Flødevigen rapportser., 1, 1984. ISSN 0333-2594
The Propagation of Cod *Gadus morhua* L.

BIOLOGY AND MANAGEMENT OF THE PACIFIC COD (*Gadus macrocephalus* Tilesius) RESOURCE IN THE EASTERN BERING SEA AND GULF OF ALASKA

V.G. Wespestad and A.M. Shimada

Northwest and Alaska Fisheries Center, National Marine Fisheries Service, 2725 Montlake Blvd. E., Seattle, WA. 98112 USA

ABSTRACT

Wespestad, V.G. and Shimada, A.M., 1984. Biology and management of the Pacific cod (*Gadus macrocephalus* Tilesius) in the eastern Bering Sea and Gulf of Alaska. In: E. Dahl, D.S. Danielssen, E. Moksness and P. Solemdal (Editors), The Propagation of cod *Gadus morhua* L. Flødevigen rapportser., 1, 1984: 819-845.

Pacific cod have been exploited in Alaska for over 100 years. Originally, the fishery was exploited in coastal waters by U.S. fishermen. This domestic fishery declined following World War I, ceasing by the early 1950's. In the mid-1950's Japanese and Soviet distant water fleets began operations in the northeastern Pacific Ocean. Pacific cod was primarily an incidental species in the harvests of these fleets. In recent years a U.S. cod fishery has redeveloped and is rapidly expanding.

Coincidental to the renewed interest in a directed U.S. cod fishery has been a strong increase in Pacific cod abundance. Most of the increase appears to have been due to the occurrence of an exceptionally strong 1977 year-class. Since cod is becoming a major commercial fishery in the northeastern Pacific Ocean it is important to develop long term estimates of yield and accompanying management strategies. One shortcoming of such efforts is the short time series of cod data in Alaskan waters. Some consequences resulting from above-average cod recruitment in 1977 and the current high abundance level are examined.

INTRODUCTION

The Pacific cod (*Gadus macrocephalus*) occurs throughout the North Pacific Ocean. In North America, cod inhabit waters of the continental shelf and upper slope from California to St. Lawrence Island in the Bering Sea (Fig. 1). Cod also are found throughout the Aleutian Islands and along the Asian coast from the Gulf of Anaydr in the Bering Sea south to the Yellow Sea (Bakkala et al., 1981). Catch statistics indicate that cod are more abundant in North America than in Asia. Abundance appears

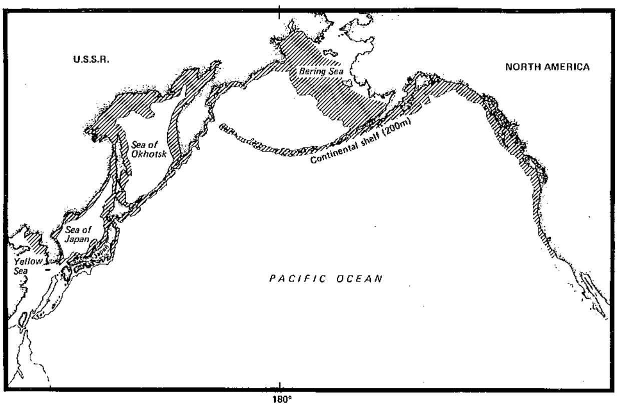

Fig. 1. General distribution of Pacific cod in the north Pacific Ocean.

greatest in the Bering Sea and decreases to the south (Table 1). Major commercial concentrations of cod in the northeastern Pacific Ocean are shown in Fig. 2. The southernmost concentration is found off the northern coast of Washington State to Vancouver Island, British Columbia, Canada. A second area is in the Queen Charlotte Sound-Hecate Strait area of Canada. Cod abundance is low in the eastern and central Gulf of Alaska and commercial concentrations only occur in the western Gulf between Kodiak Island and Unimak Island. In the Aleutian Islands, commercial concentrations are reported to occur in the

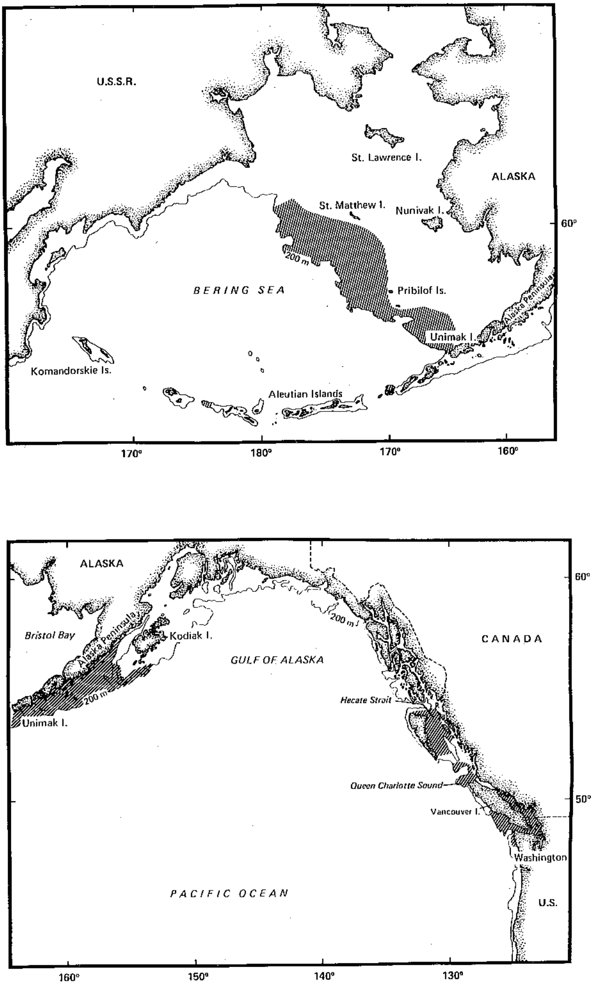

Fig. 2. Location of major fishing grounds for Pacific cod in the northeastern Pacific Ocean.

vicinity of the Islands of Four Mountains (170°W) and Buldir Island (176°E). In the Bering Sea, cod are relatively abundant along the outer continental shelf from Unimak Island to St. Matthew Island.

Pacific cod was the first demersal fish utilized commercially in the northeastern Pacific Ocean. In 1864 the schooner Alert, out of San Francisco, initiated a fishery in the Bering Sea (Cobb, 1927). This fishery, which employed sailing schooners and one-man dories as catcher boats throughout its history, continued until the early 1950's. Shortly after the demise of the North American fishery the distant water trawl fleets of Japan and the U.S.S.R. began fishing the Northeast Pacific in 1954 and 1958, respectively. These foreign fisheries concentrated on Pacific herring (*Clupea harengus pallasi*), yellowfin sole (*Limanda aspera*) and walleye pollock (*Theragra chalcogramma*) and other species. Pacific cod was generally not a target species and was primarily taken as by-catch. Catches in the Bering Sea averaged about 50 thousand tonnes and less than 10 thousand tonnes. in the Gulf of Alaska (Table 1).

In 1977, the United States instituted a 200-mile Fisheries Conservation Zone which encompassed the productive cod grounds in the eastern Bering Sea and Gulf of Alaska. Since that time the foreign distant water fleets have continued to fish for cod under permit. Catches have increased in recent years primarily due to the development of a longline fishery by Japanese vessels. Concurrent with the establishment of the U.S. 200-mile zone were the occurrence of a strong year-class of cod in the Bering Sea and Gulf of Alaska and increasing cod prices which made Pacific cod increasingly competitive in world markets. Also, traditional crab and shrimp fisheries were declining and fishermen were seeking other resources to exploit. These events have lead to a renewed interest in the exploitation of cod by the U.S. fishing industry.

This renewed interest occuring at the same time as an extremely strong year-class has presented new opportunities and problems for fisheries biologists and managers. The policy of the U.S. government is to encourage development of U.S. fisheries as rapidly as possible. However, at the same time

TABLE 1

Commercial catches (t) of Pacific cod by region of the North Pacific Ocean, 1968-1977 [a]

Year	Korea	Japan	USSR	Aleutians	Eastern Bering Sea	Gulf of Alaska	British Columbia	Washington to California	Total
1968	2.218	8.830	14.300	298	57.915	1.048	7.937	595	93.132
1969	3.279	10.465	27.700	220	50.487	1.356	5.143	249	98.899
1970	2.753	8.595	11.900	283	70.078	1.818	3.252	174	98.853
1971	2.571	18.144	29.700	2.078	43.041	656	6.489	535	103.214
1972	757	17.960	18.800	435	42.905	3.573	11.285	1.194	96.909
1973	717	19.452	26.100	977	53.386	6.059	10.116	555	117.362
1974	1.365	18.919	19.200	1.379	62.462	5.251	11.246	1.128	120.950
1975	1.653	18.325	25.816	2.838	51.551	5.958	13.130	1.981	121.252
1976	435	16.752	1.700	4.190	50.481	6.524	12.350	2.156	94.588
1977	1.156	16.112	11.454	2.166	33.320	2.225	9.643	1.993	78.069
Annual mean catch	1.690	15.355	18.667	1.485	51.563	3.447	9.059	1.056	102.323
Percent of total	1.7	15.0	18.2	1.5	50.4	3.4	8.7	1.0	

[a] Source of data: Bakkala et al., 1981

there is concern that too rapid a development may lead to overcapitalization of the fleet as has occurred in other fisheries which developed in conjunction with transient high levels of resource abundance such as the Bering Sea king crab fishery. From a biological point of view, it is difficult to provide advice to managers and the fishing industry since only catch data are available for any length of time and most biological data are rudimentary at best.

Regardless of the difficulties present the cod fisheries off Alaska are beginning to be exploited. Industry and management are asking for scientific advice on what levels of exploitation the cod resource can sustain and what impacts on other resources are brought about by intensive development of cod fisheries. This paper reviews the biology of Pacific cod and the abundance of cod in the northeastern Pacific Ocean. We will also present information on the strong 1977 year-class and its implications for management of the cod and other resources.

DISCUSSION

Pacific cod life history features

Investigations into the biology and life history of Pacific cod have proceeded intermittently from the early studies of Soviet researchers, most notably those of Moiseev in the 1950's; followed thereafter by a Canadian review of Pacific cod ecology in northwest British Columbia waters (Ketchen, 1961) and work on physical determinants of egg and larval development (Alderdice and Forrester, 1971). Since 1973, American scientists have been primarily concerned with assessments of population abundance and distribution off Alaska. Due to historically low levels of Pacific cod abundance prior to 1977 and associated low domestic landings, research interest in Pacific cod has been very limited and pursued less aggressively than for some of the high-value fishery resources such as Pacific salmon (*Oncorhynchus* spp.) and Pacific halibut (*Hippoglossus* *stenolepis*). Consequently, knowledge of such basic population characters for cod as reproduction, growth and mortality is less than complete.

Spawning and associated bathymetric movements

Pacific cod generally spawn from mid-winter to late spring with peak activity between January and March. Spawning time and depth distribution are characterized by seasonally determined vertical migration patterns first described for northwest Pacific cod by Moiseev (1953). Distinct patterns are evident in a north boreal region (50-65°N), in a transitional zone between 40-50°N, and in a south boreal region (35-40°N). This pattern is also evident in the northeast Pacific based on laboratory and commercial data (Forrester, 1977; Karp, 1982).

For south boreal stocks, spawning migrations into coastal bays (15-50 m depths) are observed during December through February when the shallow bay environment cools from 12-13°C summer temperatures. Spawning begins when temperatures reach 5-9°C. In March and April, post-spawning cod move to offshore feeding areas at depths greater than 100 m in which temperatures range between 1-7°C, thus avoiding the summer heated coastal waters.

A reverse migration pattern is observed in north boreal populations during late-winter and early-spring where spawning cod are found at depths of 80-290 m and 0-3°C. Here, movement is from shallow summer feeding areas on the inner continental shelf where summer temperatures range between 0.2-4.5°C to the outer continental shelf and slope as winter cooling of the shelf waters occur (Shimada et al., 1981). Post-spawning return movement is not stimulated until the inner shelf environment warms to 2-10°C.

Within the transition zone (Sakhalin Island in Asia and British Columbia in North America), variable timing and optimum temperature with depth is observed relative with movement towards either north or south latitudes. Comparing Asian vs North American waters, net movement within depth zones is largest in the western Pacific Ocean, 15-290 m vs 50-135 m (Ketchen, 1961)

This reflects a response to more severe temperature shifts in the upper mixed layer similar to that observed in the eastern Bering Sea which occupies the northern-most point in Pacific cod distribution.

Reproductive biology

Few studies on Pacific cod reproduction exist outside the northwest Pacific (Soviet and Japanese waters), or beyond those of southern populations in the northeast Pacific (Canada and Washington State). No explicit work has been reported, or initiated, for the eastern Bering Sea or Gulf of Alaska at present. As with other regional differences, there is a north-south cline in fecundity estimates and age-size of maturity. Karp (1982) and others suggest that a relationship between decreasing latitudes and the concomitant increase in overall water temperature exists in determining the reproductive potential of Pacific cod populations. As a general rule lower fecundity and younger age-at-maturity is observed for southern cod as compared with nothern cod.

Fecundity estimates and size-age at first maturity for those populations that have been studied indicate that northwest Pacific cod have the highest egg production (1.4-6.4 million) and mature at larger body size and older ages (65-70 cm, five to six years) (Svetovidov, 1948; Moiseev, 1953). Chyung (1977) reported size at first spawning for western Korean cod to be between 32 and 38 cm, with an estimate of 2-3 million eggs for 65-100 cm fish, as cited by Zhang (1981). Off the Canadian coast, Forrester (1977) reported that the majority of British Columbia cod are mature by age three, between 45-55 cm. Fecundity for fish 40-80 cm range between 0.270 and 3.4 million eggs (Thomson, 1963). A study in Washington State by Karp (1982) found maturity to occur at age two and fecundity varying between 0.660 and 3.5 million eggs for fish 40-70 cm in length.

Egg and larval development

The eggs of Pacific cod are demersal in contrast to the pelagic eggs of the Atlantic cod. In the northeast Pacific, pelagic eggs and larvae appear to be an exception rather than the rule with only walleye pollock and pleuronectid flatfish accounting for pelagic eggs in this region (Kendall, 1981). Thomson (1963) summarized the results of several authors and reported the mean density of fertilized eggs to be 1.050. During early development these eggs are slightly adhesive, transparent with no oil globule, spherical with diameters of 1.0 mm (Western Canada), 0.8-1.4 mm (Northern Japan) and 1.3-1.6 mm (Korea) (Yusa et al., 1977).

Laboratory work on the effects of salinity, temperature and dissolved oxygen on the early development of cod eggs indicate that optimum conditions embrace mean values of 3.79°C, salinity 14.91 o/oo, and dissolved oxygen 8.29 ppm. Pacific cod eggs are euryhaline, euryoxic and stenothermal, with temperatures between 3-5°C determining incubation success under wide variation in the former two physical parameters (Alderdice and Forrester, 1971).

If experimental evidence is correct for Pacific cod, then development must necessarily proceed at the ocean bottom. Incubation may possibly occur at some halocline at depth, given appropriate water density conditions relative to egg specific gravity. Spawning cod have been found along the continental slope in the eastern Bering Sea where depths may exceed 500 m, but there is no direct evidence for linking egg development to either the ocean floor or in the water column. Ichthyoplankton work in this region has not been definitive for Pacific cod. Water mass studies of Kihara (1982) and Schumacher and Reed (1983) indicate that warm, saline oceanic Aleutian Basin and Alaska Stream Extention water intrudes over the outer continental slope and shelf margin year-round. Physical variability within favoured winter spawning environments in the eastern Bering Sea may have significant impacts on early life stage survival. The demersal nature of Pacific cod eggs presumably ensures minimal drift from optimal conditions and maintains the developing embryos within a stable nursery refuge.

Egg development for Pacific cod in northwest waters require 10-20 days at 3-5°C. Newly hatched prolarvae are 3.27-3.80 mm total body length. Ten days after hatching, yolk sac absorption occurs at about 4 mm in 5^{o}C water. For south boreal stocks, early growth continues in protected coastal waters up to 90 mm. At 70-80 mm, cod begin out-migration, first to deeper inshore waters then finally taking up a benthic existence further offshore.

Larval collections off Kamchatka and Sakhalin Islands reported by Mukhacheva and Zvyagina (1960) indicated that cod larvae were located in coastal waters at 25-150 m depths, with the majority found between 75 and 100 m. Otherwise, for north boreal stocks (particularly the Alaskan populations we are most concerned with) far less is known about the egg and larval period. Contributing factors for our continued ignorance may be linked to the demersal nature of Pacific cod eggs, and the inability to effectively sample and identify Pacific cod larvae in field surveys. Experience in Port Townsend Bay, Washington has shown that Pacific cod young (3.8-8.0 cm) can be captured by demersal sleds (G. Walters, NMFS-NWAFC, personal communication, 1983).

Juvenile and adult distribution

Pacific cod juveniles exhibit first schooling behaviour and take on an adult appearance at about 4.5 cm (Yusa et al., 1977). In Alaska, Pacific cod are first recruited to research trawls beginning at 10-12 cm. In Bering Sea surveys, juvenile cod are encountered in coastal water surrounding St. Matthew and Nunivak Islands, along the northern shores of the Alaskan Peninsula, and south of the Alaskan mainland in northern Bristol Bay from July through October. Cobb (1927) found 5-13 cm cod along the southern side of the Alaska Peninsula from May through October. As the cod age, there is a progressive offshore movement, with 1-2 year old cod occupying the middle shelf and 3-4 year old cod the outer shelf. Cod older than four years are usually limited to the outer shelf and slope (150-500 m) with only temperature-dependent minor incursions into the inner shelf environment.

Age and growth

Determination of Pacific cod age and growth rates has always been somewhat problematic, often yielding different estimates depending on the age structure examined. Otoliths and scales have been the age structures most often used by investigators, but the results have often been unreasonable and not easily validated by other independent means. The success with which age studies have used otoliths and scales has also varied between regions. It was noted in an earlier study (Moiseev, 1953) that while age samples from the southeastern Bering Sea appeared to possess patterns which allowed them to be aged from either structure, Asiatic cod required both structures because neither one alone was satisfactory for all sizes of fish. For Canadian stocks, Ketchen (1961) reported that scales and otoliths lacked any well-defined pattern of annual checks useful for age work. Kennedy (1970) described a method using scales of adult cod from Hecate Strait which became the standard method at both the Pacific Biological Station (Nanaimo, British Columbia) and the Northwest and Alaska Fisheries Center (Seattle, Washington) during the early to mid-1970's. In 1978, problems arose when Kennedy's annuli criteria were applied to juvenile cod from areas other than Hecate Strait and further scale analysis based on his method was suspended pending new validation studies (Chilton and Beamish, 1982).

Recently, developments associated with computerized analysis of length frequency data obtained from research cruises and the commercial fisheries has offered additional age information. Length frequencies are the most common data collected from commercial fisheries, and often represents a much longer time-series than is available from research surveys. The Northwest and Alaska Fisheries Center has applied a programme adapted from MacDonald and Pitcher (1979) to assign age determinations to Pacific cod size composition data. This method separates normally distributed components from a distribution of interval measurements, by iteratively fitting normal curves to modes in a length frequency to determine age groups (Wespestad et al., 1982).

In the eastern Bering Sea, large specimens often exceed 1 m in total body length (Svetovidov, 1948) and total body weight has been recorded up to 12 kg. Pacific cod are short lived and very few older than age 10 have been identified. Table 2 gives mean lengths-at-age for Pacific cod populations throughout the North Pacific. The north-south pattern drawn from this data summary, indicates that growth rate is more rapid and natural mortality rates are higher for the southerly distributed stocks on either side of the Pacific Ocean. Effects of increased exploitation on growth rates have not been identified.

Foucher et al. (1981) compared growth of Pacific cod in the eastern Bering Sea, Gulf of Alaska and British Columbia using scale readings and length frequency methods (Fig. 3). They reported marked differences between the two methods when

TABLE 2

Mean length-by-age (cm) for Pacific cod in the North Pacific Ocean (from data of Svetovidov, 1948; Moiseev, 1953; Ketchen, 1961; Foucher et al., 1981; Karp, 1982; Bakkala and Low, 1983)

Age Region	1	2	3	4	5	6	7	8	9	10	11
E Korea	23.5	39.0	57.5	69.0	-	-	-	-	-	-	-
Japan Sea	16.8	21.3	33.9	40.9	51.5	60.8	68.7	75.5	83.7	93.6	99.5
Okhotsk Sea	19.0	31.8	37.7	46.1	55.8	67.0	75.2	83.3	91.8	94.9	-
E Kamcha-tka	18.1	30.7	41.3	49.9	57.3	63.4	68.4	73.2	78.2	82.6	87.0
Olyutor-skii	-	29.6	35.5	45.7	54.2	64.1	72.4	75.8	83.6	87.0	91.0
EBS	23.9	34.1	39.9	48.7	56.8	62.1	67.4	72.0	76.8	82.1	83.1
Aleutian Islands	-	36.2	47.5	55.3	62.4	69.3	73.3	77.2	81.9	87.6	-
GOA	29.9	41.5	50.4	56.7	62.7	68.7	74.1	78.9	83.9	88.3	93.7
B.C.	-	51.8	61.4	68.3	74.7	79.0	83.3	86.5	90.0	-	-
WA State	25.0	42.1	54.5	63.4	69.9	-	-	-	-	-	-

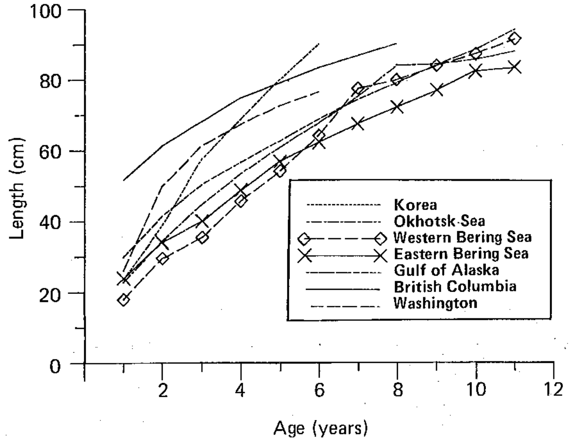

Fig. 3. Growth of Pacific cod in different regions of the north Pacific Ocean.

applied independently to eastern Bering Sea and Gulf of Alaska samples. Length frequency analysis generally estimated a greater proportion of older fish and slower growth rates, suggesting lower annual mortality and delayed recruitment. This method matched the eastern Bering Sea cod with the western Bering Sea up to age six, after which growth appears to accelerate in the northwest Pacific (Ketchen, 1961). Similarities were also found between Sea of Okhotsk and East Korean cod and the cod of Hecate Strait and Washington State, although values were limited to the first four age groups (Table 2) (Ketchen, 1961; Karp, 1982).

Tropic relationships and feeding

Pacific cod are an important component of a stable recurrent shelf group which represents the core members of the eastern Bering Sea summer benthic community (Kihara, 1983; Walters and McPhail, 1982). This prominence in the eastern Bering Sea demersal community, together with increased population abundance since 1978, suggests that Pacific cod have potential for significant impacts on co-occurring species. Food habit studies indicate that cod are feeding generalists that characteristically focus on key prey items during various stages of their life history (Mito, 1974; Feder et al., 1978). Several important energy pathways for Pacific cod which include commercially desirable pollock, shrimp and crab prey are given in Fig. 4.

Studies by June and Shimada (in prep.) have examined cod stomachs collected during summer 1981 over much of the eastern Bering Sea shelf to attempt to assess quantitatively the food requirements of cod. An additional objective was to characterize the impact of cod predation within the context of a multispecies environment. Prior studies have not examined cod feed-

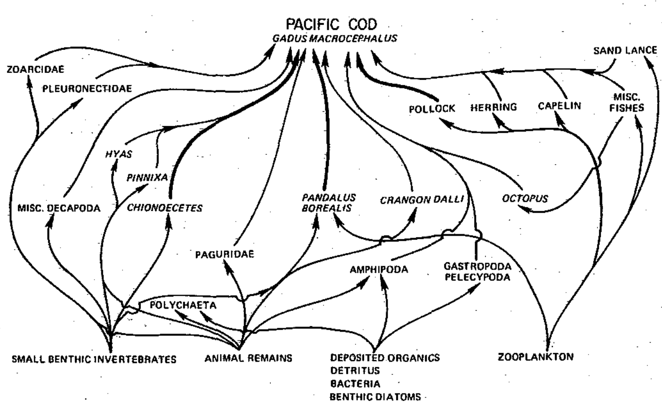

Fig. 4. A food web showing carbon flow to Pacific cod (*Gadus macrocephalus*) in the southeastern Bering Sea (Feder and Jewett, 1981). Bold lines indicate major food sources based on frequency of occurrence.

ing in a systematic fashion incorporating time-area-depth parameters, cod biology and prey availability data from the sample sites. The major prey groups identified are presented in Table 3.

Preliminary results obtained from a sample of 1,764 Pacific

TABLE 3

Index of relative importance for selected major prey categories of Pacific Cod in the eastern Bering Sea, May-August 1981 (June and Shimada, unpubl.)

Order	%Freq Occur	%Prey Count	%Prey Weight (g)	%Index of Relative Importance
Polychaeta	20.068	1.741	0.577	1.300
Gastropoda	5.952	0.441	0.433	0.145
Bivalvia	5.385	0.542	0.233	0.117
Octopeda	6.519	0.359	6.986	1.338
Mysidacea	20.011	5.276	0.099	3.005
Amphiphoda	31.916	7.402	0.132	6.717
Euphausiacea	20.125	64.171	1.529	36.940
Pleocyemata (caridea)	39.512	5.342	2.539	8.700
Anomura	16.156	0.877	7.953	3.986
Brachyura (oxyrhyncha)	16.213	1.746	5.363	3.220
Echiura	8.107	1.124	0.983	0.477
Osteichthys (teleost)	29.705	1.961	10.879	10.656
Gadoidei	16.100	1.401	43.471	20.183
Zoarcoidei	7.540	0.656	7.138	1.642
Pleuronectiformes	3.968	0.290	5.819	0.677

1) Total Stomachs	1764
2) Total Prey Count	37626
3) Total Prey Weight	103,209.726 g
4) Total IRI	3,579.277

Index-of-Relative-Importance is calculated as IRI = (N + V) x FO where N is the numerical percentage a food type contributes to the total diet, V is its volumetric percentage, and FO is its percent frequency of occurrence (i.e. that proportion of stomachs containing the food item) (Pinkas et al., 1971). % volume was replaced by % wet weight in the study of June and Shimada cod stomachs summarized across all size groups, survey times and geographic locations conform to results reported from other areas of the North Pacific (Jewett, 1978; Hunter, 1979). Fully 95.7% of all food items can be classified as either crustacea (62.5%) or teleost fish (33.2%). The remainder are distributed among annelid and echiuroid worms, cephalophods, gastropod and bivalve molluscs. Fish accounted for the bulk of prey weight consumed (68%); whereas invertebrate weights were substantially less but on a percent frequency basis were encountered most often (89%). In particular, the gadids (pollock and cod) were a prominent component by weight (43.5%). Zoarcids (eelpouts) and Pleuronectidae (flatfish) were the next largest contributors to the fish fraction in roughly equal proportions. Of invertebrates, octopus and squid represent 6.9%; second only to euphausids, shrimp and crab which were found to be significant in both weight (22.6%) and frequency of occurrence (78%).

Selectivity relationships are still unclear, but prey selection appears to vary based on abundance, relative size between predator and prey, and availability determined by geographic proximity and temporal overlap. Diet shifts with increasing cod size are given in Fig. 5. It is evident that

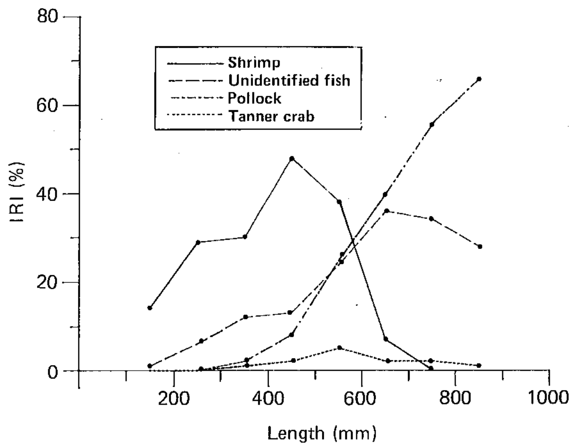

Fig. 5. Consumption of major food items by differing size groups of Pacific cod in the eastern Bering Sea.

shrimp consumption is greatest for ages two and three, and that by age four (<50 cm) the principal food items become pollock and crab.

Daan (1973) has suggested cannibalism as one mechanism governing North Sea cod populations, although in later studies this relationship becomes less clear. For eastern Bering Sea Pacific cod populations, we believe interspecific linkages are more important than intraspecific relationships. Cod predation appears to be particularly significant for pollock (Mito, 1974). Shrimp are preyed upon by specific size/age classes of cod. King (*Paralithodes camtschatica*) and tanner crabs (*Chionoecetes opilio* and *C. bairdi*) are also susceptible to cod predation during certain critical times, i.e. in the soft-shell state just after moulting, or at certain body sizes. The precipitous decline in the Bristol Bay red king crab fishery is believed by fishermen to have been directly attributable to the rapid increase in Pacific cod abundance. June and Shimada (in prep.) have documented red king crab consumption, but empirical evidence examined so far indicates that such predation is strictly determined through a narrow time-space window. Tanner crabs, another commercial species, appear to play a greater role in cod diet overall, both in terms of consumption throughout the eastern Bering shelf and through time. *C. opilio*, in particular, are found in stomach contents. An apparent sex selection by cod is evident when ratios of male and female tanner crab consumed were examined (0.28 for *C. opilio* and .004 for *C. bairdi*). Nothing in the life history or distribution of these species suggests segregation by sex, time or area. It was therefore assumed that males and females were equally available to cod, but that perhaps the smaller carapace width of mature female tanner crabs allow them to be more readily taken by cod.

Regional abundance in the northeastern Pacific Ocean

The stock structure of Pacific cod is poorly understood (Bakkala et al., 1981). Moiseev (1960) reported not less than ten individual stocks in Asiatic waters. Westrheim (1982), summarizing tagging results from British Columbia and Washington State, also reports a high degree of stock localization and little intermixing. Due to the limited information on stock structure cod populations off North America are managed primarily by geographic subdivisions. The conventional stock units are Washington-California, British Columbia, Gulf of Alaska, Aleutian Islands and eastern Bering Sea.

Pacific cod abundance is low in the Washington-California region which is also the extreme southern end of the range. Estimates of abundance are unavailable but yields on the order of 3-4.000 tonnes are believed to be sustainable (Pacific Fisheries Management Council, 1981). In British Columbia abundance appears somewhat higher based on average yield (Table 1).

In the eastern Gulf of Alaska, cod abundance is extremely low. Resource surveys conducted by the Northwest and Alaska Fisheries Center in 1981 estimated the available cod biomass in the eastern Gulf of Alaska to be >8.000 tonnes or about 2% of the total Gulf of Alaska estimates of 396,245 tonnes. The estimated potential yield for Gulf of Alaska stocks is estimated to be about 133 thousand tonnes with 59% available in the western Gulf (west of Kodiak Island), 39% in the Central Gulf (Kodiak Island to Prince William Sound) and the remaining 2% to the east of Prince William Sound (Zenger and Cummings, 1982).

Pacific cod in the North Pacific Ocean reaches its highest abundance in the eastern Bering Sea. The 1983 resource estimate for cod in the eastern Bering Sea is in excess of one million tonnes of which 232,500 tonnes is available for harvest in 1984 (Bakkala and Low, 1983). Scientific investigations into the potential yield of cod in this region have only been conducted since the late 1970's and the available data series are inadequate to fully assess the true long term yield potential for these fish. The average catch since the 1950's provides a first approximation of a long term yield of 58,000 tonnes. However, this is highly conservative since cod was a target species only rarely. Low (1983) used a multispecies ecosystem model to estimate the long term equilibrium yield of cod and other species in the eastern Bering Sea. The results of these analyses indicate that sustainable yelds of 100,000 tonnes are possible.

The relationship between Aleutian Island and eastern Bering Sea cod populations is unclear. Preliminary results from tagging studies indicate at least a moderate amount of movement between the two areas. Very little is known about the resource in this area as the first assessments of cod in the Aleutian Islands were conducted in 1980 and again in 1982. Biomass estimates from these surveys indicate the presence of 231,000-282,000 tonnes in the Aleutian Island region. It is difficult to determine the yield potential of these stocks, but if the dynamics are similar to eastern Bering Sea stocks then yields of at least 60,000 tonnes should be sustainable (Bakkala and Low, 1983).

Occurrence of 1977 year-class

In 1978 resource surveys in the Gulf of Alaska and the eastern Bering Sea found large numbers of age 1 cod. This was the first observation of an exceptionally strong year-class in the population. Strong year-classes may have occurred in the past but they are not evident in catch data. Catch data may not be reflective of cod abundance as catches have generally been small and catch and effort data available are generally regarded as unreliable (Wespestad et al., 1982). The occurrence of the strong 1977 year-class provided an opportunity to study the dynamics of a single cod year-class. Previous to the appearance of the 1977 year-class it was difficult to study age related processes due to the lack of reliable age determinations (see age and growth section). The 1977 year-class was evident as a strong mode in length frequencies for several years (Fig. 6). Following the mode of the 1977 year-class through the use of modal analysis made possible age structured analysis of the population. Comparison of age structured analyses to survey results indicate that the rate of natural mortality is high prior to sexual maturity with an approximate instantaneous rate of 0.7 (Wespestad et al., 1982). Following sexual maturity the rate of natural mortality appears to decline since recent age structured simulations and survey biomass estimates would only agree when an instantaneous natural

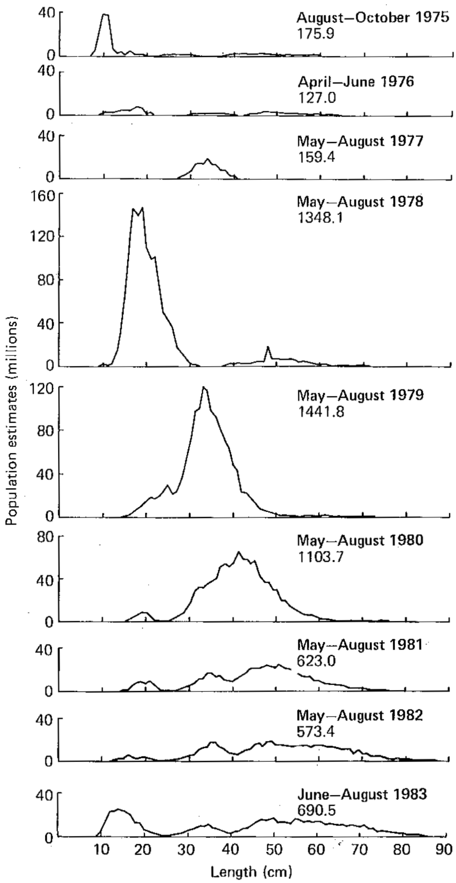

Fig. 6. Length compostion of Pacific cod in the eastern Bering Sea based on data from NWAFC recource assessment surveys, 1975-1980. Numbers below dates of the surveys are estimated population numbers in millions within the survey areas.

mortality rate of 0.5 was utilized. The age structure and modal analyses have also indicated that maximum age in the Bering Sea is about 12-15 years with very few surviving beyond age eight.

The expanded utilization of the cod resource by the U.S. fishing industry has led industry and management to be increasingly interested in the short and long term yield potential of the resource. The short term potential is fairly straightforward and rather simple to forecast as most of the exploitable biomass is comprised of the 1977 year-class which will cease being a significant part of the catch after 1984. Long term yield, on the other hand, is more complex and difficult to determine. The available estimates of potential yield are largely based on Graham-Scheffer general production type models which assume a constant level of recruitment. Available evidence in the northeastern Pacific and other areas show that cod recruitment is far from constant (Cushing, 1981). Cod recruitment is also to a high degree independent of parental stock with environmental factors having greater control of year-class size. Until a better understanding is gained of the controlling environmental variables it appears that it may be futile to try to determine long term abundance trends for Pacific cod.

Possible consequences of 1977 year-class recruitment

The rapid increase in Pacific cod abundance may have had a major impact on other commercially exploited species. In the central and western Gulf of Alaska pink shrimp (*Pandalus borealis*) contributed a major portion of the total commercial through the 1960's and 1970's (Fig. 7). In 1978 the shrimp catch began a decline which continues to date. Several factors could be involved in the decline of shrimp in the Gulf of Alaska, but the close association between shrimp decline and the rise of the 1977 year-class is noteworthy. Unfortunately, cod data available for the Gulf of Alaska are rather limited, but if estimates of cod consumption obtained by June and Shimada (in prep.) in the Bering Sea are applied to the 1979 Gulf of Alaska cod population estimate of 368,000-736,000 tonnes (Low et al., 1979) with 50% of the biomass less than 50

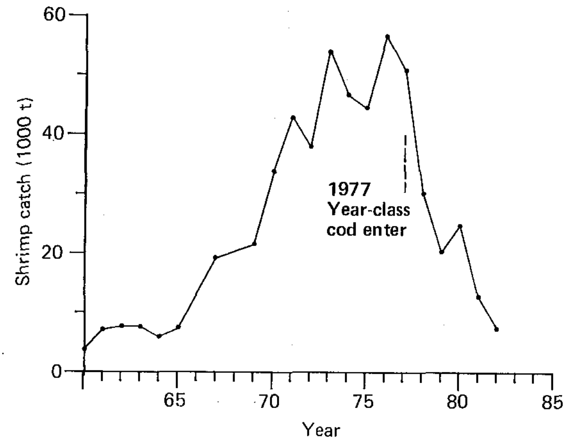

Fig. 7. Annual catch of pink shrimp (*P. borealis*) in the Gulf of Alaska, 1960-1983.

cm, then shrimp consumption in 1979 could have been between 13-199,000. The role of cod in influencing shrimp abundance is based on scant data and somewhat speculative, but if it is the primary cause of the shrimp decline then, unless the reproductive capacity of the shrimp stocks is impaired, they should increase again as predation is reduced through predator growth and the decay of the strong cohort.

In the Bering Sea and Gulf of Alaska, walleye pollock is the dominant commercial species with harvest in 1982 of approximately 1.2 and 0.166 million tonnes respectively. Pollock constitutes approximately 50% of the diet of cod larger than 50 cm (Table 4). In 1982, fish of the 1977 year-class began to exceed 50 cm and consumption of pollock increased. In 1982 the cod population in the eastern Bering Sea was about 1 million tonnes (Bakkala and Low, 1983). At this level of abundance applying the low estimate of daily consumption (.22%) it is estimated that cod consumed 396,000 tonnes of pollock, or an amount equivalent to 33% of the commercial harvest. The long term consequences of the strong 1977 year-class on pollock is unknown. Further observations are needed to quantify the relationship

TABLE 4

Total daily prey consumption rate for Pacific cod in the Bering Sea and estimated daily and annual consumption of pollock and shrimp

Size Group	Consumption rate percent body weight/day			Annual consumption of prey 1000 t/1000 tonnes cod		
	total	pollock	shrimp	total	pollock	shrimp
10-50 cm	.22-2.2	.07-.72	.02-.15	.396	.126	.036
51+ cm	.41-4.2	.22-2.2	.00-.04	.738	.396	.0

1) Assumes feeding at low rates for 180 days and no feeding during remainder of year.

better, but initial results indicate the potential for impairment of the commercial production by cod off Alaska.

The important point of the impact of the 1977 year-class on other fisheries resources is that established highly developed fisheries which appear to be well managed can be disrupted rather rapidly by the occurrence of strong year-classes of a highly predatory species such as cod. If, as in the case of the Gulf of Alaska shrimp fishery, vessels and gear are highly specialized for expoloiting one resource there is extreme social and economic dislocation associated with the resource decline. Pollock, presently exploited almost exclusively exploited by foreign fleets, is the species considered to be the most important to the long term viability of domestic groundfish fisheries. The current high level of cod and their associated higher level of pollock predation could depress pollock populations to the point that the volume of fish needed to establish an economical U.S. fishery may not be available in the near future.

The exploitation of Pacific cod off Alaska, increasing in recent years, has not been developing rapidly enough to utilize the high yield currently available. Industry analysts estimate that U.S. cod harvesting capacity will grow to about 80,000-

90,000 tonnes by 1985. This amount is far short of the estimated yield available from Alaskan waters. At present it is unclear how large a cod fishery will develop. Economic factors will play a major role especially in development of markets. Another factor which may inhibit large scale development is the dispersal of commercial concentrations following the spawning season. Also unresolved at this time is the problem of high bycatches of more valuable halibut and crabs for which established fisheries exist. If methods cannot be found to minimize the bycatch it is unlikely that those charged with regulation of the fisheries off Alaska will allow the cod fishery to increase much beyond current levels. However, if the fishery cannot be fully developed then observations from the recent increase in abundance suggest that the inability to harvest cod produces a loss of other species in addition to the cod harvest foregone.

The task, facing fishery researchers and managers in the northeastern Pacific Ocean is in determining the level of cod exploitation that maximizes the harvest of cod and minimizes the loss of other valuable fishery resources. This is a complex task that requires a multidisciplinary examination of biology, economics, fishing technology and community ecology. Presently, our knowledge is rudimentary and recent events have shown that until a better understanding of the biology and dynamics of Pacific cod is developed, the potential exists for future losses of harvest and unforeseen impacts on other species. Hopefully ways can be developed to utilize the potential yield of the valuable cod resource and develop a large stable fishery in a way that ameliorates the impact of cod predation within the fish community.

REFERENCES

Alderdice, D.F. and Forrester, C.R., 1971. Effects of salinity, temperature and dissolved oxygen on early development of the Pacific cod (*Gadus macrocephalus*). J. Fish. Board Can., 28: 883-902.

Bakkala, R.G. and Low, L.L., 1983. Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1982. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-42, 187 pp.

Bakkala, R.G., Westrheim, S., Okada, K., Zhang, C. and Brown, E., 1981. Overall distribution of Pacific cod in the North Pacific Ocean. Unpubl. rept., 11 pp. Northwest and Alaska Fish. Cent., Nat. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. (Document submitted to the International North Pacific Fisheries Commission, Vancouver, Canada, October 1981).

Chilton, D.E. and Beamish, R.J., 1982. Age determination methods for fishes studied by the groundfish program at the Pacific Biological Station. Can. Spec. Publ. Fish. Aquat. Sci., 60: 22.

Chyung, M.K., 1977. The fishes of Korea. Ilji-sa Publ. Co., Seoul, Korea, 727 pp. (In Korean. Cited by Zhang, 1981).

Cobb, J.N., 1927. Pacific cod fisheries. Rep. U.S. Comm. Fish. for 1926, Appendix VII (Doc. No. 1014): 385-499.

Cushing, D.H., 1981. Fisheries Biology - A study in Population Dynamics. University of Wisconsin Press, Madison, WI, 295 pp.

Daan, N., 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Neth. J. Sea Res., 6: 479-517.

Feder, H.M., Hilsinger, J., Hoberg, M., Jewett, S. and Rose, J., 1978. Survey of the epifaunal invertebrates of the southeastern Bering Sea. In: Environmental assessment of the Alaskan continental shelf, Annual reports of principal investigators for the year ending March 1978. Bur. Land Management, Outer Continental Shelf Environment Assessment Program, Vol. IV: 1-126.

Forrester, C.R., 1977. Effects of temperature on survival and distribution of marine fishes. In: Res. Inst. North Pac. Fish., Hokkaido Univ., Special Vol., pp. 89-93.

Foucher, R.P., Bakkala, R.G. and Fournier, D., 1981. Pacific cod growth in British Columbia, Gulf of Alaska and the eastern Bering Sea. Unpubl. rept., 21 p. Northwest and Alaska Fish. Cent., Nat. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. (Document submitted to the International North Pacific Fisheries Commission, Vancouver, Canada, October 1981).

Hunter, M.A., 1979. Food resource partitioning among demersal fishes in the vicinity of Kodiak Island, Alaska. M.S. thesis, Univ. Washington, Seattle, WA, 120 pp.

Jewett, S.C., 1978. Summer food of the Pacific cod, *Gadus macrocephalus*, near Kodiak Island, Alaska. Fish. Bull., 76: 700-706.

June, J.A. and Shimada, A.M. (in preparation). Summer feeding of Pacific cod (*Gadus macrocephalus*) on the eastern Bering Sea shelf, May-August 1981. Northwest and Alaska Fish. Cent., Nat. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Karp, W.A., 1982. Biology and management of Pacific cod (*Gadus macrocephalus* Tilesius) in Port Townsend, Washington. Ph.D. dissertation, Univ. Washington, Seattle, WA, 119 pp.

Kendall, A.W., 1981. Early life history of eastern North Pacific fishes in relation to fisheries investigations. WA Sea Grant Tech. Rep. WSG 81-3, Univ. Washington, Seattle, WA, 7 pp.

Kennedy, W.A., 1970. Reading scales to age Pacific cod (*Gadus macrocephalus*) from Hecate Strait. J. Fish. Res. Board Can., 27: 915-922.
Ketchen, K.S., 1961. Observations on the ecology of the Pacific cod (*Gadus macrocephalus*) in Canadian waters. J. Fish. Res. Board Can., 18: 513-558.
Kihara, K., 1982. Fluctuations of water temperature and salinity in the eastern Bering Sea. Bull. Japan. Soc. Fish. Oceanogr., 48: 1658-1688.
Kihara, K., 1983. Structures of the benthic species communities and their variations in the eastern Bering Sea. Bull. Japan. Soc. Fish. Oceanogr., 49: 41-47.
Low, L.L., 1983. Application of a Laevastu-Larkins ecosystem model for Bering Sea groundfish management. National Marine Fishery Service, Northwest and Alaska Fisheries Center, Process Rpt. 83-02.
Low, L.L., Alton, M., Wespestad, V., and Brown, E., 1979. Condition of groundfish resources in the Gulf of Alaska. Unpubl. rep., 43 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.
MacDonald, P.D.M. and Pitcher, T.J., 1979. Age-groups from size frequency data: a versatile and efficient method of analyzing distribution mixtures. J. Fish. Res. Board Can., 36: 987-1001.
Mito, K., 1974. Food relationships among benthic fish populations in the Bering Sea - on the *Theragra chalcogramma* fishing grounds in October and November of 1972. M.S. thesis, Hokkaido Univ., Japan, 135 pp.
Moiseev, P.A., 1953. Cod and flounders of far eastern seas. Izv. Tikhookean. Nauchnoissled. Inst. Morsk. Rybn. Khoz. Okeanogr.,40: 287 pp. (Transl. Fish. Res. Board Can., Transl. Ser. 119, 596 pp.).
Moiseev, P.A., 1960. On the habits of the codfish, *Gadus morhua macrocephalus*, in different geographical regions. Zool. Zh., 39: 558-562.
Mukhacheva, V.A. and Zvyagina, O.A., 1960. Development of the Pacific cod, *Gadus morhua macrocephalus*. Til. Acad. Nauk. SSSR Tr. Inst. Okeanol., 31: 145-165. (Transl., Fish. Res. Board Can., Nanaimo, B.C.).
Pacific Fisheries Management Council, 1981. Draft Groundfish Management Plan. Pacific Fisheries Management Council. 526 S.W. Mill St. Portland, OR 97201.
Pinkas, L., Oliphant, M. and Iverson, I., 1971. Food habits of albacore, bluefin tuna and bonito in California waters. Calif. Fish and Game, Fish. Bull., 152: 1-105.
Schumacher, J.D. and Reed, R.K., 1983. Interannual variability in the abiotic environment of the eastern Bering Sea and the Gulf of Alaska. Wa Sea Grant Prog., Univ. Washington, Seattle, WA. In press.
Shimada, A.M., June, J.A., Umeda, Y. and Bohle, M.S., 1981. Summer and winter distribution and abundance of demersal fish along the continental shelf edge of the southeastern Bering Sea. In: A special publication on fisheries and oceanography of the Bering Sea. Izv. Tikhookean. Nauchno-Issled. Inst. Rybn. Khoz. Okeanogr. (TINRO) USSR.

Svetovidov, A.N., 1948. Gadiforms. In: Fauna of USSR. Izdatelstvo Aka. Nauk., Moscow-Leningrad, 9(4): 222 pp. (Transl. Israel Prog. Sci., Transl. 1962, 232 pp.).

Thomson, J.A., 1963. On the demersal quality of the fertilized eggs of Pacific cod, *Gadus macrocephalus* Tilesius. J. Fish. Res. Board Can., 20: 1087-1088.

Walters, G.E. and McPhail, M.J., 1982. An atlas of demersal fish and invertebrate community structure in the eastern Bering Sea: part I, 1978-1981. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-35, 122 pp.

Westrheim, S.J., 1982. Pacific cod tagging. II. Migration and stock delineation. Can. MS Rep. Fish. Aquat. Sci. 1663, 77 pp.

Wespestad, V.G., Bakkala, R.G. and June, J.A., 1982. Current abundance of Pacific cod (*Gadus macrocephalus*) in the eastern Bering Sea and expected abundance in 1982-86. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-25, 26pp.

Yusa, T., Kyushin, Y. and Forrester, C.R., 1977. Outline of life history information of some marine fish. In: Res. Inst. North Pac. Fish., Hokkaido Univ., Special Vol., pp. 149-162.

Zenger, H.H. and Cummings, N., 1982. Pacific cod. In: J. Balsiger (Editor), Condition of groundfish resources of the Gulf of Alaska in 1982. Unpubl. rep., 198 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Zhang, C., 1981. Pacific cod of south Korean waters. Unpubl. rept., 27 pp. Northwest and Alaska Fish. Cent., Nat. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. (Document submitted to the International North Pacific Fisheries Commission, Vancouver, Canada, October 1981).