Yellowfin Sole, *Pleuronectes asper,* of the Eastern Bering Sea: Biological Characteristics, History of Exploitation, and Management

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ABSTRACT—Yellowfin sole, Pleuronectes asper, *is the second most abundant flatfish in the North Pacific Ocean and is most highly concentrated in the eastern Bering Sea. It has been a target species in the eastern Bering Sea since the mid-1950's, initially by foreign distant-water fisheries but more recently by U.S. fisheries. Annual commercial catches since 1959 have ranged from 42,000 to 554,000 metric tons (t). Yellowfin sole is a relatively small flatfish averaging about 26 cm in length and 200 g in weight in commercial catches. It is distributed from nearshore waters to depths of about 100 m in the eastern Bering Sea in summer, but moves to deeper water in winter to escape sea ice. Yellowfin sole is a benthopelagic feeder. It is a long-lived species (>20 years) with a correspondingly low natural mortality rate estimated at 0.12.*

After being overexploited during the early years of the fishery and suffering a substantial decline in stock abundance, the resource has recovered and is currently in excellent condition. The biomass during the 1980's may have been as high as, if not higher than, that at the beginning of the fishery. Based on results of demersal trawl surveys and two age structured models, the current exploitable biomass has been estimated to range between 1.9 and 2.6 million t. Appropriate harvest strategies were investigated under a range of possible recruitment levels. The recommended harvest level was calculated by multiplying the yield derived from the $F_{0.1}$ *harvest level (161 g at F = 0.14) by an average recruitment value resulting in a commercial harvest of 276,900 t, or about 14% of the estimated exploitable biomass.*

Introduction

Yellowfin sole, *Pleuronectes asper*, of the family Pleuronectidae (Fig. 1), is the second most abundant flatfish in the North Pacific Ocean and is the most abundant species of groundfish in the eastern Bering Sea after walleye pollock, *Theragra chalcogramma*. Yellowfin sole inhabits continental shelf waters of the North Pacific Ocean from off British Columbia, Can., (about lat. 49°N) to the Chukchi Sea (about lat. 70°N) in North American waters, and south along the Asian coast to about lat. 35°N off the South Korean coast in the Sea of Japan (Fig. 2). It is by far most abundant in the eastern Bering Sea, where current biomass has been estimated at between 1.9 and 2.6 million metric tons (t) or more.

In this paper, we describe the life history characteristics of eastern Bering Sea yellowfin sole, the history of its exploitation and long-term trends in abundance, the current condition of the resource, and the methods used for estimating biomass and yields with two forms of catch-at-age models and a yield-per-recruit model.

The Eastern Bering Sea Environment

One of the factors contributing to the high abundance of yellowfin sole in the eastern Bering Sea is the expansive nature of the continental shelf of this region (Fig. 3). The eastern Bering Sea shelf, which is 1,200 km long and >500 km wide at its narrowest point, is the widest continental shelf outside the Arctic Ocean (Coachman, 1986).

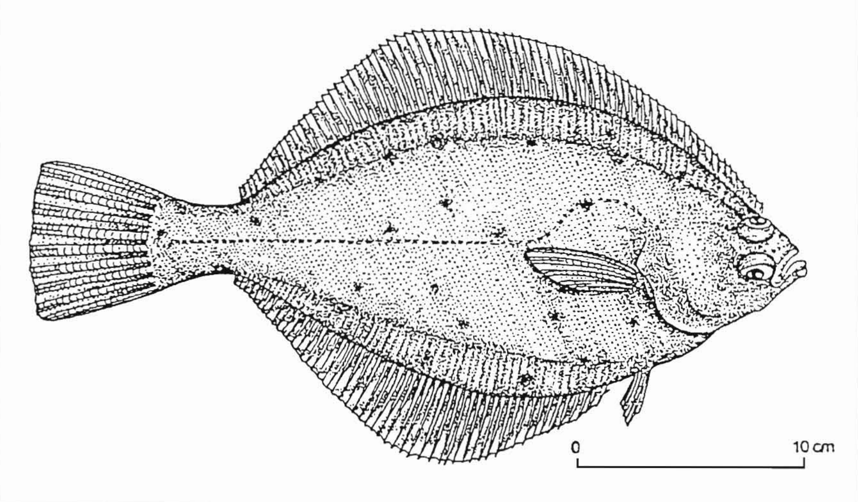

Figure 1.—Yellowfin sole, *Pleuronectes asper.*

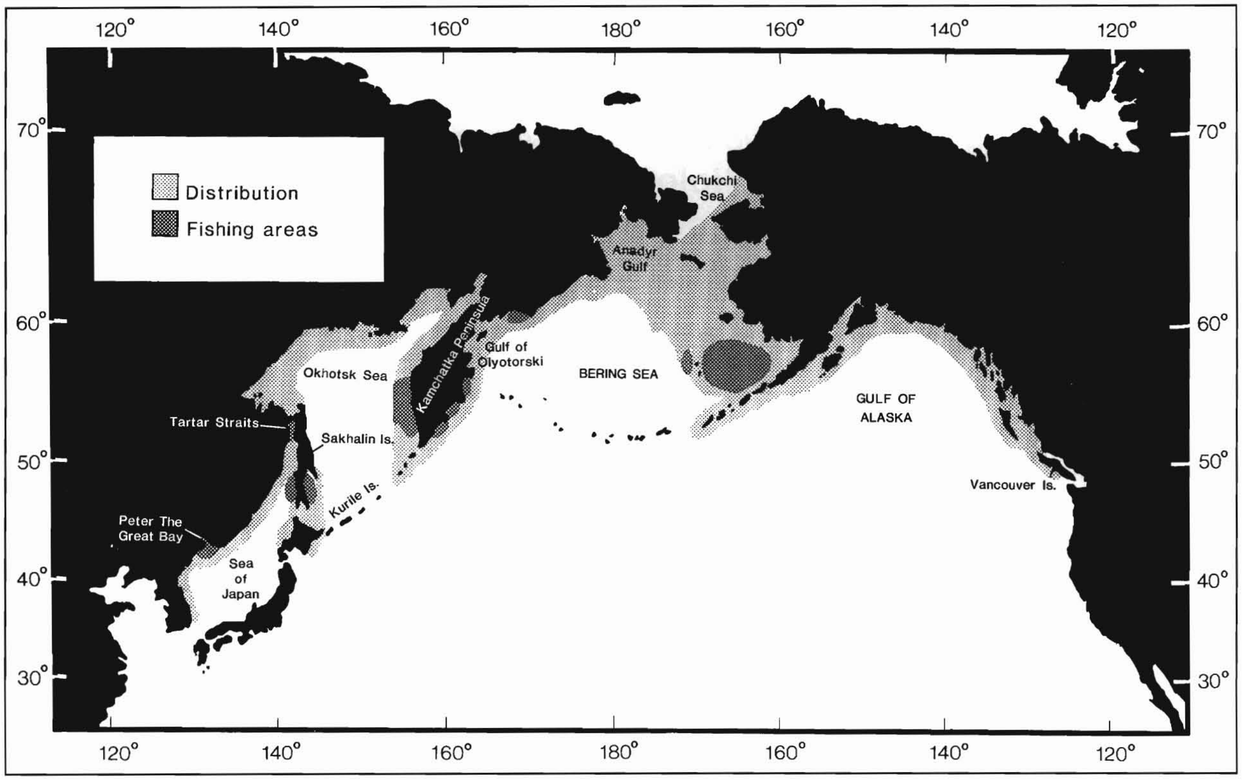

Figure 2.—Overall distribution and areas of commercial fishing for yellowfin sole (from Bakkala, 1981).

In the Atlantic Ocean, only the North Sea continental shelf approaches its breadth.

The eastern Bering Sea shelf is essentially a large, featureless plain that deepens gradually from the shore to about 170 m at the shelf break. However, there are two zones of enhanced gradients near the 50 and 100 m isobaths (Askren, 1972), related to fronts separating the shelf region into three oceanographic domains. These are the coastal, central, and outer shelf domains which are separated by the inner and middle shelf fronts at 50 and 100 m; the outer shelf domain is separated from the oceanic waters of the Aleutian Basin by the ocean break front between the 150 and 200 m isobaths. The domains are defined by temperature and salinity values, vertical structure, and seasonal changes in these properties (Schumacher et al., 1983). The outer shelf domain represents a zone of lateral water mass interaction between central shelf water above and Aleutian Basin water below. This domain differs from the rest of the shelf by having both significantly higher mean and subtidally variable flows (Coachman, 1986), resulting in a more rapid flushing of these waters (perhaps on the order of 2–3 months) than those of the other two domains. The main feature of the central shelf domain is its two-layered vertical structure, with a surface layer 10–40 m in depth overlaying a relatively homogeneous layer of cold bottom water (<0°–3°C). Flushing in the central domain is extremely slow, taking >1 year and perhaps as much as 2 years. The coastal domain is a product of direct mixing of freshwater runoff and saline water, and has a tendency toward homogeneity due to the shallowness of the domain and wind and strong tidal mixing. Because of these features there is ready heat exchange between the water column and the atmosphere, resulting in a large seasonal variation in temperature from near freezing (–1.5°C) in winter to average air temperatures (10°C) in summer. Flushing time for the coastal domain is about 6 months.

Properties of the oceanographic fronts and domains in the eastern Bering Sea divide the shelf into distinct production regions (Alexander, 1986; Walsh and McRoy, 1986). Over the outer shelf, a large portion of the annual primary production is advected off the shelf or channeled into a pelagic food web which supports the large population of semidemersal pollock and other species in this region. This leads to a relatively low biomass of macrobenthos on the outer shelf domain and reduced abundances of benthic feeding groundfish. On the central shelf, however, where the abundance of pelagic grazers is low, practically all of the primary production settles to the sea floor, providing a macrobenthic infaunal biomass 10

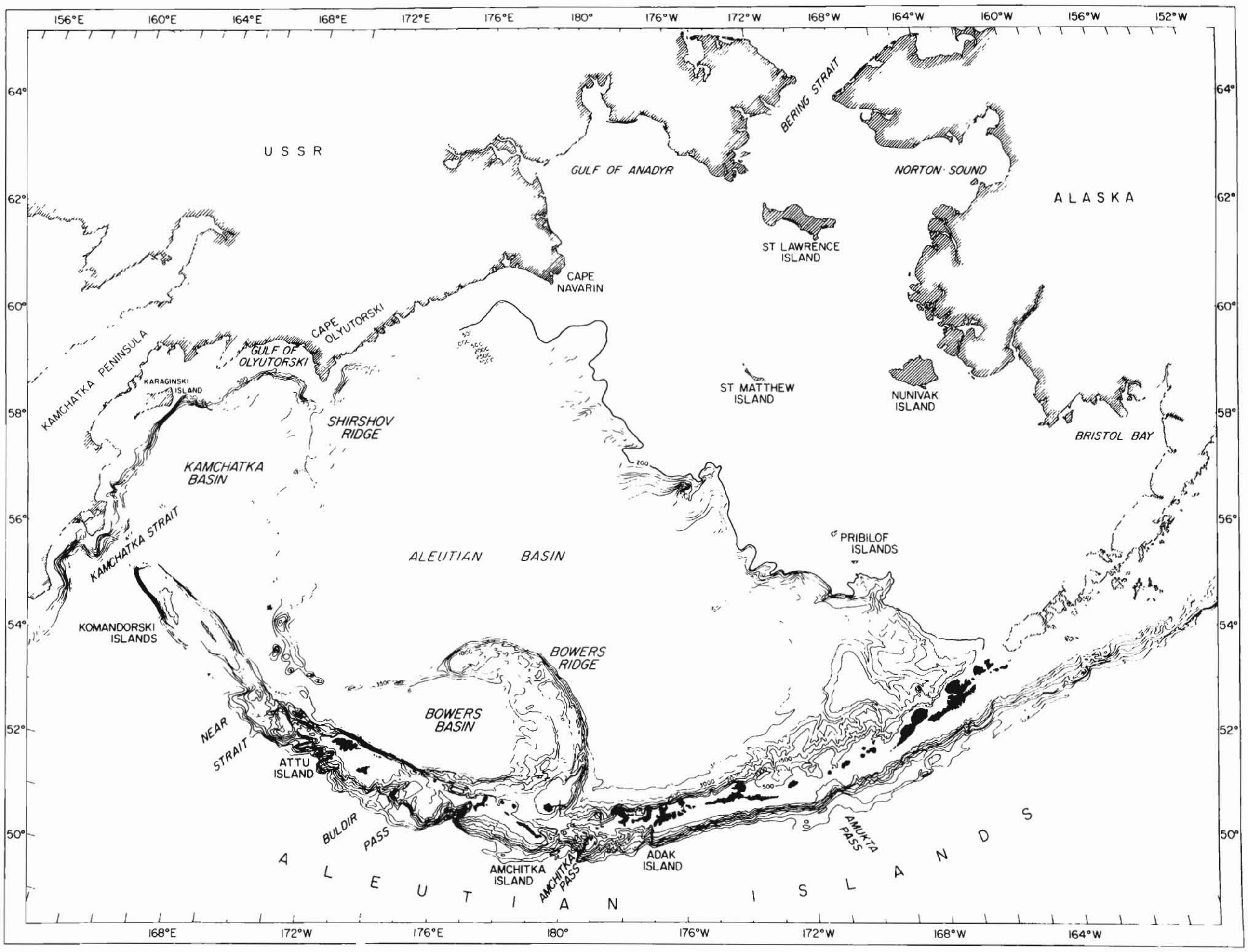

Figure 3.—The Bering Sea: About half is abyssal plain exceeding depths of 3,500 m and the other half is continental shelf of depths less than 200 m (Kinder, 1981—from a figure prepared by Noel McGary for the atlas by Sayles et al., 1979).

times greater than on the outer shelf (Haflinger, 1981) and an abundant food source for benthic feeders such as yellowfin sole and other species.

Seasonal ice cover is another characteristic of the eastern Bering Sea shelf. Ice begins to intrude into the northern Bering Sea in November. When it reaches its southern maximum in March–April, ice coverage may be as great as 80%. The intruding ice is completely melted by early July (Niebauer, 1983). There are large year-to-year deviations in the amount of ice cover, on the order of hundreds of kilometers, which have been found to be correlated with either wind fields or storm tracks (Niebauer, 1983). As discussed later, winter offshore migrations of yellowfin sole are believed to be related to avoidance of this ice cover.

History of Exploitation

Yellowfin sole was the first target species of distant-water fleets from Japan and the U.S.S.R., which initiated fisheries for groundfish in the eastern Bering Sea during the middle and late 1950's. Catches were processed for fish meal. These fisheries intensified during the early 1960's with a peak catch of 554,000 t in 1961; during the 4-year period of 1959–62, catches averaged 404,000 t (Table 1). It is generally recognized that this level of exploitation was more than the stock could sustain (Fadeev, 1965; Bakkala et al., 1982; Wakabayashi[1]). Results of cohort analysis indicate that the exploitable biomass declined sharply from an estimated 1.2 million t in 1960 to <500,000 t in 1963. As a result, catches also declined to a range of 48,000–167,000 t over the next decade. There was a further decline in catches to generally <100,000 t annually from 1972 to 1982 because of the absence of a U.S.S.R. target fishery for yellowfin sole in most of those years. Since 1982, the improved condition of

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[1] Wakabayashi, K. 1975. Studies on resources of yellowfin sole in the eastern Bering Sea. I. Biological characteristics. Unpubl. manuscr., 8 p., of Far Seas Fish. Res. Lab., Fish. Agency Jpn., 1000 Orido, Shimizu 424.

Table 1.—Annual catches of yellowfin sole in the eastern Bering Sea in metric tons[1] from 1954–91.

Year	Japan	U.S.S.R.	R.O.K.[2]	Other non-U.S. fisheries	U.S. joint ventures	U.S. domestic fisheries	Total
1954	12,562						12,562
1955	14,690						14,690
1956	24,697						24,697
1957	24,145						24,145
1958	39,153	5,000					44,153
1959	123,121	62,200					185,321
1960	360,103	96,000					456,103
1961	399,542	154,200					553,742
1962	281,103	139,600					420,703
1963	20,504	65,306					85,810
1964	48,880	62,297					111,177
1965	26,039	27,771					53,810
1966	45,423	56,930					102,353
1967	60,429	101,799					162,228
1968	40.834	43,355	—[3]				84,189
1969	81,449	85,685	—				167,134
1970	59,851	73,228	—				133,079
1971	82,179	78,220	—				160,399
1972	34,846	13,010	—				47,856
1973	75,724	2,516	—				78,240
1974	37,947	4,288	—				42,235
1975	59,715	4,975	—				64,690
1976	52,688	2,908	625				56,221
1977	58,090	283	—				58,373
1978	62,064	76,300	69				138,433
1979	56,824	40,271	1,919	3			99,017
1980	61,295	6	16,198	269	9,623		87,391
1981	63,961		17,179	115	16,046		97,301
1982	68,009		10,277	45	17,381		95,712
1983	64,824		21,050		22,511		108,385
1984	83,909	7,951	34,855	47	32,764		159,526
1985	59,460	8,205	33,041		126,401		227,107
1986	49,318		7,632	247	151,400		208,597
1987	1,117		694		179,613	4	181,428
1988					213,323	9,833	223,156
1989					151,501	1,664	153,165
1990					69,677	10,907	80,584
1991						84,482	84,482

[1] Catches from data on file at NMFS Alaska Fisheries Science Center, 7600 Sand Point Way N.E., Seattle, WA 98115.

[2] Republic of Korea.

[3] A dash indicates fishing, but any catches of yellowfin sole were not reported.

the resource has again allowed higher catches; these have exceeded 200,000 t in recent years. Since the early 1960's, yellowfin sole catches have been mainly utilized for human consumption. Based on results of cohort analysis and catch-at-age data, annual exploitation rates for exploitable ages 7–17 of yellowfin sole have ranged from 4 to 11% and have averaged 8% since 1977.

Biological Characteristics

Yellowfin sole is one of 16 species of flatfish in the eastern Bering Sea. Nine of these species have very low abundance and make up only 1–2% of the biomass of the total flatfish complex. Three large species of moderate abundance, Pacific halibut, *Hippoglossus stenolepis*; Greenland turbot, *Reinhardtius hippoglossoides*; and arrowtooth flounder, *Atheresthes stomias*, occupy both continental shelf and continental slope waters. The four remaining species, which are the most abundant and primarily occupy continental shelf waters, are yellowfin sole, Alaska plaice, *Pleuronectes quadrituberculatus*; rock sole, *Pleuronectes bilineatus*; and flathead sole, *Hippoglossoides elassodon*. The latter three species play major roles in the ecology of yellowfin sole. As might be expected in a complex of this sort, fish size is inversely related to abundance, with yellowfin sole being the smallest and most abundant species in the eastern Bering Sea.

Distribution

The winter distribution of adult yellowfin sole in the eastern Bering Sea is centered in three locations (Fig. 4). All are at depths of 100–270 m along the shelf edge and upper slope. The major group is located just north of Unimak Island near the end of the Alaska Peninsula. Concentrations are so dense that a research vessel caught over 25 t during a half-hour tow (Bakkala et al., 1982). A smaller group is located west of the Pribilof Islands, and a still smaller group is located just south of the Pribilof Islands. A fourth group, consisting almost entirely of juveniles <6 years old is found on the inner shelf, sometimes under ice cover.

Beginning in April or early May, the three adult groups begin a migration onto the inner shelf. This was shown specifically during a spring research survey in 1976 (Smith and Bakkala, 1982). At that time, portions of the yellowfin sole population were followed as the ice retreated during a particularly cold year. Japanese tagging studies (Wakabayashi, 1989) have shown that each group moves into a specific location (Fig. 4). The Unimak Island group moves into Bristol Bay, the easternmost portion of the Bering Sea. The two Pribilof Islands groups move farther north to the vicinity of Nunivak Island. Since these areas are for feeding and spawning, it was originally thought that at least two stocks existed. However, further examination of the tagging results and genetic studies using electrophoretic techniques (Grant et al., 1983) now leads to a concensus that there is only one stock.

The summer distribution of yellowfin sole extends over the inner and middle shelf to a depth of approximately 100 m (Fig. 5). However, above lat. 61°N the density decreases drastically. The summer surveys by the NMFS Alaska Fisheries Science Center (AFSC) cover the significant portions of the distribution. During the summer, yellowfin sole is closely associated with the two next most abundant flatfish species, rock sole and Alaska plaice. Estimated abundances of the latter two species in 1990 were 1.6 million t and 0.5 million t, respectively,

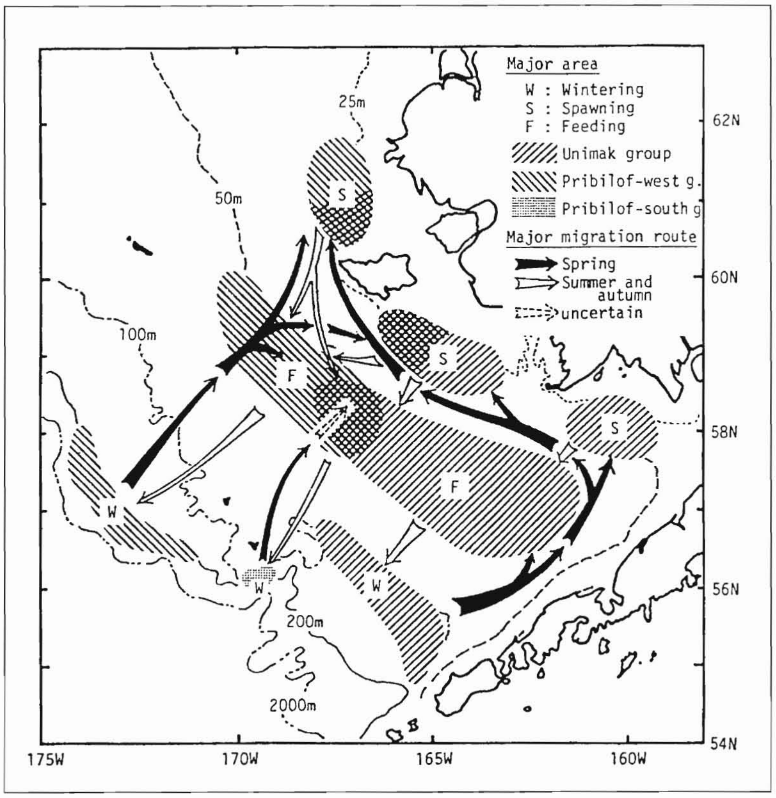

Figure 4.—Schematic diagram showing seasonal migration and distribution of yellowfin sole by wintering group in the eastern Bering Sea (from Wakabayashi, 1989).

based on survey data. This compares with the survey estimate of 2.4 million t for yellowfin sole. Although the distributions overlap almost totally, the center of abundance for yellowfin sole is located between that of rock sole to the south and Alaska plaice to the north. Yellowfin sole is found as far north as the Chukchi Sea; however, their numbers are very small (Alverson and Wilimovsky, 1966) and the maximum size was reported to be less than 20 cm.

During the summer, adults are found in almost all areas of the shelf at depths less than 100 m (Fig. 6). However, the juveniles located in the shallow waters during the winter remain in waters primarily less than 50 m during the summer.

Feeding and Predators

Yellowfin sole is characterized as a benthopelagic feeder. It could also be described as opportunistic. Feeding studies in different areas at different times of the year (Livingston et al., 1986; Wakabayashi, 1986) describe a wide variety of prey items ranging from strictly benthic bivalve siphons to small pelagic fish. In general, feeding during winter is very slight to none. Feeding begins during the spring migration to the major feeding and spawning grounds. Wakabayashi (1986) found four major groups in the diet of yellowfin sole. Over 65%, by weight, of the yellowfin sole stomach contents collected during the summers of 1970 and 1971 consisted of polychaetes, bivalves, amphipods, and echiurids. Although these categories were also important to the potential competitors, rock sole and Alaska plaice, the relative proportions of each prey were quite different for yellowfin sole than for the other species. Alaska plaice and rock sole have heads that are indented at the upper eye which provide them with more downward vision than yellowfin sole (Zhang, 1987). Livingston et al. (1986) found that while bivalves were dominant in the stomach contents of yellowfin sole during the spring, summer proportions of bivalves dropped considerably and polychaetes, echiurids, euphausids, and crangonid shrimp were most important. Although Tanner crabs, *Chionoecetes* sp., were only a small part of the stomach contents, the large yellowfin sole population is a significant predator on this valuable resource.

Daily ration estimates for yellowfin sole were made by Livingston et al. (1986) using both stomach content weight information and bioenergetic calculations. Values obtained were 0.12% body weight and 0.40% body weight respectively. Based on gross conversion efficiency, the latter value is considered most accurate.

The primary predators on yellowfin sole are two abundant gadids, Pacific cod, *Gadus macrocephalus*, and walleye pollock, the Pacific halibut, and four species of cottids (Brodeur and Livingston, 1988; Wakabayashi, 1986). On a much smaller scale, sea birds and marine mammals also consume yellowfin sole.

The yellowfin sole plays an important part in the ecosystem of the eastern Bering Sea (Fig. 7). The prey items consumed by such a large fish population represent a significant portion of the prey available to potential competitors. In turn, the yellowfin sole itself contributes a significant input to the diet of the predators and represents a large portion of the resource.

Growth and Natural Mortality

The yellowfin sole is a slow growing, long-lived flatfish. Although lengths seldom exceed 400 mm, ages above 25 are not uncommon. Lengths at age are similar for males and females during the juvenile years (Fig. 8), but females slightly outgrow males as they near the onset of sexual maturity. There is considerable variability in length at age for both sexes. How-

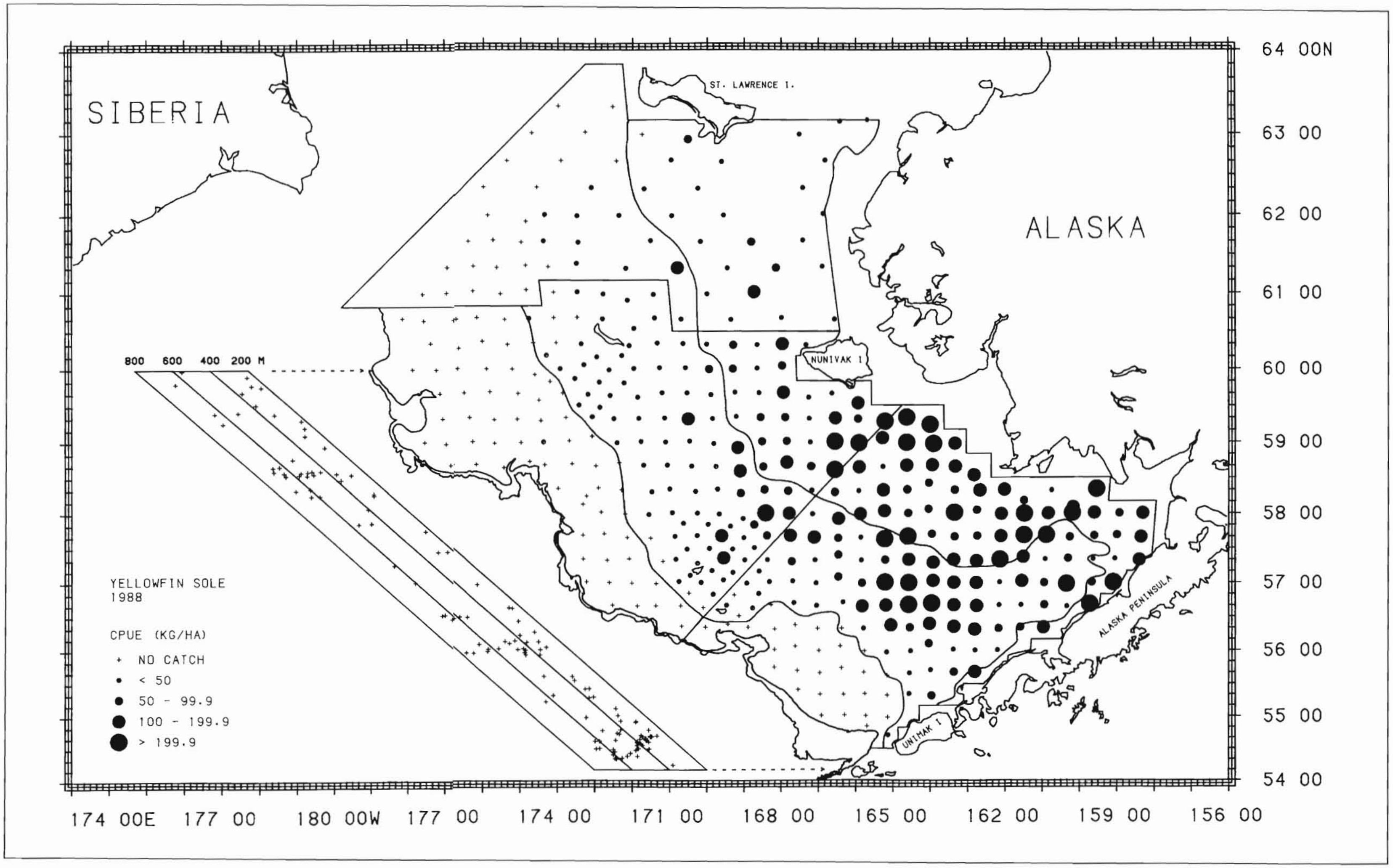

Figure 5.—Distribution and relative abundance of yellowfin sole in the eastern Bering Sea as shown by the 1988 U.S.-Japan bottom trawl survey.

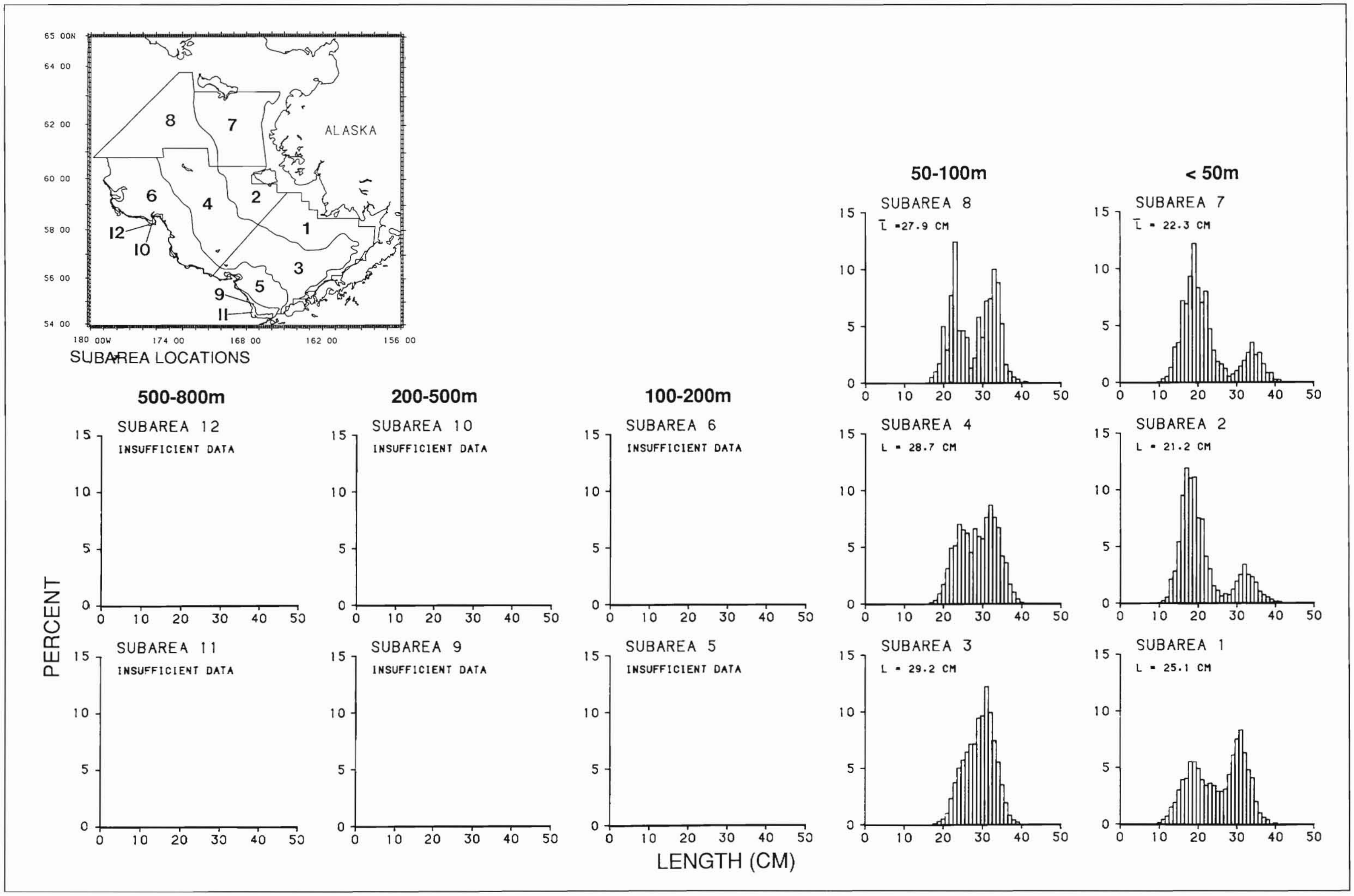

Figure 6.—Length composition of yellowfin sole by subarea and depth zone as shown by data from the 1988 U.S.-Japan bottom trawl survey.

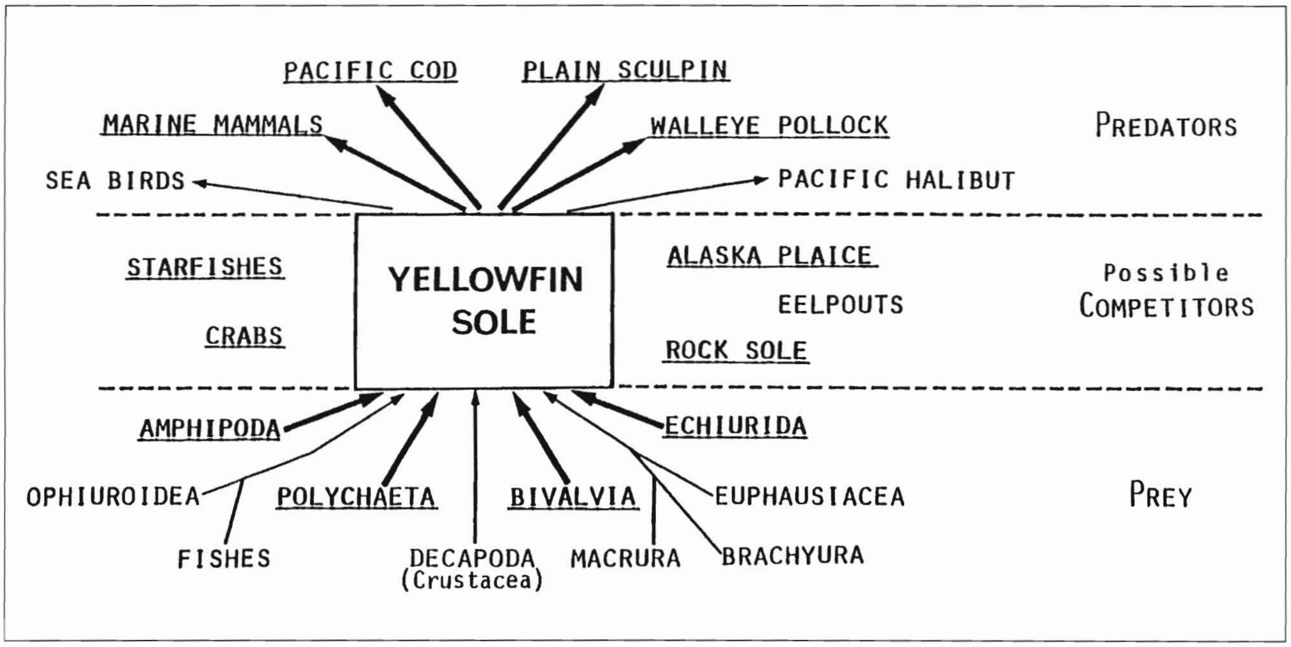

Figure 7.—Schematic diagram of interspecific feeding relationships with reference to yellowfin sole on the continental shelf of the eastern Bering Sea. Arrows indicate flow of matter. Bold-faced and underlined species are key ones for yellowfin sole; minor species are excluded (from Wakabayashi, 1986).

ever, these data are combined from virtually the entire distribution on the shelf and therefore does not reflect possible growth differences due to environmental variations from south to north. Based on data gathered in 1988, the parameters for the von Bertalanffy equation are as follows:

	t_0	L_∞ (mm)	k
Males	1.63	352	0.16
Females	2.44	376	0.17

The length-weight relationships for males and females are very similar (Fig. 9). From 1987 data, the parameters for the relationship, Weight (g) = $a \cdot \text{Length (mm)}^b$ are:

	a	b
Males	$8.955 \cdot 10^{-6}$	3.0426
Females	$5.783 \cdot 10^{-6}$	3.1231

It is to be expected that the natural mortality (M) of such a slow-growing, long-lived species would be relatively low. However, Fadeev (1970) estimated M for yellowfin sole as 0.25 and Wakabayashi[2] derived the same value using the methods of Alverson and Carney (1975). Bakkala et al.[3] believed this value to be too high. Using a simulation based on cohort analysis, they found that an M of 0.12 provided the best fit to available data. That value has been used subsequently and is used in analyses reported in this paper.

Maturity and Spawning

Fadeev (1970) reported that during 1959–64, when the population was sharply decreasing from a high level, 50% maturity was reached at a length of 16–18 cm for males and 30–32 cm for females. Wakabayashi (1989) reported 50% maturity in 1973 to occur at 13 cm for males and 25 cm for females. He suggested that the lower abundance in 1973 was responsible for the decrease in size at maturity. Males and females reached 50% maturity at about ages 5 and 9, respectively. Although the sample size was only about 1,500 fish, results of a study during the 1990 AFSC survey showed the size at 50% maturity to be 20.3 cm for males and 28.8 cm for females. Because the estimate of exploitable biomass (2 million t) is now equal to or greater than that of either of the past studies, there appears to be a relationship of increasing size at maturity with population abundance. In summary, the size at maturity has varied over time as follows:

Year(s)/source	*Males*	*Females*
1959–64, Fadeev (1970)	16–18 cm	30–32 cm
1973, Wakabayashi (1989)	13 cm	25 cm
1990, this paper	20.3 cm	28.8 cm

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[2] Wakabayashi, K. 1975. Studies on resources of the yellowfin sole in the eastern Bering Sea. II. Stock size estimated by the method of virtual population analysis and its annual changes. Unpubl. manuscr., 22 p., of Far Seas Fish. Res. Lab., Fish. Agency Jpn., 1000 Orido, Shimizu 424.

[3] Bakkala, R., V. Wespestad, T. Sample, R. Narita, R. Nelson, D. Ito, M. Alton, L. Low, J. Wall, and R. French. 1981. Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1981. Unpubl. rep., 152 p., of Alaska Fish. Sci. Cent., 7600 Sand Point Way N.E., Seattle, WA 98115.

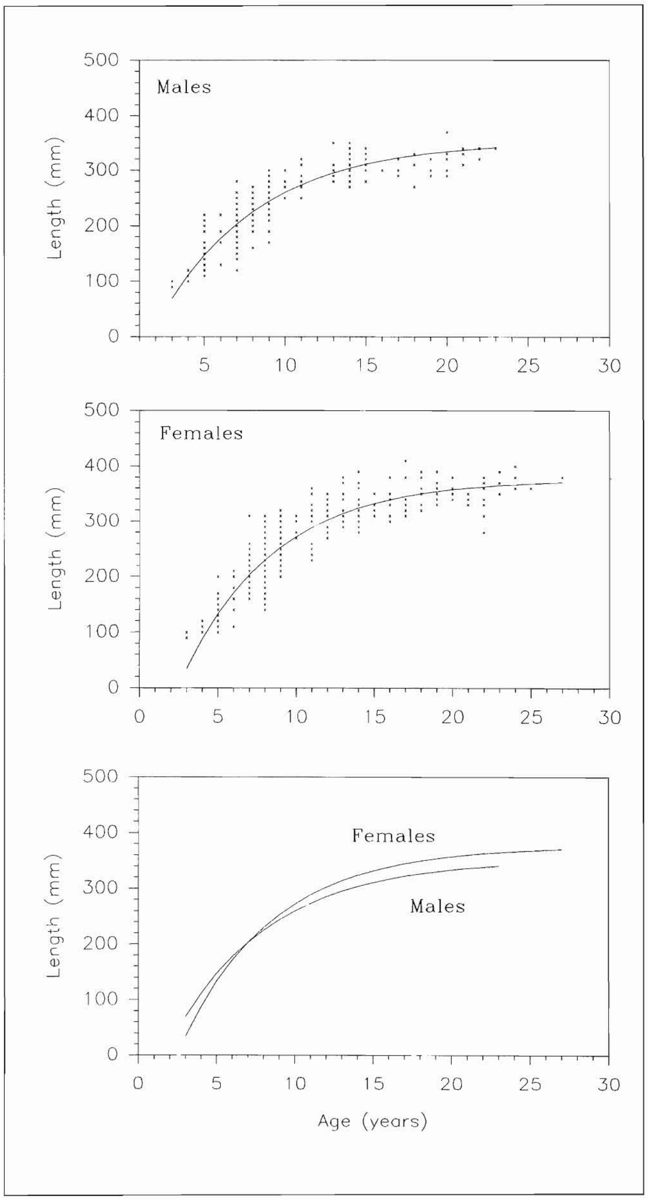

Figure 8.—Age-length relationships for yellowfin sole from data gathered during the 1988 U.S.-Japan bottom trawl survey of the eastern Bering Sea. See text for parameters of fitted curves.

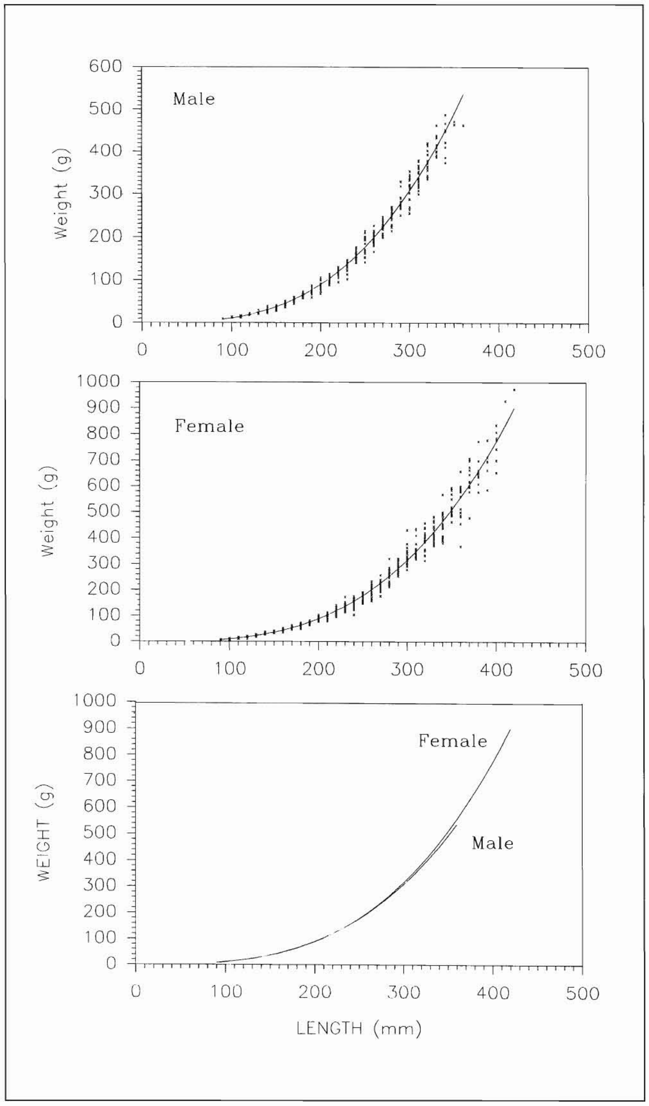

Figure 9.—Length-weight relationships for yellowfin sole from data gathered during the 1987 AFSC bottom trawl survey of the eastern Bering Sea. See text for parameters of fitted curves.

Fertilization of yellowfin sole eggs is external. The spawning period is usually considered to be July–August based on past maturity studies (Fadeev, 1970) and egg and larval surveys (Musienko, 1963, 1970). However, our experience on the annual AFSC trawl surveys suggests that the spawning period is more variable and protracted, perhaps beginning as early as late May. Evidence from the 1990 survey showed about 10% of females and 20% of males were ripe and running or spent during the month of June.

Spawning takes place primarily in shallow water (Musienko, 1970; Kashkina, 1965; Waldron, 1981); eggs have been found to the limits of the inshore ichthyoplankton sampling. However, evidence from the surveys suggests that large females may spawn in waters out to a depth of around 50 m. While the majority of the spawning occurs in Bristol Bay, significant numbers of early-stage eggs were found north of Nunivak Island (Kashkina, 1965). It appears that spawning takes place over a wide range of inshore waters from Bristol Bay to at least as far north as Nunivak Island. It is unknown whether spawning takes place as far north as Norton Sound or the Chukchi Sea, or whether fish found there are the result of egg and larval drift or adult migrations.

Fecundity and Early Life History

The fecundity of yellowfin sole varies with size and was reported by Fadeev (1970) to range from 1.3 to 3.3 million eggs for fish 25–45 cm long. Egg diameters range from 0.68 to 0.86 mm (Musienko, 1963). Prolarvae and larvae measured 2.2–5.5 mm in July and 2.5–12.3 mm in late August–early September. The age or size at metamorphosis is unknown.

Assessment Methods

Resource Assessment Surveys

Since 1971, the AFSC has conducted summer bottom trawl surveys in the eastern Bering Sea to estimate abundance and study the biology of fish and important invertebrate species. In 1975, and annually since 1979, these surveys have covered the major portion of the shelf to lat. 61°N (465,000 km^2). The depth range extends from about 10 m near the mainland to about 200 m at the shelf break (subareas 1–6 in Fig. 10). In 1979, and triennially since, the surveys have been extended north to include Norton Sound (>64°N) and to cover the continental slope to a depth of at least 800 m (Fig. 10). Although the survey's primary role is to provide fishery-independent abundance estimates for management purposes, they also provide a wealth of additional biological information on the multispecies complex of fishes that inhabits the eastern Bering Sea.

The standard survey area on the shelf is divided into a 37×37 km grid (20×20 n.mi.) with a sampling location at the center of each grid block. In some areas of special interest, the corners of the blocks have also been sampled. The sampling gear is an "eastern" otter trawl with a 25.3 m headrope and 34.1 m footrope. Otter doors are 1.8×2.7 m and weigh about 800 kg each. At each sampling site the trawl is towed for 0.5 h at a speed of 5.6 km/h. The operating width between the wings varies from about 10 to 18 m as a function of the amount of trawl warp payed out and therefore indirectly as a function of depth. The operating trawl height varies from 2 to 3 m. Due to the relatively flat, unobstructed bottom on the shelf, the trawl is operated without roller gear; it is actually constructed to dig slightly into the bottom to improve the catches of invertebrates.

In recent years, about 355 sites have been sampled during a standard survey year. In the triennial years the sampling on the north shelf between St. Mathew Island and St. Lawrence Island is usually carried out on every other grid block (Fig. 10). Sampling also occurs in Norton Sound, where very few yellowfin sole are captured, and along the continental slope, where none are found.

Estimates of biomass and population are made using the "area swept" method described by Wakabayashi et al. (1985). Explained briefly, the mean catch-per-unit-effort (CPUE) of a group of tows of known area swept is expanded to estimate the biomass within the total area of a stratum. The area swept is considered to be the product of the operating net width between the wings and the distance fished. The potential herding effect of the doors and dandylines is unknown.

Cohort Analysis

Cohort analysis, following the procedures described in Pope (1972), have previously been carried out for yellowfin sole by Bakkala and Wespestad (1986) and Wakabayashi et al.[4] The former analysis has been updated through 1990 for this report (Table 2). This method assumes knife-edge recruitment with equal availability and selectivity for all recruited ages and constant natural mortality over all ages and years; it also assumes that all catches are aged without error. The input terminal fishing mortality values (*F*) were tuned to make the estimated 1990 population age composition closely match the 1990 trawl survey age composition while generally coinciding with the observed biomass trend from trawl surveys since 1975.

Stock Synthesis Model

The abundance, mortality, recruitment and selectivity of yellowfin sole were also assessed using a stock synthesis model (Methot[5]). The synthesis model is a separable catch-age analysis that uses survey estimates of biomass and age composition as auxiliary information. The synthesis model operates by simulating the dynamics of the population and comparing the expected values of the population characteristics to the characteristics observed from surveys and fishery sampling programs. The goodness of fit of the simulated values to the observable characteristics is evaluated in terms of log (likelihood).

The model assumes that fishing mortality can be separated into age-specific and year-specific components. A double logistic selectivity curve is used to model the age-specific survey and fishery selectivities, allowing the synthesis model the utility to fit most species and gear selectivities by age. The year-specific fishing mortality rates are tuned to the levels necessary to match the observed catch biomass, and thus are not estimated as parameters. The model inputs include the same catch-at-age information used in the cohort analysis as well as survey age composition since 1975, trawl survey biomass estimates and their attendent 95% confidence intervals, and age-specific maturity ogives of female yellowfin sole.

Results and Evaluation of Methods

Long-term Changes in Abundance from Cohort Analysis and Survey Data

Biological data collections for yellowfin sole by Japanese scientists during the early years of their target fisheries for this species allow an examination of historical trends in abun-

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[4] Wakabayshi, K., R. Bakkala, and L. Low. 1977. Status of the yellowfin sole resource in the eastern Bering Sea through 1976. Unpubl. manuscr., 45 p., on file at Northwest NMFS Alaska Fish. Sci. Cent., Seattle, Wash.

[5] Methot, R. D. 1986. Synthetic estimates of historical abundance and mortality for northern anchovy, *Engraulis mordax*. NMFS Southwest Fish. Cent. Admin. Rep. LJ-86-29, SWFC, P.O. Box 271, La Jolla, Calif. Unpubl. rep.

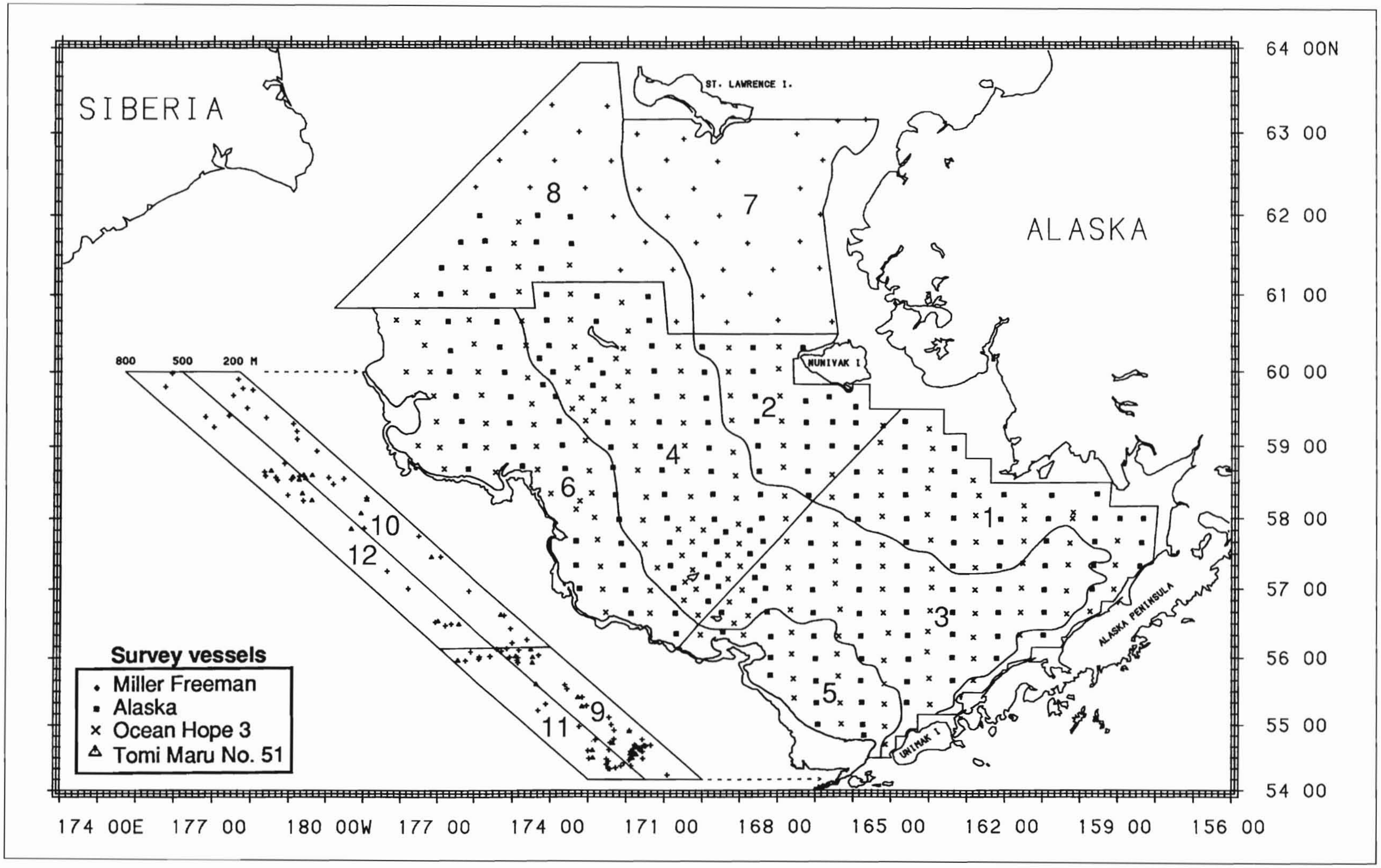

Figure 10.—Stations sampled during the 1988 U.S.-Japan bottom trawl survey of the eastern Bering Sea continental shelf and slope.

Table 2.—Results of the updated cohort analysis using yellowfin sole catch at age data for 1977–90.

	Age										
Year	7	8	9	10	11	12	13	14	15	16	17+
Yellowfin sole catch-at-age											
1977	18,650,512	42,546,480	35,679,240	70,547,589	48,273,404	15,812,391	4,738,649	2,888,802	2,179,272	582,828	253,404
1978	66,837,397	131,677,784	113,767,109	97,791,937	104,343,723	38,879,270	21,592,660	12,294,087	4,493,270	2,683,481	686,472
1979	20,654,198	49,428,494	89,612,568	82,949,924	61,254,688	45,056,133	22,902,840	7,120,701	4,080,870	1,540,737	1,290,887
1980	33,140,657	19,740,704	41,251,153	64,094,844	60,753,036	47,678,239	42,362,204	23,223,262	7,353,264	10,094,428	4,196,986
1981	31,066,415	46,191,267	41,740,204	51,734,340	67,242,816	70,640,739	58,389,770	40,197,601	18,477,135	5,721,428	4,413,815
1982	27,726,700	58,892,000	45,084,000	42,162,000	71,458,000	75,040,000	39,648,000	20,103,500	10,373,300	2,691,900	457,350
1983	56,236,000	39,638,000	75,910,000	53,494,000	53,525,000	77,054,000	57,885,000	32,317,000	16,486,000	5,212,100	2,883,100
1984	13,194,000	26,294,000	33,997,000	70,530,000	72,153,000	94,146,000	107,810,000	102,080,000	56,541,000	23,616,000	11,348,000
1985	36,878,000	52,146,000	107,220,000	105,950,000	127,860,000	108,810,000	108,490,000	103,920,000	66,100,000	29,533,000	15,437,000
1986	49,338,000	40,699,000	67,598,000	111,576,000	82,476,000	74,687,000	64,265,000	40,151,000	56,498,000	51,783,000	28,807,000
1987	18,242,800	49,363,000	33,487,000	49,330,000	55,419,000	59,587,000	73,360,000	60,991,000	26,298,000	40,131,000	42,251,000
1988	29,010,110	57,536,690	140,511,500	40,824,530	71,655,720	89,379,400	53,641.690	104,146,700	82,114,400	34,830,910	57,536,690
1989	2,541,111	33,831,360	47,028,480	73,072,270	29,536,800	20,466,530	52,028,580	32,164,660	45,298,170	44,542,890	33,831,360
1990	8,831,887	7,042,442	53,350,411	29,166,551	49,380,263	19,997,872	18,449,330	16,882,833	17.397,808	23,208,050	7,042,442
Yellowfin sole population numbers											
1977	3,146,176,675	2,093,705,062	1,458,033,290	1,216,656,729	1,005,364,746	230,142,415	271,661,195	112,494,125	7,269,256	1,440,724	269,074
1978	2,126,336,138	2,772,844,000	1,816,881,042	1.259,558,080	1,012,638,500	846,216,359	189,226,462	236,479,174	97,052,767	4,394,891	728,921
1979	1,832,170,359	1,822,945,886	2,335,282,544	1,504,287,099	1,025,031,672	799,862,563	713,911,465	147,493,615	198,160,077	81,846,480	1,370,711
1980	1,955,653,080	1,605,537,944	1,570,257,959	1,986,815,876	1,256,063,674	851,434,045	666,982,186	611,613,586	124,109,078	171,909,003	71,140,304
1981	2,292,397,501	1,703,297,988	1,405,393,319	1,353,845,002	1,701,785,353	1,056,813,488	710,252,581	551,664,910	520,581,745	103,149,834	59,143,217
1982	1,405,642,831	2,003,916,945	1,467,188,499	1,207,162,613	1,152,031,233	1,446,021,310	870,782,537	574,948,115	451,426,208	444,313,478	175,095,390
1983	1,401,488,193	1,260,492,750	1,721,852,495	1,258,820,952	1,030,950,515	954,463,435	1,211,835,841	734,975,748	491,000,470	390,609,924	231,226,559
1984	1,000,637,266	1,190,047,450	1,080,627,118	1,455,656,821	1,066,095,276	863,963,135	773,966,402	1,020,287,933	621,430,007	419,952,421	549,625,256
1985	695,449,515	875,059,999	1,030,714,647	926,413,107	1,224,629,131	877,590,552	677,603,197	584,914,985	808,778,896	497,910,665	779,697,865
1986	1,665,760,414	582,077,995	726,999,343	813,185,892	721,874,765	965,734,590	675,879,596	498,808,089	420,904,883	655,071,896	987,612,485
1987	1,182,966,578	1,430,932,175	477,927,995	581,129,176	616,152,867	562,572,510	786,192,177	538,928,929	404,590,300	320,101,330	1,215,806,652
1988	3,171,946,582	1,032,016,812	1,222,634,667	392,347,237	468,958,098	494,286,921	442,840,133	628,202,063	420,547,920	334,072,882	1,756,688,739
1989	450,681,674	2,785,943,555	861,130,788	952,050,925	309,533,688	348,445,706	354,218,823	342,246,123	459,083,579	295,660,116	1,634,477,654
1990	1,958,447,010	397,325,659	2.439,049,100	719,464,740	775,576,550	246,715,043	289,768,965	265,165,242	273,253,545	364,510,399	1,466,780,319
Yellowfin sole fishing mortality values											
1977	0.0063	0.0218	0.0263	0.0635	0.0523	0.0758	0.0187	0.0276	0.3832	0.5613	0.0001
1978	0.0339	0.0517	0.0688	0.0860	0.1159	0.0500	0.1292	0.0568	0.0504	1.0451	0.0001
1979	0.0120	0.0292	0.0416	0.0603	0.0656	0.0617	0.0347	0.0526	0.0221	0.0202	0.0001
1980	0.0182	0.0131	0.0283	0.0349	0.0527	0.0613	0.0698	0.0412	0.0650	0.0644	0.0001
1981	0.0145	0.0292	0.0320	0.0414	0.0429	0.0736	0.0913	0.0805	0.0384	0.0607	0.0001
1982	0.0205	0.0317	0.0332	0.0378	0.0681	0.0567	0.0496	0.0378	0.0247	0.0065	0.0001
1983	0.0435	0.0340	0.0479	0.0462	0.0567	0.0896	0.0521	0.0478	0.0363	0.0143	0.0001
1984	0.0141	0.0237	0.0340	0.0528	0.0746	0.1230	0.1601	0.1123	0.1016	0.0616	0.0001
1985	0.0580	0.0654	0.1170	0.1295	0.1175	0.1412	0.1863	0.2091	0.0908	0.0651	0.0001
1986	0.0320	0.0771	0.1040	0.1575	0.1293	0.0857	0.1064	0.0893	0.1538	0.0877	0.0001
1987	0.0165	0.0373	0.0773	0.0945	0.1004	0.1193	0.1043	0.1280	0.0715	0.1429	0.0001
1988	0.0098	0.0610	0.1301	0.1171	0.1770	0.2132	0.1377	0.1936	0.2323	0.1173	0.1000
1989	0.0060	0.0130	0.0597	0.0850	0.1068	0.0644	0.1696	0.1051	0.1107	0.1743	0.1000
1990	0.0048	0.0190	0.0235	0.0440	0.0700	0.0900	0.0700	0.0700	0.0700	0.0700	0.1000
Yellowfin sole biomass (t)											
1977	352,372	282,650	231,827	225,081	211,127	53,393	71,719	31,611	2,152	514	98
1978	238,150	374,334	288,884	233,018	212,654	196,322	49,956	66,451	28,728	1,569	265
1979	205,203	246,098	371,310	278,293	215,257	185,568	188,473	41,446	58,655	29,219	499
1980	219,033	216,748	249.671	367,561	263,773	197,533	176,083	171,863	36,736	61,372	25,895
1981	256,749	229,945	223,458	250,461	357,375	245,181	187,507	155,018	154,092	36,824	74,217
1982	162,472	270,529	233,283	223,325	241,927	335,477	229,887	161,560	133,622	158,620	97,525
1983	156,967	170,167	273,775	232,882	216,500	221,436	319,925	206,528	145,336	139,448	231,247
1984	112,071	160,656	171,820	269,297	223,880	200,439	204,327	286,701	183,943	149,923	334,268
1985	77,890	118,133	163,884	171,386	257,172	203,601	178,887	164,361	239,399	177,754	428,149
1986	186,565	78,581	115,593	150,439	151,594	224,050	178,432	140,165	124,588	233,861	535,236
1987	132,492	193,176	75,991	107,509	129,392	130,517	207,555	151,439	119,759	114,276	671,066
1988	355,258	139,322	194,399	72,584	98,481	114,675	116,910	176,525	124,482	119,264	685,820
1989	50,476	376,102	136,920	176,129	65,002	80,839	93,514	96,171	135,889	105,551	644,528
1990	219,346	53,639	387,809	133,101	162,871	57,238	76,499	74,511	80,883	130,130	582,849

dance through cohort analysis. Survey data are also available to provide periodic independent estimates of biomass.

Cohort analyses (Bakkala et al., 1982; Bakkala and Wespestad, 1986) have indicated that the biomass of yellowfin sole (ages 7–17) may have been approximately 1.2 million t in 1959–60, the time the fishery intensified for this species (Fig. 11). This intense exploitation, which continued through 1962, apparently reduced the population biomass to less than half the level in 1959–60.

After 1963, cohort analysis indicates that biomass remained at a reduced level through the early 1970's. Biomass estimates from the International Pacific Halibut Commission and Japan Fishery Agency surveys from 1965 to 1971, which were standardized to the AFSC survey areas of 1975 and 1979–86 (Bakkala, 1988), agree quite well with results of the cohort analysis and suggest that biomass probably ranged around 500,000 t during this period (Fig. 11).

Both cohort analysis and AFSC survey data show that the yellowfin sole population began to recover in the early 1970's. Abundance of the population continued to increase through the early 1980's. This sustained increase was the

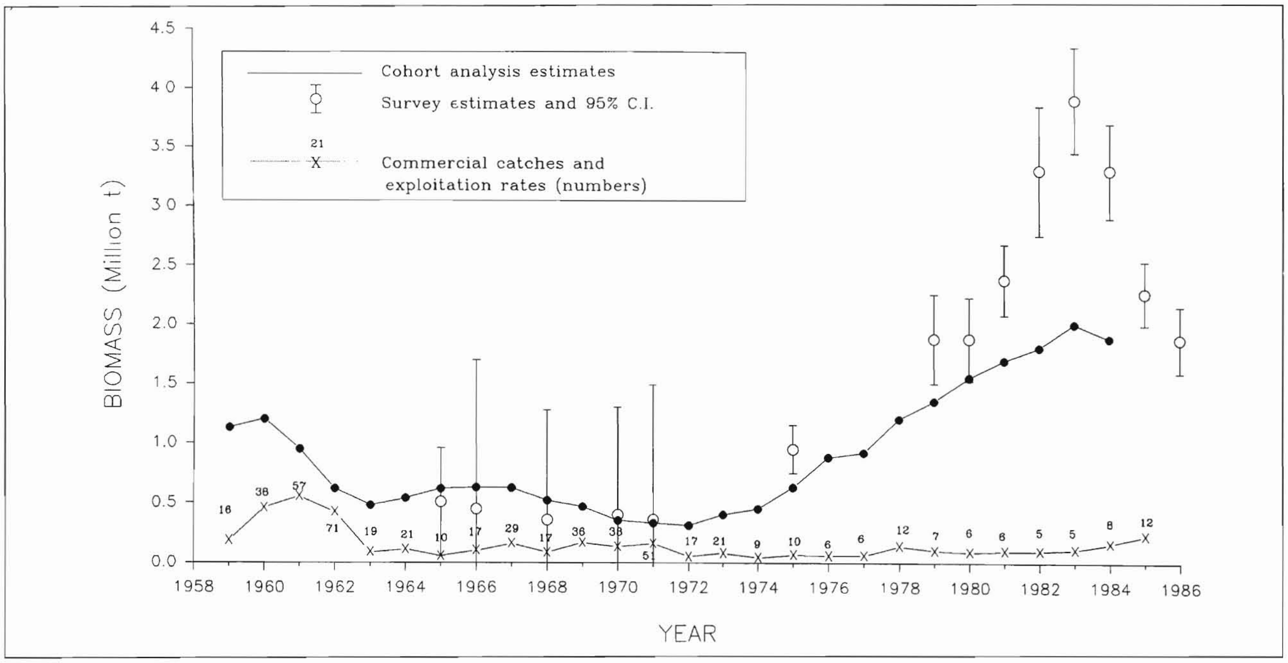

Figure 11.—Biomass estimates for eastern Bering Sea yellowfin sole from cohort analysis (ages 7–17) and from trawl survey data (all ages sampled). Commercial catches and exploitation rates (catch as percent of biomass estimates from cohort analysis) are also shown.

result of the recruitment of a series of strong year classes from 1968 to 1976 (Fig. 12). Cohort analysis indicates that the biomass of yellowfin sole peaked in 1984 at just over 2.0 million t, suggesting that the population during the 1980's was as high, if not higher, than that in 1959–60.

As mentioned above, the AFSC survey data also shows the increase in abundance of yellowfin sole, and there was reasonably good agreement in the magnitude of biomass estimates between the survey data and cohort analysis during 1975–81 (Fig. 11). In 1982–84, the survey biomass estimates fluctuated unreasonably and were much higher than those from cohort analysis. The survey estimates (for ages 7–17) increased from 2.1 million t in 1981 to 3.7 million t in 1983, and then decreased to 2.1 million t in 1985, an estimate similar to that from cohort analysis in 1985. Fluctuations of this magnitude are not possible for a long-lived and slow-growing species like yellowfin sole.

The reasons for these fluctuations in survey biomass estimates are unknown, but may be related to changes in the availability or vulnerability of yellowfin sole to the survey trawls. Interestingly, a similar problem has been encountered in trawl survey abundance estimates for an Atlantic species of flatfish of the same genus as yellowfin sole (yellowtail flounder, *Limanda ferruginea*) as reported by Collie and Sissenwine (1983).

Updated Cohort Analysis

The age range used in previous cohort analyses for yellowfin sole was 7–17, although ages well over 20 years have been recorded for this species. However, until the mid-1980's, population numbers for age groups exceeding 17 years was very low and did not contribute significantly to the total population abundance. Because of the recruitment of the 1968–77 series of strong year classes to age groups 18 and older during the late 1980's, it is no longer satisfactory to truncate the age range at age 17. For example, survey data in 1990 indicated that fish older than 17 years comprised 22% of the total estimated biomass in 1988, 26% in 1989, and 18% in 1990. These older age groups also contributed significantly to fishery catches—19% of the 1988 catch, 26% in 1989, and 18% of the 1990 catch. Therefore, in updating the cohort analysis, these older age groups were included.

Estimated biomass from the updated cohort analysis (which includes ages >17) indicates that survey estimates may have underestimated the yellowfin sole biomass during the period of increasing stock size in the late 1970's and early 1980's (Fig. 13). Since the peak year of 1983, survey estimates have shown unexplained fluctuations (Table 3), while cohort analysis indicates a gradual decline in stock abundance through 1990 to 1.96 million t.

The updated cohort analysis primarily differs from the previously described analysis of Bakkala and Wespestad (1986) by estimating a higher level of stock abundance during the late 1970's and early 1980's. This results from the addition of the age groups older than 17 years in the updated cohort analysis, which increases year-class abundance in early years in order to produce the for the estimation of the exploitable biomass of yellowfin sole.

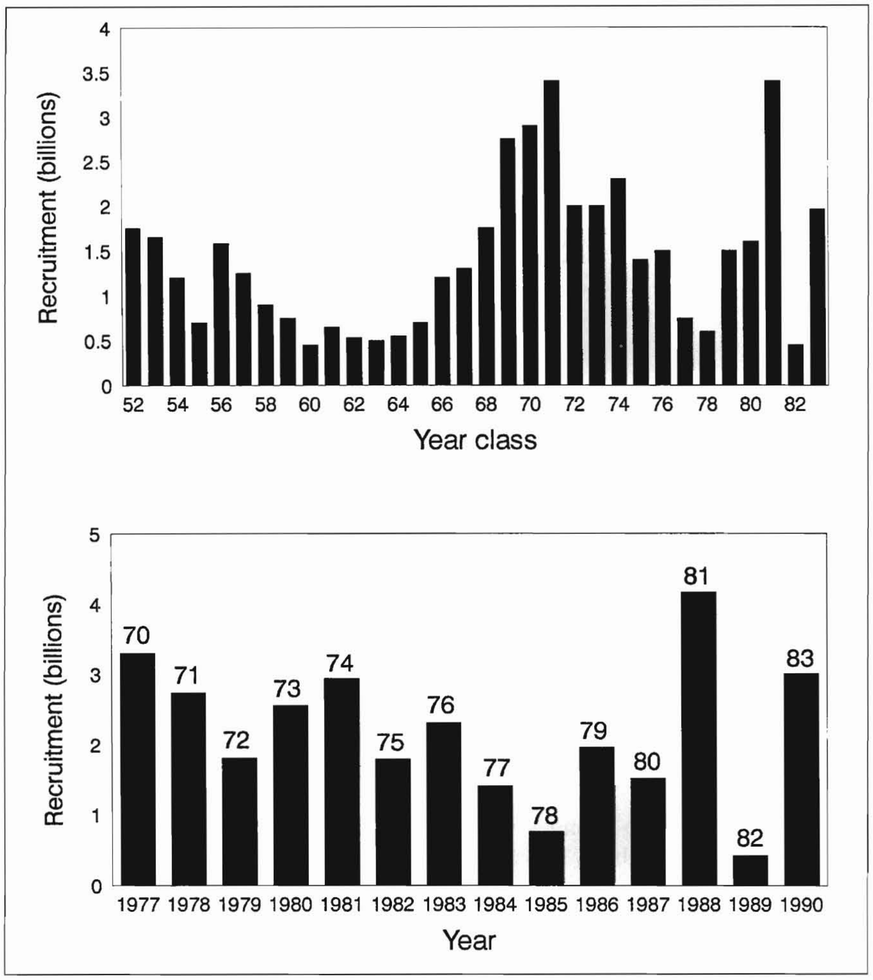

Figure 12.—Year-class strength at age 7 for yellowfin sole of the eastern Bering Sea as estimated by cohort analysis (top) and the stock synthesis model (bottom; year class is indicated on top of the bar).

present age distribution. The updated cohort analysis indicates that the biomass of yellowfin sole reached a peak of about 2.3 million t in 1983 and has since slowly declined.

Examination of fishery selectivities through age-specific *F* values calculated from the updated cohort analysis, age-specific catch to population ratios (cohort analysis), and selectivities estimated by the stock synthesis model indicate that the model assumption of knife-edge recruitment was violated (Fig. 14). Yellowfin sole are only partially recruited to the fishery bottom trawls at age 7 and may not be fully selected until age 13. In addition, the cohort analysis method does not perform well at predicting the current population abundance as the current estimate is only as good as the estimate of the terminal fishing mortalities. Other sensitivity analyses (Megrey[6]) indicate that cohort analyses are more accurate at estimation when the population has experienced a prolonged period of high exploitation, unlike yellowfin sole, where average *F* values have ranged from 0.02 to 0.18 since 1977 (Table 2). For these reasons, other age-structured analyses (such as the stock synthesis model) may provide a preferred alternative to cohort analysis for the estimation of the exploitable biomass of yellowfin sole.

Stock Synthesis Analysis

The synthesis model has the utility of allowing emphasis to be placed on different, observable characteristics of the population to evaluate the fit of the simulated population parameters. The emphasis placed on each component of the total log (likelihood) function determines how closely the model estimate will approach the observations of that population component. For this analysis, sensitivity of the results when emphasis was placed on survey biomass, survey and catch age composition, and the 1990 trawl survey age composition were investigated. A desirable simulation of yellowfin sole population dynamics would require a good fit to the trawl survey biomass trend since 1977 and the 1990 trawl survey age composition, as well as a reasonable fit to the survey and fishery age compositions since 1977.

The synthesis model was run with the selectivity curve fixed asymptotically for the older fish in the fishery and survey, but still was allowed to estimate the shape of the logistic curve for young fish. The oldest year classes in the most recent surveys and fisheries (1989 and 1990) were truncated at 20 and allowed to accumulate into the age category 17+ years. Emphasis on survey age composition and survey biomass were varied over a log scale range to evaluate the fit of the model to these factors and the 1990 survey age composition.

When emphasis was placed on the survey biomass, the fit to the survey biomass gradually improved towards matching the biomass exactly at high emphasis levels (Fig. 15). At emphasis levels greater than 10, the fit to the survey age composition and the catch age composition degraded substantially. When emphasis was placed on the survey age composition, the fit improved marginally as the emphasis factor was increased, but there was an accompanying degradation to the fit of the survey biomass and fishery catch age composition, particularly at emphasis levels greater than 100. The effect of placing a large emphasis on a particular observ-

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[6] Megrey, B. A. 1983. Review and comparison of three methods of cohort analysis. U.S. Dep. Commer., NOAA, NMFS Northwest Alaska Fish. Cent., Seattle. NWAFC Proc. Rep. 83-12, 24 p.

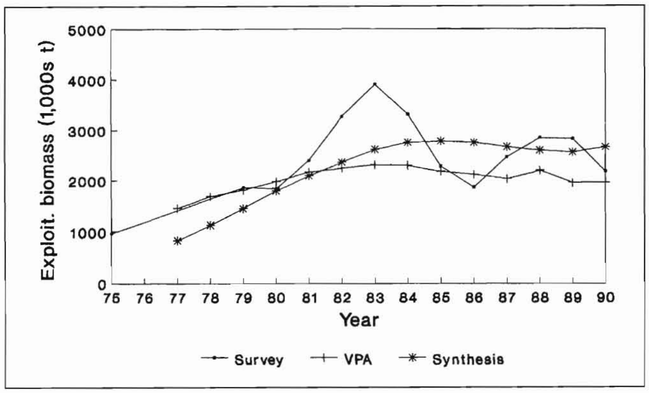

Figure 13.—Estimated biomass (t) of yellowfin sole in the eastern Bering Sea for 1979–90 derived from three methods—trawl survey data, cohort analysis, and a stock synthesis model.

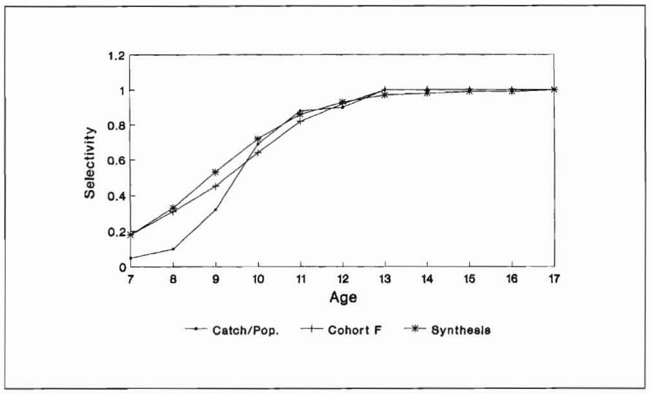

Figure 14.—Estimated age-specific fishery selectivity of yellowfin sole from three methods; ratio of catch to population number from cohort analysis, average *F* by age estimated from cohort analysis, and estimates from a stock synthesis model.

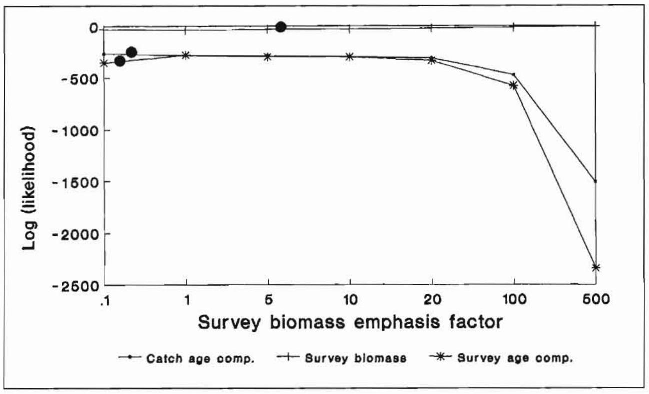

Figure 15.—Synthesis model fit (in terms of log {likelihood}) of catch age composition, survey biomass, and survey age composition with varying emphasis placed on fitting the survey biomass.

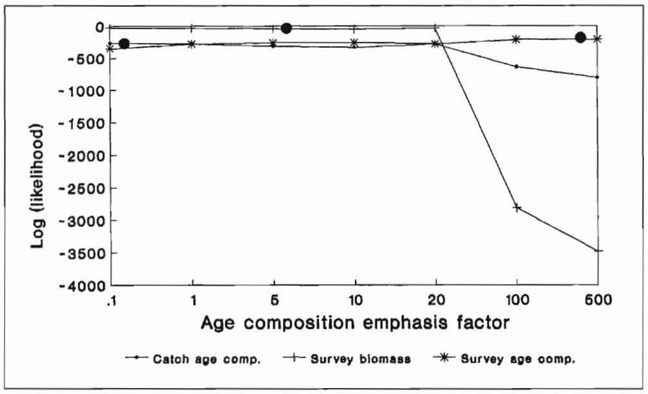

Figure 16.—Synthesis model fit (in terms of log {likelihood}) of catch age composition, survey biomass, and survey age composition with varying emphasis placed on fitting the survey age composition.

able characteristic of the population has been shown to improve the fit to this characteristic at the expense of degrading the fit of other observable aspects of the population. Figure 16 shows that little improvement to the model's fit results from placing an emphasis factor greater than 5 on the survey biomass or the survey age composition.

Table 3.—Estimated biomass (t) and 95% confidence intervals of yellowfin sole from Alaska Fisheries Science Center trawl surveys in 1975 and during 1979–90.

	Age groups			95% Confidence interval
Year	0–6	7+	Total	of total
1975	169,500	803,000	972,500	812,300–1,132,700
1979	211,500	1,655,000	1,866,500	1,586,000–2,147,100
1980	235,900	1,606,500	1,842,400	1,553,200–2,131,700
1981	343,200	2,051,500	2,394,700	2,072,900–2,716,500
1982	665,700	2,609,600	3,275,300	2,733,600–3,817,100
1983	222,500	3,688,100	3,910,600	3,447,800–4,373,300
1984	183,500	3,136,800	3,320,300	2,929,800–3,710,800
1985	155,000	2,122,400	2,277,400	2,003,000–2,551,900
1986	78,700	1,787,700	1,866,400	1,587,000–2,149,300
1987	120,000	2,345,800	2,465,800	2,091,100–2,840,600
1988	53,800	2,800,600	2,854,600	2,393,900–3,315,200
1989	239,300	2,592,500	2,831,800	2,422,300–3,241,200
1990	69,600	2,114,200	2,183,800	1,886,200–2,479,400

It is desirable for the model to closely approach the observed 1990 age composition since it would depict the current population age profile. A synthesis model run was made to investigate the fit to the current population age profile by placing emphasis on fitting the 1990 survey age composition while placing slight emphasis on the survey biomass component of the total likelihood and then comparing the overall fit to the trend in biomass and recruitment from information obtained from trawl surveys. An emphasis level of 5.0 was placed on the survey biomass to provide a reasonable compromise between the fit to the various types of observable data. The resulting fit to the observable likelihood components is indicated in Figures 15 and 16 as a black dot from the final synthesis run and indicates that this final run exhibited a good fit to all the important observable population characteristcs.

The stock synthesis biomass estimates indicate that yellowfin sole biomass was nearly 1.5 million t in 1979, gradually increased to a peak of 2.8 million t in 1985, and decreased slightly to 2.56 million t in 1989 before increasing to 2.66 million t in 1990 as the strong 1981 and 1983 year classes recruited to the fishable biomass (Fig. 13). Trawl survey and cohort analysis estimates both indicate that yellowfin sole biomass peaked in 1983. Estimates from cohort analyses have remained stable at lower levels since 1983. The survey estimates have fluctuated around the stock synthesis and cohort analysis estimates since 1983. All three estimation procedures indicate that the yellowfin sole resource has slowly increased during the 1970's and early 1980's, to a peak level during the mid-1980's, and that the resource has remained abundant until the present. This is indicative of a slow-growing species with a low natural mortality rate which is known to have been lightly exploited while experiencing average to strong recruitment during the past 15 years. Good recruitment from the 1979–81 and 1983 year classes is expected to maintain the abundance of yellowfin sole at a high level in the near future.

The natural mortality rate value of 0.12 was also evaluated using the synthesis model. Values of natural mortality were varied from 0.09 to 0.18 to determine which level would fit the observable population characterics best (Fig. 17). Maximum log (likelihood) values occurred at $M = 0.12$. This value agrees with earlier assessments.

Recruitment Strengths

The primary reason for the sustained increase in abundance of yellowfin sole during the 1970's and early 1980's has been the recruitment of a series of stronger-than-average year classes spawned in 1968–76 (Fig. 12). Many of these year classes still comprise the major portion of the exploitable population. This long series of strong year classes also creates a healthy spawning population. Of the later year classes, the 1978 year class is weak, but the 1979 and 1980 year classes appear to be above average and the 1981 and 1983 year classes are two of the strongest yet observed. Thus there appears to be continuing good recruitment entering the exploitable population to sustain the stock at its present abundant level.

Current Management and Estimation of Yield

Yellowfin sole is one component of 13 species or species groups of groundfish of the eastern Bering Sea managed under the auspices of the Magnuson Fishery Conservation and Management Act of 1976. The act created eight regional councils responsible for the fishery resource management within their geographic jurisdiction. The North Pacific Fishery Management Council (NPFMC) has an area of authority including the U.S. exclusive economic zones of the Arctic Ocean, Bering and Chukchi Seas, and the North Pacific Ocean in the Gulf of Alaska.

The primary function of the councils is to develop and maintain fishery management plans (FMP) for fisheries in need of conservation and management. The FMP must specify the present and future condition of the resource and establish a maximum sustainable yield (MSY) and optimum yield for each species. Each year the NPFMC determines the total allowable catch (catch quota) for each species derived from the acceptable biological catch (ABC). The total allowable catch may be further influenced by social and economic factors. Recommendations concerning the ABC are provided to the council by fishery biologists from both state and Federal fisheries management agencies. The determined ABC may be above or below MSY based on seasonally determined biological factors.

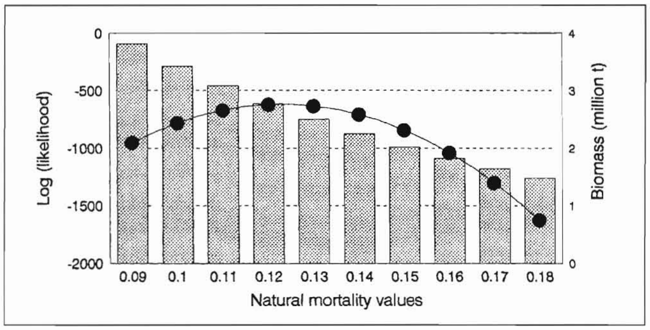

Figure 17.—Synthesis model fit (in terms of log {likelihood}) of a range of natural mortality values and the simulated biomass which would occur for each value.

Maximum Sustainable Yield

Estimates of MSY have ranged from 78,000 to 260,000 t (Bakkala and Wilderbuer, 1991) based on the yield equation of Schaefer (1957) and the method of Alverson and Pereyra (1969) using ranges in M of 0.12 to 0.25 and virgin biomass estimates of 1.3 to 2.0 million t. Exploitation of the yellowfin sole population from 1959 to 1981 averaged 150,000 t, which may represent a reasonable estimate of MSY. This figure is similar to the long-term sustainable yield (175,000 t) estimated from an ecosystem model (Low, 1984). These latter estimates, however, are lower than the recent estimate of 252,000–284,000 t obtained by fitting catch and biomass in logistic stock production modeling (Zhang et al., 1991).

Acceptable Biological Catch For 1992

After increasing during the 1970's and early 1980's, biomass estimates from cohort analysis and stock synthesis analysis have been stable at 2 million t or more since 1982. The mean 1990 estimate of exploitable biomass from stock synthesis projected ahead 1.5 years (discounting for 1991 fishing and 1.5 years natural mortality and accounting for growth and recruitment) provides an estimate of 2.66 million t of exploitable biomass for the beginning of 1992. This is believed to be the best estimate of current yellowfin sole exploitable biomass.

Two methods were used to estimate ABC: 1) Results from the yield-per-recruit model of Beverton and Holt (1957) and 2) the $F_{0.1}$ fishing rate (Gulland and Boerema, 1973) derived from the Beverton and Holt model yield curve applied to the estimate of exploitable biomass for 1992.

The yield-per-recruit model of Beverton and Holt (1957) uses the following input data: $M = 0.12$ and von Bertalanffy growth parameters ($k = 0.11$, $t_0 = 0.22$ years, and $W_{inf} = 745$ grams). Age 9, at which nearly 50% of a cohort is recruited to the fishery, was used as the age of recruitment. The medium, low, and high levels of recruitment were derived from the mean number and 95% confidence interval around the mean of age 9 recruits in 1977–90 estimated from cohort analysis and the synthesis model. Results of the analysis follow.

Cohort analysis estimated age 9 recruitment:

Yield/recruit			(Billions of fish)			ABC		
M	F_{01}	Grams[8]	Low	Avg.	High	Low	Avg.	High
Cohort analysis								
0.12	0.14	161	1.10	1.40	1.70	177,100	225,400	273,700
Stock synthesis model								
0.12	0.14	161	1.37	1.72	2.08	220,570	276,920	334,880

The validity of the ABC values for this model assumes that an equilibrium condition exists for the chosen level of recruitment.

The second method of estimating ABC involves applying the $F_{0.1}$ exploitation rate from the yield-per-recruit model to the 1992 exploitable biomass. Applying the $F_{0.1}$ exploitation rate (0.14) from the Beverton and Holt model to the 1992 projected biomass (2.66 million t) provides an ABC of 372,400 t. This estimate exceeds the high recruitment values from the yield per recruit analysis in method 1. Survey and fishery information indicate that sustained high recruitment is not realistic for the yellowfin sole population. Even during a time period of generally good recruitment and reduced exploitation, below-average year classes were produced as in 1978 and 1982. Accordingly, it is believed that 276,900 t, derived from the continued average recruitment scenario, is the best estimate of ABC for 1992.

Biomass Projections

Total biomass through 1996 is projected using the delay difference equation of Deriso (1980). This model incorporates growth, natural mortality, recruitment, and 2 years of biomass and catch estimates to predict future biomass. Recruitment was assumed constant over the period of the projection using the average recruitment values of age 9 yellowfin sole from the cohort analysis model. Results indicate that a harvest level based on the average recruitment scenario from the yield per recruit exploitation strategy will result in a stable population through 1996 (Fig. 18).

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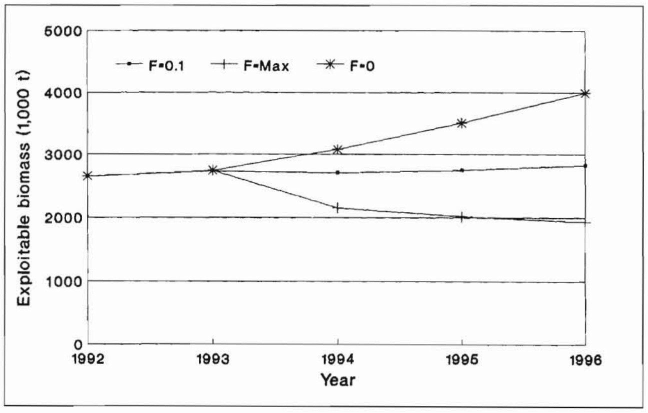

Figure 18.—Projections of estimated biomass for yellowfin sole for 1992–96 from the delay-difference equation under three harvest strategies ($F = 0$, $F = F_{0.1}$, and $F = F_{max}$).

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[8] F_{01} value.

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