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Distribution, Diet, and Bycatch of Chum Salmon in the Eastern Bering Sea

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Abstract: Diet and foraging behavior of chum salmon (*Oncorhynchus keta*) on age-0 walleye pollock (*Gadus chalcogrammus*) are highlighted as an integral part of their bycatch in U.S. groundfish fisheries in the eastern Bering Sea. Annual bycatch exploitation rates on regional stock groups (western Alaska, Russia, Gulf of Alaska, and Japan) of chum salmon were estimated to be low (< 1.5%) and covaried with bycatch numbers, indicating that factors other than stock abundance are responsible for changes in their bycatch numbers over time. Stock structure and spatial distribution patterns of chum salmon indicate that their bycatch primarily stems from the movement of large chum salmon from the Bering Sea basin and the Gulf of Alaska onto the eastern Bering Sea shelf. Age-0 walleye pollock increased significantly in surface trawl catch data and in the diet of chum salmon during a period of increased bycatch (2004 to 2006). Chum salmon bycatch is positively correlated with surface trawl catch data of age-0 walleye pollock on the eastern Bering Sea shelf ($r = 0.83$, $p < 0.01$) and particularly in ecoregions where bycatch occurs ($r = 0.91$, $p < 0.001$). The close association between chum salmon bycatch, their diet, and surface trawl catch of age-0 walleye pollock highlights the importance of foraging behavior of chum salmon (particularly on age-0 walleye pollock) to their bycatch in eastern Bering Sea groundfish fisheries.

Keywords: Chum salmon, distribution, diet, bycatch, eastern Bering Sea, groundfish fisheries, walleye pollock

INTRODUCTION

Incidental capture (bycatch) of chum salmon (*Oncorhynchus keta*) is an important management issue in eastern Bering Sea groundfish fisheries, particularly for the walleye pollock (*Gadus chalcogrammus;* hereafter referred to as pollock) trawl fisheries. Chum salmon are an important economic and cultural resource in Alaska and they are classified as a prohibited species (cannot be retained) in U.S. groundfish fisheries. The number of chum salmon captured as bycatch in U.S. groundfish fisheries in the eastern Bering Sea has varied significantly over time, ranging from a high of 700,000 in 2005 to a low of 13,000 in 2010 (Fig. 1). Although chum salmon from all areas of the North Pacific contribute to bycatch in the eastern Bering Sea, a large portion of the bycatch originates from Japan and Russia due to the extensive use of the Bering Sea by Asian chum salmon stocks (Fredin et al. 1977; Myers et al. 2007; Sato et al. 2009; Urawa et al. 2009). Japanese and Russian stocks of immature and maturing chum salmon are the dominant stocks of chum salmon in the Bering Sea basin during the summer and fall (Urawa et al. 2009). North American chum salmon (including stocks from western Alaska) primarily rear in the Gulf of Alaska during their immature life-history stage, but occur in the Bering Sea bycatch (Wilmot et al. 1998; Seeb et al. 2004; Marvin et al. 2011). Bycatch of chum salmon primarily occurs during late summer and fall and is largely absent in winter fisheries (Stram and Ianelli 2009), which is consistent with the seasonal migratory patterns of Asian chum salmon in the Bering Sea (Fredin et al. 1977; Urawa et al. 2001, 2009; Urawa 2004).

Chum salmon have the largest biomass of all Pacific salmon species in the North Pacific Ocean (Eggers 2009). Although the number of pink salmon harvested each year exceeds that of chum salmon (NPAFC 2016), the presence of multiple cohorts or ages of chum salmon in the ocean (pink salmon are from a single cohort) and the larger average size of chum salmon results in a larger biomass of chum salmon than pink salmon in the North Pacific Ocean. Chum salmon are primarily harvested in salmon commercial fisheries

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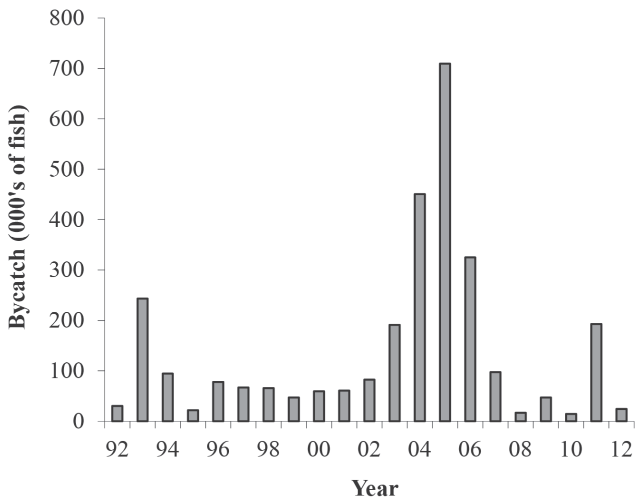

Fig. 1. Total bycatch of chum (non-Chinook) salmon in Bering Sea-Aleutian Islands (BSAI) groundfish fisheries (1992 to 2012).

that operate in terminal regions (average annual harvest of approximately 95 million fish, 325,000 t (metric ton), since 2000), but chum salmon also support culturally significant subsistence fisheries (approximately 1 million fish annually since 2000) and sport fisheries (approximately 300,000 fish annually since 2000; NPAFC 2016). Over 50% of the chum salmon harvest in the North Pacific from 1974 to 2014 were Japanese chum salmon (NPAFC 2016), primarily due to the success of their hatchery program.

Bycatch controls have played an important role in shaping the management and regulation of groundfish fisheries, particularly pollock fisheries, in the eastern Bering Sea. The eastern Bering Sea pollock fishery is one of the largest fisheries in the world with an average annual harvest of approximately 1.2 million t (Ianelli et al. 2014). Pollock are harvested during winter and summer fishing seasons for fillet, surimi, and roe products (Fissel et al. 2014). Groundfish fisheries were principally developed by foreign fleets during the 1950s. Salmon bycatch controls applied to the foreign fleet included observer programs, prohibiting the retention of salmon, time and area closures, and Chinook salmon bycatch caps (Nelson et al. 1981; Witherell and Pautzke 1997). The Magnuson-Stevens Fishery Conservation and Management Act in 1976 allowed for greater domestic control over groundfish resources in the eastern Bering Sea and groundfish were harvested through joint venture fisheries (foreign and domestic); by 1990, groundfish resources in the Bering Sea were harvested entirely by a domestic fishing fleet (Guttormsen et al. 1992). Salmon have retained their prohibited species status in domestic fisheries and bycatch is monitored by the North Pacific Fisheries Observer Program (Queirolo et al. 1995; AFSC 2012). Salmon bycatch controls placed on domestic pollock fisheries have included time and area closures (chum and Chinook salmon savings areas) in 2005 (Witherell and Pautzke 1997), and bycatch caps placed on Chinook salmon as part of Amendment 91 to the Bering Sea Aleutian Islands Groundfish Fishery Management Plan in 2011 (NMFS 2010). The North Pacific Fisheries Management Council is currently developing a consolidated bycatch management plan for both Chinook and chum salmon (NPFMC 2015). The pollock fishing industry has also taken an active role in developing measures to limit salmon bycatch through trawl design modifications (salmon excluders) and rolling hot-spot closures to adaptively direct fishing effort to minimize bycatch (Haflinger and Gruver 2009). Bycatch hot-spots are locations where bycatch rates (the number of bycatch species relative to target species) are higher than average.

Due to the complex, dynamic, and polarizing nature of bycatch, many sources of information and perceptions impact approaches used to address bycatch. Research directed at improving bycatch predictability, and our understanding of the factors that contribute to changes in bycatch over time are expected to help stabilize decisions related to bycatch and bycatch control (Murphy 1995; Witherell et al. 2002; Stram and Ianelli 2009, 2015; Ianelli et al. 2010; Ianelli and Stram 2014). In the following paper, we estimate bycatch exploitation rates on regional stock groups of chum salmon, connect bycatch patterns of chum salmon in the eastern Bering Sea to broad-scale patterns of chum salmon distribution, size, and diets from surface trawl research survey data in the Bering Sea, and highlight the importance of foraging behavior of chum salmon on age-0 pollock to their bycatch in U.S. groundfish fisheries in the eastern Bering Sea.

MATERIALS AND METHODS

Bycatch Impact

Bycatch exploitation rates, the ratio of the return year adult equivalent (AEQ) bycatch to the terminal run size of chum salmon, were used to estimate the impact of bycatch on chum salmon (Table 1). AEQ models discount bycatch numbers by the natural mortality that is expected to occur prior to returning to terminal fishing or spawning regions. Terminal run size consists of the harvest of mature chum salmon harvested in terminal regions and the number of chum salmon that spawn in natal rivers. Total run can differ from terminal run sizes when interception or bycatch occur in non-terminal regions. Estimates of AEQ bycatch are only included for the Bering Sea Aleutian Islands (BSAI) pollock fishery, but this fishery represents 98% of the total bycatch of chum salmon in U.S. groundfish fisheries in the eastern Bering Sea (NMFS 2015) and therefore provides a reasonable approximation to total AEQ bycatch of chum salmon in eastern Bering Sea groundfish fisheries. Bycatch exploitation rates were estimated for four regional aggregate stock groups: Japan, Russia, western Alaska, and the Gulf of Alaska (including stocks from British Columbia and the Pacific Northwest). Aggregate stock groups were used to simplify

Table 1. Return year adult equivalent (AEQ) bycatch of chum salmon and bycatch impacts (exploitation rates) of the eastern Bering Sea pollock fishery on four regional stock groups of chum salmon (western AK, Gulf of Alaska, Japan, and Russia), 1994 to 2009. Exploitation rates are based on the ratio of return year AEQ bycatch to terminal run size.

Year	AEQ bycatch (000's)	Western Alaska	Gulf of Alaska	Japan	Russia
1994	153.01	0.38%	0.07%	0.08%	0.20%
1995	55.27	0.08%	0.03%	0.02%	0.07%
1996	61.76	0.14%	0.03%	0.02%	0.10%
1997	68.87	0.26%	0.04%	0.03%	0.13%
1998	76.28	0.28%	0.03%	0.04%	0.12%
1999	55.15	0.24%	0.03%	0.03%	0.09%
2000	61.04	0.56%	0.03%	0.04%	0.08%
2001	61.20	0.28%	0.04%	0.03%	0.09%
2002	79.85	0.27%	0.04%	0.04%	0.11%
2003	163.51	0.50%	0.08%	0.07%	0.28%
2004	376.59	1.19%	0.21%	0.16%	0.64%
2005	677.13	1.31%	0.62%	0.26%	0.88%
2006	502.39	0.91%	0.30%	0.18%	0.52%
2007	178.62	0.43%	0.12%	0.07%	0.19%
2008	53.96	0.14%	0.04%	0.03%	0.05%
2009	42.36	0.12%	0.03%	0.02%	0.03%
Average	166.69	0.44%	0.11%	0.07%	0.22%

the analysis and minimize sampling and genetic assignment errors when estimating AEQ bycatch. Methods used to estimate return year AEQ bycatch estimates are described and included in the Environmental Assessment of Chum Salmon Bycatch (NPFMC 2012, 2015). Adult returns and AEQ bycatch for southwest Alaska (Alaska Peninsula) were not included in this analysis as they account for less than 2% of the bycatch (Kondzela et al. 2012) and harvests in this region are mixed stock in nature (Seeb and Crane 1999) and therefore do not reflect terminal runs to this region.

Terminal run sizes of the four regional stock groups of chum salmon were constructed from data summarized in Eggers (2009), the Environmental Assessment of Chum Salmon Bycatch (NPFMC 2012), and chum salmon harvest statistics (NPAFC 2016). Terminal run sizes of western Alaska chum salmon (includes the coastal western Alaska and the upper/mid-Yukon genetic stock groups, 1994 to 2009) were provided by the Alaska Department of Fish and Game and summarized in the Environmental Assessment of Chum Salmon Bycatch (NPFMC 2012). Terminal run size for chum salmon originating from Japan, Russia, and the Gulf of Alaska from 1994 to 2005 (Eggers 2009), were extended to 2009 with the relationship between terminal run size and harvest statistics from the North Pacific Anadromous Fish Commission (NPAFC; Fig. 2). Non-parametric Mann-Whitney-Wilcoxon tests and Pearson product-moment correlations implemented in R (R Core Team 2013) were used to test for differences in average exploitation rate by stock group, and covariance between exploitation rate and bycatch, respectively. Significance tests were also completed on first differenced data to adjust for time series autocorrelation. Correlations were considered significant for p-values < 0.05.

CHUM SALMON DISTRIBUTION

Available catch and effort data (2002 to 2012) from fall (August–October) Bering-Aleutian Salmon International Surveys (BASIS; NPAFC 2001) were used to construct a multi-year summary of immature and maturing chum salmon distribution in the Bering Sea (chum salmon that have spent at least one winter in marine habitats). Data from the U.S. BASIS survey in 2006 were used to describe chum salmon distribution in the southern Bering Sea region within a single year. Data from the R/V *TINRO* surveys from 2002 to 2004 were used to describe chum salmon distributions within the Russian exclusive economic zone (EEZ). Data from the R/V *Kaiyo maru* surveys during 2002 and 2003 and U.S. survey vessels from 2002 to 2012 were used to describe chum salmon distribution within the U.S. EEZ and international waters of the Bering Sea. Trawl catch and effort data (catch per km^2) were adjusted by the area swept fishing power coefficients estimated for U.S., Russian, and Japanese surface

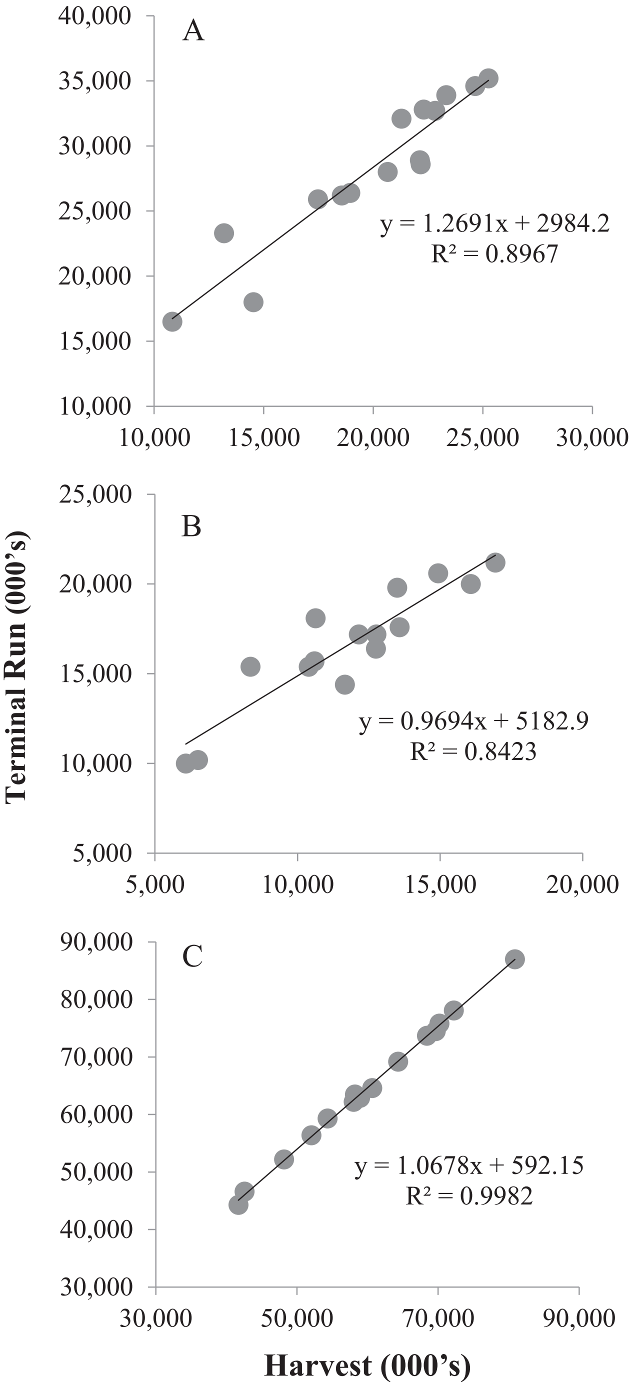

Fig. 2. Relationships between harvest and terminal run size for stock groups of chum salmon originating from the Gulf of Alaska (A), Russia (B), and Japan (C) from 1991 to 2005.

trawl gear during a fishing power experiment conducted in 2002 (Murphy et al. 2003). The distribution of chum salmon in the Bering Sea was estimated with a neighborhood regularized spline curve fitting routine implemented in ArcGIS and modeled using a smoothing parameter of 0.001 and a minimum and maximum neighborhood of 5 and 10 points within each of four sectors of the circular search radius offset by 45° (Johnston et al. 2001). A regularized spline is an interpolation method that estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes through the input data points (Johnston et al. 2001).

Bycatch distribution maps of chum salmon were constructed for the summer (July–October, B-season) fishery during 1991 to 2003 and 2004 to 2006. Chum salmon bycatch and fishing effort data were provided by the North Pacific Observer Program (AFSC 2012). Bycatch densities (bycatch per hour of trawling) were estimated by dividing non-parametric kernel density prediction surfaces (search radius of 20 km) of bycatch numbers and effort (trawl hours) within ArcGIS (Johnston et al. 2001), and overlaid onto ecoregions of the eastern Bering Sea Shelf (Ortiz et al. 2012; Baker and Hollowed 2014) and chum salmon savings areas (Witherell et al. 2002). Kernel density estimation is a data smoothing approach where the density of a random variable is estimated within a given search radius. A larger search radius produces a smoother density prediction surface.

Chum Salmon Size

Length-frequency distributions were used to describe size distributions of chum salmon from surface trawl surveys in the Bering Sea and bycatch in U.S. groundfish fisheries. Juvenile chum salmon (chum salmon that have entered marine habitats during the year of sampling) were excluded and separated from older ages of chum salmon based on length (all juveniles were assumed to have fork lengths less than 30 cm). Juveniles were not considered in this analysis as they are known and expected to reach peak abundances in coastal habitats near primary chum salmon producing river systems and fishing power calibrations between the national BASIS surveys were only completed on the immature/maturing life-history stage of chum salmon (Murphy et al. 2003). Size distributions of chum salmon captured during fall (August–October) BASIS surveys were summarized within three regions of the Bering Sea: the Russian EEZ (R/V *TINRO* surveys during 2002–2004), deep-water habitats of the Bering Sea basin (U.S. basin; R/V *Kaiyo maru* survey in 2003 and U.S. BASIS surveys, 2002–2012), and the eastern Bering Sea shelf (U.S. BASIS surveys 2002 to 2012). Length-frequency distributions were adjusted by the subsample (typically 50 fish at each station) fractions from BASIS surveys by

$$L'_l = \sum_i \frac{L_{l,i}}{\theta_i},$$

where L'_l is the estimated number of individual fish within the length interval l, $L_{l,i}$ is the number of lengths measured at station i in length interval l, and θ_i is the subsample fraction at station i. L'_l is expressed as a proportion of the total

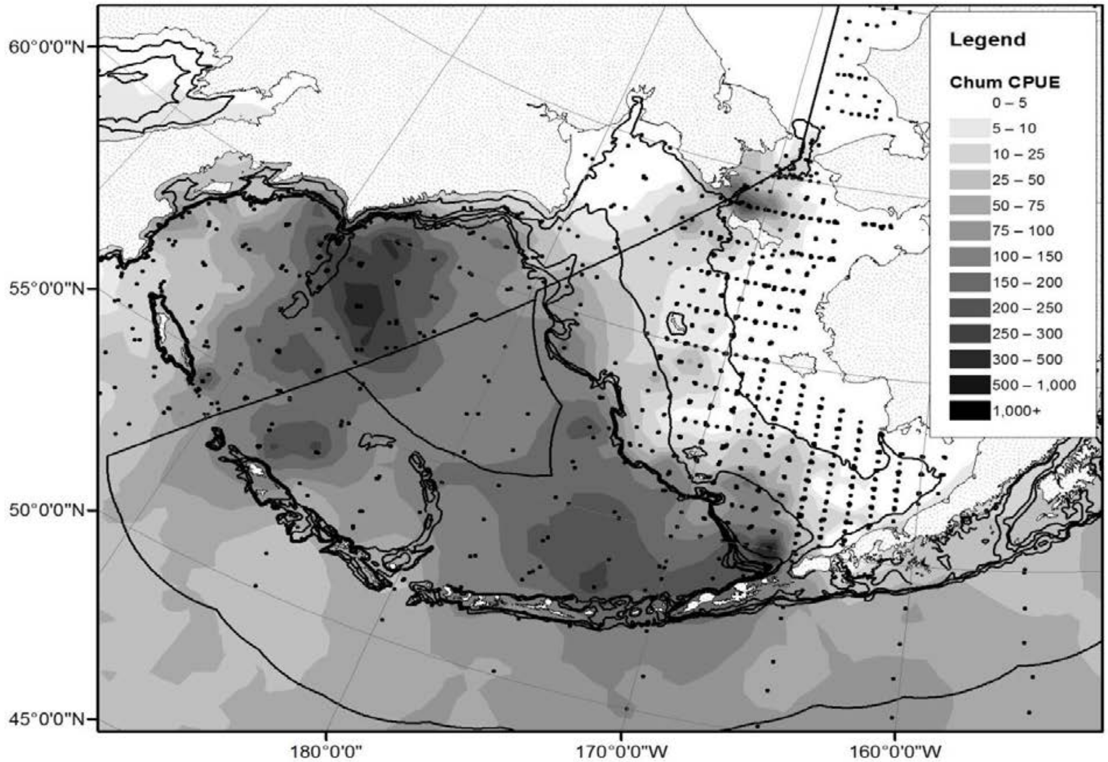

Fig. 3. Distribution of immature/maturing (non-juvenile) chum salmon within the Bering Sea from Bering-Aleutian Salmon International Surveys (BASIS) during the fall (August to October), 2002 to 2012. Shaded contours indicate chum salmon catch-per-unit-effort (CPUE: catch per km²); points indicate surface trawl locations.

or sum of L'_l. Size distributions of chum salmon captured as bycatch in eastern Bering Sea groundfish fisheries were summarized with annual (2003 to 2006) and multi-year (1991 to 2006) data provided by the North Pacific Observer Program (AFSC 2012). Length corrections for bycatch subsample fractions were not used in this analysis as sampled lengths were believed to provide a reasonable approximation of bycatch lengths due to the limited size variation of bycatch.

Chum Salmon Diet

Chum salmon diet data have been collected during U.S. BASIS surface trawl surveys on the eastern Bering Sea shelf since 2003. When within-station length variation was large, a random subsample of 10 chum salmon were selected for diet analysis from each 10-cm length bin, otherwise a random sample of 10 chum salmon were selected from each station. Stomach contents of chum salmon were combined, weighed to the nearest gram, and prey were sorted to the lowest possible taxonomic level. Prey groups were either weighed separated or visually assigned a volumetric proportion to estimate the contribution of each taxonomic prey group (by weight) to the diet of chum salmon at each station. Content weights were scaled to the distribution of chum salmon with a catch-weighted stomach content index (SCI) as

$$SCIC_j = \sum_i \frac{\sum_n Prey_{j,i,n}}{\sum_n Pred_{j,i,n}} \times C_i,$$

where the stomach content index (ratio of prey (*Prey*) weight to predator (*Pred*) weight) for the j^{th} prey species is estimated by pooling n stomachs at the i^{th} station and multiplying by the catch (C_i) at a given station. Diet composition is expressed as the proportion of $SCIC_j$ to total *SCIC*. Multi-year summaries (2003 to 2012) of immature and maturing chum salmon diets were based on average annual diet proportion within the northern Bering Sea shelf (north of 60˚N) and southern Bering Sea shelf regions. Annual summaries of chum salmon diet were estimated for the two primary ecoregions of the eastern Bering Sea shelf where bycatch occurs (South Outer and the Alaska Peninsula ecoregion) (Ortiz et al. 2012; Baker and Hollowed 2014). BASIS stations within the Alaska Peninsula region were restricted to deep-water locations (> 50 m) for consistency with the deeper shelf habitats where the pollock fishery and bycatch occurs.

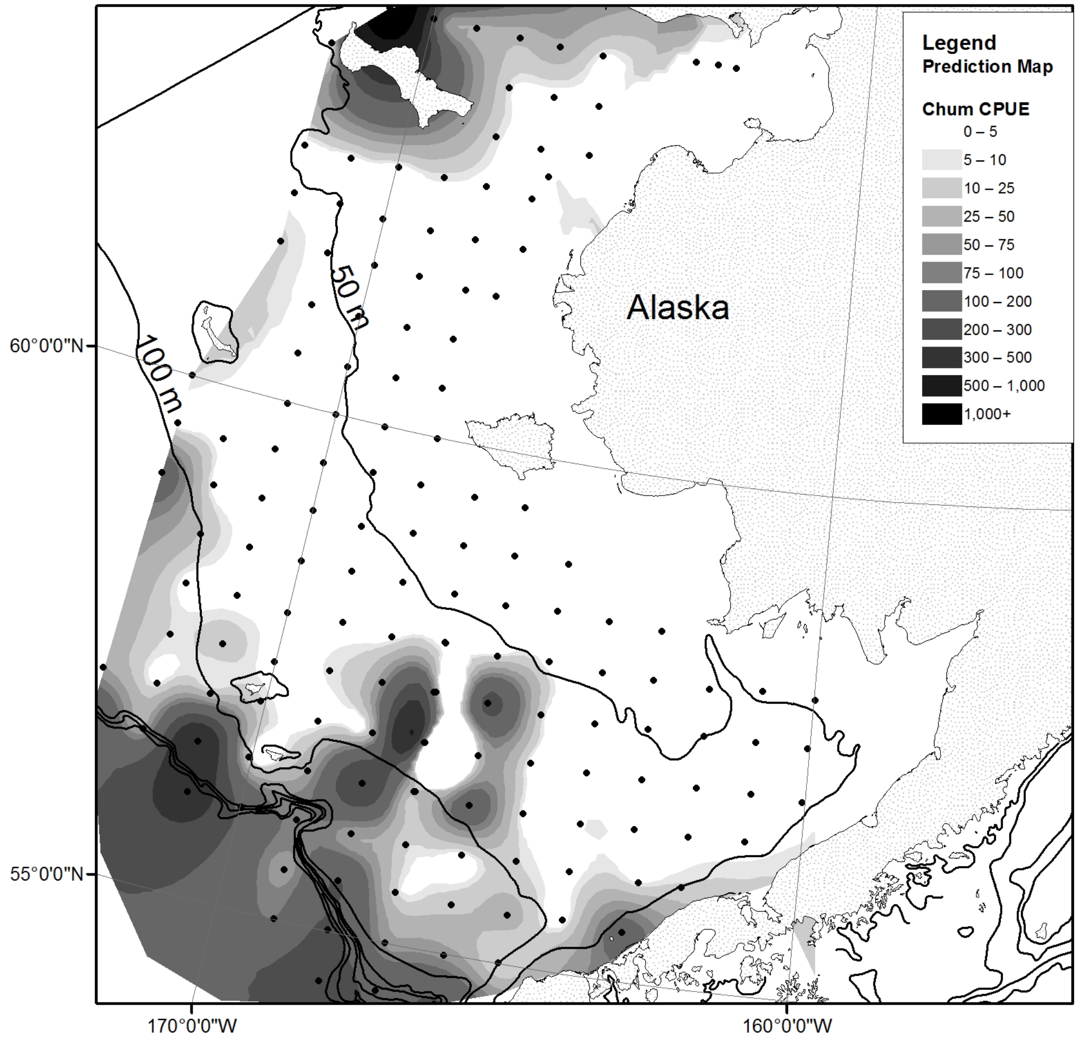

Fig. 4. Distribution of immature/maturing (non-juvenile) chum salmon in the eastern Bering Sea from the U.S. Bering-Aleutian Salmon International Survey (BASIS) during the fall (August to October), 2006. Shaded contours indicate chum salmon catch-per-unit-effort (CPUE: catch per km^2); points indicate surface trawl locations. Depth contours in the eastern Bering Sea are included at 50-m intervals.

Surface trawl catch-per-unit-effort (CPUE) of age-0 pollock (000's·km^{-2}) was summarized for all station locations within the eastern Bering Sea shelf and within ecoregions of the surface trawl survey where bycatch occurs (South Outer and Alaska Peninsula ecoregions). Stations within the Alaska Peninsula ecoregion were restricted to locations deeper than 50 m for consistency with the deeper shelf habitats where the pollock fishery and bycatch occur. Pearson product moment correlation analysis was used to evaluate the co-variation between chum salmon bycatch and age-0 pollock densities. Significance tests were also completed on first differenced data to adjust for time series autocorrelation. Correlations were considered significant with p-values < 0.05.

RESULTS

Bycatch Impact

Annual bycatch impact (exploitation rate) on the aggregate stock groups of chum salmon were all below 1.5% and highly correlated ($p < .0001$) with return year adult equivalent (AEQ) bycatch over time (Table 1). Average bycatch impacts were significantly higher ($p < 0.05$) on chum salmon originating from western Alaska (0.44%) and Russia (0.22%) than stocks from the Gulf of Alaska (0.11%), and Japan (0.07%); the average impact on western Alaska chum salmon stocks was significantly ($p < 0.05$) higher than other chum salmon stock groups.

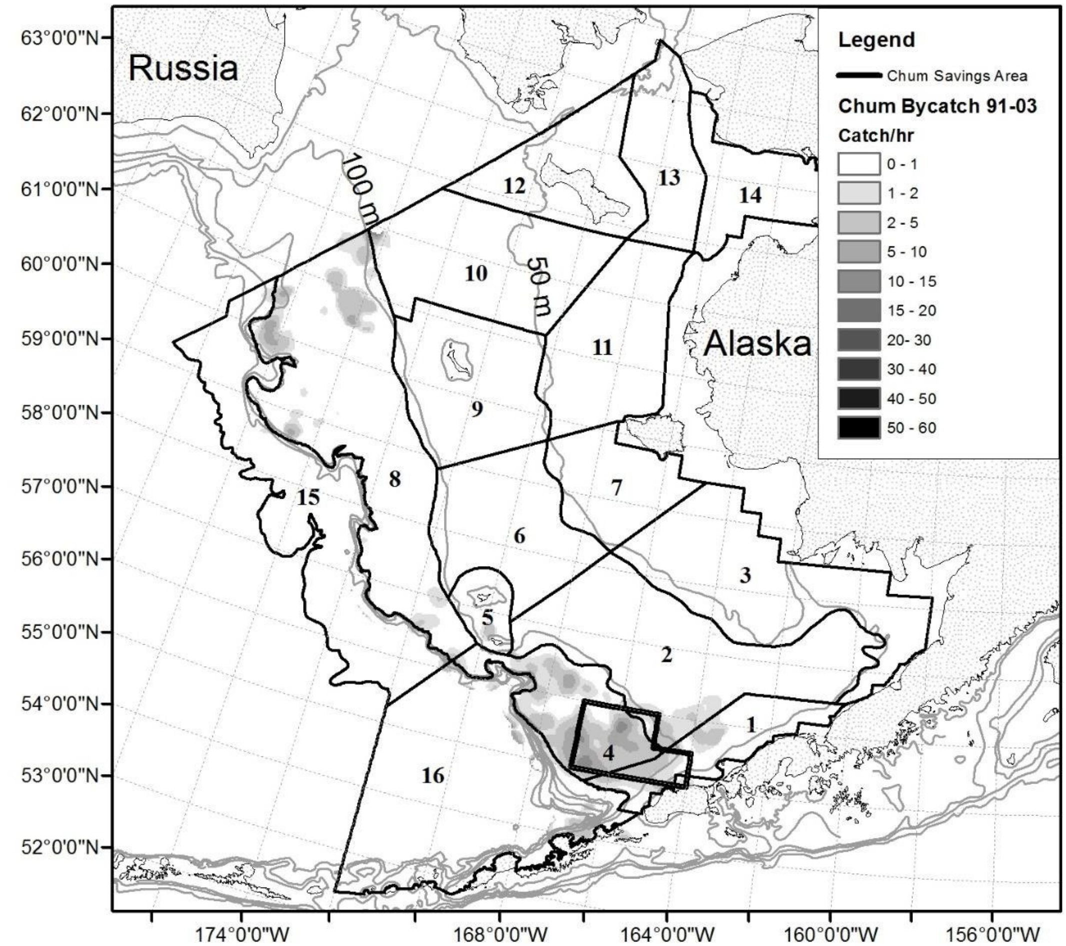

Fig. 5. Distribution of chum salmon bycatch during the B-season (July to October) of the eastern Bering Sea pollock fishery (pelagic trawl), 1991 to 2003. Shaded contours indicate the number of chum salmon captured as bycatch per hour of trawling. Numbered spatial strata are eastern Bering Sea ecoregions of the eastern Bering Sea shelf. The chum salmon savings area (thick black polygon) spans both the Alaska Peninsula (1) and South Outer (4) ecoregions with a border outlined in black that follows latitude and longitude coordinates. Grey lines are depth contours at 50-m intervals.

Chum Salmon Distribution

Chum salmon were distributed throughout the Bering Sea and North Pacific during August–October. Immature/maturing (non-juvenile) life-history stages of chum salmon primarily occurred in offshore habitats of the Bering Sea basin and reached higher densities in the Bering Sea than locations south of the Aleutian Islands (Fig. 3). Within the Bering Sea, chum salmon tended to have a western distribution in the Russian EEZ and an eastern distribution just north of the Aleutian Islands and adjacent to the eastern Bering Sea shelf during August–October. The highest densities of chum salmon on the eastern Bering Sea shelf occurred in deep-water habitats (150 to 200 m) of the southern shelf region and just south of the Bering Sea Strait (where Russia and Alaska are the closest). The U.S. BASIS surveys were primarily restricted to locations on the shelf; however, the U.S. survey grid was extended off the shelf in 2006 and provided the opportunity to examine the distribution of chum salmon on and off the shelf (Fig. 4). Patchiness in the spatial distribution of chum salmon is more evident in the catch distribution from a single year. Still, the relatively coarse sampling grid (approximately 30 nautical miles) limits the ability of U.S. BASIS surveys to precisely map chum salmon distributions. The highest densities of chum salmon in the southern region of the eastern Bering Sea shelf were present along the shelf break and in patches or hot-spots of chum salmon farther inshore in the Middle Domain of the shelf (between 50 and 100 m).

Chum salmon were primarily captured as bycatch in the Outer Domain (100 to 150 m) of the eastern Bering Sea shelf; but significant numbers of chum salmon were also captured along the Alaska Peninsula (Figs. 4, 5). Bycatch-per-unit-effort (catch per hour trawled) was highest in the

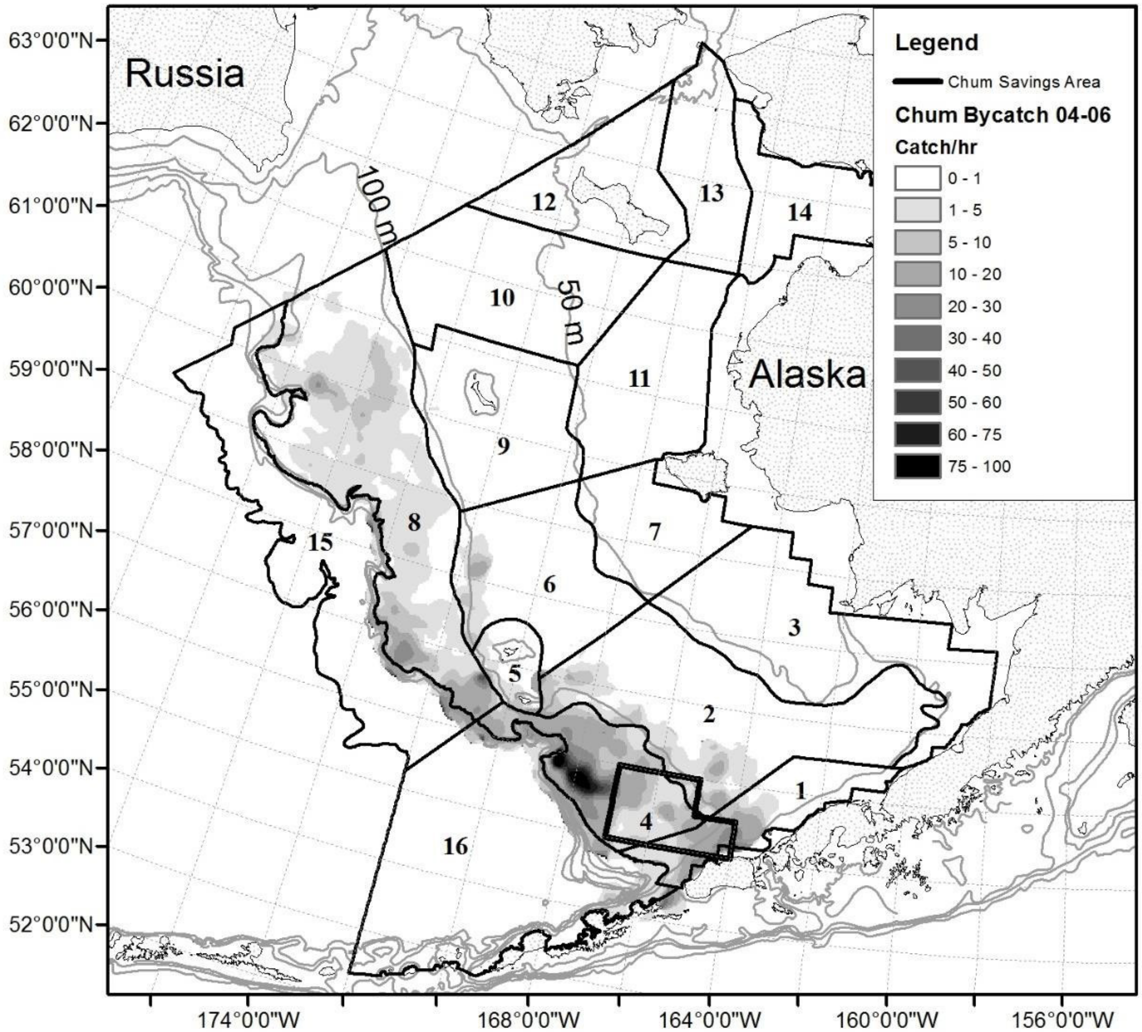

Fig. 6. Distribution of chum salmon bycatch during the B-season (July to October) of the eastern Bering Sea pollock fishery (pelagic trawl) 2004 to 2006. Shaded contours indicate the number of chum salmon captured as bycatch per hour of trawling. Numbered spatial strata are eastern Bering Sea ecoregions of the eastern Bering Sea shelf. The chum salmon savings area (thick black polygon) spans both the Alaska Peninsula (1) and South Outer (4) ecoregions with a border outlined in black that follows latitude and longitude coordinates. Grey lines are depth contours at 50-m intervals.

South Outer (Region 4) and the Alaska Peninsula (Region 1) ecoregions. Chum salmon bycatch was spread more broadly across the fishery in the southern Bering Sea and within the chum salmon savings area prior to 2004 (Fig. 5). Peak bycatch locations of chum salmon shifted during 2004 to 2006, with much of the bycatch occurring close to the shelf break (200 m) and outside of the chum salmon saving area (Fig. 6).

Chum Salmon Size

Length-frequency distributions of chum salmon from BASIS research surveys varied by region in the Bering Sea due to differences in the age structure of chum salmon by region (Fig. 7). Most of the chum salmon captured within the Russian EEZ were within the 30- to 40-cm size range during August–October, consistent with the 0.1 age class of chum salmon (European age designation: freshwater.marine ages). The proportion of age-0.2 chum salmon (approximately 40 to 55 cm) was higher in the central Bering Sea basin than the Russian EEZ, and chum salmon typically reach their largest average size on the eastern Bering Sea shelf, with most falling within the 55- to 65-cm size range (consistent with age-0.3 chum salmon).

Length-frequency data of chum salmon captured as bycatch are relatively stable over time (Fig. 8), were similar to the size distributions of chum salmon captured during surface trawl surveys on the shelf (BASIS surveys), and were consistent with the size range expected for age-0.3 chum salmon. Surface trawl surveys tended to have a slightly higher proportion of 0.1 and 0.2 chum salmon than present in the bycatch. (Fig. 7).

Chum Salmon Diet

The diet of chum salmon varied by region and over time in the eastern Bering Sea shelf (Table 2, Fig. 9). The Arctic hyperiid amphipod, *Themisto libellula,* was the most important prey species of chum salmon in the northern Bering Sea shelf (31%). The subarctic hyperiid amphipod, *Themisto pacifica*; was the primary species utilized by chum salmon in the southern Bering Sea shelf. *T. libellula* was present in the diet of chum salmon in the southern Bering Sea shelf, but only above the cold pool when it extends into the southern shelf. Jellyfish (Scyphozoa) were consumed in a higher proportion in the northern Bering Sea shelf (32% by weight) than the southern shelf (14%). However, the low nutritional value of jellyfish does not allow a direct comparison of nutritional value of jellyfish to other prey species. Oikopleurans were more important in the diet of chum salmon in the northern Bering Sea shelf (12%) than the southern shelf (2%) and reflects the abundance of the Arctic oikopleuran, *Oikopleura vanhoeffeni*, in the northern Bering Sea shelf. The pteropod species, *Limacina helicina*, and its predator, *Clione limacina*, were an important component of chum salmon diets in the southern Bering Sea shelf (8%), particularly in deeper shelf habitats. Age-0 pollock were, on average, the largest contributor to the diet of chum salmon in the southern shelf (32%). Age-0 pollock were present in chum salmon diets in the northern Bering Sea (8%) when age-0 pollock distributions extend northward during warm years.

The importance of age-0 pollock in the diet of chum salmon in the southern Bering Sea stems from the large contribution of age-0 pollock in their diet from 2004 to 2006 (Table 2). Age-0 pollock comprised over 90% of chum salmon diet during this period, but have been largely absent from the diet from 2007 to 2012 when pteropods, jellyfish, and euphausiids were the most important prey items of chum salmon in the southern Bering Sea. Ecosystem and fishery dynamics during 2004–2006 are particularly important to bycatch as these years resulted in the highest bycatch levels of chum salmon in eastern Bering Sea groundfish fisheries (Fig. 1).

Surface trawl catches of age-0 pollock also increased during the 2004–2006 time period (Table 3, Fig. 10), and the increase in age-0 pollock abundance is believed to be the primary reason why age-0 pollock became such a large component of the diet of chum salmon. Catches of age-0 pollock for the entire survey peaked at 84,000 • km^{-2} in 2004, but reached a peak of approximately 197,000 • km^{-2} in 2005 within ecoregions where most of the bycatch occurs (South Outer and Alaska Peninsula). Although surface trawl catches of age-0 pollock dropped in 2006 (age-0 pollock catch dropped to 11,000 • km^{-2} for the entire survey and 21,000 • km^{-2} in bycatch ecoregions), chum salmon diets were still predominately age-0 pollock.

Significant and positive relationships were present between the surface trawl catch of age-0 pollock and the number of chum salmon captured as bycatch in eastern Bering

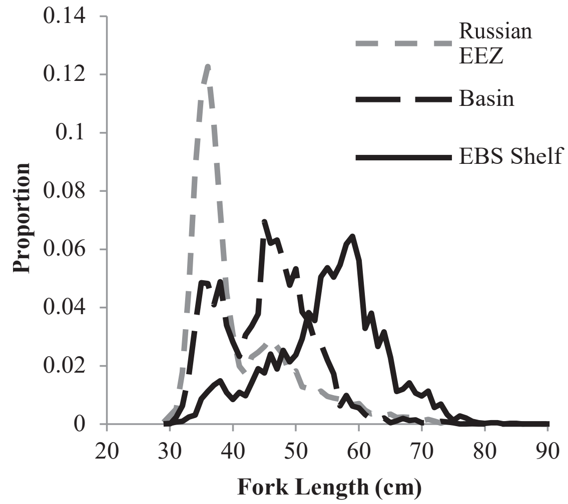

Fig. 7. Length-frequency distributions of immature/maturing (non-juvenile) chum salmon captured during late summer/fall surveys (August–October) of the Bering-Aleutian Salmon International Survey (BASIS) trawl surveys in the Russian exclusive economic zone (EEZ), deep-water habitats of the Bering Sea basin (Basin), and U.S. surveys on the eastern Bering Sea shelf (EBS Shelf) (2002 to 2012).

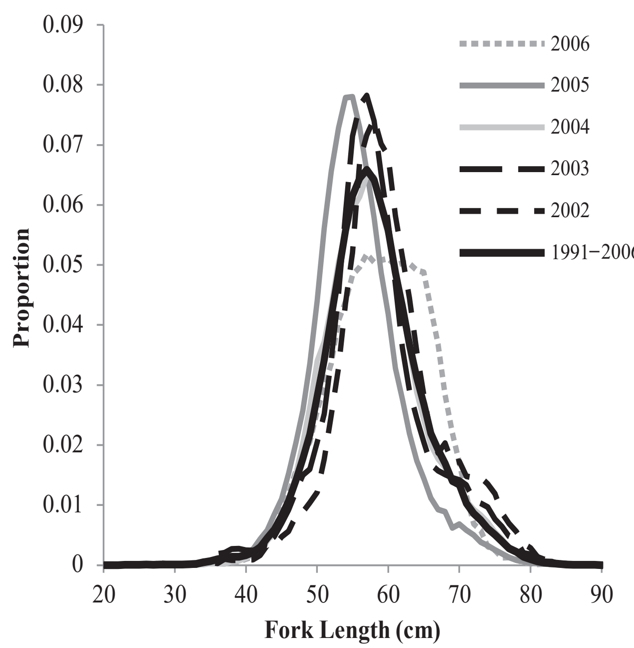

Fig. 8. Size distributions of chum salmon captured as bycatch in the summer B-season (July–October) of the Bering Sea Aleutian Island pelagic trawl fisheries for each year from 2002 to 2006, and over multiple years (1991 to 2006).

Table 2. Prey composition in chum salmon stomach contents by weight in the South Outer shelf and Alaska Peninsula (> 50-m) ecoregions of the eastern Bering Sea shelf during fall (August to October) Bering Aleutian Salmon International Surveys, 2003–2007 and 2009–2012.

Prey Group	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Pollock	34%	91%	91%	93%	0%		0%	10%	0%	1%
Pteropod	55%	7%	5%	1%	20%		14%	26%	45%	16%
Jellyfish	2%	0%	1%	1%	24%		64%	0%	0%	1%
Euphausiid	0%	1%	1%	3%	5%		1%	35%	2%	63%
Oikopleura	0%	0%	0%	0%	19%		0%	0%	1%	0%
Shrimp/Crab	3%	0%	1%	1%	9%		7%	1%	6%	1%
Fish	6%	0%	0%	1%	5%		3%	22%	11%	14%
Amphipod	0%	0%	0%	1%	9%		2%	5%	18%	2%
Other	1%	1%	1%	0%	8%		8%	0%	18%	2%

Sea groundfish fisheries (Table 3, Fig. 11). The proportion of age-0 pollock in the diet of chum salmon in the southern Bering Sea was significantly correlated with catches of age-0 pollock for the entire survey ($r = 0.77$, $p < 0.05$) and the South Outer and Alaska Peninsula ecoregions ($r = 0.76$, $p < 0.05$). Age-0 pollock catches for the entire U.S. BASIS survey were significantly correlated with the number of chum salmon captured as bycatch ($r = 0.83$, $p = 0.002$) and the correlation increases when BASIS data were selected within the ecoregions where bycatch occurs (South Outer and Alaska Peninsula ecoregions; $r = 0.91$, $p < 0.0001$). First differenced data (previous year data subtracted from current) of age-0 pollock catches and bycatch remained significantly correlated for the entire shelf ($r = 0.65$, $p = 0.042$) and within ecoregions where bycatch occurs ($r = 0.84$, $p = 0.002$). The strength of these correlations highlights the importance of foraging patterns of chum salmon (particularly on age-0 pollock) to the formation of bycatch hot-spots and changes in bycatch levels of chum salmon over time.

DISCUSSION

A broad spatial and ecological context of chum salmon is needed to gain insight into the dynamic processes that impact bycatch levels, to estimate bycatch impacts, and to evaluate bycatch assessments. The population structure of chum salmon (size/age/stock) is complex and requires information

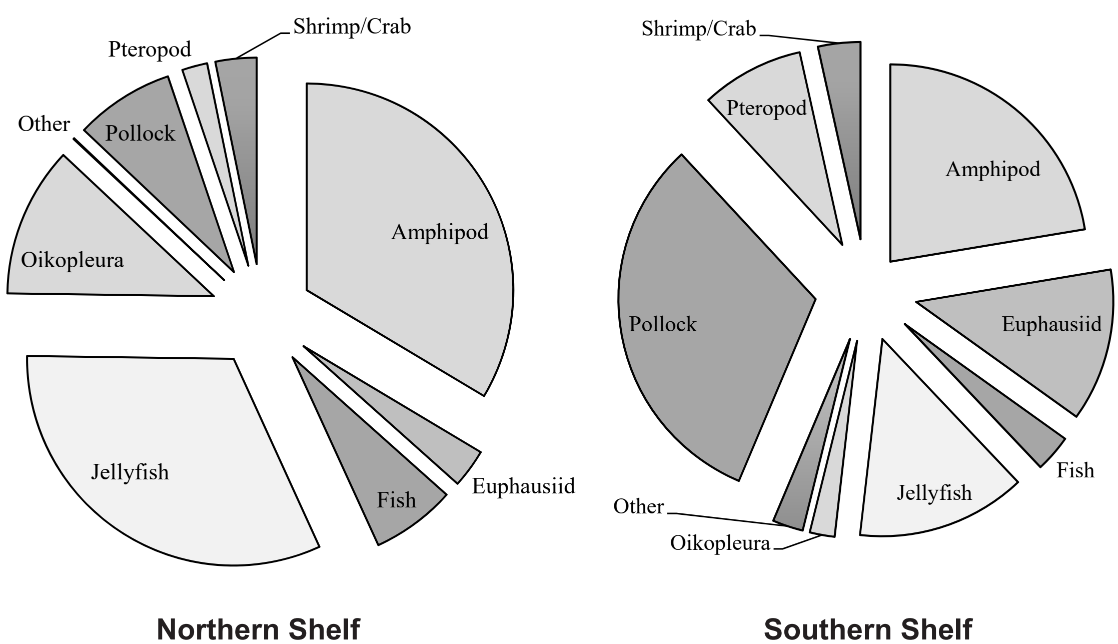

Fig. 9. Regional differences in chum salmon diets in the northern Bering Sea shelf (60°N to 65°N) and the southern Bering Sea shelf (< 60°N) during fall (August to October) Bering-Aleutian Salmon International Survey surface trawl operations in the eastern Bering Sea, 2003 to 2012.

at multiple space/time scales to describe migratory patterns of chum salmon. Prey fields, water temperature, and ocean currents are an integral part of the dynamic migration and distribution patterns of salmon in the North Pacific Ocean and Bering Sea (Murphy 1994; Welch et al. 1995; Aydin et al. 2000; Azumaya and Ishida 2004; Azumaya et al. 2007; Myers et al. 2007; Nagasawa and Azumaya 2009). The BASIS was a large-scale surface trawl survey developed by member nations of the NPAFC designed to improve our understanding of the role of salmon in Bering Sea ecosystems (NPAFC 2001). U.S. BASIS surveys have occurred during the fall (August to October) and primarily in the eastern Bering Sea, consistent with the period when chum salmon bycatch occurs in eastern Bering Sea groundfish fisheries (July to October, peak in August and September). Research data collected during the BASIS surveys allow us to examine bycatch within the context of the large-scale marine ecology of chum salmon in the Bering Sea (Murphy and Farley 2012).

The impact of bycatch on chum salmon is best described by stock-specific exploitation rates on terminal run sizes of chum salmon and requires that bycatch numbers be converted to stock-specific adult equivalent (AEQ) estimates of bycatch. Multiple sources of information in addition to bycatch numbers of chum salmon are needed to estimate bycatch exploitation rates, including: natural mortality rates, maturation rates, and terminal run abundances of chum salmon, as well as age and stock composition of bycatch (Witherell et al. 2002; Ianelli and Stram 2014). Bycatch exploitation rates on regional stock aggregates or groups (western Alaska, Russia, Gulf of Alaska, and Japan) of chum salmon were estimated to be low (< 1.5%), highest for western Alaska chum salmon, and varied with bycatch levels. Although western Alaska chum salmon stocks appeared to have the largest bycatch impact (average annual exploitation rate of 0.44%), uncertainty associated with bycatch stock composition estimates and/or terminal run estimates for western Alaska chum salmon could be contributing to the larger average annual exploitation rates for this stock group. For example, 50% to 70% of the chum salmon in Area-M or Alaska Peninsula salmon fisheries originate from western Alaska

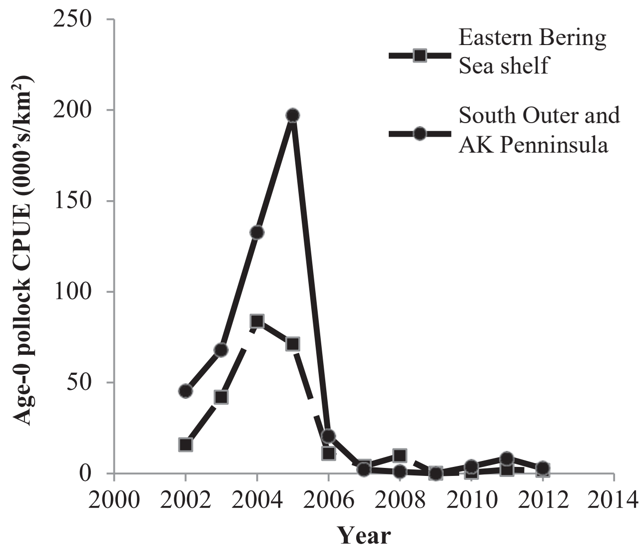

Fig. 10. Annual variation in age-0 pollock catch-per-unit-effort (CPUE; catch per km^2) during fall (August to October) Bering-Aleutian Salmon International Survey surface trawl operations on the eastern Bering Sea shelf and within the South Outer and Alaska Peninsula (> 50-m) ecoregions of the eastern Bering Sea shelf, 2002 to 2012.

Table 3. Chum salmon bycatch numbers in Bering Sea Aleutian Island (BSAI) groundfish fisheries in the eastern Bering Sea and age-0 pollock catch-per-unit-effort (CPUE, catch per km^2) during surface trawl (BASIS) surveys on the eastern Bering Sea shelf and within the South Outer and Alaska Peninsula (> 50-m) ecoregions of the eastern Bering Sea shelf, 2002 to 2012.

Year	BSAI chum salmon bycatch (000's)	Eastern Bering Sea age-0 pollock (000's/km^2)	South Outer and Alaska Peninsula age-0 pollock (000's/km^2)
2002	80.79	15.77	45.21
2003	187.04	42.00	68.02
2004	449.51	83.76	132.62
2005	708.36	71.32	197.01
2006	322.87	10.95	20.63
2007	87.71	4.01	2.08
2008	16.36	16.36	9.72
2009	46.97	0.06	0.02
2010	14.20	0.62	3.82
2011	192.49	2.15	8.31
2012	24.01	1.67	2.84

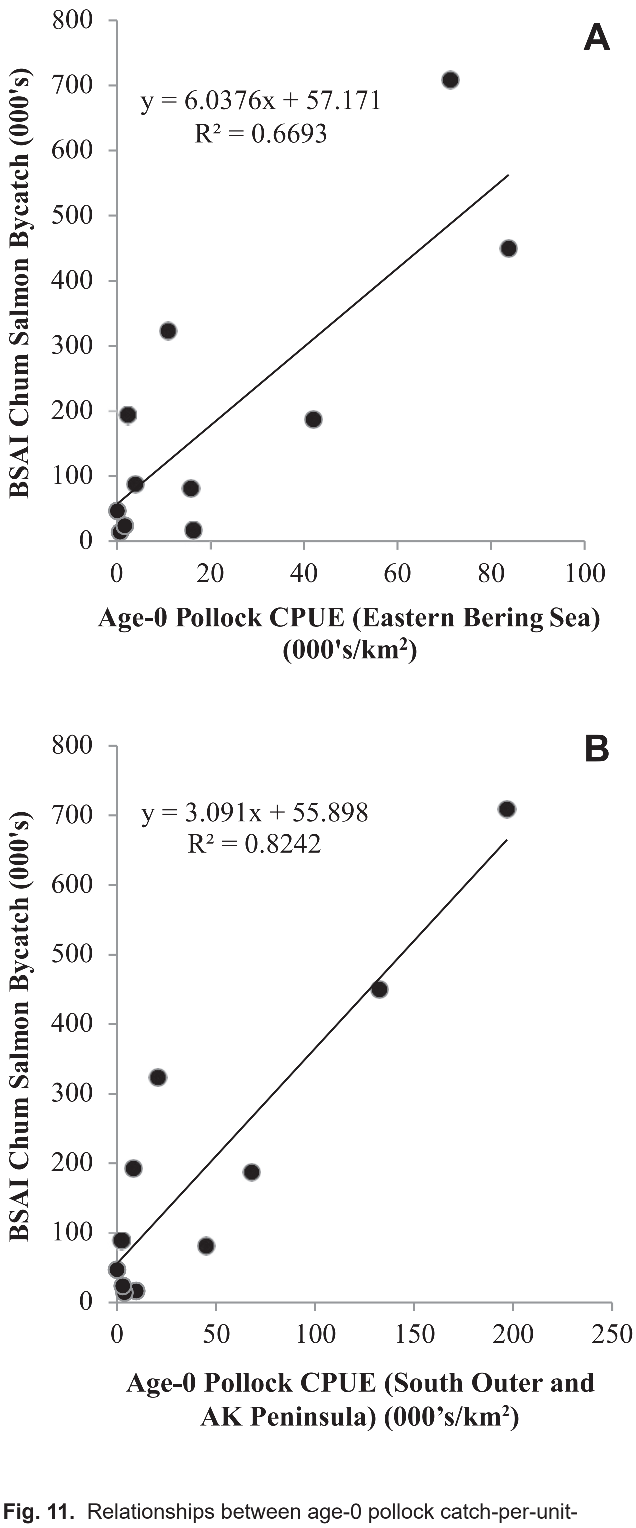

Fig. 11. Relationships between age-0 pollock catch-per-unit-effort (CPUE: 000's/km^2) and chum salmon bycatch in Bering Sea Aleutian Island (BSAI) groundfish fisheries, 2002 to 2012. Age-0 pollock CPUE data are from fall (August to October) Bering-Aleutian Salmon International Survey surface trawl operations on the eastern Bering Sea shelf (A) and within the South Outer and Alaska Peninsula (> 50-m) ecoregions of the eastern Bering Sea shelf (B).

(Seeb and Crane 1999), therefore terminal run estimates for western Alaska chum salmon are not equivalent to total run estimates and introduce an upward bias in bycatch impacts on western Alaska chum salmon. Information on the stock and age structure of chum salmon captured in the Area-M or Alaska Peninsula salmon fisheries will be required to accurately evaluate the bycatch impact on western Alaska chum salmon in eastern Bering Sea groundfish fisheries. Bycatch impacts on individual stocks are not directly comparable to the aggregate stock groups unless their bycatch is proportional to their abundance within the aggregate stock group. Ultimately, bycatch impact covaries with bycatch numbers for all stock groups of chum salmon, indicating that stock abundance is not the primary driver of changes observed in bycatch numbers over time.

Size and age of chum salmon are equally as important as stock origin when considering the population structure of chum salmon in the Bering Sea. The increase in age of chum salmon from the Russian EEZ to the eastern Bering Sea shelf is believed to primarily reflect the dispersal pattern of Asian chum salmon, with chum salmon progressively increasing in age with distance from their origin. Similar dispersal patterns could be present in chum salmon stocks originating from the Gulf of Alaska; however improved integration of size and age of chum salmon with stock origin will be needed before migratory patterns of chum salmon can be adequately described. Age structure is more evident in the size of chum salmon from the entire Bering Sea than within a single region due to the age-structured distribution of chum salmon in the Bering Sea. The size of chum salmon on the eastern Bering Sea shelf indicates that the dominant age of chum salmon on the eastern Bering Sea shelf is 0.3, and is consistent with scale ages of chum salmon captured as bycatch (Patton et al. 1998). However, surface trawl catches tend to include a higher proportion of 0.1 and 0.2 chum salmon than is present in the bycatch, which may reflect a shallower vertical distribution of these younger ages of chum salmon and increased availability of these ages to surface trawl surveys. Limited variability in the size/age of chum salmon captured as bycatch indicates that there is less concern over matching bycatch samples to the spatial and temporal scales of bycatch for size and age data than for stock composition.

Movement patterns of chum salmon introduce an important spatial component to the stock structure of chum salmon in the southern Bering Sea shelf. The 2006 spatial distribution of chum salmon in the southern Bering Sea shelf is believed to support on-shelf movement of chum salmon and the passage of chum salmon through the fishery and onto the shelf. Groundfish fisheries and bycatch generally occur within the Outer Domain of the eastern Bering Sea (100 to 150 m). Bycatch of chum salmon in the groundfish fishery occurred in two pulses in 2006 (Marvin et al. 2011): the first pulse occurred prior to the BASIS survey in 2006 (late June–early July) and the second pulse occurred during the BASIS survey (August). Chum salmon that were distributed in the Middle Domain (50 to 100 m) during the BASIS survey are likely part of the first pulse of chum salmon bycatch. Chum salmon that were distributed in the Outer Domain during BASIS surveys are believed to have contributed to bycatch during the second pulse (August). This general movement pattern of chum salmon is consistent with shelf currents, which typically flow to the north and northwest on the shelf (Stabeno et al. 1999). Although chum salmon are captured as bycatch in the northern Bering Sea shelf (North Outer ecoregion), most of the chum salmon are captured in the southern Bering Sea shelf (South Outer and Alaska Peninsula ecoregions). Stock mixtures of chum salmon in the southern Bering Sea support movement of chum salmon from the Bering Sea basin (predominantly Asian origin) and the Gulf of Alaska via the Alaska Coastal Current onto the southern Bering Sea shelf (Seeb et al. 2004). This is evident in chum salmon stock mixtures from U.S. BASIS surveys (McCraney et al. 2010). Chum salmon stock mixtures in the northern Bering Sea shelf (83% Asian origin) were similar to mixtures in the Bering Sea basin (81% Asian) during 2006 and 2007. However, only 49% of the chum salmon on the southern shelf were of Asian origin. The increase in North American chum salmon on the southern shelf is believed to reflect the movement/transport of chum salmon onto the southern Bering Sea shelf from the Gulf of Alaska, which has a higher proportion of North American chum salmon stocks. Bycatch hot-spots that form from the movement of chum salmon from the Bering Sea basin onto the shelf are expected to have a higher proportion of Asian-origin chum salmon than hot-spots that form through the movement of chum salmon from the Gulf of Alaska onto the eastern Bering Sea shelf.

The location of chum salmon bycatch shifted during the period of increased bycatch (2004 to 2006), and may have important implications for stock mixtures present in the bycatch. Prior to 2004, much of the bycatch occurred throughout the fishing areas of the southern shelf and along the Alaska Peninsula and provided the basis for the chum salmon savings area (Witherell et al. 2002). The location of peak bycatch shifted northwest along the shelf break and outside of the savings area in 2004 to 2006. Due to the closer proximity of bycatch to the basin and the association of bycatch with age-0 pollock during 2004 to 2006, it is believed that bycatch during this period principally stemmed from increased on-shelf movement of chum salmon from the Bering Sea basin to forage on age-0 pollock. It is unclear why there was not an increase in Asian-origin chum salmon in the bycatch with the shift in bycatch location (Marvin et al. 2011; Kondzela et al. 2012). However, this likely reflects limitations in the genetic analysis and tissue collections during this period. Due to the limited number of genetic tissues collected from the bycatch in 2005, spatial stratification of bycatch samples to correct for bycatch location was not completed (Guyon et al. 2010). Recognizing potential complications with genetic tissue collections of the bycatch, the North Pacific Fishery Management Council recommended that genetic samples be collected proportionally to bycatch and this strategy has been in place since 2011 (NMFS 2010).

Chum salmon exhibit a high degree of plasticity in their diet, which tends to reflect the availability of prey species over time and space (Davis et al. 2000, 2009). This is evident in diet differences between the northern and southern Bering Sea shelf regions. The diet of chum salmon in the northern Bering Sea primarily consisted of Arctic prey species such as *T. libellula* and *O. vanhoeffeni;* these species were minimally present in the diets of chum salmon in the southern Bering Sea shelf. Zooplankton communities are different in the northern and southern shelf regions largely due to the persistence of winter sea ice in the northern Bering Sea, which maintains an ecosystem that is more similar to other high Arctic ecosystems like the Chukchi Sea than the southern Bering Sea (Stabeno et al. 2012; Pinchuk et al. 2013). Chum salmon diets in the southern Bering Sea shelf were variable over time with a significant shift to age-0 pollock during the years of high bycatch (> 90% of the diet of chum salmon was age-0 pollock in 2004 to 2006). Although surface trawl catches of age-0 pollock declined in 2006, the diet of chum salmon was still predominantly age-0 pollock. This may reflect a change in the vertical distribution of age-0 pollock (deeper distribution) in response to cooler conditions (Parker-Stetter et al. 2013) in 2006, making them less available to surface trawl gear, but still available as chum salmon prey. Even with potential shifts in the vertical distribution of age-0 pollock, significant correlations are present between surface trawl catch rates of age-0 pollock, chum salmon diet, and their bycatch, supporting the importance of foraging behavior of chum salmon on age-0 pollock to their bycatch in U.S. groundfish fisheries in the eastern Bering Sea.

CONCLUSION

The efficiency of bycatch management and avoidance strategies used to limit bycatch of chum salmon will improve with a greater understanding of the underlying ecological processes that determine bycatch levels of chum salmon over time. Movement of large immature chum salmon (rather than selective bycatch) onto the eastern Bering Sea shelf is believed to contribute to the large size and older ages of chum salmon in the bycatch than is typically present in the Bering Sea. Movement of chum salmon from the Gulf of Alaska as well as the Bering Sea basin onto the southern Bering Sea shelf introduces an important and potentially complex spatial component to the population structure of chum salmon in this region. The close association between chum salmon bycatch, diet, and catch of age-0 pollock highlights the importance of foraging behavior of chum salmon (particularly on age-0 pollock) to changes observed in bycatch levels of chum salmon in U.S. groundfish fisheries in the eastern Bering Sea over time.

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