18a. Assessment of squids in the Gulf of Alaska

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Executive Summary

In 2008, the North Pacific Fishery Management Council (NPFMC) adopted an alternative to set aggregate overfishing levels (OFLs) and acceptable biological catch (ABC) for the Other Species complex in the GOA (squids, sharks, sculpins, and octopus). OFL and ABC are now calculated separately for each species group and combined to create the aggregate Other Species specifications. Although a full assessment was performed in 2008 in conjunction with that change, another full assessment was repeated for 2009 because new survey data are available.

Summary of Changes

Changes in the input data:

1. Total catch for GOA squids has been updated with complete 2008 and partial 2009 data; in addition, 2003-2007 catch data has been updated due to changes in the Catch Accounting system.
2. Biomass information is updated with data from the 2009 GOA bottom trawl surveys.
3. Data on retention of squids in observed catches have been added to the catch reporting.
4. A new map of squid catch distribution has been added.
5. Information on squid predation by seabirds has been added to the Ecosystem Considerations section.

Summary of Results

Because reliable estimates of squid biomass and natural mortality rate do not exist, we recommend a modified Tier 6 approach setting OFL equal to maximum historical catch and ABC equal to 0.75 * OFL. We include two options for applying a Tier 6 approach: 1) using all available years of catch data (1990-2008) and 2) using catch data from only the years 1997-2007 (this period was chosen by the SSC for applying Tier 6 to octopus and sharks). For purposes of comparison we include the Tier 5 alternative approaches described in the 2008 report. The alternative approaches result in a range of OFL and ABC recommendations, presented below. **We recommend using a Tier 6 (max) approach using the years 1997-2008 as a baseline, which results in an ABC of 1,148 t and an OFL of 1,530 t**. These numbers are slightly higher than the 2009 recommendations (ABC = 1,451 t and OFL = 1,934 t) due to changes in the Catch Accounting System. By definition, the catch of squids has not exceeded the OFL. Data are not available to assess whether squids are overfished.

Harvest recommendations for 2010-2011

	Tier 6 (max)	Tier 6 (max)
time period used for catch	1990-2008	1997-2007
average survey biomass (t)	N/A	N/A
ABC (t)	1,148	**1,148**
OFL (t)	1,530	**1,530**

Responses to SSC Comments

The SSC requests that the sections on Ecosystem effects include information on seabirds, particularly albatrosses, as predators of squid.

The Ecosystem Considerations section has been expanded to include a brief description of the role of squid in Seabird diets, including the addition of a figure depicting seabird diet composition.

The SSC would also like to see in future assessments a map of catch density of squid.

The existing map, which was outdated, has been replaced with a new showing the most recent data regarding the distribution of squid catches in the AFSC trawl survey (2009) and commercial fisheries (2008).

Introduction

Description, scientific names, and general distribution

Squids (order Teuthoidea) are cephalopod molluscs which are related to octopus. Squids are considered highly specialized and organized molluscs, with only a vestigial mollusc shell remaining as an internal plate called the pen or gladius. They are streamlined animals with ten appendages (2 tentacles, 8 arms) extending from the head, and lateral fins extending from the rear of the mantle (Figure 1). Squids are active predators which swim by jet propulsion, reaching swimming speeds of up to 40 km/hr, the fastest of any aquatic invertebrate. Members of this order (*Archeteuthis* spp.) also hold the record for largest size of any invertebrate (Barnes 1987).

There are at least 15 squid species found in the mesopelagic regions of the Eastern Bering Sea (EBS; Table 1). Less is known about which squid species inhabit the GOA, but the species are likely to represent both EBS species and more temperate species in the genus *Loligo*, which are regularly found on the U.S. West Coast and in British Columbia, Canada, especially in warmer years (MacFarlane and Yamamoto 1974). Squid are distributed throughout the North Pacific, but are common in large schools in pelagic waters surrounding the outer continental shelf and slope (Sinclair et al. 1999). The most common squid species in the Eastern Bering Sea are all in the family Gonatidae. Near the continental shelf, the more common species are *Berryteuthis anonychus* and *Berryteuthis magister*. Further offshore, the likely common species are *Gonatopsis borealis*, *Gonatus middendorfi* and several other *Gonatus* species, according to survey information collected in the late 1980's (Sinclair et al. 1999). In addition, marine mammal food habits data and recent pilot studies indicate that *Ommastrephes bartrami* may also be common, in addition to *Berryteuthis magister* and *Gonatopsis borealis* (B. Sinclair, ASFC, personal communication). Much more research is necessary to determine exactly which species and life stages are present seasonally in the Bering Sea and Aleutian Islands (BSAI) and Gulf of Alaska (GOA) groundfish Fishery Management Plan (FMP) areas.

Management Units

The squid species complex is part of the Other Species FMP category. Historically, GOA squids were managed along with sharks, sculpins, and octopuses under an aggregate gulfwide TAC established annually as ≤5% of the sum of all target species TACs. Beginning in 2008, aggregate ABCs and OFLs for the Other Species complex have been set by summing the individual OFL and ABC recommendations for each species group. The 2008 assessment was the first one to be used in setting the Other Species TAC (Ormseth and Gaichas 2008). Since 2003, the NMFS Alaska Regional Office (AKRO) has reported total squid catch, without breaking down the squid catch by species. Prior to 2003, catch of squids was not reported separately from the Other Species category, but observer species composition sampling was used to estimate catches of each Other Species component (see below). Catch of GOA Other Species has never exceeded TAC over the course of the domestic fishery (Table 2).

Life history and stock structure
Relative to most groundfish, squids are highly productive, short-lived animals. They display rapid growth, patchy distribution and highly variable recruitment (O'Dor, 1998). Unlike most fish, squids may spend most of their life in a juvenile phase, maturing late in life, spawning once, and dying shortly thereafter. Whereas many groundfish populations (including skates and rockfish) maintain stable populations and genetic diversity over time with multiple year classes spawning repeatedly over a variety of annual environmental conditions, squids have no such “reserve” of biomass over time. Instead, it is hypothesized that squids maintain a “reserve” of biomass and genetic diversity in space with multiple cohorts spawning and feeding throughout a year and over a wide geographic area across locally varied environments (O’Dor 1998). Many squid populations are composed of spatially segregated schools of similarly sized (and possibly related) individuals, which may migrate, forage, and spawn at different times of year (Lipinski 1998). Most information on squids refers to *Illex* and *Loligo* species which support commercial fisheries in temperate and tropical waters. Of North Pacific squids, life history is best described for western Pacific stocks (Arkhipkin et al. 1995; Osako and Murata 1983).

The most commercially important squid in the north Pacific is the magistrate armhook squid, *Berryteuthis magister*. This species is distributed from southern Japan throughout the Bering Sea, Aleutian Islands (AI), and Gulf of Alaska to the U.S. West coast as far south as Oregon (Roper et al. 1984). The maximum size reported for *B. magister* is 28 cm mantle length. The gladius and statoliths (similar to otoliths in fish) were compared for ageing this species (Arkhipkin et al. 1995). *B. magister* from the western Bering Sea are described as slow growing (for squid) and relatively long lived (up to 4 years). Males grew more slowly to earlier maturation than females. An analysis of *B. magister* in the EBS suggests that individuals there have shorter lifespans (approximately one year) and mature earlier than western populations (Drobny 2008). *B. magister* were dispersed during summer months in the western Bering Sea, but formed large, dense schools over the continental slope between September and October. Stock structure in this species is complex, with three seasonal cohorts identified in the region: summer-hatched, fall-hatched, and winter-hatched. Growth, maturation, and mortality rates varied between seasonal cohorts, with each cohort using the same areas for different portions of the life cycle. For example, the summer-spawned cohort used the continental slope as a spawning ground only during the summer, while the fall-spawned cohort used the same area at the same time primarily as a feeding ground, and only secondarily as a spawning ground (Arkhipkin et al. 1995).

Timing and location of fishery interactions with squid spawning aggregations may affect both the squid population and availability of squid as prey for other animals (Caddy 1983; O’Dor 1998). The essential position of squid within North Pacific pelagic ecosystems, combined with the limited knowledge of the abundance, distribution, and biology of many squid species in the FMP areas, make squid a good candidate for management distinct from that applied to other species (as has been done for forage species in the BSAI and GOA). In the EBS, fishery interactions with squid happen in predictable locations (Gaichas 2005), suggesting that in some cases, squid may be most effectively managed by spatial restrictions rather than by quotas.

Fishery

Directed fishery
Squid in Alaska are generally taken incidentally in target fisheries for pollock, but have been the target of Japanese and Republic of Korea trawl fisheries in the past. There are no directed squid fisheries in Alaskan waters at this time. Squids could potentially become targets of Alaskan fisheries, however. There are many fisheries directed at squid species worldwide, although most focus on temperate squids in

the genera *Illex* and *Loligo* (Agnew et al. 1998, Lipinski et al. 1998). For instance, the market squid *Loligo opalescens* supports one of the largest fisheries in the Monterey Bay area of California (Leos 1998), and has also been an important component of bycatch in other fisheries in that region (Calliet et al. 1979). There are fisheries for *B. magister* in the Western Pacific, including Russian trawl fisheries with annual catches of 30,000 - 60,000 metric tons (Arkhipkin et al. 1995), and coastal Japanese fisheries with catches of 5,000 to 9,000 t in the late 1970's-early 1980's (Roper et al. 1982; Osaka and Murata 1983). Therefore, monitoring of catch trends for species in the squid complex is important because markets for squids exist and fisheries might develop rapidly.

Bycatch and discards

Squids have historically represented a small proportion (~1-2%) of the Other Species catch in the GOA (Table 2). This began to change in 2003, when the proportion rose to 5%, and increased to an especially large catch in 2006 (1,530 t, 39% of the Other Species catch; Table 2). The catch declined to 412 t in 2007 and 84 t in 2008. The 2009 catch as of October is similar to that in 2007 (Table 2). The 2006 GOA squid catch was similar to catch levels in the BSAI during the 2000s (Ormseth and Jorgenson 2007). Analysis of fishery observed data suggests that retention of squids varies considerably; estimates of retention rates range from 19% to 97%, although retention has been high for the last several years (Table 2).

Most squid are caught incidentally in the pollock fishery (Table 3), which has the highest observer coverage in the central Gulf of Alaska (areas 620 & 630). Thus, it is not surprising that though most squid catch apparently comes from this area (Table 4). However, the distribution of squid catch in unobserved fisheries is not known. The spatial distribution of the observed portion of the squid catch has changed over time, with the highest catches shifting from areas 610 and 630 in the mid-1990s to area 620 since 2001 (Table 4 & Figure 2). Given the relatively low levels of observer coverage in GOA groundfish fisheries, and the generally low catches of squid in years before 2004, it is difficult to determine whether the apparent redistribution of squid catch results from changes in observer coverage over time, changing fishing patterns, or changes in squid distribution.

The predominant species of squid in commercial catches in the GOA is believed to be *B. magister* (often called "red squid"), although there is no way to verify this because the majority (99%) of squid catch is reported as "squid unidentified" (the remainder is identified as *Moroteuthis* spp, or "giant squid unidentified"). Squid catches from 1990-2002 are estimated using the Blend system, which combines observer catch data with landings data. Since 2003 the AKRO's Catch Accounting System (CAS), using a similar approach, has reported catches of squid and Other Species groups. Because squids are delicate and almost certainly killed in the process of being caught, 100% mortality of discards is assumed.

The prevalence of *B. magister* in bottom trawl surveys (Table 5) and the spatial overlap of the surveys with incidental squid catches (Fig. 3) support the hypothesis that fishery catches are dominated by *B. magister*. However, incidental catches occur most often in pelagic trawls and differences in the depth distribution of squid species may confound this result.

Data

Survey Data

Survey biomass in aggregate and by species

The AFSC bottom trawl surveys are directed at groundfish species, and therefore do not employ the appropriate gear or sample in the appropriate places to provide reliable biomass estimates for most squids, which are assumed to be generally pelagic and to reside off bottom. Biomass estimates for the GOA have fluctuated considerably since 1984, with the 2009 estimate for all squids being 8,603 t (Table 5). This may be due to variability in squid biomass and distribution, but may also reflect the poor nature of biomass estimates from bottom trawl surveys. However, the survey estimates have surprisingly low coefficients of variation (Table 5), suggesting that squid survey catch (especially of *B. magister*) is fairly evenly distributed throughout the survey area. Survey biomass estimates can be compared with biomass estimates from mass-balance ecosystem models. For example, salmon in the GOA are estimated to consume between 200,000 and 1.5 million t of squid each year and whales may consume 100,000-200,000 t of squid each year (see the ecosystem considerations section in this document). Thus, the ecosystem models suggest that the actual biomass of squids in the GOA may be many times greater than what the bottom trawl surveys indicate.

Analytic Approach

The available data do not support population modeling for squids in the GOA, so many of the standard sections of text usually required for NPFMC SAFE reports are not relevant. Although the biomass estimates for squid are not sufficiently reliable for a Tier 5 approach, we present a discussion of *M* estimation for comparison purposes and for future use if reliable biomass estimates become available.

Parameters Estimated Independently: *M*

The natural mortality rate *M* is most often measured in monthly increments for squids (e.g., Osako and Murata 1983), or even in days for mature spawners on fishing grounds (Macewicz et al 2004). Due to high turnover rates of squid populations, annual natural mortality rates calculated by standard methods applied to groundfish often exceed 1.0. For example, applying the Hoenig regression to the maximum (Bering Sea-wide) age of *B. magister* (4 years), we estimate an annual natural mortality rate of 1.06. While this may actually reflect the natural mortality rate of highly productive species such as squids, it is problematic for managing squids under Tier 5, where $F_{OFL} = M$ (the OFL would equal the estimated squid biomass). In addition, because squid biomass estimates are highly variable applying a high fishing mortality rate does not seem like a precautionary approach. We assume an *M* of 1.0 for GOA squids and suggest the following alternatives for applying the Tier 5 approach.

Tier 5 alternatives

Normally, the overfishing level (OFL) under Tier 5 is calculated as the F_{OFL} (based on the natural mortality rate *M*) multiplied by estimated biomass. We present two options for determining the appropriate F_{OFL} for squid:

Option 1: Under option 1, the standard Tier 5 methodology is adapted for species such as squid with high turnover rates and values of *M* approaching 1.0. Tier 5 criteria are modified based on previous experience with Japanese squid fisheries that suggests overfishing may occur at fishing rates of half to one quarter of *M* (Osako and Murata 1983). As a proxy for a sustainable fishing mortality rate, we suggest that *M* = 1.00 is a reasonable value for the longer lived North Pacific squid found in the GOA, but we recommend using 25% of *M* to establish F_{OFL} and establishing F_{ABC} as 0.75 * adjusted *M* (i.e., 0.1875). This approach is supported by a yield-per-recruit analysis conducted for *Loligo pealei*, a squid species inhabiting the northwest Atlantic Ocean with roughly similar life history characteristics to *B. magister* (longevity approx. 2 years, max. length approx. 25 cm; Lange and Sissenswine 1983). For this species, F_{max} was determined to be approximately 0.3, depending on assumptions regarding M (Lange and Sissenswine 1983). A more conservative approximation of F_{MSY} is $F_{0.1}$ (Quinn and Deriso 1999). Although the raw data were not available from the *L. pealei* study for estimation of $F_{0.1}$, it is likely that $F_{0.1}$ values would be close to 0.25, the value that we suggest as F_{OFL} under this option.

Option 2: For option 2, the methodology is adapted to account for the effect of harvesting and natural mortality on squid biomass throughout the year by including a decay function based on total mortality (G. Thompson, AFSC, pers. comm. 2006,). Using this approach, we calculate OFL as average survey biomass * F_{OFL} * (1-exp(-Z))/(Z), where $Z = M + F_{OFL}$, $M = 1.00$ and $F_{OFL} = M = 1.00$. ABC is calculated using the same approach, but substituting $F_{ABC} = 0.75 * M$ for F_{OFL}. A potential problem with this approach is that while it accounts for a high mortality rate, it does not account for additional recruitment that likely occurs during the year.

Average survey biomass: The biennial GOA bottom trawl surveys almost certainly underestimate the biomass of squids in the GOA, but they do provide estimates of minimum biomass. Populations of squids in the GOA appear to fluctuate widely from year to year, so we recommend using at least three surveys to calculate average survey biomass. The 2007 survey biomass estimate was much larger than in previous years, and the 2009 estimate is closer to the long-term average. We use the last three surveys (2005, 2007, 2009) to estimate average biomass.

Tier 6 alternatives

Under the "normal" Tier 6, OFL is established as equal to the average historical annual catch from 1978-1995, and ABC is established as 0.75 * OFL. Tier 6 is problematic for squids because fishing pressure on squid appears to be low and average catch may not be a good indicator of productivity in a lightly fished population (see SSC minutes from 2006 at http://www.fakr.noaa.gov/npfmc/minutes/SSC206.pdf). In addition, squid catch has only been recorded since 1990. We recommend a Tier 6 approach setting OFL equal to the maximum, rather than average, historical catch, and ABC equal to 0.75*OFL. At the 2009 September Plan Team meetings, the Plan Teams discussed Tier 6 time periods to be used for species with only more recent catch histories. The provisional decision was to use the years 1997-2008 as an alternative time period for octopus in both FMP areas. Thus, we include two alternatives for estimation under Tier 6: 1) setting OFL equal to the maximum catch catch during 1990-2008 (i.e. using all available data) and 2) setting OFL equal to the maximum catch observed during 1997-2008.. Although both these approaches yield the same value, we include both values for the Plan Team to decide on an approach.

Alternative approaches

While the analytical approach employed here allows the tier system to be applied to GOA squid populations, there may be better alternatives to squid management. The high turnover rates and the likelihood of multiple cohorts within populations of each species suggest that the temporal and spatial scales for assessment of squids are different from the annual and basinwide scales we apply to most groundfish. Therefore, even if we have a reliable estimate of biomass, we would have to understand the relative composition of cohorts and their movements and different mortality rates in order to apply TAC management effectively. If we use survey biomass estimates from previous years to set a TAC for the following years for squids, there is potential for the TAC to be too high or low relative to the current year's biomass due to the substantial temporal variability of squid stocks (Caddy 1983; Paya 2005). To avoid this problem, biomass would have to be estimated for a given species and TAC set and taken within a very short time period, potentially less than one year. Even this intensive management scenario would leave open the possibility that an entire seasonal cohort could be eliminated by fishing unless additional temporal or spatial management measures ensured that fishing pressure was distributed between cohorts.

Effort controls (i.e., time or area closures) may be more effective tools for squid management (Caddy 1983; O'Dor 1998). Temporal closures for two days out of a week improved catch rates for market squid (*Loligo opalescens*) in Monterey, California, while allowing squid to spawn without fishery interference for at least part of the spawning season (Leos 1998). For the Monterey fishery, the critical spatial information on catch is derived by methods not applicable to groundfish fisheries, with satellite remote sensing of high-powered squid fishing lights giving a measure of effort in specific locations (Maxwell et al. 2004). The observation that the majority of squid catches occur in a few clearly defined areas provides support for consideration of area closures. In the eastern Bering Sea, the majority of squid catches occur in a few specific areas along the shelf break and in submarine canyons (Gaichas 2005). In the Gulf of Alaska patterns of squid bycatch are broadly similar, with squid catch from the 2009 survey and observed fisheries in 2008 concentrated primarily in Shelikof Strait, in smaller portions of the shelf incised by submarine canyons, and along the length of the shelf break (Figure 3). Year-round closures in areas of high squid abundance would be the most conservative measure, providing protection to all cohorts of each species that potentially occupy the area and minimizing incidental catches of squids overall. However, this approach may be excessively restrictive on target fisheries, especially those for pollock. As an alternative, temporary area closures may be an effective management tool for squids. A better understanding of seasonal squid movements could allow us to close areas only when high numbers of squids are likely to be present. In 2006, the pollock fleet in the BSAI voluntarily prohibited fishing by their members in areas of high squid catches on a temporary basis. Determining a threshold catch level that would close an area would still require some knowledge of squid abundance and life history. Given that squid populations do not appear threatened by the current level of fishing mortality, a different management priority may be to maximize prey availability during certain seasons for protected resources. Monitoring and management of squid catch could be focused on pinniped and cetacean foraging areas (see below).

Results

Harvest recommendations for 2010-2011

	Tier 6 (max)	Tier 6 (max)
time period used for catch	1990-2008	1997-2007
average survey biomass (t)	N/A	N/A
ABC (t)	1,148	**1,148**
OFL (t)	1,530	**1,530**

As discussed previously, all of these recommendations are problematic in some way. Because biomass estimates for squids are not reliable, and estimates of M are problematic, we recommend a Tier 6 approach. Because squid are highly productive and the catch of a nontarget species may not be reflective of sustainability, we further suggest using a modified Tier 6 approach where OFL = maximu historical catch and ABC = 0.75*OFL. In addition, we recommend using the years 1997-2008 as a baseline for consistency with other Tier 6 species groups.

Ecosystem Considerations

Fishery management should attempt to prevent negative impacts on squid populations not only because of their potential fishery value, but also (and perhaps more so) because of the crucial role they play in marine ecosystems. Squid are important components in the diets of many seabirds, fish, and marine mammals, as well as voracious predators themselves on zooplankton and larval fish (Caddy 1983, Sinclair et al. 1999).

Squids are central in food webs in the GOA (Figure 4). These food webs were derived from mass balance ecosystem models assembling information on the food habits, biomass, productivity and consumption for all major living components in each system (Aydin et al. 2007). While it might appear convenient to apply similar management to squids in all Alaskan federal waters, the EBS, AI, and GOA are physically very different ecosystems, especially when viewed with respect to available squid habitat and densities. While direct biomass estimates are unavailable for squids, ecosystem models can be used to estimate squid densities based upon the food habits and consumption rates of predators of squid. The AI has much more of its continental shelf area in close proximity to open oceanic environments where squid are found in dense aggregations, hence the squid density as estimated by predator demand in each system is much greater in the AI relative to the EBS (labeled "BS" in the figures) and GOA (Figure 5, upper panel).

In contrast with predation mortality, estimated fishing mortality on squid is currently very similarly low in all three ecosystems. Figure 5 (lower panel) demonstrates the estimated proportions of total squid mortality attributable to fishing vs. predation, according to food web models built based on early 1990's information from the AI, EBS, and the GOA. Fishing mortality is so low relative to predation mortality that it is not visible in the plot, suggesting that current levels of overall fishery bycatch may be insignificant relative to predation mortality on squid populations. The fish predators of squids in the GOA are primarily salmon, which account for nearly half of the squid mortality in the ecosystem model (Figure 6). Marine mammals such as sperm whales and other toothed whales account for a total of 14% of squid mortality, and the primary groundfish predators of squids are sablefish, pollock, and grenadiers (labeled "deep demersals" and or "large demersals" in Figure 6) in the GOA, which combined account for another 10% of squid mortality. While estimates of squid consumption are considered uncertain, the ecosystem models incorporate uncertainty in partitioning estimated consumption of squid between their major predators in each system. The predators with the highest overall consumption of squid in the GOA are salmon, which are estimated to consume between 200 thousand and 1.5 million metric tons of squid annually, followed by sperm and toothed whales combined, which consume 100 to 200 thousand metric tons of squid annually.

Although salmon have the highest consumption of squids in the GOA and account for nearly half of their estimated mortality, squid are not dominant in salmon diets, so salmon do not appear to be as dependent on squids as some other predators are. Squid make up about 20% of the diet of GOA salmon, 86% of the diet of GOA sperm whales, 67% of the diet of other toothed whales, and 21% of the diet of sablefish (Figure 7). In addition, squids are important constituents of seabird diets (Figure 8). The input data for the AFSC ecosystem models suggests that squids make up nearly half the diet of fulmars, storm petrels, and the albatross/jaegers group (Figure 8; Aydin et al. 2007). These input data are largely based on diet composition and preference data reported by Hunt et al. (2000).

The importance of squids within the GOA ecosystem was assessed using a model simulation analysis where squid mortality was increased by 10% to determine the effects on other living GOA groups. This analysis also incorporated the uncertainty in model parameters, resulting in ranges of possible outcomes which are portrayed as 50% confidence intervals (boxes in Figure 9) and 95% confidence intervals (error bars in Figure 9). Species showing the largest changes from baseline conditions are presented in descending order from left to right. Therefore, the largest change resulting from a 10% increase in GOA squids mortality is a median 10% decrease in squid biomass (Figure 9), as might have been expected from such a perturbation. Of more ecological interest are the negative effects on the biomass of sperm and beaked whales (which includes only sperm whales in the GOA model), which significantly decrease in biomass in response to the decrease in squids. Similarly, grenadiers (the majority of the aggregation "miscellaneous fish deep") are predicted to decrease significantly in response to a decrease in squids. Some other predators showed declines, but the 95% confidence interval included no change, so the declines are not certain; these were salmon sharks, porpoises, returning adult salmon (and the salmon fishery), and sablefish. Other groups in the ecosystem responded to simulated squid declines with increased biomass, including small forage fishes such as myctophids, eulachon, other pelagic smelts and forage fishes, juvenile (outgoing) salmon, and some zooplankton prey of squids including pelagic amphipods and chaetognaths (Figure 9). It is unclear to what extent these increases are competitive releases or direct predation releases caused by lower squid survival.

Diets of squids are poorly studied, but currently believed to be largely dominated by euphausiids, copepods and other pelagic zooplankton in the GOA (Figure 10, upper panel). Assuming these diets are assessed correctly, squids are estimated to consume on the order of one to five million metric tons of these zooplankton species in the GOA annually. Squids are also reported to consume forage fish as a small portion of their diet, which could amount to as much as one million metric tons annually in the GOA ecosystem (Figure 10, lower panel). In a simulation where each species group in the ecosystem had survival reduced by 10%, the strongest effects on GOA squids were from reduced survival of squids (the direct effect), followed by the bottom-up effects from large and small phytoplankton, and to a lesser extent by zooplankton (Figure 11). While there is much uncertainty surrounding the quantitative ecological interactions of squids, as is apparent in the wide ranges of these estimates from food web models, it is clear that squids are intimately connected with both very low trophic level processes affecting secondary production of zooplankton, and in turn they comprise a significant portion of the diet of both commercially important (salmon) and protected species (whales) in the GOA.

While overall fishing removals of squid are very low relative to predation at the ecosystem scale, local-scale patterns of squid removals should still be monitored to ensure that fishing operations minimize impacts to both squid and their predators. Many squid populations are composed of spatially segregated schools of similarly sized (and possibly related) individuals, which may migrate, forage, and spawn at different times of year (Lipinski, 1998). The timing and location of fishery interactions with squid spawning aggregations may affect the availability of squid as prey for other animals as well as the age, size, and genetic structure of the squid populations themselves (Caddy 1983, O'Dor 1998). The essential position of squids within North Pacific pelagic ecosystems, combined with our limited knowledge of the abundance, distribution, and biology of squid species in the FMP areas, illustrates the difficulty of managing an important nontarget species complex with little information.

Ecosystem Effects on Stock and Fishery Effects on the Ecosystem: Summary

In the following table, we summarize ecosystem considerations for GOA squids and the entire groundfish fishery where they are caught incidentally. The observation column represents the best attempt to summarize the past, present, and foreseeable future trends. The interpretation column provides details on how ecosystem trends might affect the stock (ecosystem effects on the stock) or how the fishery trend affects the ecosystem (fishery effects on the ecosystem). The evaluation column indicates whether the trend is of: *no concern, probably no concern, possible concern, definite concern,* or *unknown.*

Ecosystem effects on GOA Squids *(evaluating level of concern for squid populations)*

Indicator	Observation	Interpretation	Evaluation
Prey availability or abundance trends			
Zooplankton Forage fish	Trends are not currently measured directly, only short time series of food habits data exist for potential retrospective measurement	Unknown	Unknown
Predator population trends			
Salmon	Increased populations since 1977, stable throughout the 1990s to present	Mortality higher on squids since 1977, but stable now	Probably no concern
Toothed whales	Unknown population trend	Unknown	Unknown
Sablefish	Cyclically varying population with a downward trend since 1986	Variable mortality on squids slightly decreasing over time	Probably no concern
Grenadiers	Unknown population trend	Unknown	Unknown
Changes in habitat quality			
North Pacific gyre	Physical habitat requirements for squids are unknown, but are likely linked to pelagic conditions and currents throughout the North Pacific at multiple scales.	Unknown	Unknown

Groundfish fishery effects on ecosystem via squid bycatch *(evaluating level of concern for ecosystem)*

Indicator	Observation	Interpretation	Evaluation
Fishery contribution to bycatch			
Squid catch	Stable, generally <100 tons annually except for 2005, 2006, and 2007	Extremely small relative to predation on squids	No concern
Forage availability for salmon	Depends on magnitude of squid catch taken in salmon foraging areas	Squid catch generally low, small change to salmon foraging at current catch	Probably no concern
Forage availability for toothed whales	Depends on magnitude of squid catch taken in toothed whale foraging areas	Squid catch generally low, small change to toothed whale foraging at current catch	Probably no concern
Forage availability for sablefish	Depends on magnitude of squid catch taken in sablefish foraging areas	Squid catch generally low, small change to sablefish foraging at current catch	Probably no concern
Forage availability for grenadiers	Squid catch overlaps somewhat with grenadier foraging areas along slope	Small change in forage for grenadiers	Probably no concern
Fishery concentration in space and time	Bycatch of squid is mostly in shelf break and canyon areas, no matter what the overall distribution of the pollock fishery is	Potential impact to spatially segregated squid cohorts and squid predators	Possible concern
Fishery effects on amount of large size target fish	Effects of squid bycatch on squid size are not measured	Unknown	Unknown
Fishery contribution to discards and offal production	Squid discard an extremely small proportion of overall discard and offal in groundfish fisheries	Addition of squid to overall discard and offal is minor	No concern
Fishery effects on age-at-maturity and fecundity	Effects of squid bycatch on squid or predator life history are not measured	Unknown	Unknown

Data gaps and research priorities

Clearly, there is little information for stock assessment of the squid complex in the GOA. However, ecosystem models estimate that the proportion of squid mortality attributable to incidental catch in groundfish fisheries in the GOA region is extremely small relative to that attributable to predation mortality. Therefore, improving the information available for squid stock assessment seems a low priority as long as the catch remains at its current low level.

However, investigating any potential interactions between incidental removal of squids and foraging by sensitive species (e.g. toothed whales, albatrosses) is a higher priority for research. Limited data suggest that squids may make up 67 to 85% of the diet (by weight) for toothed whales in the GOA. Research should investigate whether the location and timing of incidental squid removals potentially overlap with foraging seasons and areas these species, and whether the magnitude of squid catch at these key areas and times is sufficient to limit the available forage.

In 2007, observers began measuring the length of squids caught in pollock target fisheries. Although these data are not yet available for the GOA, they will be useful for investigating potential ecosystem effects (e.g., "large" squid the size of *Moroteuthis robusta* are more predator than prey in the ecosystem, while smaller squid species may be most important as prey). In the future, it might also be important to be able to estimate the species composition of squid complex bycatch to determine relative impacts on marine mammals and other predators that depend on squids for prey, as well as relative impacts to the squid populations themselves.

Acknowledgements

We acknowledge all of the AFSC and AKRO staff that have contributed to the development of the analytical approaches and assisted in obtaining data from a variety of resources.

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Tables

Table 1. Taxonomic grouping of squid species that have been found in the BSAI. It is not known whether all of these species occur in the GOA.

Class Cephalopoda; Order Oegopsida	
Family Chiroteuthidae	
Chiroteuthis calyx	
Family Cranchiidae	"glass squids"
Belonella borealis	
Galiteuthis phyllura	
Family Gonatidae	"armhook squids"
Berryteuthis anonychus	minimal armhook squid
Berryteuthis magister	magistrate armhook squid
Eogonatus tinro	
Gonatopsis borealis	boreopacific armhook squid
Gonatus berryi	Berry armhook squid
Gonatus madokai	
Gonatus middendorffi	
Gonatus onyx	clawed armhook squid
Family Onychoteuthidae	"hooked squids"
Moroteuthis robusta	robust clubhook squid
Onychoteuthis borealijaponicus	boreal clubhook squid
Class Cephalopoda; Order Sepioidea	
Rossia pacifica	North Pacific bobtail squid

Table 2. Estimated total catches of squid (t) in the Gulf of Alaska groundfish fisheries, 1990-2008 (1990 is the earliest year for which GOA squid catch data are available), with estimated annual retention rates. Table also includes annual TACs for the Other Species complex and estimated Other Species catch, 1990-2008. "Squid %" shows the percentage of squids in the total Other Species catch.

	squid catch (t)	% squid catch retained	Other Species catch (t)	Other Species TAC (t)	squid % of Other Species	management method
1990	60		6,289		1%	Other Species TAC
1991	117		5,700		2%	Other Species TAC (incl. Atka)
1992	88		12,313	13,432	1%	Other Species TAC (incl. Atka)
1993	104		6,867	14,602	2%	Other Species TAC (incl. Atka)
1994	39		2,721	14,505	1%	Other Species TAC
1995	25		3,421	13,308	1%	Other Species TAC
1996	42		4,480	12,390	1%	Other Species TAC
1997	97	87%	5,439	13,470	2%	Other Species TAC
1998	59	50%	3,748	15,570	2%	Other Species TAC
1999	41	19%	3,858	14,600	1%	Other Species TAC
2000	19	52%	5,649	14,215	0%	Other Species TAC
2001	91	37%	4,804	13,619	2%	Other Species TAC
2002	43	61%	3,748	11,330	1%	Other Species TAC
2003	92	60%	1,682	11,260	5%	Other Species TAC
2004	162	78%	3,580	12,942	5%	Other Species TAC (no skates)
2005	635	88%	2,512	13,871	25%	Other Species TAC (no skates)
2006	1,530	97%	3,882	13,856	39%	Other Species TAC (no skates)
2007	412	94%	3,026	4,500	14%	Other Species TAC (no skates)
2008	84	84%	2,984	4,500	3%	Other Species TAC (no skates)
2009*	336*	91%*	2,085*	4,500	16%*	Other Species TAC (no skates)

Data sources and notes: squid catch 1990-1996, Gaichas et al. 1999; squid catch 1997-2002, AKRO Blend; squid catch 2003-2009, AKRO CAS; Other Species catch, AKRO Blend and CAS; TAC, AKRO harvest specifications. Other Species catch from 1990-2003 does not include catch of skates in the IFQ Pacific halibut fishery, and after 2003 includes no skate catch at all . Estimates of retention rates are from fishery observer data provided by the AFSC Fishery Monitoring and Analysis group.

*2009 catch data are incomplete; retrieved on October 7, 2009.

Table 3a. Estimated catch (t) of all squid species in the Gulf of Alaska combined by target fishery, 1997-2002. Data sources: AKRO Blend.

target fishery	1997	1998	1999	2000	2001	2002
deep flatfish	5	3	6	1	1	1
flathead sole	1	0	0	0	1	0
other target	14	0	0	0	0	0
Pacific cod	1	1	1	0	1	0
rex sole	1	1	4	2	3	1
rockfish	8	6	7	7	9	7
sablefish	0	0	2	0	0	0
shallow flatfish	0	0	0	0	0	0
arrowtooth	1	3	1	1	2	7
pollock	66	46	20	7	74	28
total	97	60	41	18	91	44

Table 3b. Estimated catch (t) of all squid species in the Gulf of Alaska combined by target fishery, 2003-2009. Data sources: AKRO CAS. *2009 data are incomplete; retrieved October 7, 2009.

target fishery	2003	2004	2005	2006	2007	2008	2009*
arrowtooth flounder	3	1	2	1	2	0	7
deep flatfish	0	1	0	0	0	0	0
flathead sole	0	0	0	0	0	0	0
other target	0	0	0	0	0	0	0
Pacific cod	14	0	0	0	0	0	0
rex sole	2	0	0	0	0	0	2
rockfish	9	12	2	10	3	5	14
sablefish	0	4	0	0	0	0	0
shallow flatfish	0	0	0	0	1	0	1
pollock	64	145	631	1,518	405	78	312
total	92	162	635	1,530	412	84	336

Table 4. Estimated catch (t) of all squid species in the Gulf of Alaska combined by NMFS statistical area, 1997-2008. Data sources: 1997-2002, AKRO Blend; 2003-2008, AKRO CAS. *2009 are incomplete; retrieved October 7, 2009.

	NMFS statistical area							
	610	**620**	**630**	**640**	**649**	**650**	**659**	**total**
1997	46	4	36	2	6	4	0	98
1998	18	8	21	3	9	0	0	59
1999	6	11	14	2	8	0	0	41
2000	7	2	8	2	0	0	0	19
2001	19	54	17	1	0	0	0	91
2002	19	12	10	1	0	0	0	42
2003	19	43	13	2	15	0	0	92
2004	15	129	11	2	5	0	0	162
2005	13	606	11	2	3	0	0	635
2006	12	1,485	14	5	14	0	0	1,530
2007	3	403	5	0	0	0	0	412
2008	4	77	2	0	0	0	0	84
*2009	11	314	9	1	0	0	0	*336

Table 5. Biomass estimates (t) of squid species from NMFS GOA bottom trawl surveys, 1984-2007. CV = coefficient of variation.

	unidentified squids		*B. magister*		all squids	
year	biomass (t)	CV	biomass (t)	CV	biomass (t)	CV
1984	546	0.35	2,762	0.15	3,308	0.14
1987	577	0.30	4,506	0.34	5,083	0.30
1990	276	0.43	4,033	0.17	4,309	0.16
1993	1,029	0.73	8,447	0.13	9,476	0.14
1996	26	0.28	4,884	0.14	4,911	0.14
1999	254	0.46	1,873	0.13	2,127	0.13
2001	703	0.62	5,909	0.30	6,612	0.27
2003	71	0.23	6,251	0.18	6,322	0.18
2005	249	0.51	4,650	0.18	4,899	0.18
2007	310	0.45	11,681	0.20	11,991	0.20
2009	188	0.61	8,415	0.16	8,603	0.16

Figures

Figure 1. *Berryteuthis magister*, the magistrate armhook or red squid, is a common species in the GOA and shows the general physical characteristics of species in the Order Teuthoidea.

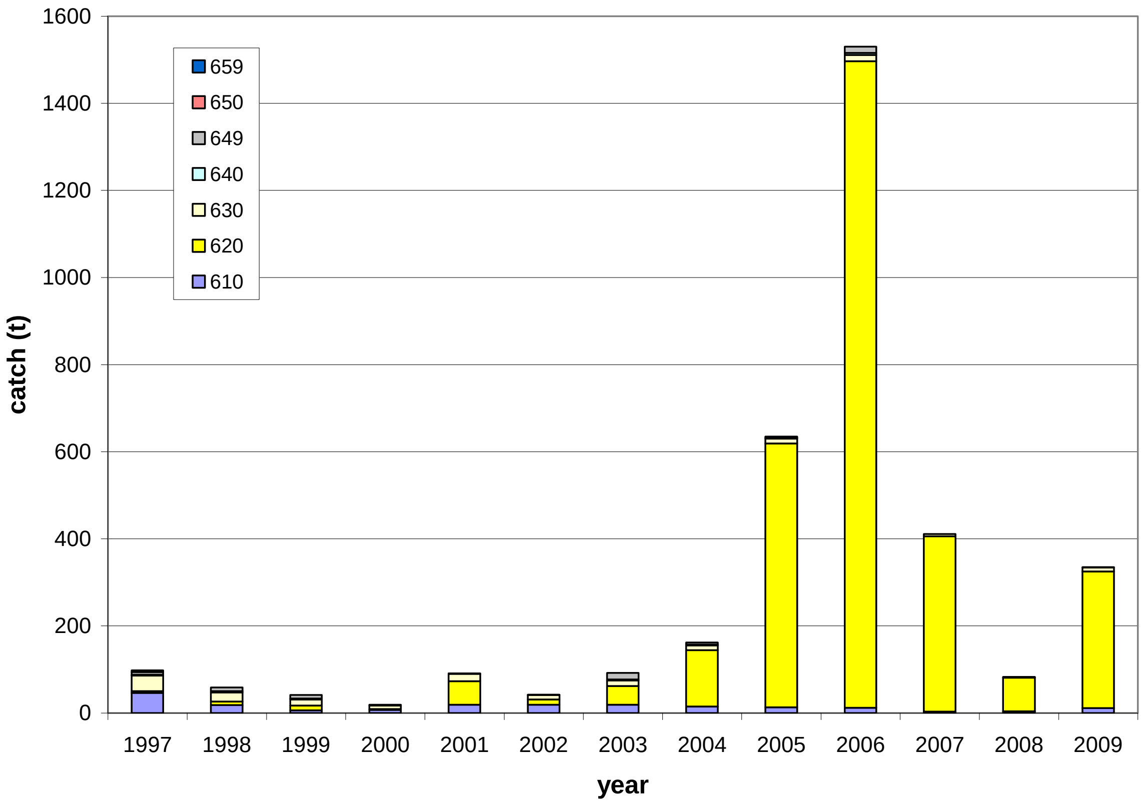


Figure 2. Estimated catch (t) of all squid species combined in the Gulf of Alaska by NMFS statistical area, 1997-2009. Data sources: 1997-2002, AKRO Blend; 2003-2009, AKRO CAS. *2009 data are incomplete; retrieved October 7, 2009.

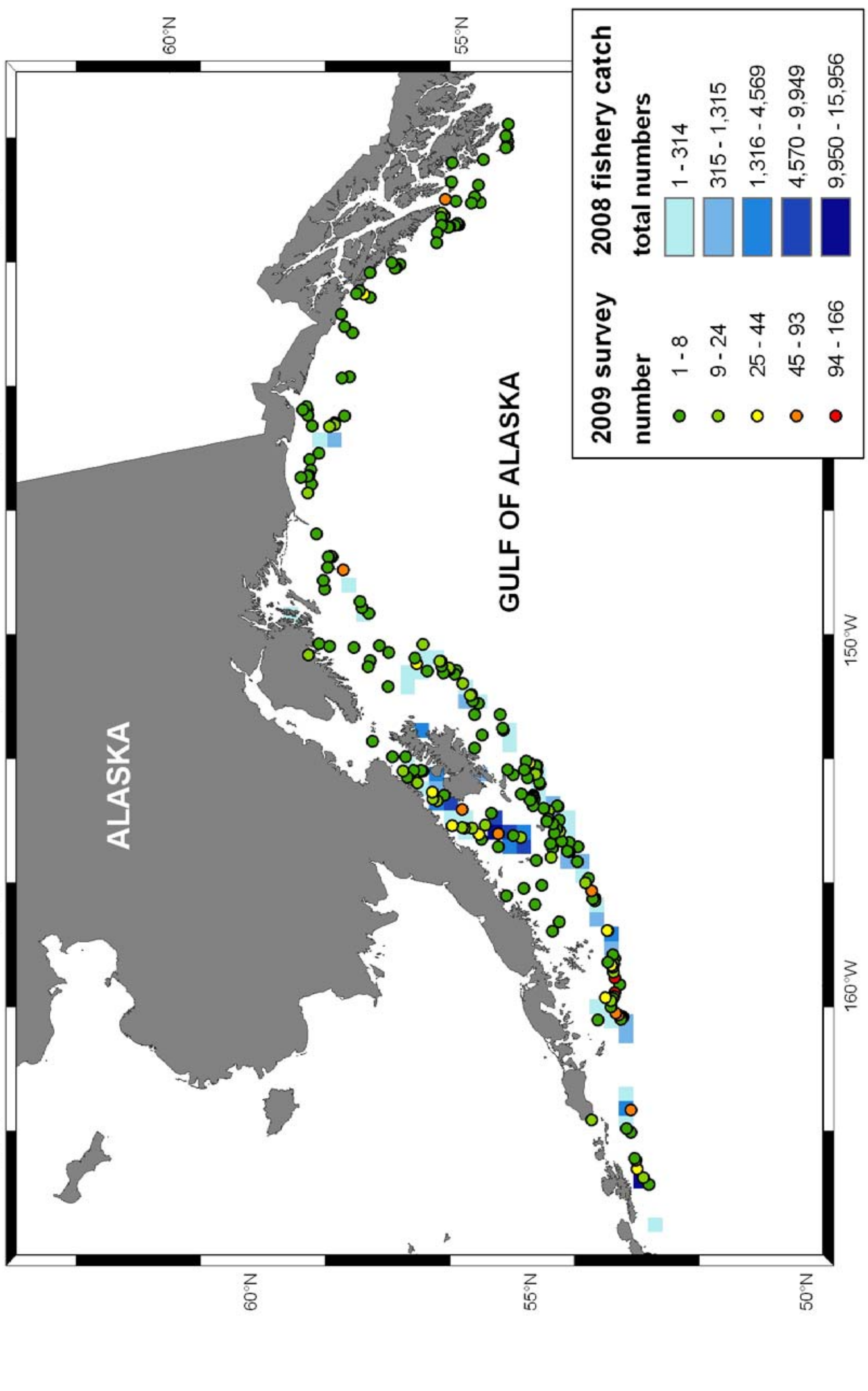


Figure 3. Distribution of survey and commercial fishery catches of all squids in the GOA. Colored circles indicate catches during the 2009 AFSC bottom trawl survey. Catch data are total number caught in each grid cell (30 km x 30 km.

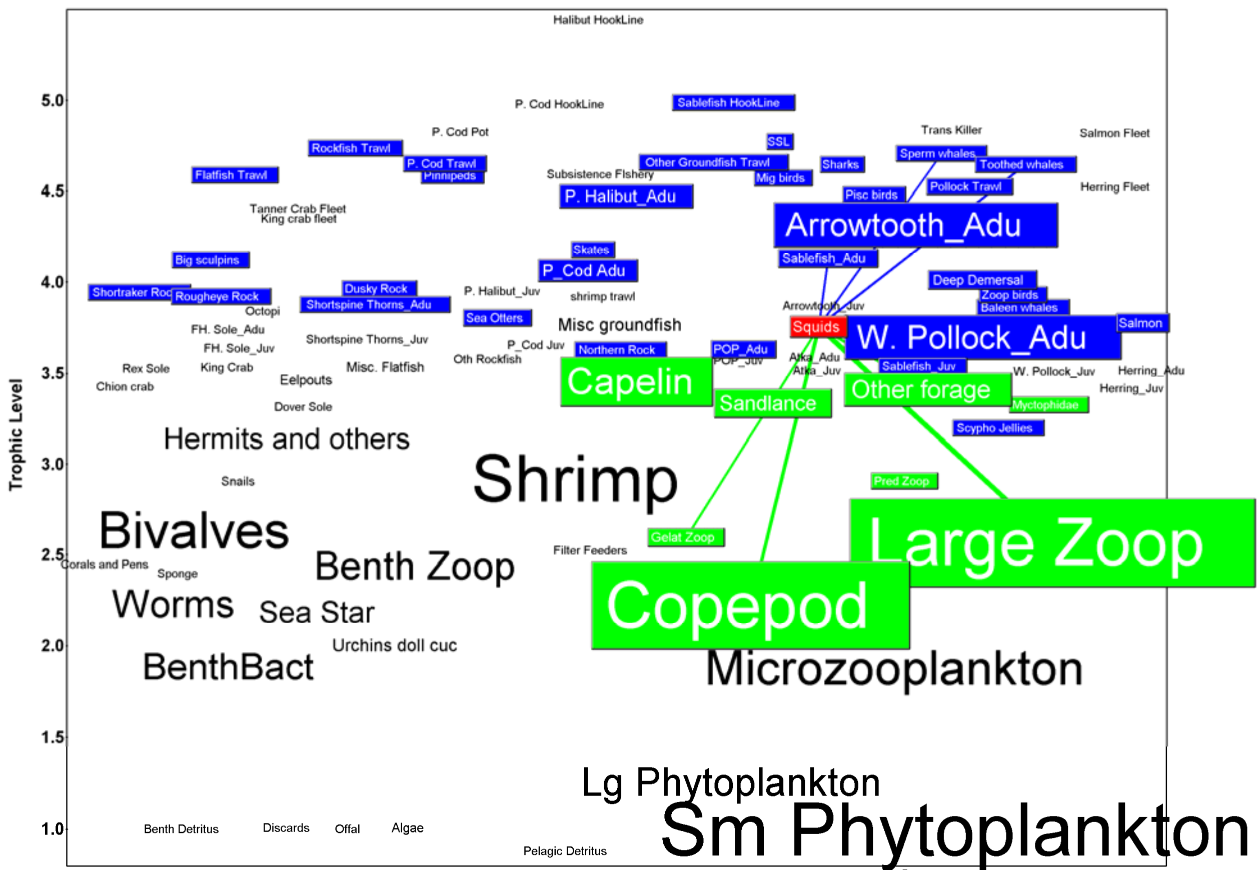


Figure 4. Food web of squids in the Gulf of Alaska, with squids highlighted in red, their predators in blue, and prey in green. Box size is proportional to the biomass of the group in the Gulf of Alaska, and lines between boxes indicate the strength of the flow between groups. If a group is highlighted but there is no line connecting it to squid, then the flow between those groups is less than 5% of all energy flows into or out of squid. Wider lines indicate stronger flows, for instance the strongest prey flow into squid comes from large zooplankton, followed by copepods.

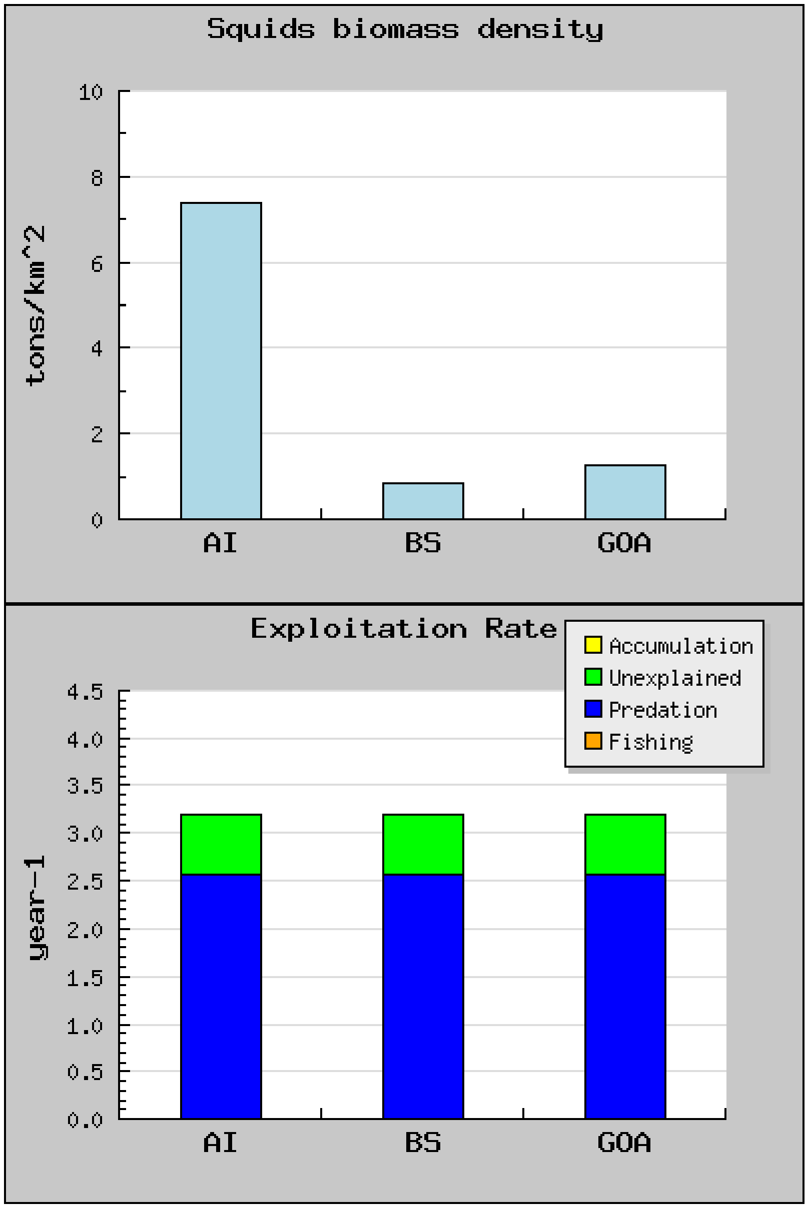


Figure 5. (Upper) Biomass density (tons per square kilometer) estimated by ecosystem models of the AI, EBS, and GOA. (Lower) exploitation rates partitioned into mortality due to predation, fishing, and unexplained sources. (Fishing mortality has been included in this calculation, but is too small to show on the plot.)

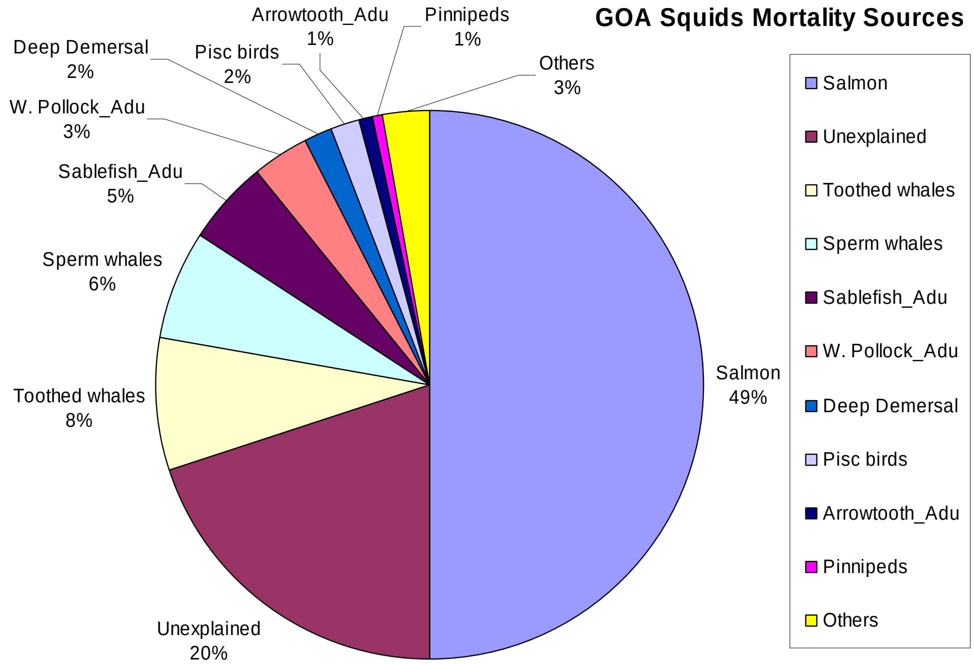


Figure 6. Proportion of mortality of squids attributable to each of their predators in the Gulf of Alaska. Lg. or Deep demersals is primarily grenadiers (Macrouridae) in the GOA.

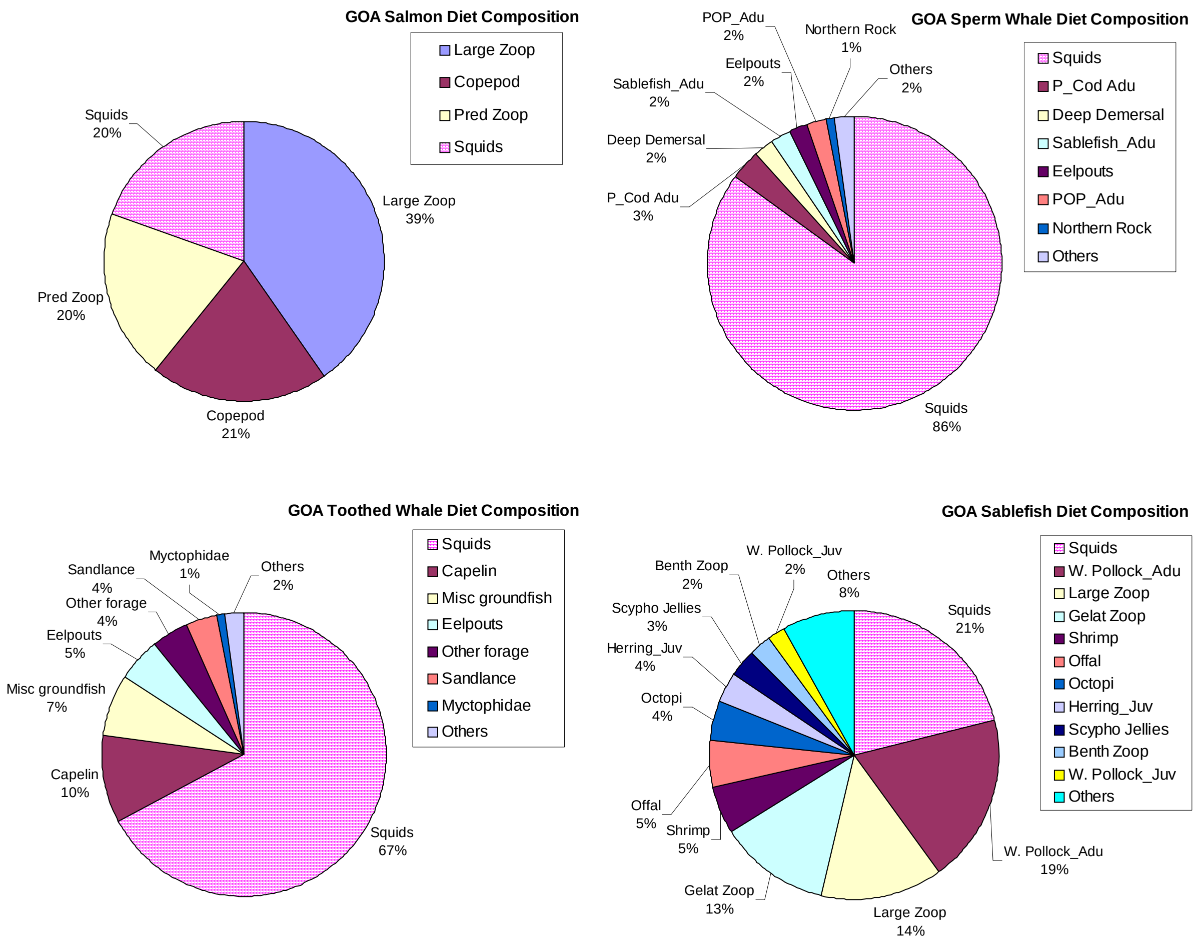


Figure 7. Proportion of squids in diets of major squid consumers in the GOA: salmon (top left), sperm whales (top right), other toothed whales (bottom left), and sablefish (bottom right). Note that squids are always the patterned section of each plot; colors for other species groups are not consistent between plots.

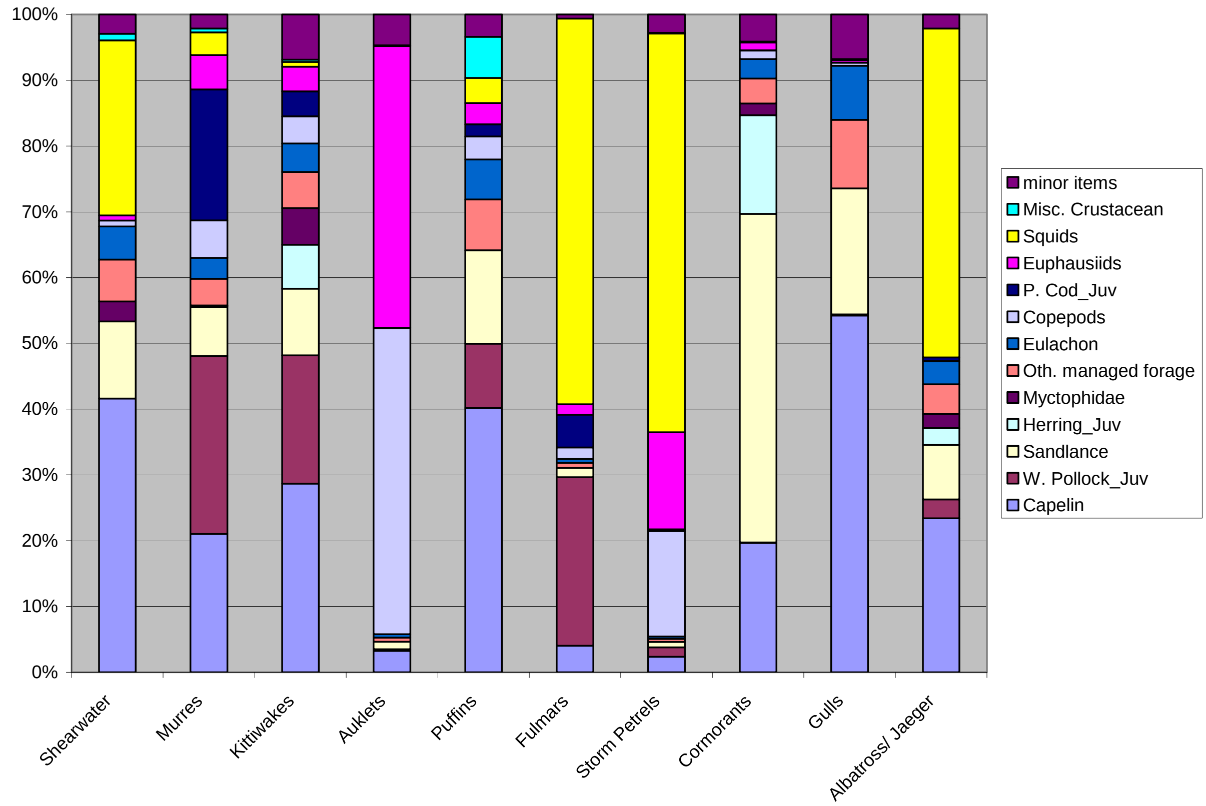


Figure 8. Estimated diet composition of seabirds in the GOA. Data are the inputs used in ecosystem modeling performed at the AFSC (Aydin et al. 2007) and are based largely on Hunt et al. (2000). Albatrosses and jaegers are considered a single functional group for modeling purposes.

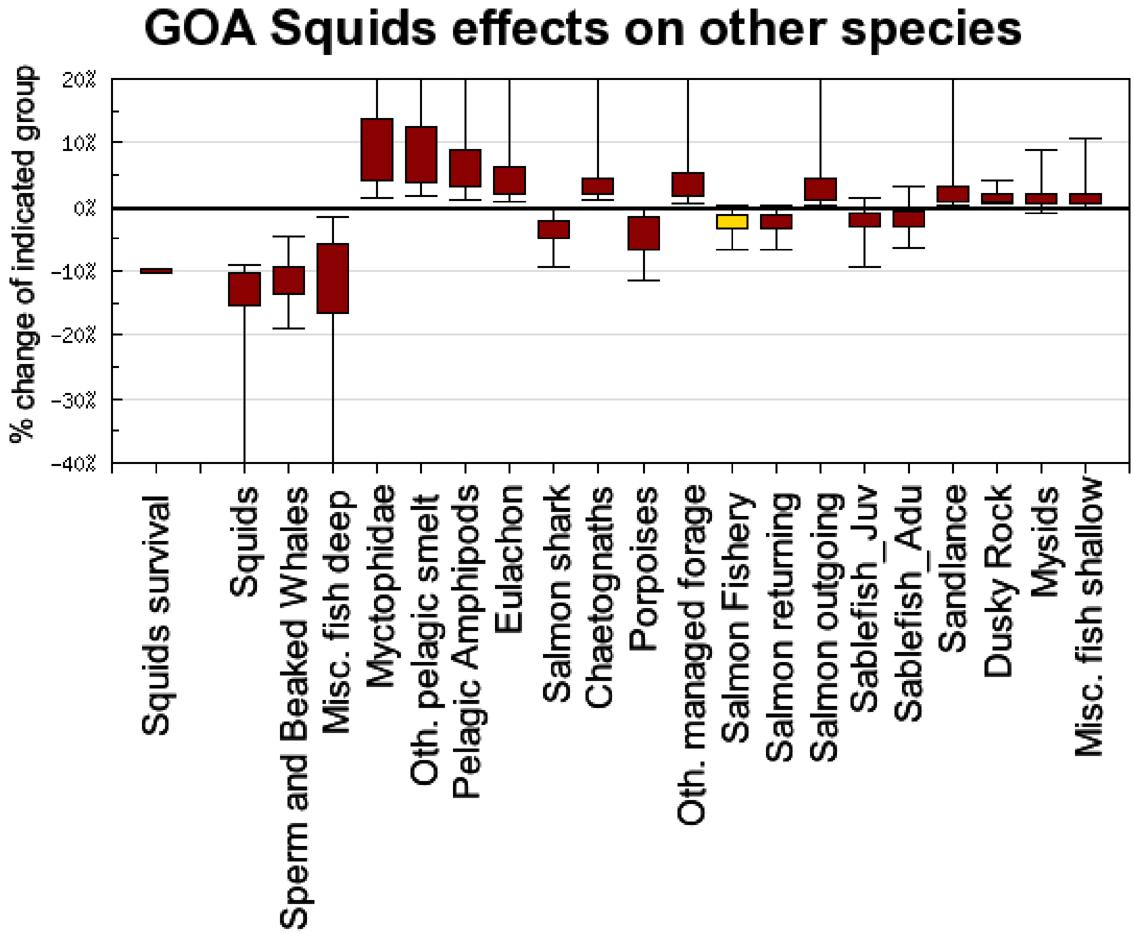
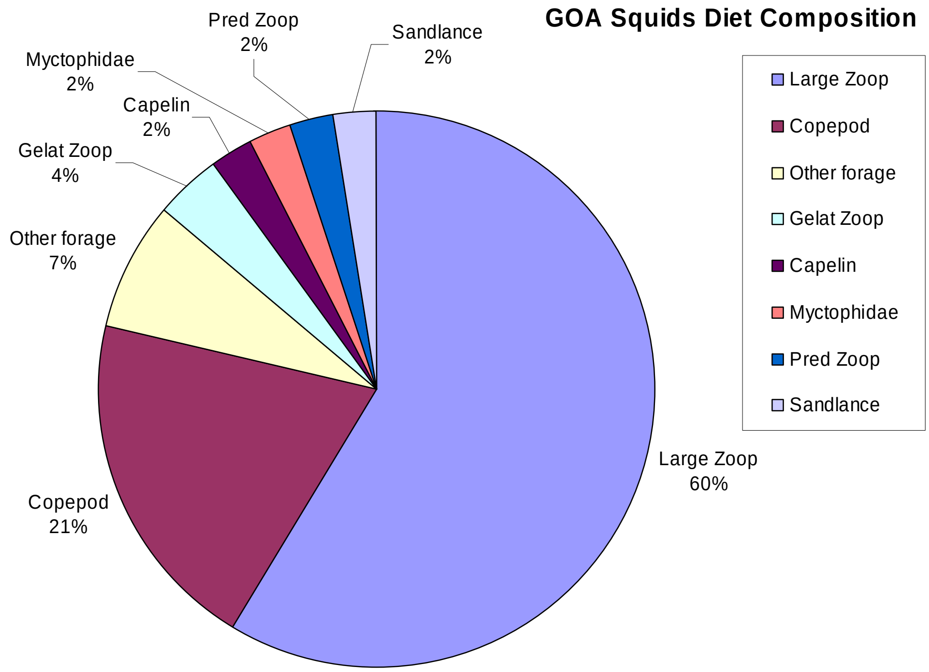


Figure 9. Results of a simulation analysis where squid mortality was increased (survival was decreased) by 10% in the GOA ecosystem model. Boxes represent the 50% confidence interval, and error bars reflect the 95% confidence interval of the percent change in biomass relative to the baseline condition in the model. The leftmost bar indicates the type of perturbation (Squids survival decreases 10%), and every other bar from left to right shows the outcome to each living group in the GOA ecosystem model in order of descending effect from largest to smallest (effects to groups not shown were insignificant). In this simulation, the group aggregated as “toothed whales” in previous plots are included in the groups “Sperm and beaked whales” and “Porpoises.” This change was made for comparison across the GOA, EBS, and AI models. In all cases, the underlying model is the same.



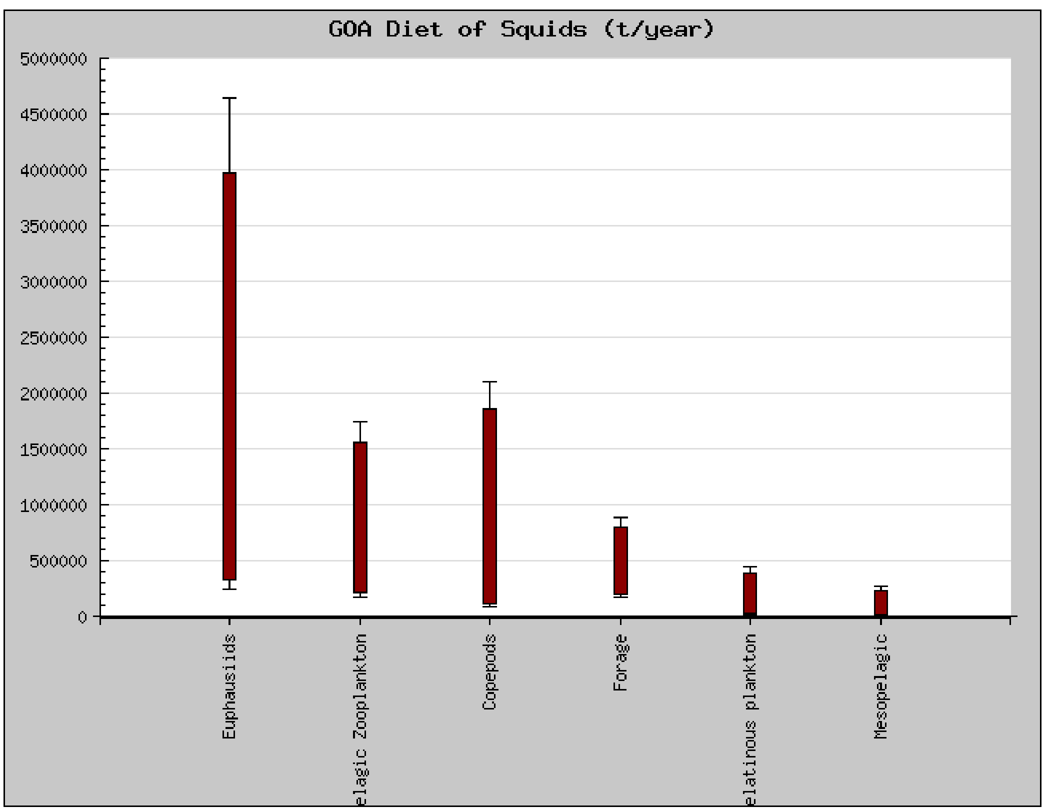


Figure 10. Diet composition (upper) and consumption (lower) by squid in the Gulf of Alaska.

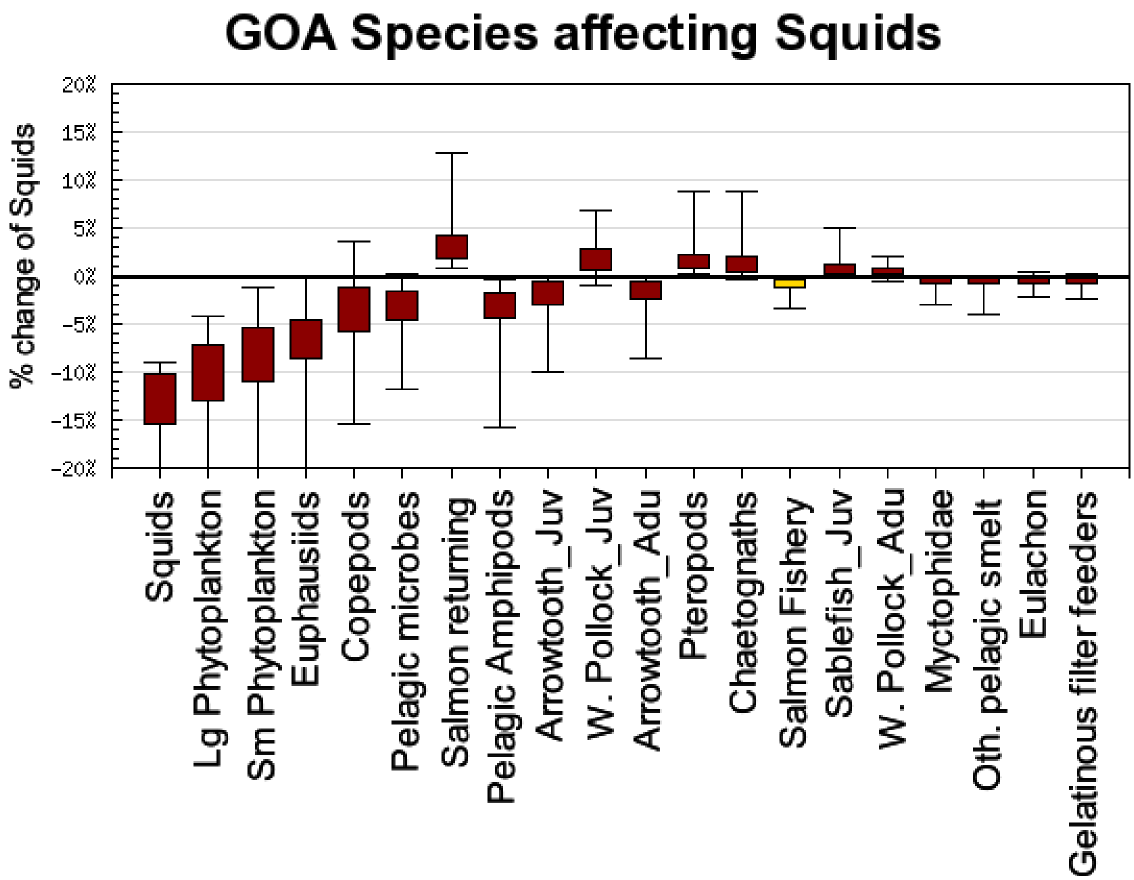


Figure 11. Predicted change in GOA squids biomass resulting from a series of perturbations where each species group in the ecosystem had its survival decreased by 10%. Species groups affecting squids are listed in descending order from left to right by the largest percent change in squid biomass resulting from that species decreased survival. Therefore, biomass of GOA squids is most affected by a 10% reduction in squid survival, as might be expected. The next largest effects after the direct effect of squid on squid are the bottom up effects felt by the entire ecosystem of reducing survival of large and small phytoplankton.

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