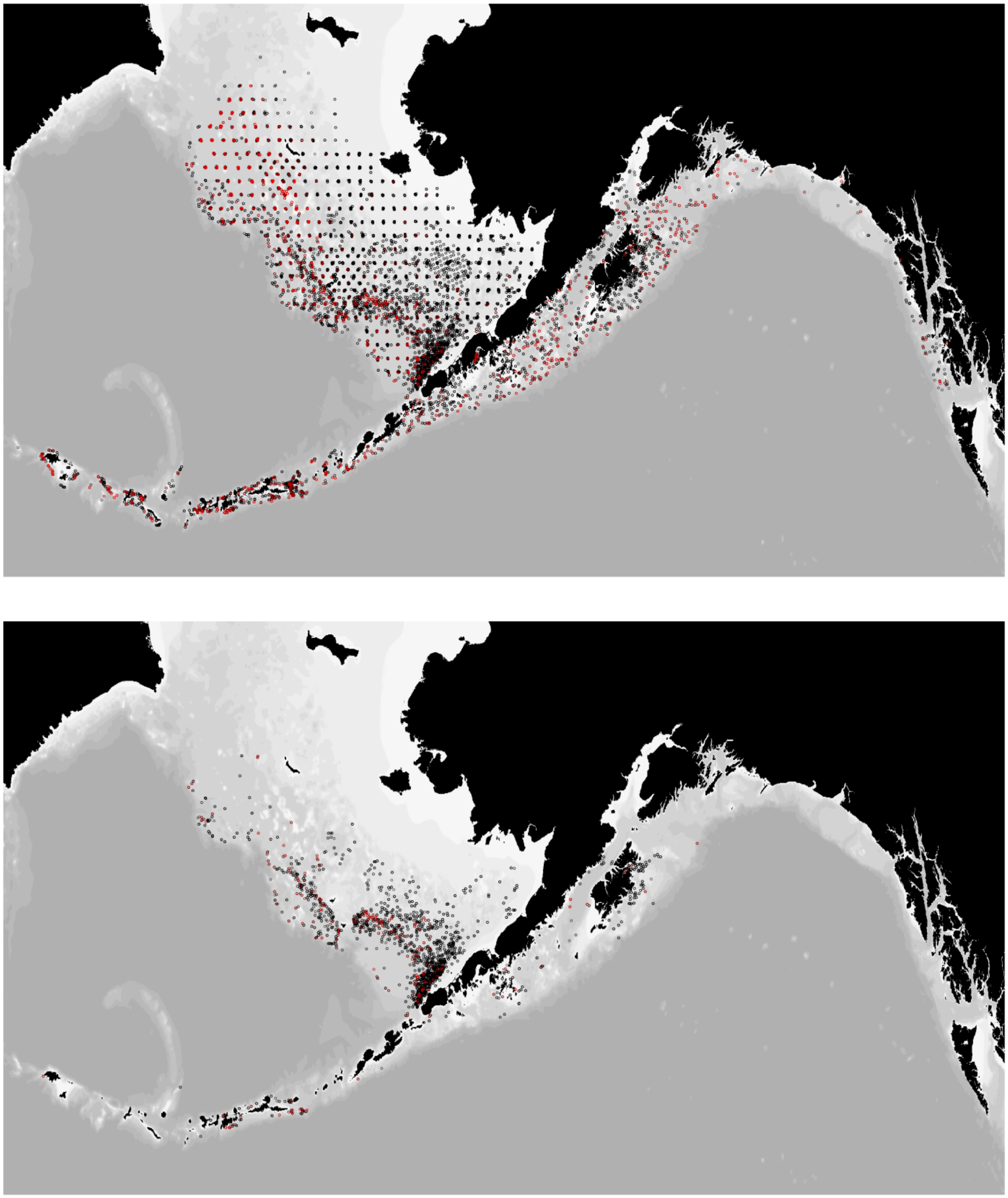


Figure 22.A1.2. Frequency of occurrence of octopus in Pacific cod stomachs, all years, regions, and seasons, as a function of bottom depth (top panel) and Pacific cod fork length (bottom panel). Gray area shows the 95% confidence interval calculated from logit-transformed data (empirical logit transformation).

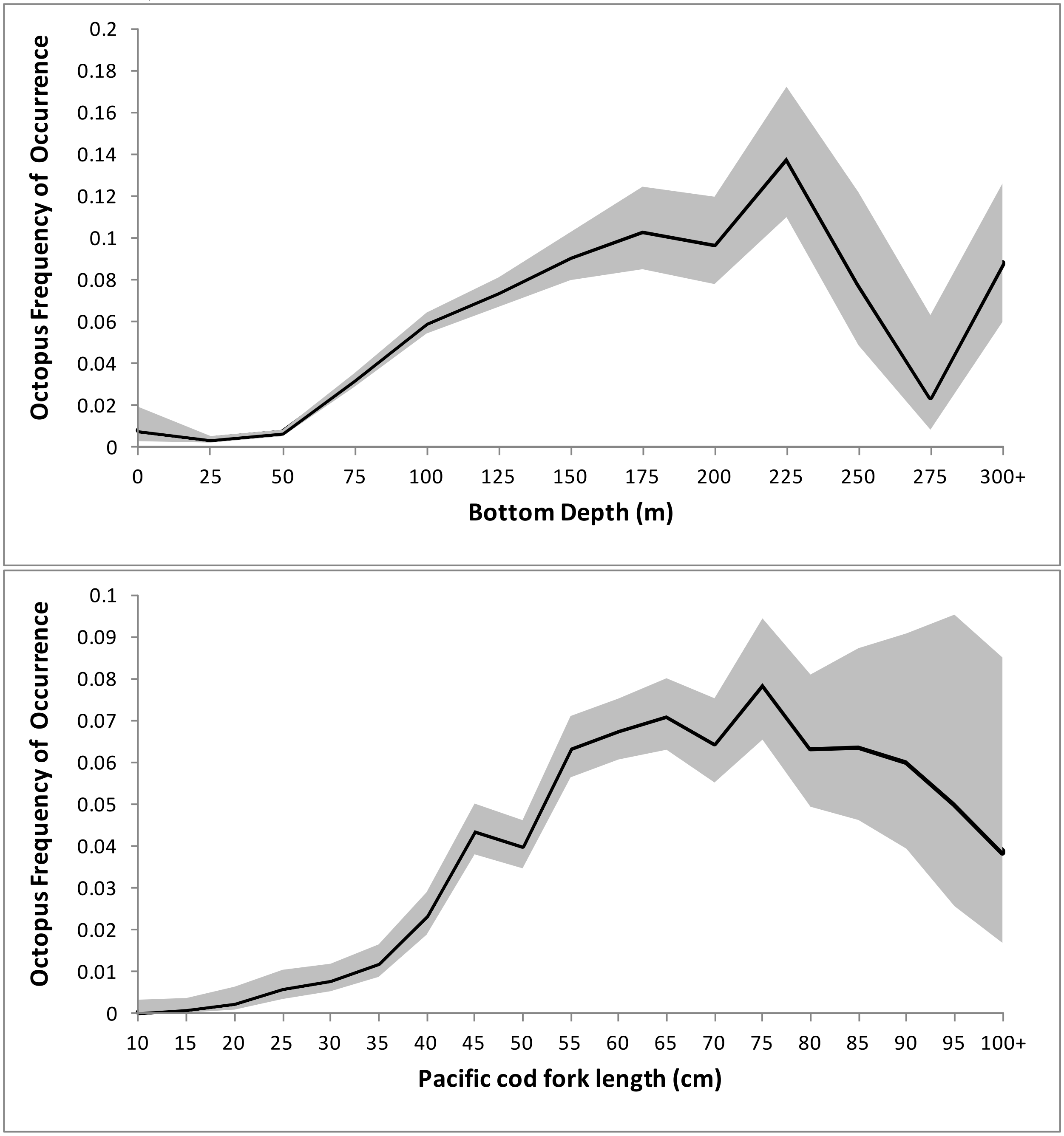


Figure 22.A1.3. Percent diet by weight in Pacific cod stomachs sampled in water **<100m**, all years and seasons, for Aleutian Islands (top panel), Bering Sea (middle panel), and Gulf of Alaska (bottom panel).

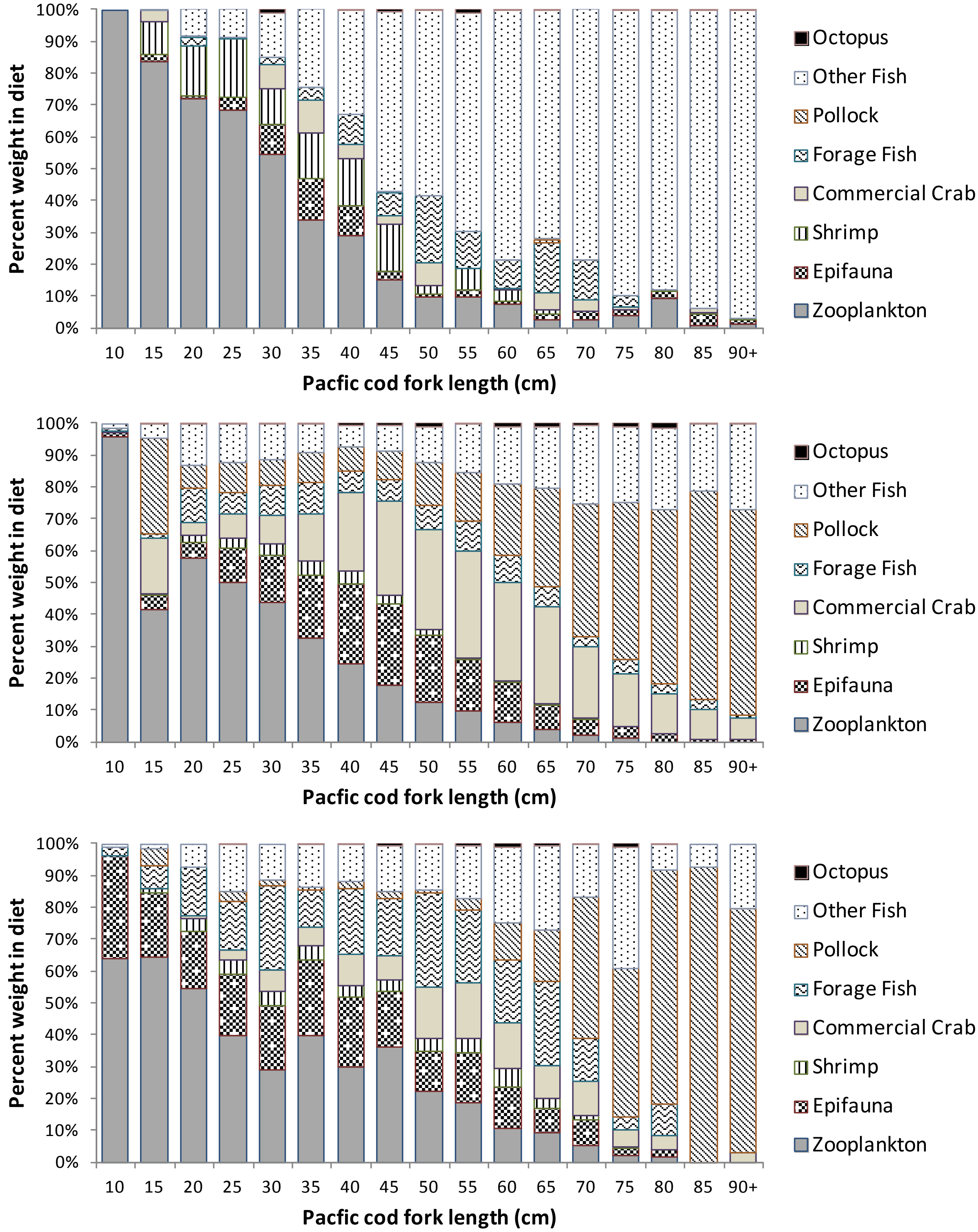


Figure 22.A1.4. Percent diet by weight in Pacific cod stomachs sampled in water **≥100m**, all years and seasons, for Aleutian Islands (top panel), Bering Sea (middle panel), and Gulf of Alaska (bottom panel).

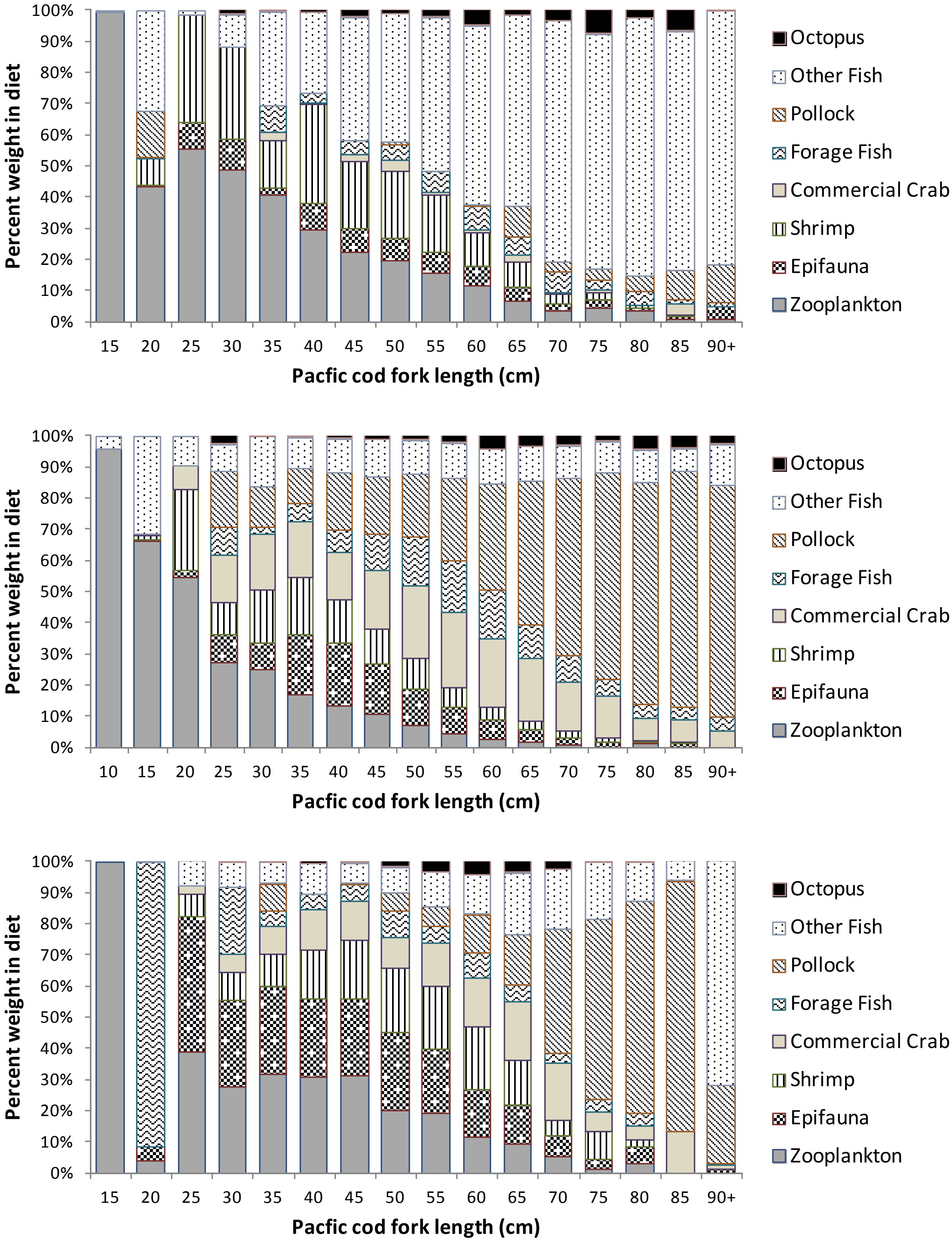


Figure 22.A1.5. (Top panel): Relationship between upper and lower beak hood length and Pacific octopus total weight, measured from fisheries-sampled octopus. (Bottom panel): Length frequency of upper and lower beaks sampled from Pacific cod stomachs.

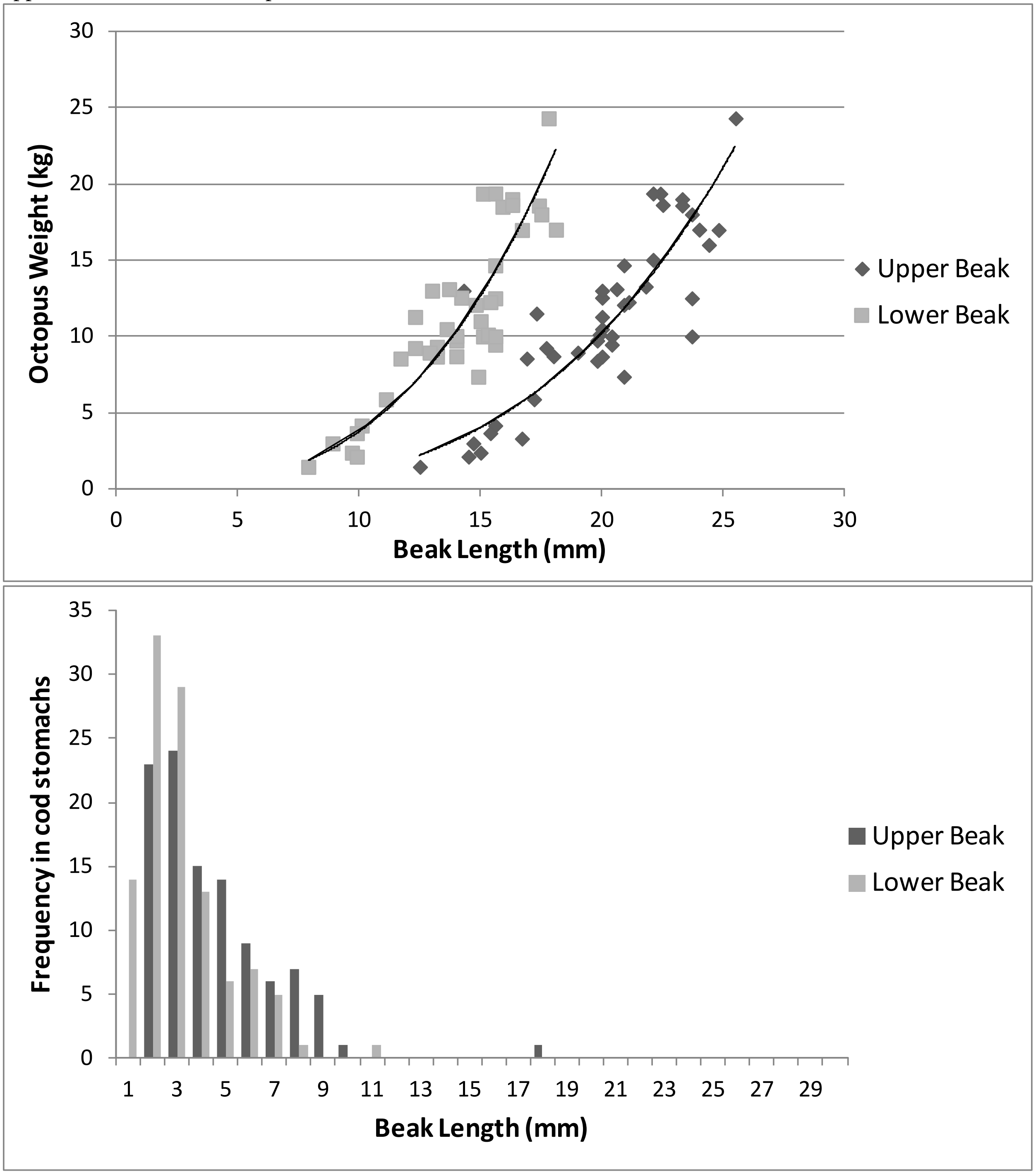


Figure 22.A1.6. Beak hood lengths of octopus removed from Pacific cod stomachs as a function of cod fork length.

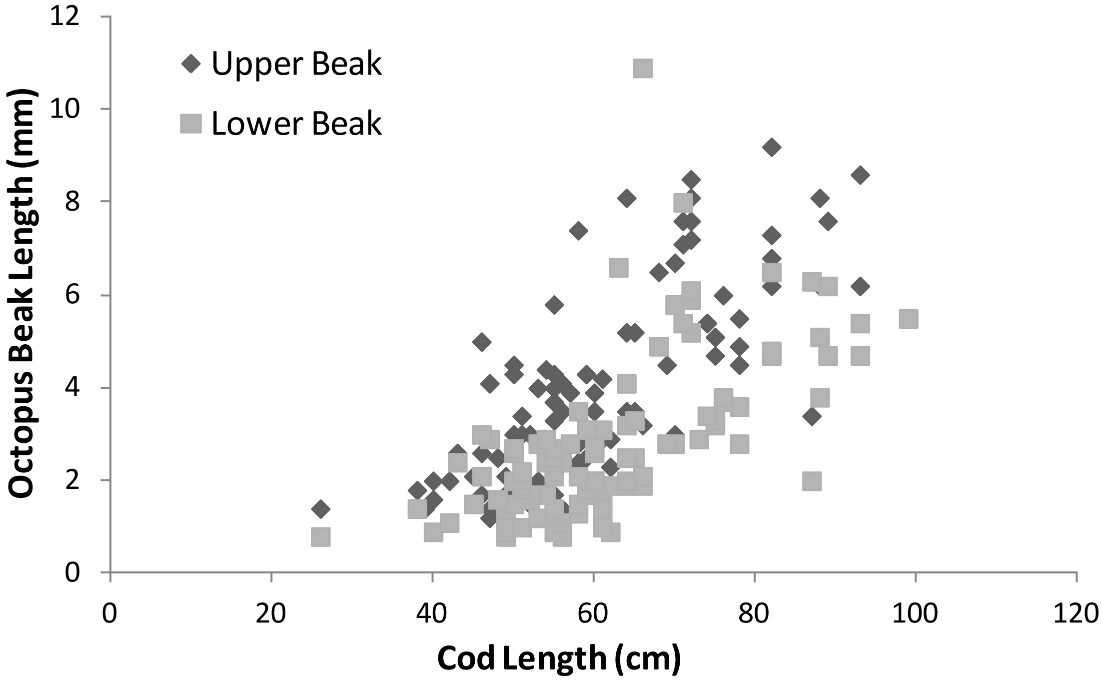
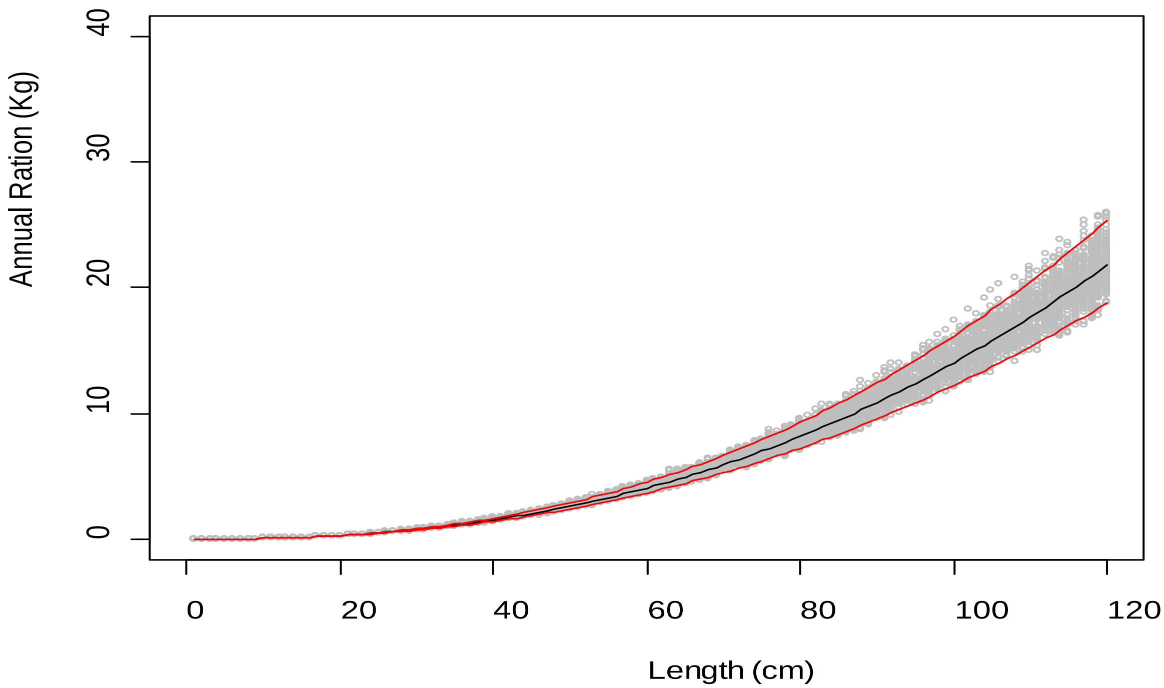


Figure 22.A1.7. Annual ration of Pacific cod as a function of fork length, as estimated from fit von Bertalanffy parameters. Points indicate MCMC posterior distribution for fit; black and red lines show estimate and 95% confidence intervals.



Appendix 22.A2 Summary of Octopus Research

A number of research projects have been completed in the last 5-7 years and are published or nearing publication. Areas of research, publications, and major results are summarized below.

Reproductive Cycle and Life History of E. dofleini

GOA: NPRB Project 906 included development of maturity indices for *E. dofleini* and collection of octopus specimens for dissection.

- Sexually mature octopus of both sexes were present in all seasons, suggesting spawning is not fully synchronous for this species in the GOA. The Gonadosomatic Index (GSI) of females was highest in late winter to early spring, however, suggesting a high proportion of egg laying in early spring.
- In the Gulf of Alaska, this species was found to mature between 10-20 kg with size at 50% maturity values of 13.7 kg (95% CI = 12.5-15.5 kg) for females and 14.5 kg (95% CI = 12.5-16.3 kg) for males. Size at maturity was highly variable for this species, particularly for male octopus.
- Fecundity for this species in the Gulf of Alaska was found to range from 41,600 to 239,000 eggs/female with an average fecundity of 106,800 eggs/female. Fecundity was significantly and positively related to the weight of the female ($n = 33$, $P < 0.001$).

Conners, M. E., C. L. Conrath, and R. Brewer. 2012. Field studies in support of stock assessment for the giant Pacific octopus *Enteroctopus dofleini*. NPRB Project 906 Final Report. North Pacific Research Board, Anchorage, AK.

Conrath, C.A. and M.E. Conners. 2014. Aspects of the reproductive biology of the giant Pacific octopus (*Enteroctopus dofleini*) in the Gulf of Alaska. Fishery Bulletin, U.S. 112(4):253-260.

BSAI: NPRB Projects 906 and 1005 also included collection of octopus specimens and examination of gonad maturity.

- In the southern Bering Sea, *E. dofleini* were reproductively active in the fall with peak denning occurring in the winter to early spring months.
- *E. dofleini* in the Bering Sea were found to have size at 50% maturity values of 12.8 kg for females and 10.8 kg for males. Animals smaller than 10 kg tended to be immature, but male and female octopus in the size range between 10 – 20 kg were found to be immature, maturing, and mature.

Brewer, R.S. and B.L. Norcross. (in Review) 2016. Seasonal changes in the sexual maturity and body condition of the North Pacific giant octopus (*Enteroctopus dofleini*).

Brewer, R.S. 2016. Population biology and ecology of the North Pacific Giant Octopus in the eastern Bering Sea. PhD thesis, Univ. Alaska Fairbanks.

Octopus Tagging Study

Reid S. Brewer conducted a three-year, five season tagging study on Giant Pacific Octopus captured with commercial cod pots. The study was conducted in a 25 km^2 area north of Unalaska Island in depths ranging from 50 to 200 m. A total of 1,714 *E. dofleini* were tagged and 246 were recaptured. While most of the recaptures occurred within a few weeks after tagging (same season), 32 octopus were recaptured between seasons after 60 days. Cormack-Jolly-Seber models were used to estimate survival and study-area abundance for *E. dofleini* in the size range vulnerable to commercial pot bycatch.

- The tagging method using Visual Implant Elastomers (VIE tags) was feasible. Tags were readily visible in recaptured animals and had no associated tissue damage
- In autumn when temperatures were warmest, *E. dofleini* had higher growth rates, moved more and both sexes were predominantly mature when compared to colder winter months.
- Size and water temperature also played a role in growth of tagged *E. dofleini*. The mean specific growth rate (SGR) for short-term recaptures was 0.75% d-1 ± 0.09; SGR was positively related to temperature and negatively related to size at initial capture. The mean SGR for long-term recaptures was 0.20% d-1 ± 0.03 and SGR was negatively related to size at initial capture
- Average annual survival rate of tagged octopus was estimated at 3.33% ± 2.69 SE. The survival for this population was modeled using recaptures of mostly mature individuals. Female survival estimates were lower than male survival due to sex-specific post-spawning reproductive activities.
- The abundance estimate for octopus in the study area was 3,180 octopus or 127 octopus per km^2. If this density is applied the three statistical areas in the southeast Bering Sea where most of the incident catch occurs (areas 509, 517, and 519) the estimate for octopus abundance in the 3,500 km^2 area was 1.47 million octopus.
- Mean size of octopus captured in this study was 14.1 kg, the estimated biomass estimate of octopus in the study area was 44.8 t and in the three statistical areas was 20,697 t, an order of magnitude larger than the current biomass estimate for the entire EBS.

Brewer, R.S. and B.L. Norcross. 2012. Long-term retention of internal elastomer tags in a wild population of North Pacific giant octopus (*Enteroctopus dofleini*), Fisheries Research 134-136: 17-20.

Brewer, R.S. 2016. Population biology and ecology of the North Pacific Giant Octopus in the eastern Bering Sea. PhD thesis, Univ. Alaska Fairbanks.

Brewer, R.S. and B.L. Norcross. (in Review) 2016. Seasonal changes in the sexual maturity and body condition of the North Pacific giant octopus (*Enteroctopus dofleini*).

Brewer, R.S., B.L. Norcross, and E. Chenoweth (in press). Temperature and size-dependent growth and movement of the North Pacific giant octopus (*Enteroctopus dofleini*) in the Bering Sea. Marine Biology Research

Species of Octopus Bycatch

A NOAA Cooperative Research Program project was conducted in 2006 and 2007 by AFSC scientist Elaina Jorgensen. Species identification of 282 animals at Harbor Crown Seafoods in Dutch Harbor and 102 animals at Alaska Pacific Seafoods in Kodiak confirmed that all individuals were *E. dofleini*. All plant deliveries of octopus were from pot fishing vessels.

Octopus Discard Mortality

In 2006-2007 and 2010-2012, some fishery observers collected data for a special project on octopus size frequency and condition at discard. Data from this project allowed qualitative comparisons of size frequency by gear type and the immediate capture mortality of octopus from different gear types. Two follow-up studies were conducted to examine short-term and long-term delayed mortality for octopus captured with commercial pot gear.

- The size frequency of octopus taken by different fishing gears was very distinct, with pot gear capturing almost exclusively large octopus (>10kg). Pelagic trawl and longline gear captured mostly small octopus (<2 kg), and bottom trawl gear captured a range of sizes. Patterns in size distribution for the different gear types were similar for all three ecosystems (EBS, GOA, and AI).
- Pot gear in all regions caught a much higher proportion of males than trawl and longline gears. There was also seasonal difference in sex ratios in both the EBS and GOA, with a higher proportion of males caught during the fall fishing season than during the winter. Males were generally slightly larger than females.
- Initial condition at capture was best in pot gear, with over 90% of octopus discarded from pot vessels alive in excellent condition. Octopus taken in trawl gear had the highest immediate mortality rate, with 68-94% dead or injured at discard.
- Octopus captured during Pacific cod fishing in the southeast Bering Sea in winter 2013 were held for 24 to 60 hours in circulating seawater tanks. Octopus captured ranged in size from 5.5 kg to 22.0 kg. Of the 36 octopus held, none showed any delayed mortality or decline in condition. Statistical power analysis showed that the probability of the observed result of no mortality out of 36 trials would be very small ($p < 0.05$) unless the true underlying mortality rate was larger than 8%.
- Separate long-term delayed mortality studies collected octopus on commercial pot vessels in Kodiak, Alaska and held individuals for 21 days in a running seawater laboratory. This study showed no long-term delayed mortality of uninjured octopus, and a 50% delayed mortality rate for visibly injured octopus.
- The current catch accounting for octopus assumes 100% mortality for all catch, but studies show that the discard mortality rates for octopus from pot gear are much lower. The studies discussed above provide quantitative estimates of immediate and delayed mortality rates that could be used to conduct gear-specific accounting of octopus discard mortality.

Conners, M. E. and M. Levine. 2016 (in press). Characteristics and discard mortality of octopus bycatch in Alaska groundfish fisheries. Fishery Bulletin

Conrath, C.A. and N. B. Sisson. 2016 (in press). Delayed discard mortality of the giant Pacific octopus in pot fisheries in the Gulf of Alaska. Fishery Bulletin

Habitat Pot Gear for Directed Octopus Survey & Research

NPRB Project 906 and an NMFS Cooperative Research Project included testing and developing a specialized gear for octopus fishing. The gear consists of small "habitat pots" that act as artificial den space for octopus. A large number of these pots can be longlined as a clip-on gear.

- A variety of pot designs and materials were tested for use in Alaska. In the NPRB study, plywood box pots and scrap ATV tires captured octopus much more effectively than pots made of various plastic materials. One vessel in the CR study also caught octopus using plastic pots purchased from Korea, at similar rates to plywood box pots.
- Bycatch of crabs and other species in plywood box pots was close to zero. Starfish were occasionally seen.
- Habitat pots were successfully deployed on longlines fished as tub gear, off a longline reel, and using a commercial crab hauling block. Experimentation is still needed to determine optimal pot spacing and soak times
- Octopus captured in habitat pots ranged in size from smaller than 2 kg to over 20 kg, giving a broader and more consistent size distribution than fishing and survey gears.
- Overall capture rates varied widely between seasons and locations, ranging from less than ten percent to over 50% occupancy. More development is needed to determine most productive places and seasons for fishing.
- The gear is suitable for comparative scientific studies and may be suitable for index surveys at fixed locations. Suitability of the habitat pot gear for directed commercial fishing will depend on ex-vessel prices and catch rates.

Age Determination in Giant Pacific Octopus

Collections of octopus beaks, stylets and statoliths were made during NPRB projects and from AFSC surveys. Preliminary analyses have been conducted, but a funded research project would be needed to determine if accurate methods for age determination can be developed.

- Hood length of both upper and lower octopus beaks is strongly correlated with octopus weight and can be measured on beaks in stomach contents.
- Statoliths of *E. dofleini* are too soft and chalky for age reading, but beaks and stylets both show banding patterns in cross section that may be correlated with age.
- Translating beak or statolith bands to age will require a validation study using octopus marked with radioisotopes or chemicals and held for known time periods.

Appendix 22.A3. Theoretical Octopus Population Model

General Model Formulation

The base model is a stage-based model based on total weight and reproductive status of the octopus. Computer code is designed to allow the number of stages and the size range of each stage to be changed as needed. Initial inputs include the number of stages and the average weight of each stage. The final stage always represents reproductive adults: sexually mature animals that will mate, lay eggs, and die within the next time step. The remaining stages represent various sizes of immature animals. The model is not age-based because there is as yet no established method for aging *E. dofleini*. If the growth parameters are set so that each immature stage grows to the next size stage in each time step, with none remaining in the current stage, then the stage model is identical to an age-based model. There is an additional important life stage that is not explicitly included in the model. The planktonic paralarval stage is not modeled, but is considered to be a major source of early natural mortality and recruitment variability. The first size stage of the model represents small octopus after they have settled from the paralarvae to a fully benthic habitat, approximately one year after mating of mature octopus.

The transition matrix for the model is determined by parameters for growth and maturation. In this formulation, the survivors of each immature size stage are presumed to either grow to the next size stage, stay in the same size stage, or mature into reproductive adults. Immature octopus were assumed to not grow more than one size stage in each time step, and individual weight loss to a smaller size step was assumed not to occur. The larger size stages may also mature into reproductive adults (stage 6). The transition probabilities, conditioned on survival, are thus made up of three input vectors: the probability of staying in the same size range (g0, failing to grow enough to reach the next stage), the probability of maturing into reproductive adults (mat), and the probability of growing to the next size class (g1). This last vector is calculated to ensure that the conditional transition probabilities sum to one. The transition matrix (conditional probability of growth or maturity given survival) has the vector g0 along the diagonal, g1 above the diagonal, and mat in the final column.

The mortality matrix is composed of natural mortality and the sum of any fishery and survey mortalities. Natural mortality is a parameter that is input as a vector of stage-based natural mortalities. The natural mortality for the reproductive adult stage is set high to produce 100% post-spawning mortality of this size class. Fishery mortality from each source is the product of an overall fishing rate (*Ff*) and a vector representing size selectivity for the fishery for each size stage. The overall fishing rate is assumed to be proportional to abundance, with an unknown capture efficiency (*q*). Total mortality is calculated as the sum of natural and fishery mortality. Numbers of individuals in the successive time step is the product of instantaneous mortality and the conditional transition probabilities.

Recruitment is initially assumed constant, then is treated as a random variable with a mean recruitment level and recruitment variance as input parameters. There is also an option to use a general Beverton-Holt stock-recruitment function to model recruitment by specifying steepness as an input parameter. The random model is probably most representative of recruitment in *E. dofleini*; the population is largely unfished and there is strong and interannually variable mortality in the planktonic paralarval stage. Given the high fecundity of *E. dofleini* (90,000 eggs/female in the GOA, Conrath and Conners 2014) effects of reduced spawning biomass on recruitment are not likely to be seen unless fishing pressure is extremely heavy.

The model simulates population dynamics from input parameters and starting conditions. As with any steady-stage model, if parameters are constant then the population converges to a stable stage distribution which is determined by the growth and maturity parameters. The simulation code tracks numbers and biomass is each stage in each simulated year, and calculates catch-at-stage vectors and total yield for each fishery or survey. Output statistics include the mean, variance, minimum, and maximum of population numbers over the simulation period, after allowing an initial period for burn-in. These statistics are also calculated for the recruitment, biomass, spawning biomass, and fishery yield time series.

Equations for the model are as follows:

For years t (1:nyr) and size stage a (1:nclass)

N[t,1] = R[t]   R(t) is generated ~ Normal (Rbar, sigmaR) for all t
N[1,a] = N0   Initial population size, input vector

$N[t+1,a] = N[t,a]*G0_a*S_a + N[t,(a-1)]*G1_{(a-1)}*S_a$ a = 2,3,…,(nclass-1)
$N[t+1,nclass] = \text{Sum } (a = 1,2,\ldots,(nclass-1)) \text{ of } (N[t,a] * S_a * mat_a)$
where $S_a = \exp(-Za)$ and Za = NatM + FishM

Octopus Population Simulations
The model explored for the octopus assessment is defined as having 6 stages: 5 immature stages and one stage for reproductive adults (Figure 22.A2.1). The five immature stages are selected to represent the range of octopus sizes seen in fishery and research data, and to roughly correspond to the presumed maximum lifespan of *E. dofleini*. The first size stage consists of newly settled octopus weighing < 3kg, the remaining stages are 6 kg intervals. The growth parameters are set so that the immature stages may either grow one size step with Pr(g1) or stay in the same size class with Pr(g0). Stages 2-5 also have a fixed probability of maturing (transitioning to stage 6) in each time interval. Natural mortality is presumed to decrease with increasing size for immature octopus as the number of predators decreases. The natural mortality of the final stage is set very high so that there is virtually 100% mortality. The fishery is modeled to represent the Pacific cod pot fishery, with maximum selectivity on the largest animals. There is also a simulation of the AFSC Bottom Trawl survey, which selects for small octopus but catches some larger octopus, and Pacific cod predation, which selects exclusively for small-medium octopus.

The model and some typical outputs are shown graphically below. This simulation model was run for a variety of input parameters and fishing scenarios; the results of these simulations were presented to the Plan Teams at their September 2016 meetings and will eventually be presented in a scientific publication. The population model will also be used to generate a range of simulated data sets with different levels of variance in the population parameters; these simulated data sets can then be submitted to a quantitative catch-at-age model to see how accurately it estimates the true population parameters. The Teams are encouraged to suggest additional scenarios for simulation.

Simulation Models run as of 9/1/16:

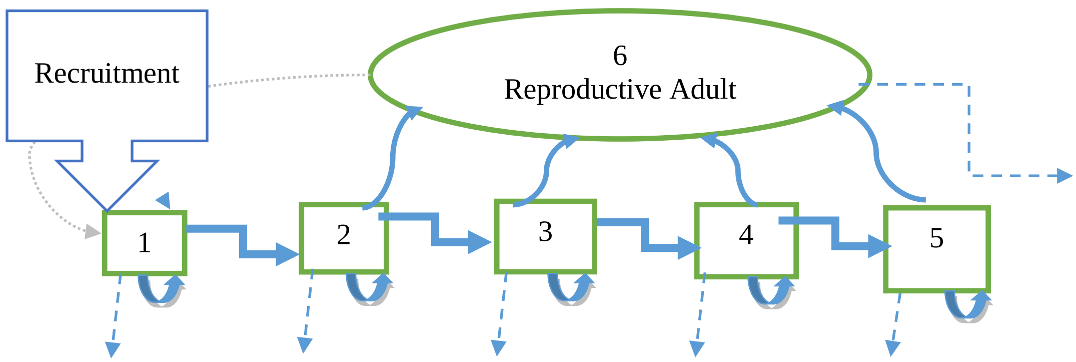
Model 0 – fully deterministic (all input parameters constant), constant recruitment, no fishing
  Sensitivity analysis

Model 1 – fully deterministic model, constant recruitment, fishing effects
  Model 0 with FPot ranging from 0.01 to 0.6 – Yield, population effects
  Cordue model – age based (g)=0 with same parameters from CIE review

Model 2 – deterministic growth, maturity, and mortality; random recruitment, fishing effects
  Recruitment variance vs. Biomass and Yield variance
  Model 2 with added directed fishery on sizes 2-3

Model 2 simulating catch-at-age data for fitting with SS3

Fig 22.A2.1 Size-Stage Octopus Population Model and Base Parameter Values



Population Structure and Growth Variables

	1	2	3	4	5	Adult
Size (kg)	< 3	3 < 9	9 < 15	15 < 21	21 +	
Mean Wt (kg)	0.5	6	12	18	24	22
Mnat	0.7	0.5	0.2	0.1	0.1	10
Pr(Mature)	0	0.1	0.5	0.75	1.0	
Pr(grow 0)	0	0	0	0	0	
Pr(grow 1)	1.0	0.9	0.5	0.25	0	
InitSize%	0.55	0.15	0.10	0.08	0.02	0.1
N0	5,500	1,500	1,000	800	200	1,000
Fsel – Pots	0	0.1	0.5	1.0	1.0	1.0
Fsel– BTsur	1.0	0.1	0.1	0.1	0.1	0.1
Fsel- Cod	1.0	0.5	0	0	0	0

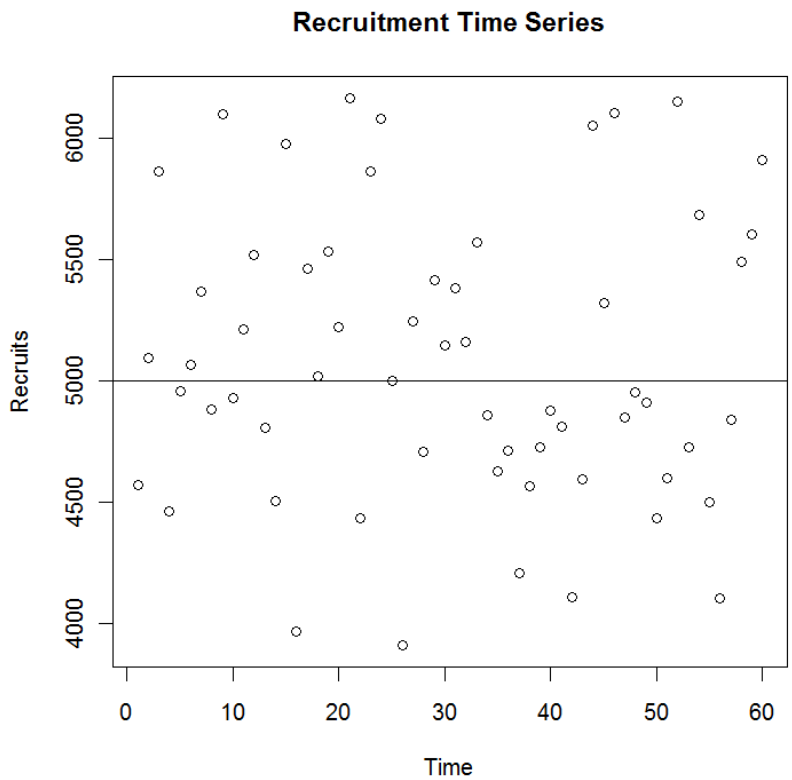
Run Variables

Nclass	6
Yrs, burn	60,10
N0_all	10,000
Rbar	5,000
sigmaR	0
Ftot - Pots	0
Ftot- BTsurv	0
Ftot- Cod	0

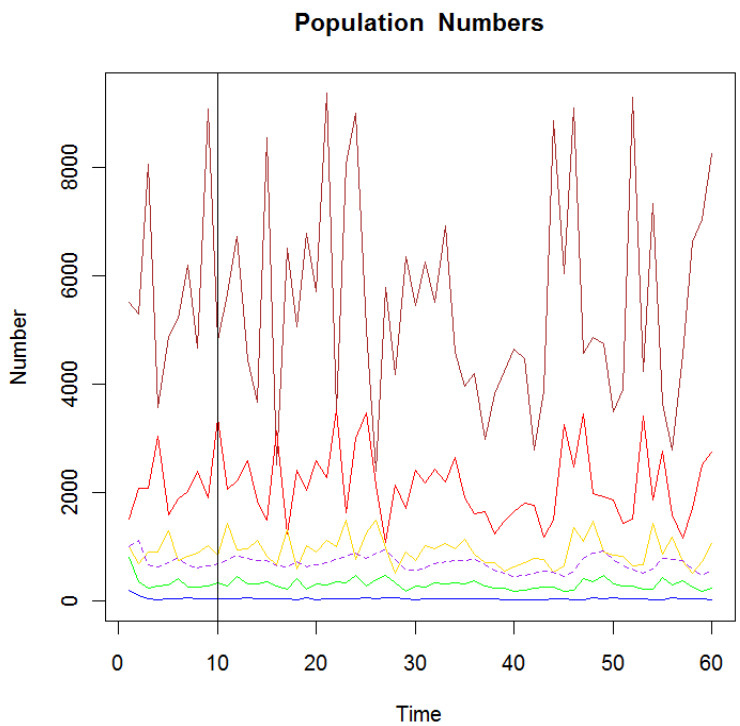
Calculated Variables / Outputs (units)

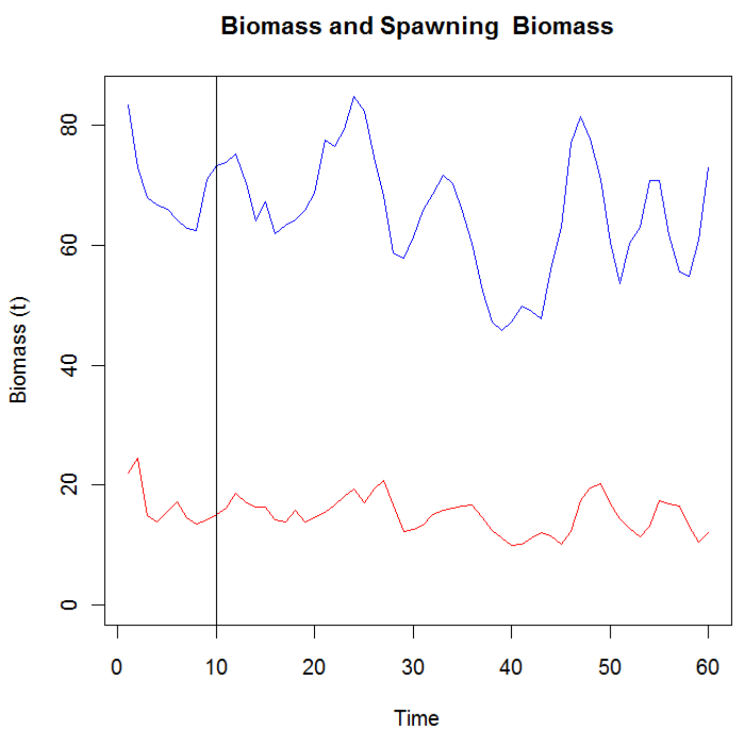
N(t,i) vector	Numbers at stage i	#	Matrix
N(t+1,i)	Numbers next year	#	
SF(t,i)	Size Frequency	%	Matrix
R(t)	Recruitment	#	Vector
B(t,i), B(t)	Biomass	t	Vector
SpB(t,i), SpB(t)	Spawning Biomass	t	Vector
CAAF(t,i)	Catch by stage	#/stage	Matrix
Yield (t)	Fishery Yield	t	Vector

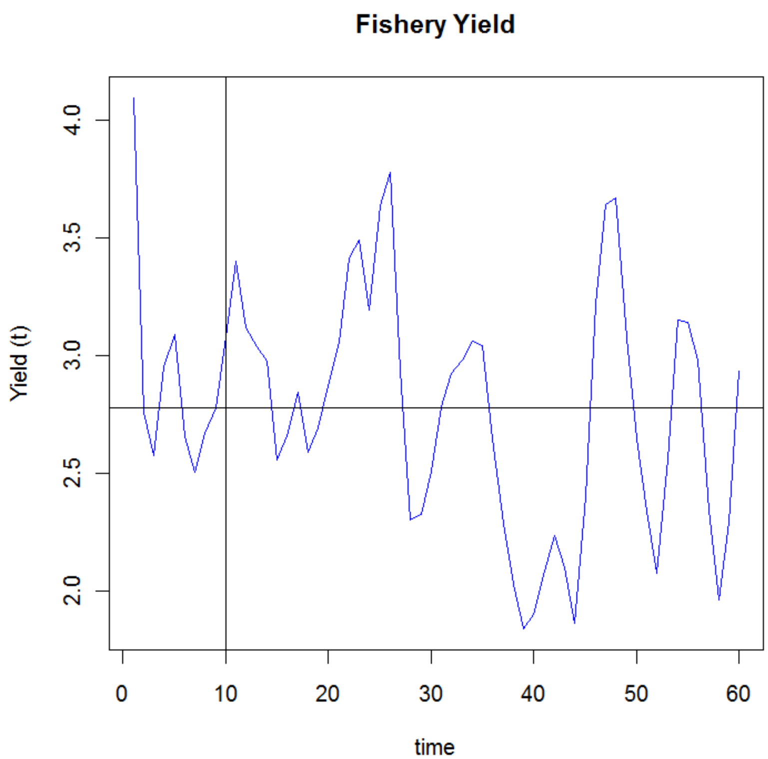
Fig 22.A2.2 Examples of Population Simulation – Model 2



Colors for population numbers plot: Stage1 brown, Stage2 red, Stage3 yellow, Stage4 green, Stage 5 blue, and Stages 6 dashed violet







R screen output:
Initial Biomass and Population Size = 83.4 10000
Final Biomass and Population Size = 64.19 12850
Average Fishery Yield = 2.77
Ending Size Frequency = 0.642 0.212 0.082 0.017 0.001 0.042

Mean, Stdev, Min, and Max of time series (after burn-in) for Nt[i] plus Rt, Bt, SBt, Yield

	Mean	StDev	Min	Max
N1	5439.621	1928.922	2396.300	9362.232
N2	2111.981	655.904	1080.014	3517.209
N3	926.392	273.844	508.435	1494.725
N4	297.731	82.156	173.443	475.272
N5	36.803	10.030	21.300	58.368
N6	678.445	129.686	452.450	946.847
Rt	5439.621	1928.922	2396.300	9362.232
Bt	64.956	10.011	45.855	84.812
SBt	14.926	2.853	9.954	20.831
Yield	2.752	0.515	1.840	3.776

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