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Origins of Chum Salmon Caught Incidentally in the Eastern Bering Sea Walleye Pollock Trawl Fishery as Estimated from Scale Pattern Analysis

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Abstract.—Approximately 74,500 chum salmon *Oncorhynchus keta* were intercepted in the 1994 U.S. walleye pollock *Theragra chalcogramma* B-season fishery in the eastern Bering Sea and Aleutian Islands. Using scale pattern analysis, we estimated the stock composition of age-0.3 chum salmon (fish that had spent three winters in the ocean) from this incidental catch. A conditional maximum-likelihood discrimination model, assessed through a series of simulation runs using hypothetical stock mixtures, was 83.3–92.3% accurate. Our fleetwide, unstratified proportion estimates closely resembled results of a concurrent stock composition study based on allelic frequencies of the 1994 chum salmon bycatch. Interception estimates weighted by time, which depend on the accuracy of National Marine Fisheries Service week-stratified bycatch estimates, indicated that about 50% of the incidentally caught chum salmon originated from Asia (Russia and Japan), 18% from western and central Alaska, and 32% from southeastern Alaska, British Columbia, and Washington. The western and central Alaskan proportion increased over the course of the B-season fishery, although the numbers intercepted remained stable. A comparison of our regional interception estimates with estimated run sizes indicates that bycatch in the 1994 B-season walleye pollock fishery did not greatly affect returns to western Alaskan chum salmon fisheries.

The fishery resources of the U.S. Exclusive Economic Zone in the eastern Bering Sea and the Aleutian Islands are under the regulatory authority of the North Pacific Fishery Management Council (NPFMC). The largest fishery in the Bering Sea and Aleutian Islands (BSAI) management area is the midwater trawl fishery for walleye pollock *Theragra chalcogramma.* Interceptions of Pacific salmon *Oncorhynchus* spp. in the BSAI walleye pollock fishery jumped from approximately 25,000 fish in 1990 to over 280,000 in 1993, a change driven by a sharp increase in the interception of chum salmon *O. keta* (Queirolo et al. 1995; Berger 1997). Chum salmon bycatch in the walleye pollock fishery has occurred almost exclusively in late summer, during the B-season non-roe fishery (Patton 1997). The National Marine Fisheries Service (NMFS) estimated that during the 1994 B-season, which ran from August 15 to October 8, approximately 74,500 chum salmon were incidentally caught in BSAI walleye pollock trawls (M. Furuness, NMFS, personal communication).

The interception of western Alaska chum salmon was of particular concern during the early 1990s because many western Alaska commercial and subsistence fisheries experienced exceptionally low returns during years of peak chum salmon bycatch in the adjacent Bering Sea groundfish fisheries (Patton 1997). The origins of the incidentally caught chum salmon, however, could only be inferred from historical high-seas tagging research conducted by the member nations of the International North Pacific Fisheries Commission (INPFC; Neave et al. 1976; Salo 1991; Myers et al. 1996). Salo (1991) noted that the historical high-seas tagging data provide "no evidence to indicate that any chum salmon of North American origin reenter the Bering Sea prior to returning as mature fish." Yet, Wilmot et al. (1995) found that 88.5% of chum salmon bycatch from the 1994 walleye pollock B-season were immature.

Inferring the origins of intercepted stock mixtures on the basis of historical high-seas tagging distributions is problematic because of tagging mortality and disproportionate tagging and recovery effort. Very few tagging data are available on the distribution of immature chum salmon in the eastern Bering Sea. Likewise, coded wire tag recoveries have provided only limited information on the possible origins of BSAI chum salmon mixtures and have similar biases resulting from unequal tagging and recovery effort (Myers et al. 1996).

We used scale pattern analysis to estimate the composition of the chum salmon stock mixture intercepted incidentally in the 1994 U.S. B-season walleye pollock fishery in the BSAI. We compared those results with findings of a concurrent study by NMFS that analyzed allele frequencies of 1994–1996 B-season incidentally caught chum salmon to identify stock mixtures (Wilmot et al.

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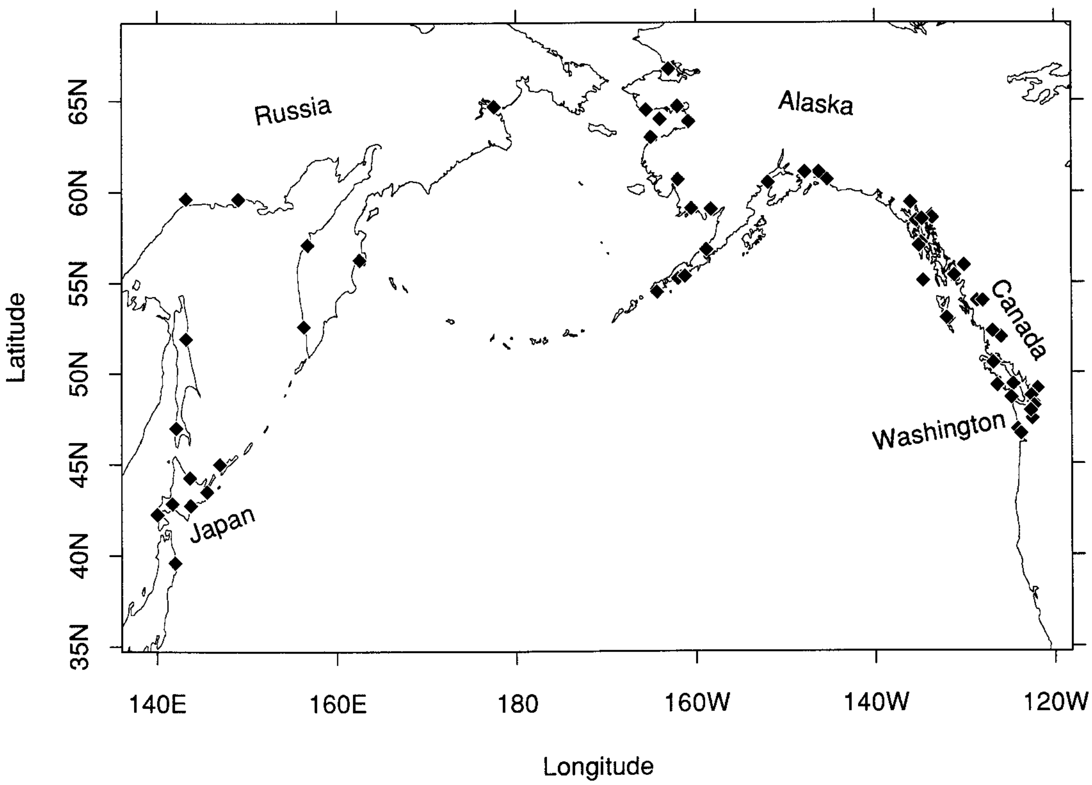

FIGURE 1.—Locations (diamonds) of the 65 chum salmon stocks represented in the chum salmon stock baseline. The scale samples were collected from terminal commercial fisheries in 1994 (and in 1995 for a few Russian stocks). Stocks from adjacent rivers tend to appear as a single symbol. In several cases, separate stocks were collected from successive runs in the same river or location.

1995, 1998). We also assessed the effect of B-season interceptions on the returns of adult chum salmon to Alaska.

Methods

Patton (1997) gives a detailed description of the methods used in our study. Briefly, the scale patterns of unidentified fish from the 1994 chum salmon bycatch mixture, sampled by U.S. groundfish observers, were measured and compared with characteristic scale patterns of known North Pacific chum salmon stocks, sampled at terminal fisheries and hatcheries. We assumed that the geographic and temporal distribution of the observer sample was representative of the B-season chum salmon bycatch. We analyzed 1,204 age-0.3 scales (chum salmon that had spent no winters in freshwater and three winters in the ocean) from the bycatch mixture because that age-group offered the largest sample (64.9% of the total aged sample). No information was available on the maturity of the fish sampled. To estimate chum salmon bycatch composition, we stratified the observer sample by week (all areas combined) and by NMFS statistical reporting area (all weeks combined) in which they were intercepted. Because of sample-size limitations, some area strata were eliminated and the final 2 weeks of the fishery were combined into one stratum. The scale pattern stock baseline, compiled from the same year-class of fish as the 1994 mixed-stock bycatch sample, contained 2,893 fish representing 65 chum salmon stocks from around the North Pacific Rim (Figure 1).

Scale samples were prepared and measured and age was determined according to the procedures used by the Fisheries Research Institute (FRI), as described by Davis et al. (1990). Considering chum salmon life history (Neave et al. 1976), the first year of growth on the scale (termed the first ocean zone), is most useful in characterizing the chum salmon stocks of different geographic regions. Variability in the first ocean zone was quantified by circulus counts and a series of linear

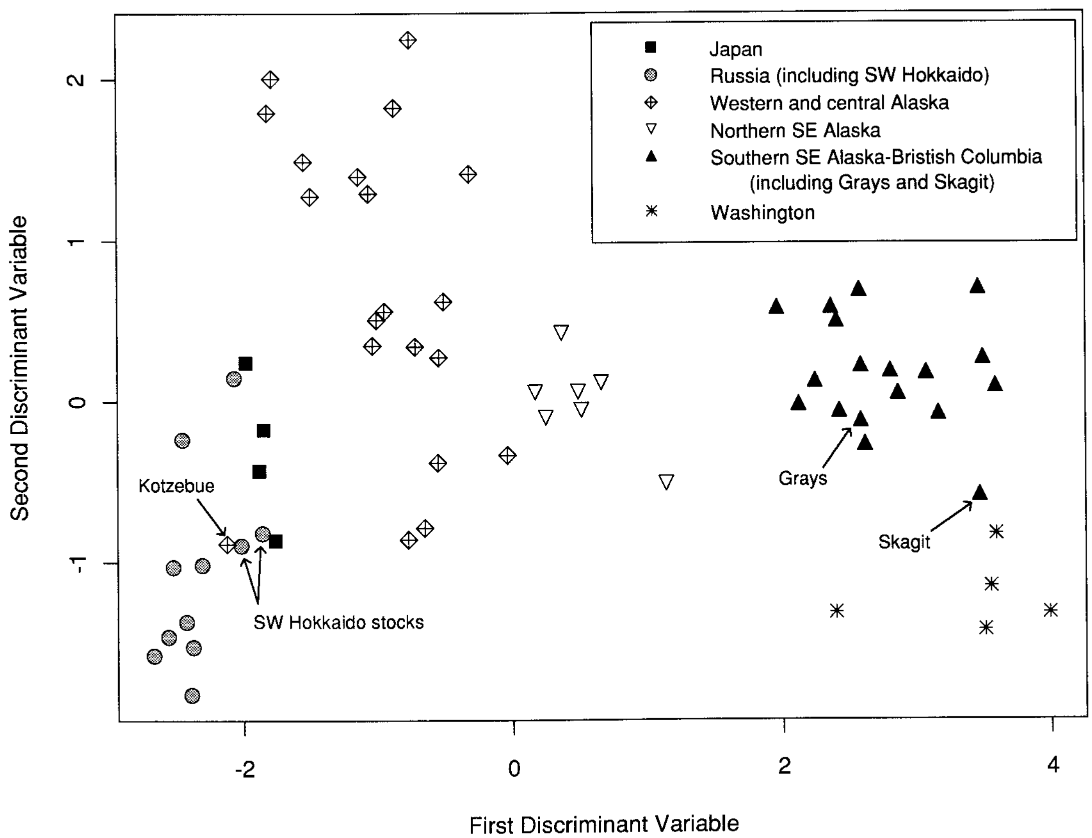

FIGURE 2.—The standardized baseline stock means plotted against the first and second canonical discriminant variables, indicating the regional stock groups chosen for composition analysis. A discriminant analysis of the 65 baseline stocks, using the original scale pattern variables, was used to evaluate the separation of stock centroids along the first two orthogonal dimensions of multivariate Euclidean space. Each plotted point represents the multivariate mean for one stock. With the exception of the Kotzebue Sound stock, the regional stock groups we selected formed discernible clusters reflecting scale pattern similarities. Stock groups that appear to overlap in the first two dimensions of Euclidean space often showed greater definition in the third and higher dimensions.

circulus distances measured along the longest radial axis of the scale.

The 65 stocks in the North Pacific chum salmon baseline were combined into six regional groups according to the similarity of their scale pattern characteristics with exceptions made to conform to a priori designations of North American versus Asian fish. We used a hierarchical agglomerative cluster-analysis algorithm to investigate similarities in scale patterns among the baseline stocks (Patton 1997). The similarity of baseline stocks in multivariate scale pattern space was also evaluated from a two-dimensional plot depicting the Euclidean distances between stock centroids with respect to the first and second canonical discriminant variables (Figure 2). To ensure equal weighting among scale variables, we standardized each of the variables to a mean of zero and standard deviation of one prior to calculating Euclidean distances. Six regional stock groups were formed: Japan; Russia (including southwestern Hokkaido); western and central Alaska; northern southeastern Alaska; southern southeastern Alaska and British Columbia (including the Skagit River and Grays Harbor in Washington); and Washington. Except for the inclusion of Kotzebue Sound chum salmon in the western and central Alaskan stock group, which was done to avoid mixing of Asian and North American stocks, the canonical-variable plot generally supported the regional stock groups we selected (Figure 2).

A conditional maximum-likelihood discrimination model was used to estimate stock composition (Millar 1987, 1990). To address problems

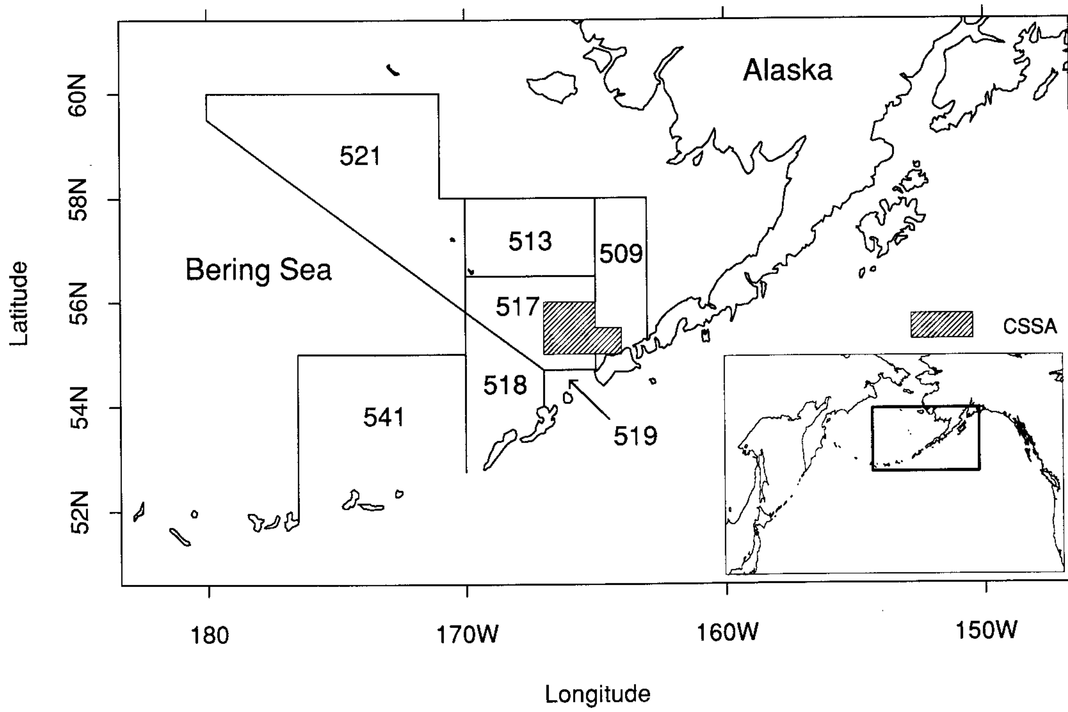

FIGURE 3.—The Bering Sea and Aleutian Islands management area (BSAI) in the eastern Bering Sea, showing the NMFS statistical reporting areas from which chum salmon scale samples were analyzed. The shaded area represents the 4,500 square miles Chum Salmon Savings Area (CSSA) closure established in 1995 under Amendment 35 to the BSAI fishery management plan.

TABLE 1.—Regional stock-group proportions estimated for the chum salmon bycatch samples from the 1994 B-season walleye pollock fishery, stratified by week and by NMFS statistical reporting area. Each proportion is the percentage of the mixture sample for that stratum (SDs are in parentheses). Standard deviations of extrapolated interception estimates were based on 500 bootstrapped composition estimates with random resampling of both the mixture and baseline samples.

		Percentage composition estimate (SD) for stocks from:					
Stratum	*N*	Japan	Russia[a]	Western and central Alaska	Northern southeastern Alaska	Southern southeastern Alaska and British Columbia[b]	Washington
				Week strata			
Aug 15–Aug 20	200	8.3% (0.034)	53.6% (0.046)	12.5% (0.035)	13.7% (0.034)	10.0% (0.027)	1.9% (0.015)
Aug 21–Aug 27	83	19.3% (0.066)	43.0% (0.073)	6.3% (0.048)	18.3% (0.055)	11.1% (0.042)	2.1% (0.020)
Aug 28–Sep 3	321	21.1% (0.034)	13.6% (0.027)	22.9% (0.034)	7.9% (0.024)	28.7% (0.030)	5.9% (0.018)
Sep 4–Sep 10	282	13.0% (0.037)	13.7% (0.033)	35.4% (0.048)	3.9% (0.026)	31.8% (0.032)	2.3% (0.013)
Sep 11–Sep 17	133	9.6% (0.045)	17.6% (0.047)	21.0% (0.049)	8.7% (0.042)	28.7% (0.050)	14.4% (0.040)
Sep 18–Sep 24	129	9.2% (0.042)	15.3% (0.044)	45.0% (0.071)	5.8% (0.047)	23.9% (0.041)	0.7% (0.008)
Sep 25–Oct 4	56	10.0% (0.060)	35.9% (0.078)	44.4% (0.083)	3.1% (0.040)	4.7% (0.036)	1.9% (0.018)
				Area strata			
NMFS Area 509	49	6.5% (0.064)	26.6% (0.089)	13.0% (0.067)	26.1% (0.087)	9.9% (0.055)	18.0% (0.068)
NMFS Area 513	110	15.5% (0.054)	38.6% (0.058)	21.9% (0.056)	10.8% (0.043)	11.5% (0.034)	1.7% (0.015)
NMFS Area 517	796	12.8% (0.021)	20.9% (0.021)	22.3% (0.025)	10.0% (0.018)	29.9% (0.021)	4.1% (0.010)
NMFS Area 519	94	26.2% (0.073)	19.8% (0.054)	30.6% (0.073)	0.4% (0.010)	19.8% (0.045)	3.2% (0.023)
NMFS Area 521	149	14.6% (0.053)	37.8% (0.053)	36.7% (0.059)	0.9% (0.016)	6.6% (0.026)	3.3% (0.019)

[a] Including southwest Hokkaido.
[b] Including Grays Harbor and Skagit River.

TABLE 2.—Extrapolated interceptions of chum salmon from each regional stock group stratified by week and by NMFS statistical reporting area. The weekly estimates were summed to provide an overall estimate of interceptions for each regional group. The total percentage of interceptions from each regional group is also indicated. The area-stratified interception estimates were not pooled because several areas provided insufficient samples for analysis. Total interceptions by stratum were based on stratified NMFS chum salmon bycatch estimates. Confidence intervals (90%) were based on 500 bootstrapped estimates with random resampling of both the mixture and baseline samples.

	Estimated interceptions (90% CI)		
Stratum	Japan	Russia[a]	Western Alaska–central Alaska
Week strata			
Aug 15–Aug 20	2,700 (850–4,549)	17,431 (14,991–19,871)	4,072 (2,210–5,934)
Aug 21–Aug 27	2,442 (1,066–3,818)	5,451 (3,925–6,978)	794 (0–1,800)
Aug 28–Sep 3	2,694 (1,973–3,415)	1,733 (1,164–2,302)	2,925 (2,210–3,640)
Sep 4–Sep 10	883 (470–1,295)	929 (565–1,294)	2,408 (1,875–2,942)
Sep 11–Sep 17	303 (70–536)	558 (315–800)	663 (407–919)
Sep 18–Sep 24	477 (120–834)	791 (413–1,169)	2,326 (1,720–2,932)
Sep 25–Oct 4	149 (0–298)	536 (344–728)	662 (458–866)
Pooled	9,648 (4,550–14,746)	27,430 (21,718–33,142)	13,850 (8,879–19,033)
Percentage	12.9% (6.1–19.8%)	36.8% (29.1–44.4%)	18.6% (11.9–25.5%)
Area strata			
NMFS area 509	125 (0–326)	509 (227–790)	248 (36–460)
NMFS area 513	475 (203–748)	1,189 (896–1,482)	673 (390–956)
NMFS area 517	7,793 (5,710–9,877)	12,695 (10,554–14,836)	13,562 (11,105–16,019)
NMFS area 519	178 (96–259)	134 (73–194)	207 (125–289)
NMFS area 521	1,147 (458–1,836)	2,977 (2,291–3,663)	2,894 (2,131–3,657)

[a] Including southwest Hokkaido.
[b] Including Grays Harbor and Skagit River.

of variable correlation in scale patterns, we used principal components analysis to convert interrelated scale pattern variables into eight orthogonal scale pattern components. The maximum-likelihood program employed in this analysis was written by Millar (1987, 1990) for use with continuous variables; it uses an expectation–maximization algorithm to search for the most likely mixture composition. Its use in scale pattern analysis was described by Bernard and Myers (1996). We used a series of computer simulations to test our baseline model's ability to correctly estimate the composition of hypothetical stock mixtures created by randomly selecting and removing fish from the stock baseline. For each simulation, we calculated an overall measure of the model's accuracy, gauged by the divergence of the estimated proportions from the actual simulated composition. Model performance in these simulations also provided a criterion for comparing alternative baseline stock groupings, ensuring that the six-group model was our most accurate predictor of stock composition.

We further evaluated the performance of our scale pattern baseline model through a direct comparison of an unweighted composition estimate for the 1994 chum salmon bycatch mixture with a corresponding estimate produced by the concurrent allele-frequency stock composition study. Solely for this comparison, we estimated the unweighted fleetwide composition of the unstratified 1994 B-season chum salmon bycatch sample using seven alternative regional stock groups that were analogous to the regional groups used by Wilmot et al. (1995, 1998). Wilmot et al. (1995) combined 77 chum salmon stocks into eight regional groups.

Estimates of the proportions of the 1994 BSAI bycatch mixture that had originated from each of the six regional stock groups were produced for each week stratum (all areas combined) and for each NMFS statistical reporting area stratum (all weeks combined). Of the NMFS areas in the eastern Bering Sea (Figure 3), areas 509, 513, 517, 519, and 521 provided sufficient sample sizes to allow stratification. Standard deviations and 90% confidence intervals of the composition estimates were computed from 500 bootstrap resamplings of the baseline and mixture samples. Within each stratum, we extrapolated the estimated regional proportions to the total numbers of intercepted chum salmon originating from each regional stock group by multiplying our stratified estimates by the NMFS estimate of total chum salmon interception in each stratum. In making this extrapo-

TABLE 2.—Extended.

Stratum	Estimated interception (90% CI)			Total
	Northern southeastern Alaska	Southern south-eastern Alaska–British Columbia[b]	Washington	
Week strata				
Aug 15–Aug 20	4,448 (2,639–6,257)	3,268 (1,824–4,711)	624 (0–1,421)	32,543
Aug 21–Aug 27	2,316 (1,169–3,463)	1,402 (517–2,287)	265 (0–678)	12,671
Aug 28–Sep 3	1,006 (507–1,505)	3,670 (3,035–4,305)	759 (386–1,132)	12,787
Sep 4–Sep 10	268 (0–560)	2,162 (1,799–2,525)	156 (12–300)	6,806
Sep 11–Sep 17	275 (54–495)	908 (647–1,169)	455 (249–662)	3,162
Sep 18–Sep 24	300 (0–699)	1,232 (880–1,585)	37 (0–108)	5,163
Sep 25–Oct 4	46 (0–145)	71 (0–159)	28 (0–73)	1,492
Pooled	8,658 (4,368–13,125)	12,713 (8,702–16,742)	2,325 (647–4,375)	
Percentage	11.6% (5.9–17.6%)	17.0% (11.7–22.4%)	3.1% (0.9–5.9%)	
Area strata				
NMFS area 509	500 (225–775)	189 (15–363)	345 (129–561)	1,916
NMFS area 513	332 (115–550)	355 (181–529)	52 (0–129)	3,076
NMFS area 517	6,058 (4,285–7,832)	18,142 (16,056–20,228)	2,461 (1,484–3,437)	60,711
NMFS area 519	3 (0–15)	134 (84–184)	21 (0–47)	677
NMFS area 521	74 (0–287)	523 (190–856)	263 (21–505)	7,878

lation, we assumed that all age-groups of chum salmon in the BSAI bycatch shared the same regional compositions and that the NMFS bycatch estimates were accurate.

Results

Performance of the Conditional Maximum-Likelihood Model

The mean accuracy of the conditional maximum-likelihood model derived from our chum salmon stock baseline ranged from 83.3% (in simulations classifying mixtures with balanced compositions) to 92.3% (in simulations classifying mixtures with highly skewed compositions). In addition, our maximum-likelihood model produced unweighted stock composition estimates that were quite similar to those produced by the allele-frequency study by Wilmot et al. (1995, 1998). The scale pattern and allele-frequency models attributed nearly equivalent unweighted proportions to stocks from Russia (19.4% versus 20.2%, respectively), western Alaska (27.3% versus 22.3%), central and southeastern Alaska (3.4% versus 4.3%), and Washington (6.0% versus 5.6%). The scale pattern model allocated fewer fish to Japan (17.1% versus 26.7%) and more to British Columbia (26.9% versus 14.4%). These estimates were unweighted by week strata and therefore less precise than the weighted proportion estimates produced from week-stratified estimates of chum salmon interception.

Stratified Chum Salmon Interception Estimates

Stratified weekly composition estimates indicated an increasing trend in the proportion of western and central Alaskan stocks contributing to the chum salmon bycatch mixture over the course of the 1994 B-season walleye pollock fishery (Table 1). There was a decreasing trend in the proportion of incidentally caught fish from Russia and a similar declining trend in the proportion from northern southeasern Alaska. No clear geographic trend was evident from the area-stratified composition estimates (Table 1).

Although the proportion of western and central Alaskan chum salmon in the incidental catch increased over the B-season, the extrapolated total numbers of western and central Alaskan chum salmon intercepted did not (Table 2). Area-stratified extrapolations suggested that only NMFS statistical reporting area 517 accounted for substantial numbers of chum salmon interceptions from any regional group (Table 2).

Summing the regional interception estimates across all weeks (Table 2), the estimate of total interception from each region, weighted by week strata, indicated that approximately 37% of the chum salmon caught incidentally during the

B-season had originated from Russia (including the Japanese Chitose and Yurappu rivers). More than half of these fish were intercepted during the first 6 d of the season (August 15–20). Approximately 19% came from western and central Alaska, 17% from southern southeastern Alaska and British Columbia (including Grays Harbor and the Skagit River in Washington state), 13% from Japan, 12% from northern southeastern Alaska, and 3% from Washington state.

Discussion

Stratified Chum Salmon Bycatch and Interception Estimates

Our stratified weekly composition estimates indicated that while the numbers of western and central Alaskan chum salmon in the incidental catch remained relatively stable over the course of the B-season fishery (Table 2), the proportion of those stocks increased steadily (Table 1). This was due to a sharp decline in the numbers of chum salmon intercepted from other regions, particularly Asia. Interceptions of Russian chum salmon dropped precipitously after the first week of the fishery and continued to decline throughout the B-season fishery, whereas western and central Alaskan chum salmon continued to be intercepted in moderate numbers.

We found no clear geographic pattern of regional interception among the NMFS statistical reporting areas in the BSAI management area (Table 2). However, because our analysis examined only age-0.3 chum salmon, geographic trends may have been obscured by age-specific spatial distributions of chum salmon in the BSAI area. In a preliminary analysis, we found that the age distribution of chum salmon intercepted in the 1993 walleye pollock B-season fishery varied somewhat among NMFS statistical reporting areas. Area-stratified interception extrapolations indicated that the overwhelming majority of all incidentally caught chum salmon, and over 97% of those from western and central Alaska (approximately 13,500 fish), were caught in NMFS statistical reporting area 517 (Table 2).

The accuracy of our regional interception estimates depends on the stratified bycatch estimates provided by NMFS, which are considered preliminary. Furthermore, our assumption that the observer bycatch sample adequately reflects the distribution of chum salmon bycatch in the 1994 B-season walleye pollock fishery may not be supported. The highest level of chum salmon bycatch occurred during the first week of the fishery, yet the observer scale sample from that week was relatively small. It was therefore critical that our estimate of fleetwide bycatch composition be weighted by the total number of interceptions in each week stratum.

The similarity of our unweighted composition estimates and the unweighted estimates of Wilmot et al. (1995, 1998) corroborate the findings of both studies. Differences in the proportions estimated for Japan and British Columbia may have arisen because our estimate was for age-0.3 chum salmon only, whereas Wilmot et al. (1995, 1998) analyzed all age-groups. Nevertheless, both estimates indicated that the incidental catch of the 1994 BSAI walleye pollock B-season fishery contained large proportions of chum salmon from multiple regions throughout the North Pacific Rim. This conclusion is strengthened by the fact that each study independently sampled chum salmon from the incidental catch of the 1994 walleye pollock B-season. Recent studies of chum salmon ocean distribution also lend credence to these findings. Coded wire tag recoveries in the eastern Bering Sea include several summertime catches of chum salmon originating from southeastern Alaska, British Columbia, and Washington (Myers et al. 1996). An otolith thermal mark recovery study conducted by NMFS also confirms the presence of southeastern Alaska and British Columbia chum salmon in a sample of the 1996 Bering Sea walleye pollock fishery bycatch (Ignell et al. 1997).

Management Implications of Chum Salmon Interceptions

The National Marine Fisheries Service estimated that BSAI B-season walleye pollock trawls caught nearly 74,500 chum salmon in 1994. Our weighted interception estimates (Table 2) indicate that approximately 13,800 of these originated from western and central Alaska. The total chum salmon runs in western and central Alaska in 1994 were 4.4 and 3.8 million fish, respectively (Geiger and Simpson 1995; D. E. Rogers, FRI, personal communication). Therefore, according to our research, ocean interception of western and central Alaskan chum salmon in the 1994 walleye pollock fishery was negligible relative to overall run sizes. Indeed, even the total volume of chum salmon bycatch in the walleye pollock fishery (<300,000 fish in the peak year, 1993) cannot account for the many-fold decline in western Alaska chum salmon landings observed over the same period (1–2 million fish; Rogers, personal communication).

Most commercial salmon fisheries in western Alaska had already ended prior to the start of the 1994 walleye pollock B-season. By late August and early September, maturing western Alaskan chum salmon typically have emigrated from the walleye pollock fishing grounds. Because most of the incidentally caught chum salmon were presumably immature (Wilmot et al. 1995, 1998), a time lag of at least 1 year should be expected before observing any effects of B-season interceptions on western Alaskan commercial chum salmon fisheries. Therefore, it is doubtful that the peak bycatch observed in 1993 was responsible for the simultaneous drop in western Alaskan commercial chum salmon yields.

Chum salmon interceptions in the BSAI walleye pollock fishery have remained lower since the 1993 peak (Queirolo et al. 1995; Berger 1997), and commercial chum salmon catches in western Alaska improved in 1994 and 1995 (Geiger and Simpson 1995; Geiger and Frenette 1996). Bycatch caps were implemented for the B-season BSAI pollock fishery in 1995, triggering closures in areas of high chum salmon bycatch (Figure 3). With no record of chum salmon ocean abundance fluctuations during this period, however, it is difficult to determine just how important a role the new trawling restrictions played in reducing chum salmon bycatch in the BSAI groundfish fisheries.

Myers and Rogers (1988) speculated that high ocean abundance led to high chinook salmon *O. tshawytscha* bycatch levels in the Bering Sea trawl fisheries in 1979 and 1980. Considering the anticipated time lag between the ocean interception of immature chum salmon and possible effects on spawning runs, the rebound of Alaskan chum salmon runs observed in 1994 and 1995 suggests that the high chum salmon bycatch that occurred in 1993 and 1994 could have resulted from an exceptionally high abundance of immature chum salmon in the North Pacific, caused by one or more strong year-classes.

Acknowledgments

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