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THE YELLOWFIN SOLE (LIMANDA ASPERA) RESOURCE OF THE EASTERN BERING SEA -- ITS CURRENT AND FUTURE POTENTIAL FOR COMMERCIAL FISHERIES

by

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ABSTRACT

Yellowfin sole (*Limanda aspera*) is a major fishery resource of the eastern Bering Sea, ranking second in abundance only to walleye pollock (*Theragra chalcogramma*). Yellowfin sole are relatively small, slow-growing flatfish. They averaged 26.5 cm (10.4 in) and 27.7 cm (10.9 in) in foreign trawl catches in 1979 and 1980, respectively. These sizes are representative of fish 11-12 yr of age. Even at the oldest ages (15-20 yr), most of the fish average less than 1 lb. Recent commercial catches have ranged between 87,000 and 99,000 metric tons (t) annually. However, the population is presently capable of supporting larger catches.

The abundance of yellowfin sole was reduced by intense exploitation in early years of the foreign fishery when catches averaging 400,000 t annually were taken over the 4-yr period of 1959-62. Cohort analyses have indicated that population abundance remained at a reduced level until the early 1970's. Cohort analyses and resource assessment data both show that abundance has been increasing since the early 1970's and in recent years has reached a level that may have approximated or even exceeded the biomass of the stock prior to the period of intense exploitation that began in the late 1950's. The total population biomass in 1981 was minimally estimated to be 2.0 million t. The primary reason for this increase has been the recruitment to the population of a series of strong year-classes spawned in 1966-70. These year-classes at ages 11-15 continued to provide the major share of commercial catches in 1981. Recent survey data indicate that a new series of strong year-classes have entered the population (the 1973-76 year-classes). These year-classes should maintain the resource in good condition for a number of years.

Future trends in abundance of the yellowfin sole population and potential levels of harvest were examined in this report using a numeric population simulator. The simulator projects numbers-at-age from given numbers-at-age in a base year using estimates of natural (M) and fishing (F) mortality and recruitment. The value of M used in the simulation was 0.12. F values were varied (corresponding to exploitation rates of 0.05, 0.10, 0.15, and 0.20) to examine the response of the population to various levels of exploitation. An F value corresponding to a constant catch of 214,500 t was also used which represents an estimate of maximum sustainable yield. The simulations were run with two levels of recruitment: 1.403 billion fish, which is the average recruitment at age 7 in 1959-81 based on cohort analysis, and 1.074 billion fish, which is the average abundance of age 7 fish in this same period of years, excluding the exceptionally strong year-classes of 1969, 1970, 1973, and 1974.

The simulations indicate that population biomass will remain high at least through 1985. Abundance of primary age groups in the fishable stock (ages 8-17) is expected to range between 1.4 and 2.0 million t in 1985, varying within this range depending on the levels of exploitation and recruitment. Based on these findings, it is believed that the resource can sustain catches of at least 200,000 t annually until 1985.

Long-term equilibrium yields were also examined for yellowfin sole using the PROBUB ecosystem model. Calculations based on the model indicate that the equilibrium biomass (the biomass of yellowfin sole that would be in equilibrium with other components of the ecosystem) ranges from 880,000 - 1,328,000 t. Annual catches of as much as 175,000 t were found to maintain the population within this range and was, therefore, considered an estimate of the long-term equilibrium yield.

The current biomass of yellowfin sole is apparently at the upper end of a natural cycle in abundance and exceeds intermediate levels of abundance which, according to the ecosystem model, keeps the overall ecosystem in equilibrium. Catches should, therefore, be increased to 200,000 t or more to take advantage of this surplus.

Contents

INTRODUCTION

Yellowfin sole (Limanda aspera) is a major fishery resource of the eastern Bering Sea, ranking second only to walleye pollock (Theragra chalcogramma) in abundance. During a major demersal trawl survey by the Northwest and Alaska Fisheries Center (NWAFC) in 1979, yellowfin sole represented 63% of the total estimated flatfish biomass and 22% of the total fish biomass in the region. Current estimated biomass is about 2 million metric tons (t), based on research vessel surveys.

Yellowfin sole was the initial target species of distant water fisheries from Japan and the U.S.S.R. in the eastern Bering Sea following World War II. Yellowfin sole was utilized for the production of fish meal and this fishery expanded very rapidly in the late 1950's to harvest an average 400,000 t annually in the 4-year period of 1959-62. Catches of this magnitude apparently exceeded equilibrium yield, and the population size was considerably reduced.

Population abundance remained at a reduced level until the early 1970's. In about 1972, the resource began to recover and abundance has since increased. In 1979-81, the estimated biomass had reached a level that is believed to be at least as high as the size of the population prior to the intense exploitation in the late 1950's and early 1960's.

There is current interest in yellowfin sole as a potential resource for exploitation by U.S. fisheries, particularly through joint venture operations with foreign processing vessels. This report is intended to provide information on the characteristics of the resource, its present condition, and potential future abundance as a possible aid to the development of U.S. fisheries.

COMMERCIAL FISHERY

Historical Catch Statistics

Annual catches of yellowfin sole throughout the history of the post World War II fishery are given in Table 1 (Japan also had a small-scale fishery in the eastern Bering Sea in 1933-37 and 1940-41 for pollock and flatfish with annual catches of all species ranging from 3,300-43,400 t). The data illustrates the rapid expansion of the Japanese and U.S.S.R. fisheries in the late 1950's when catches reached a peak of 554,000 t in 1961. Catches then declined just as rapidly, falling below 100,000 t in 1963. This decline is believed to stem from reduced availability of yellowfin sole as a result of overfishing in 1959-63, but the severity of the decline may have been heightened by the diversification of these fisheries to other species and areas of the Bering Sea. For example, in 1964 the Japanese begin utilizing walleye pollock which then became the primary target species of Japanese fisheries and later of U.S.S.R. fisheries. Since the mid-1960's, catches of yellowfin sole have fluctuated between 42,000 t (in 1974) and 167,000 t (in 1969). In the most recent 3 yr, catches have ranged between 87,000 and 99,000 t.

The U.S.S.R. has not been allowed to conduct a directed fishery for yellowfin sole in the U.S. fishery conservation zone since early 1980. However, joint venture operations between U.S. catcher boats and Soviet processing vessels produced catches of about 9,600 t in 1980 and 16,000 t in 1981. A second recent development in the fishery has been increased utilization of yellowfin sole by Republic of Korea fishing vessels with catches increasing to the 16,000 to 17,000 t range in 1980 and 1981.

Table 1.--Annual catches of yellowfin sole in the eastern Bering Sea (east of 180° and north of 54°N) in metric tons.1/

Year	Japan	USSR	ROK	Others 2/	Joint Venture 3/	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	-4/			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			56,201
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

1/ Source: Wakabayashi and Bakkala (1978) for catches through 1976; catch data for 1977-79 from data submitted to the U.S. by nations fishing in the U.S. 200-mile fishery conservation zone. Catch data for 1980 and 1981 are estimates from the U.S. observer program (French et al. 1981, 1982).

2/ Other nations are Taiwan, West Germany, and Poland.

3/ Joint venture operations between U.S. catcher boats and USSR processing vessels.

4/ - indicates fishing but no reported catch.

Fishery Products

Yellowfin sole are presently utilized for freezing after various degrees of processing. Based on U.S. observer reports, they are frozen in the round on Soviet processing vessels while only the smaller fish are utilized in this manner on Japanese processing vessels. Fish greater than 140 g (0.3 lb) may be headed, gutted, and the tails removed manually before freezing on Japanese processors or a stamping machine may be used to remove the head, tail, fins, and viscera. The dark side may also be skinned from these latter two products. The larger yellowfin sole (approximately 0.5 lb and larger) may also be filleted. Wastes from the processing operations are used for fish meal along with some other species from the catch.

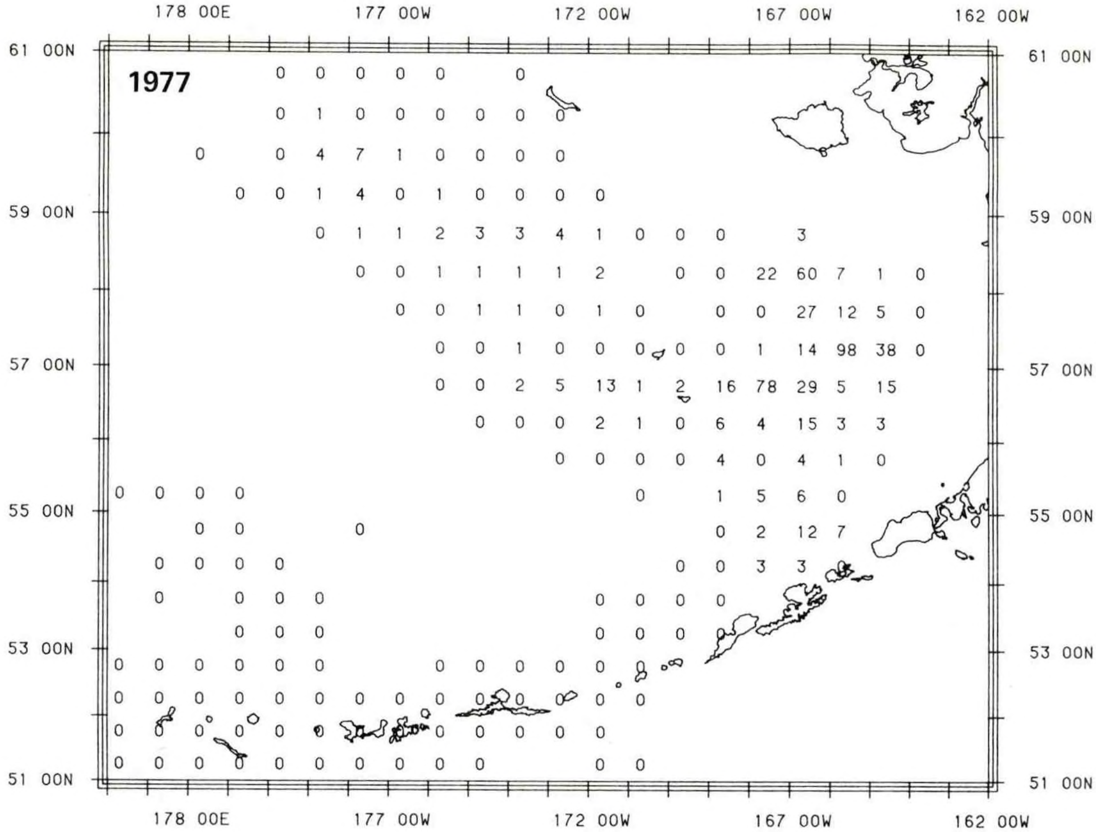
Fishing Areas

Distribution of catches of yellowfin sole by trawl fisheries in 1977 and 1980 are illustrated in Figure 1. Two years of catch data are shown because the Japanese fishery for yellowfin sole, which has usually taken the major share of the catch, has shifted from a winter fishery (September-February) prior to 1978 to a summer-early fall fishery (June-October) in recent years. However, the area of major catches were similar in the two seasons with a large portion of the catches coming from the central shelf region east of the Pribilof Islands. Catches south and northwest of this area were much smaller and represent incidental catches of yellowfin sole taken by target fisheries for other species, primarily pollock.

POPULATION CHARACTERISTICS

Seasonal Distribution

Yellowfin sole conduct seasonal migrations from waters of the outer shelf of the eastern Bering Sea, which they occupy during winter and early spring



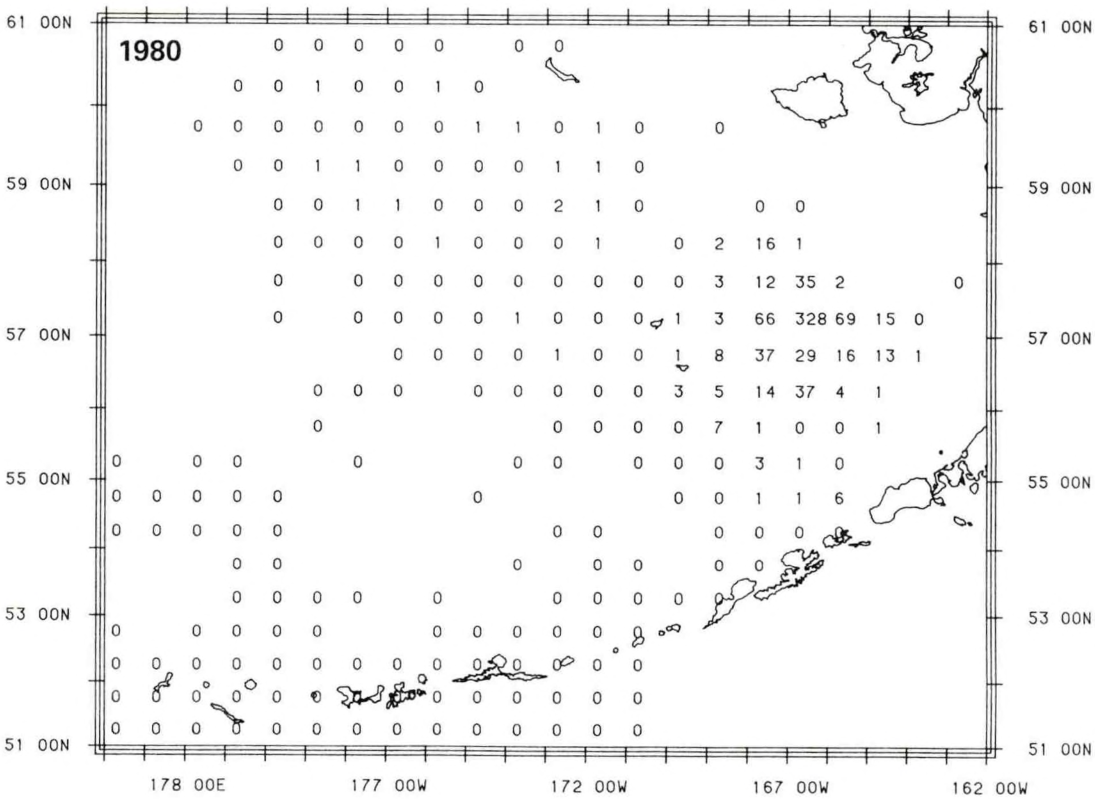


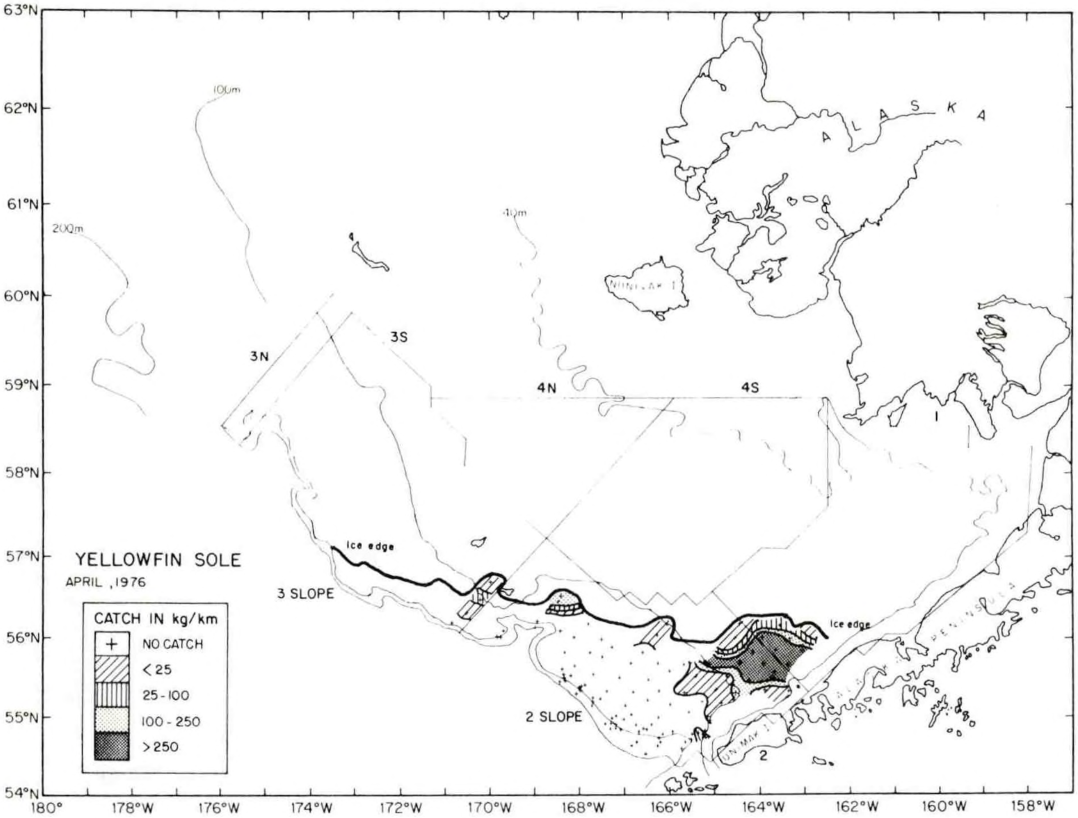
Figure 1.--Distribution of catches of yellowfin sole (in 100t units) by the foreign trawl fishery in 1977 and 1980.

months to central and inner shelf regions in summer. The migrations to deeper water in winter are probably in response to the advance of pack ice that covers extensive, but variable portions of the eastern Bering Sea in winter and spring. Inshore migrations are for feeding and spawning; spawning takes place in near-shore waters along the Alaska mainland in July to September.

Figure 2 illustrates the distribution of yellowfin sole observed in April and May 1976 during a NWAFC resource assessment survey. The spring of 1976 was particularly cold and the pack-ice distribution in April was at an extreme southern location. The distribution in April was, therefore, probably typical of the late winter-early spring distribution of yellowfin sole during years of extensive ice cover in the eastern Bering Sea. Fadeev (1970) and Wakabayashi (1974) have observed winter concentrations in similar locations in years prior to 1976. Yellowfin sole may also remain in central shelf waters throughout the winter in warmer years, such as 1977, as is indicated by the location of major catches east of the Pribilof Islands by the foreign trawl fishery in September to February 1977 (Figure 1).

In April 1976, yellowfin sole formed the largest concentration north of Unimak Island (Figure 2). Some extremely high catches, estimated at 22,700-27,200 kg (50,000-60,000 lb) per half hour tow, were made in this concentration during the spring 1976 survey. In May 1976, this Unimak Island concentration had begun to move inshore, apparently following the receding ice edge.

Two other lesser winter concentrations have been described by Fadeev (1970) and Wakabayashi (1974) and they were also evident in April and May 1976 (Figure 2); one located west and the other southeast of the Pribilof Islands. These concentrations also migrate inshore in spring and in 1976 had left these offshore waters by June.



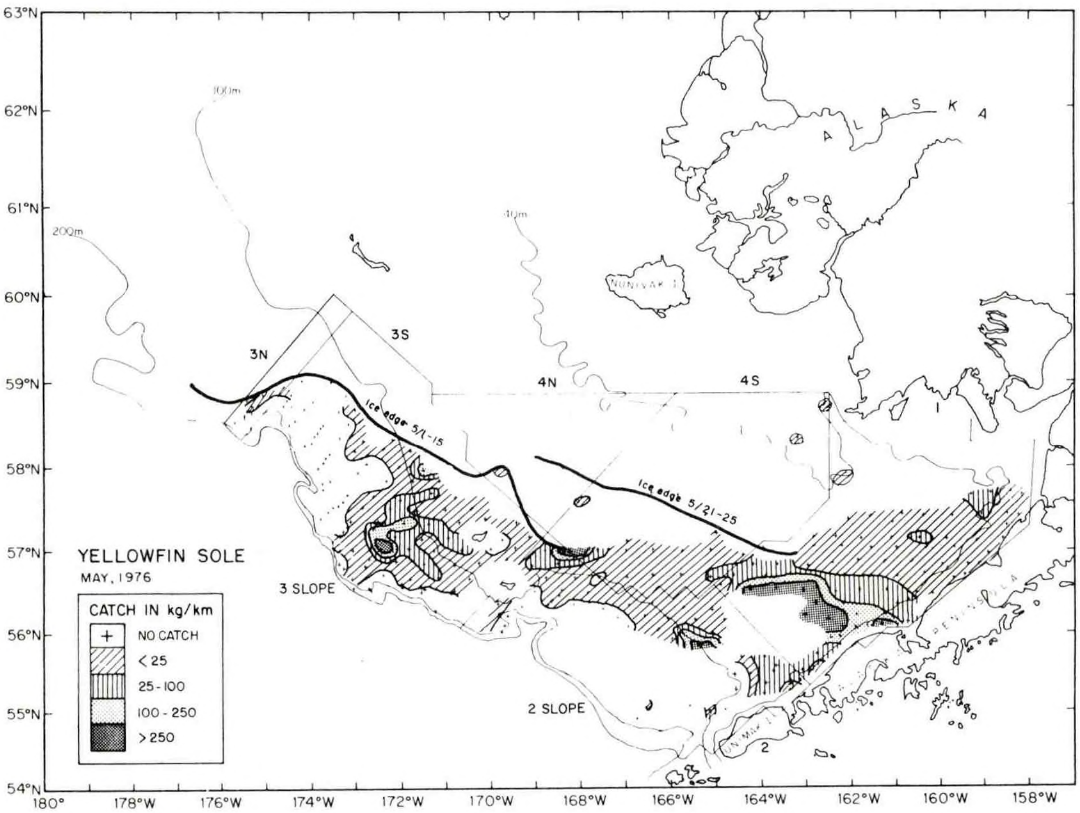


Figure 2.--Distribution and relative abundance of yellowfin sole in April and May as shown by a trawl survey of the Northwest and Alaska Fisheries Center in 1976.

Figure 3 illustrates the summer distribution of yellowfin sole as shown by NWAFC surveys in 1975 and 1979. They become distributed in waters of less than 100 m (55 fathoms) from the Alaska peninsula to as far north as Norton Sound. Main concentrations, however, are limited to waters south of Nunivak Island.

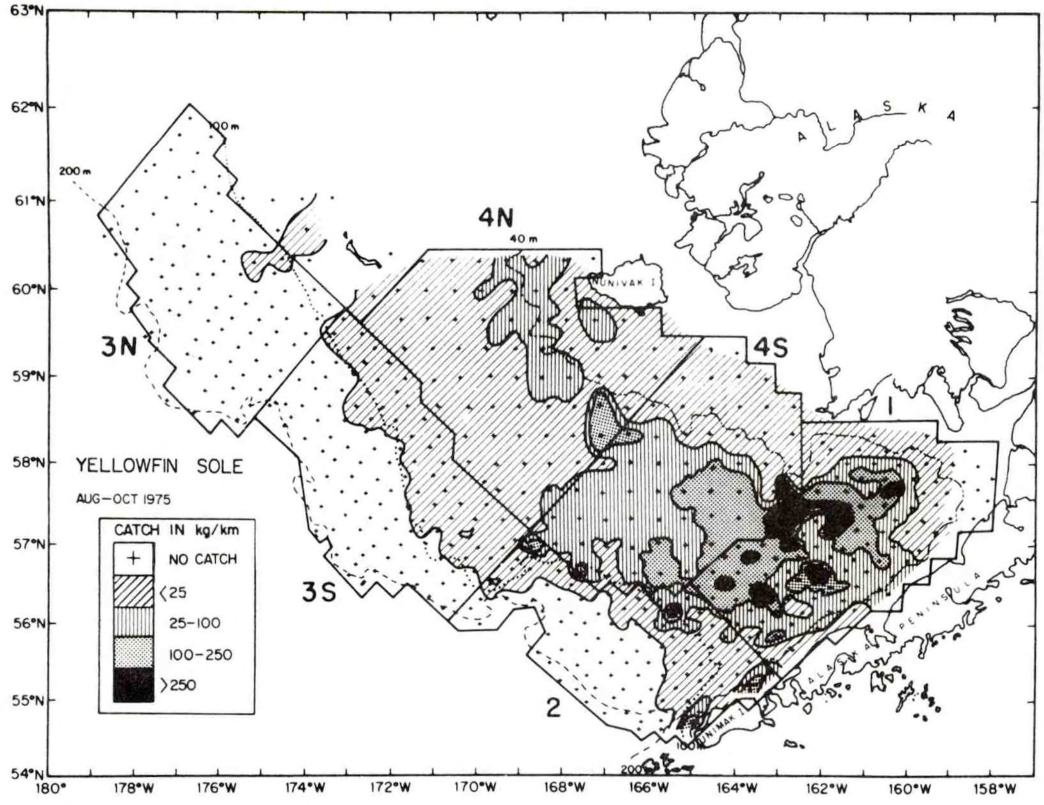
Some variation in distribution can be noted between 1975 and 1979 which may be related to differences in temperature conditions. The environment was colder in 1975, and the major area of concentration was located further south than in 1979, which was a considerably warmer year. Bottom temperatures near the Alaska Peninsula in June averaged 0.9°C in 1975 and 5.4°C in 1979 (International Pacific Halibut Commission 1975, 1980).

Size Composition

Yellowfin sole are relatively small, slow-growing flounders. When they begin to recruit to the fishery at age 5, they average only 17 cm (about 7 in) and 56 g or about 1/8 lb (Table 2). At age 9, when they are fully recruited to the fishery, average length is 24 cm (9.5 in) and average weight 159 g or 1/3 lb (Table 2). Even at the oldest ages (15-20 yr), most of the fish average less than a pound.

The length distribution of yellowfin sole as shown by NWAFC survey and Japanese commercial fishery data in 1979 and 1980 are illustrated in Figure 4. Almost all of the surveyed population ranged between 10 and 35 cm (about 4-14 in). They averaged between 23 and 24 cm (9.0-9.5 in) in the two years. In 1979, 47% and in 1980, 42% of the surveyed population were 25 cm or larger, which is considered a commercially usable size in the U.S.-U.S.S.R. joint venture fishery.

Yellowfin sole taken by the Japanese trawl fishery (Figure 4) primarily ranged between 20 and 35 cm (about 8-14 in). They averaged 26.5 cm (10.4 in)



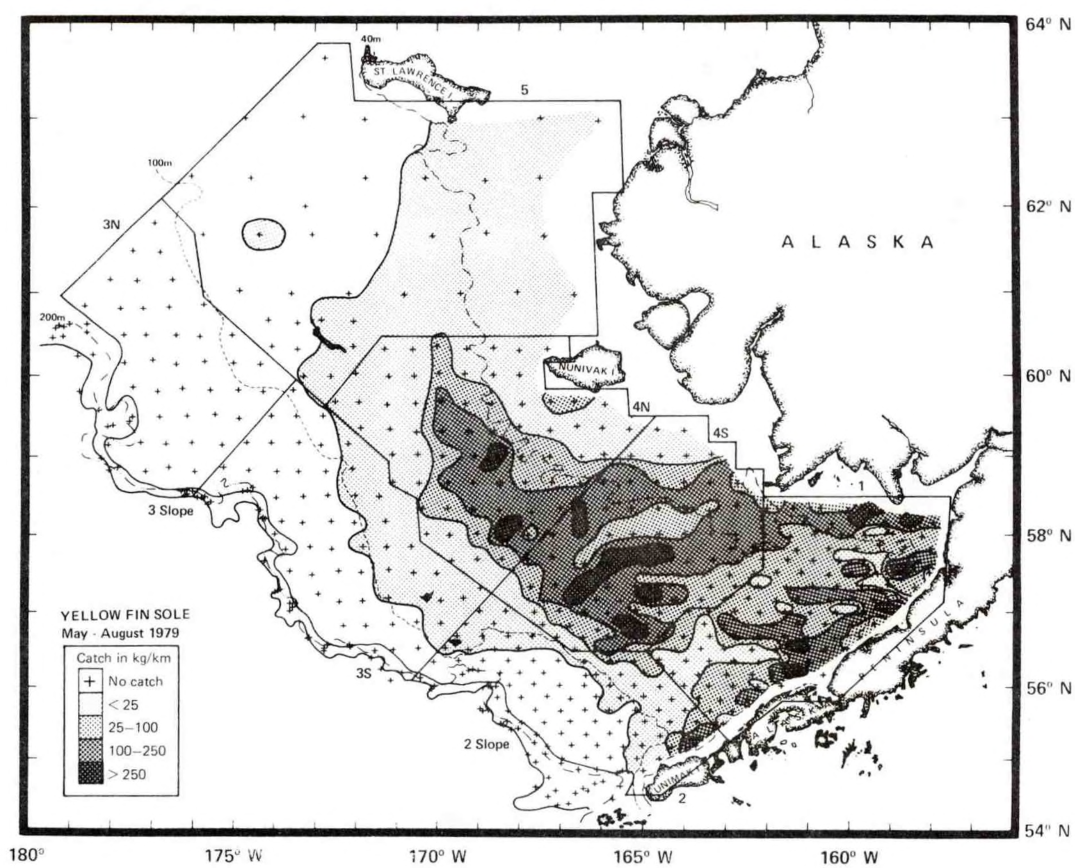


Figure 3.--Distribution and relative abundance of yellowfin sole in August-October 1975 and in May-August 1979 as shown by trawl surveys of the Northwest and Alaska Fisheries Center.

Table 2.--Mean length and weight at age of yellowfin sole of the eastern Bering Sea as shown by 8 yr of survey data of the Northwest and Alaska Fisheries Center.

Age	Length		weight	
	cm	in	g	lb
3	11.6	4.6	17.50	0.04
4	14.3	5.6	33.19	0.07
5	17.1	6.7	56.37	0.12
6	19.8	7.8	87.70	0.19
7	21.5	8.5	112.26	0.25
8	22.9	9.0	134.57	0.30
9	24.2	9.5	158.54	0.35
10	25.4	10.0	184.59	0.41
11	26.5	10.4	209.67	0.46
12	27.4	10.8	231.88	0.51
13	28.6	11.3	263.68	0.58
14	29.3	11.5	281.34	0.62
15	29.8	11.7	296.15	0.65
16	31.7	12.5	357.45	0.79
17	31.9	12.6	364.22	0.80

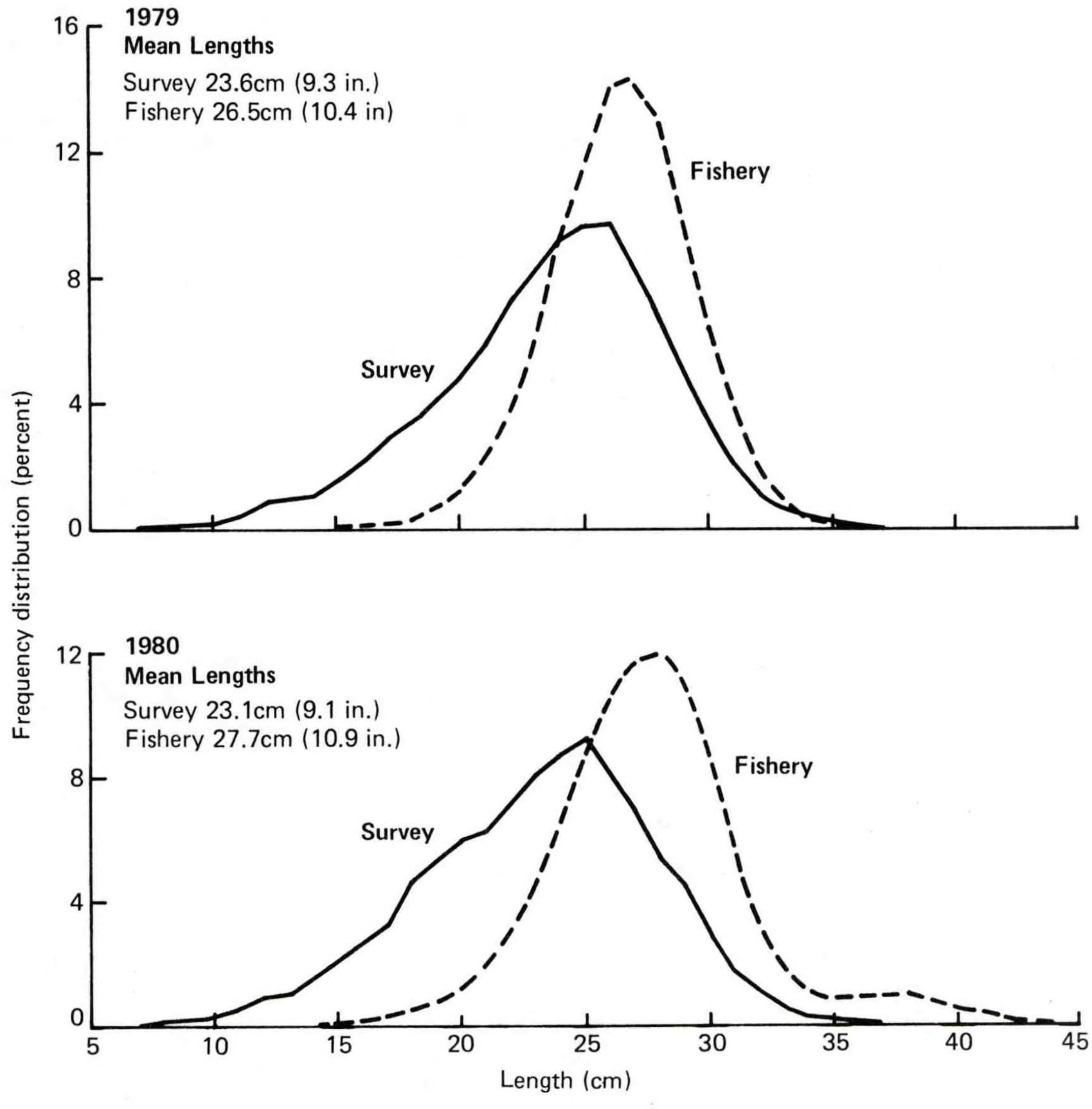


Figure 4.--Length-frequency distributions of yellowfin sole in the eastern Bering Sea in 1979 and 1980 as shown by surveys of the Northwest and Alaska Fisheries Center and U.S. observer samples from the foreign trawl fishery.

in 1979 and 27.7 cm (10.9 in) in 1980. About 74% in 1979 and 81% in 1980 of the fish taken in the trawl fishery for yellowfin sole were 25 cm or larger.

Age Composition

Yellowfin sole is a long-lived species reaching ages of 20 yr or more. A fairly long series of age data is now available from the eastern Bering Sea from both NWAFC surveys and from U.S. observer samples taken in the foreign fishery (Figure 5). During this period, there has occurred a marked change in the age structure of the population, resulting from the recruitment and advancement through the population of a series of strong year-classes originating from spawning in 1966-70. These year-classes have predominated research vessel catches as well as catches by the commercial fishery since 1973. These strong year-classes are now relatively old ranging from 11-15 yr in 1981. They still contribute the major share of commercial catches (55% in 1981), however, and may continue to contribute substantially to the commercial fishery in the next 3 or 4 yr.

The 1980 and 1981 NWAFC survey data indicates that a new series of strong year-classes has entered the population (Figure 5). These are the 1973 to 1976 year-classes which appear to be as strong or possibly even stronger than the 1966-70 year-classes. The age structure of the population appears to be excellent and should maintain the resource in a healthy state in the foreseeable future.

ABUNDANCE ESTIMATES 1959-81

Resource Assessment Surveys

Biomass estimates from NWAFC surveys for years in which a major portion of the eastern Bering Sea continental shelf has been sampled are shown in Table 3.

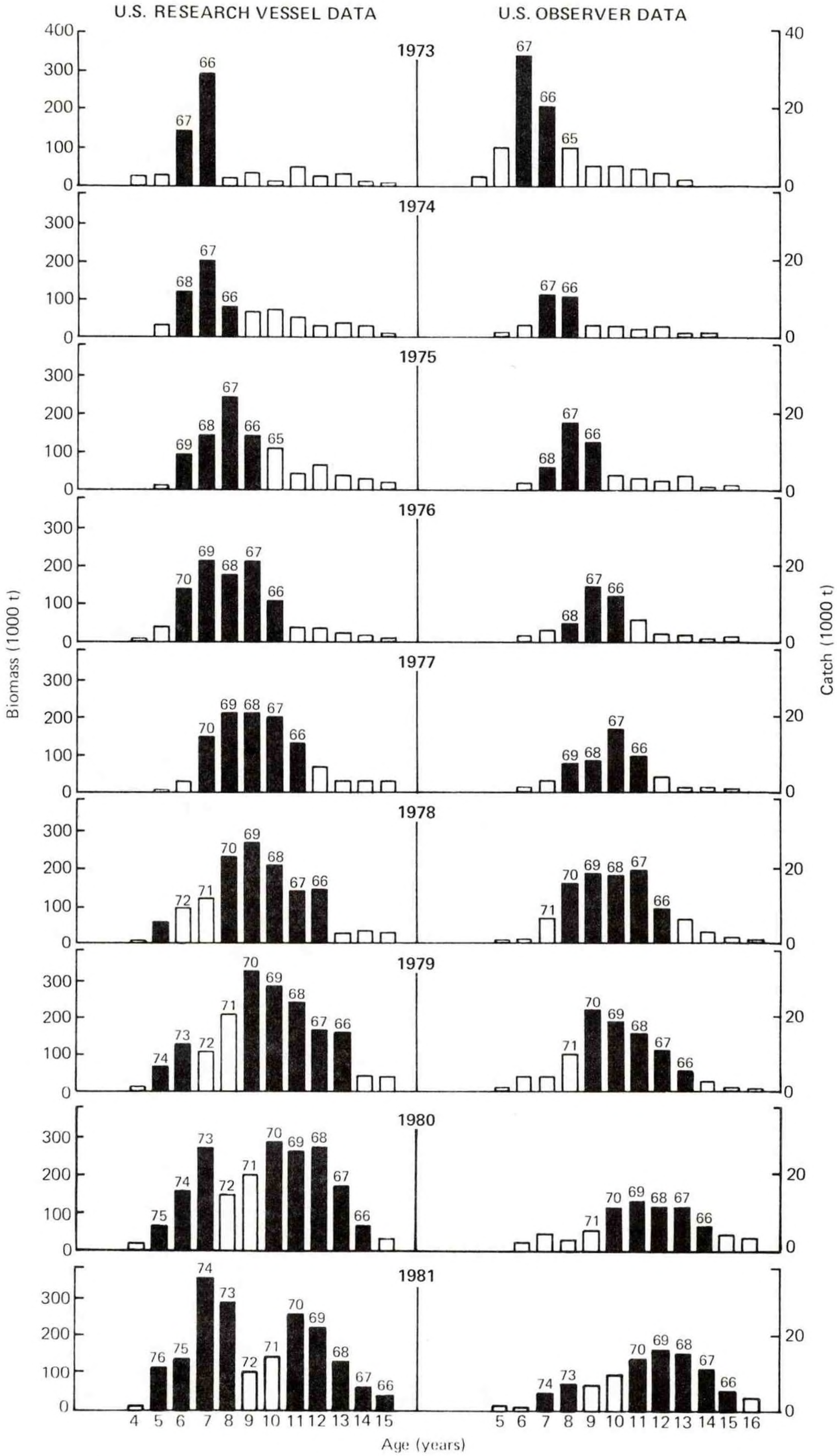


Figure 5.--Age composition of yellowfin sole of the eastern Bering Sea as shown by data from trawl surveys of the Northwest and Alaska Fisheries Center and by U.S. observer data from the foreign fishery. Year-classes for more abundant ages are shown with the appropriate bars, and darkened bars represent stronger than average year-classes.

Methods of data collection and analysis used in developing these estimates are described by Smith and Bakkala (1982) and Wakabayashi et al. (1982).

Table 3.--Biomass estimates of the sampled population of eastern Bering Sea yellowfin sole, as shown by large-scale NWAFC resource assessment surveys.[1/]

Year	Mean estimate (t)	95% Confidence interval (t)
1975	1,038,400	870,800 - 1,206,400
1976	1,192,600	661,700 - 1,723,600
1978	1,523,400	1,103,300 - 1,943,600
1979	1,932,600	1,669,000 - 2,196,100
1980	1,965,900	1,716,000 - 2,215,900
1981	2,039,919	1,791,006 - 2,288,832

1/ Areas of the eastern Bering Sea continental shelf surveyed in these years were variable, but the major portion of the yellowfin sole distribution was sampled in all years.

Mainly as a result of the recruitment of the strong 1966-70 year-classes, the overall abundance of the population has shown a marked increase since the mid-1970's. The survey estimates indicate an almost doubling of biomass between 1975 and 1979 and then a leveling off of abundance at about 2.0 million t in 1980 and 1981. Thus, the increase in population weight resulting from the 1966-70 year-classes may now have reached a peak.

Cohort Analysis

Cohort analysis or virtual population analysis utilizes commercial catch data to estimate population size. Basically, the method back calculates population size by sequentially adding the catch from the oldest age in a year-class to the next youngest age, e.g. if 4 fish were caught at age 20 the virtual population is 4 and if 10 fish were caught at age 19 the virtual population is 4 + 10 or 14. The analysis also accounts for natural or nonfishing mortality and adds the numbers lost to natural mortality to the virtual population. Since the analysis is based on fisheries data, it provides an independent estimate of abundance that can be used to assess the validity of estimates from research vessel surveys.

Cohort analyses have previously been conducted on eastern Bering Sea yellowfin sole by Wakabayashi (1975), Wakabayashi et al. (1977), and Bakkala et al. (1981). The analysis presented here is an update of the latter analysis.

Methods

A FORTRAN program based on the equations of Pope (1972) was used for the cohort analysis.

Catch-at-age data used in the analysis for the years 1959-63 were from Wakabayashi (1975) and those for 1964-75 from Wakabayashi et al. (1977). For 1976-81, the catch in numbers at age was derived using catch data reported by commercial fisheries and age composition data collected by U.S. observers from these fisheries. Weight-length relationships and growth parameters used to convert catch weights to numbers of fish and numbers of fish from the cohort analysis to biomass were calculated from research survey data. Survey data were used because weight data collected by U.S. observers from the fishery appeared to be variable and inconsistent.

For 1976 to 1979, a single overall annual age distribution was used because age distributions were not available from some elements of the fishery. Applying a single annual age distribution to all elements of the fishery was thought to create less bias than applying age distributions from one element of the fishery to catches in another. Biological sampling was more complete in 1980 and 1981 and catches were apportioned to age by nation, vessel class, and quarter year in these years. The catch-at-age data used in the analysis are shown in Table 4.

Natural Mortality

An estimate of natural mortality (M), either age specific or an average value for all ages, is a necessary input variable for the cohort analysis. Natural mortality has not been clearly defined for yellowfin sole. Fadeev (1970) estimated M as 0.25 based on catch curve analysis of samples collected in 1958 prior to the development of an intensive fishery. In the same paper, he reported M as 0.16 during the early 1960's following the intense exploitation of the population in 1959-62, based on comparisons of total mortality and effort between years. Wakabayashi (1975) used the Alverson and Carney (1975) procedure to estimate M as 0.25. However, natural mortality for yellowfin sole is likely much lower than 0.25 based on comparisons with other flatfish with similar life histories (Table 5).

Bakkala et al. (1981) ran cohort analyses varying M between 0.08 and 0.26 in increments of 0.02. They used an M of 0.12 based on the findings that the biomass of age 6 and older fish showed a decrease in abundance between 1978 and 1979 using M values greater than 0.14, while an M of 0.12 produced a positive trend in biomass comparable to that shown by research vessel surveys. In the present analysis M was estimated by a least squares analysis (Bledsoe and Lynde 1982). Catch-at-age data were fitted to pair trawl effort data while varying the catchability coefficient (q) and M simultaneously. The best fit to the data (the point where the residual variance was minimal) occurred with an M of 0.12 and q of 0.000067. The value of 0.12 used by Bakkala et al. (1981) was, therefore, retained as the estimate of M.

Table 4.--Catch in number of yellowfin sole in the eastern Bering Sea, 1959-81.

AGE	1959	1960	1961	1962	1963	1964
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	6723594
4	0	0	12211000	20000	0	11670211
5	43000	11000	25665000	12791000	1387000	19719090
6	6283000	25642000	23507000	138609000	25592000	50360512
7	24204000	120295000	158641000	256176000	35328000	133465272
8	55879000	175910000	422399000	361625000	63990000	233559552
9	112106000	248989000	591953000	356925000	94275000	55570601
10	158045000	306535000	550774000	273029000	89065000	62969061
11	143862000	291699000	369201000	184237000	63595000	66999397
12	95054000	219639000	197358000	115955000	40318000	46275989
13	53197000	141313000	92785000	70104000	24975000	14672095
14	27940000	83469000	41263000	41784000	15618000	5939147
15	14483000	47679000	18227000	25082000	9815000	1151574
16	7579000	27251000	8264000	15386000	6144000	259040
17	4057000	15924000	3922000	9728000	3830000	0

AGE	1965	1966	1967	1968	1969	1970
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	598	5014	87464	0	1285	0
5	90509	35104	87464	238488	1043630	297410
6	1589045	811237	13825254	1362450	8367549	14054843
7	5639029	14580560	38051627	28933263	6928205	68608781
8	44352622	43836654	99373388	30452429	96990292	100576270
9	88833776	98842534	147145423	68903375	95491015	116358621
10	22124437	156105171	161736086	77131269	173961524	33464440
11	28150136	35307411	210406160	77338053	162682588	54684283
12	31096470	36809015	29106300	66943150	148507158	75496141
13	20079130	38612673	24403737	20036129	77383376	46522144
14	6183445	22385463	30626707	11410842	25164822	53240382
15	2127964	6720280	19690784	9849302	9273980	3491150
16	323315	1931171	7237420	6684740	6035161	2338472
17	260968	527349	1181296	3815143	8041342	0

AGE	1971	1972	1973	1974	1975	1976
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	80781	0	0	0	25974
5	190992	3861702	2725872	531754	502396	4467442
6	25464974	32756203	14271388	8448739	2896033	15246445
7	164834257	66426170	90269313	29532672	24721512	24882614
8	103298779	22441324	87217312	69979393	42327088	28648771
9	102127987	38100420	59427732	47770398	112219136	80128250
10	104085462	25018629	38651846	20367250	84126344	55635239
11	26949318	21883206	39891960	21747765	33730543	25713766
12	48856493	13816074	37660524	12316794	13410457	8311520
13	44422501	10807110	28522871	12009322	16042210	8285547
14	48937687	7032301	13667326	8241797	10861805	1740225
15	39448665	0	6966172	5002828	4797379	4337575
16	1608163	1193096	1356458	1801061	3674851	1220755
17	0	0	3287656	303444	976733	441550

AGE	1977	1978	1979	1980	1981
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	41642	0	0
4	380106	1560163	541340	206500	3510487
5	3522311	12730933	6162946	3251003	20190664
6	9578660	14103876	23194331	17797899	6757851
7	18650512	66837397	20654198	33140657	31066415
8	42546480	131677784	49428494	19740704	46191267
9	35679240	113767109	89612568	41251153	41740204
10	70547589	97791037	82949924	64094844	51734340
11	48273404	104343723	61254688	60753036	67242816
12	15812391	38879270	45056133	47678239	70640739
13	4738649	21592660	22902840	42362204	58389770
14	2888802	12294087	7120701	23223262	40197601
15	2179272	4493270	4080870	7353264	18477135
16	582828	2683481	1540737	10094428	5721428
17	253404	686472	1290887	4196986	4413815

Table 5.--Life history parameters of yellowfin sole and other flatfish.[a]

	North Sea sole	Yellowfin sole	Pacific halibut	American plaice
M	0.10	0.12	0.19	0.23
T_m (yr)[b]	3	9	12	13
$T_{0.01}$ (yr)[c]	14	17	23	30
K	0.39	0.12	0.13	0.09
L_{∞}	32.90	43.79	109.60	59.40

a/ Parameters for species other than yellowfin sole from various authors cited by Gunderson (1980).

b/ T_m = age at which 50% of the females in a cohort are mature.

c/ $T_{0.01}$ = age at which abundance is 1% of abundance at T_m.

Fishing Mortality

In addition to estimates of M, estimates of terminal fishing mortality (F) must be estimated for all ages in the last year of catch data used in the analysis and for the oldest age in prior years. Terminal F's for the last year of catch data (1981) were computed by adjusting the terminal F's for the corresponding age in 1979 (the last year in the cohort analysis by Bakkala et al. 1981) by the change in survey CPUE and the age structure measured by research surveys. This assumes that the survey measures the population age structure and accurately reflects abundance changes. After an initial trial, F's in the terminal year were adjusted until the estimated population age distribution approximated the age distribution of fully recruited fish (age 7 and older) observed in the survey. Terminal F's for the oldest age in years prior to 1981 were adjusted to approximate the computed values of the next youngest ages in the same year based on the assumption that catchabilities were similar. The terminal F's and the F values generated in the analysis are shown in Table 6.

Results

The results of the cohort analysis are given in Table 7 in terms of numbers and in Table 8 in terms of biomass. It should be noted that cohort analysis is based on numbers of fish and conversion to biomass requires weight-at-age data. In this analysis conversion to biomass was based on the average weight-at-age obtained from research vessel surveys since 1973 (Table 2). Therefore, actual biomass may have been higher or lower in past years if growth rates were different than shown by these averages.

The cohort analysis indicates that the biomass of age 7 and older yellowfin sole, in the early years of high exploitation (1959-60) was approximately 1.1-1.2 million t. At the end of this period of high exploitation (1962), the biomass had decreased to about half that level. The analysis shows that it remained at approximately this lower level through 1967 when there was a further decline to 273,000 t in 1972. Since then, the abundance has increased substantially due mainly to the recruitment to the population of the strong 1966-70 year-classes and the more recent series of strong year-classes spawned in 1973-76. In 1981, the abundance of age 7 and older yellowfin sole was estimated to be about 2.0 million t, the largest estimated biomass in the period 1959-81 based on results of the cohort analysis.

ABUNDANCE PROJECTIONS, 1982-89

Future trends in abundance of the yellowfin sole population and potential levels of harvest were examined using a numeric population simulator. The

Table 6.--Estimates of fishing mortality (F) by age for yellowfin sole of the eastern Bering Sea, 1959-81.

AGE	1959	1960	1961	1962	1963	1964	1965	1966	1967
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0065	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0072	0.0000	0.0000	0.0193	0.0000	0.0000	0.0001
5	0.0000	0.0000	0.0123	0.0085	0.0012	0.0211	0.0002	0.0000	0.0001
6	0.0036	0.0225	0.0313	0.0786	0.0195	0.0490	0.0019	0.0017	0.0193
7	0.0139	0.0811	0.1725	0.4961	0.0238	0.1232	0.0064	0.0203	0.0954
8	0.0386	0.1216	0.4069	0.6617	0.1995	0.1977	0.0504	0.0575	0.1714
9	0.1015	0.2206	0.6743	0.6510	0.3226	0.2436	0.0984	0.1390	0.2538
10	0.2006	0.3994	0.9561	0.6944	0.2986	0.3378	0.1322	0.2293	0.3218
11	0.2802	0.6202	1.0984	0.9263	0.3055	0.3497	0.2264	0.2935	0.4971
12	0.3114	0.8137	1.0657	1.2310	0.4721	0.3470	0.2473	0.4692	0.3813
13	0.3089	0.9478	0.9121	1.4357	0.8888	0.2845	0.2268	0.4987	0.5934
14	0.2886	1.0223	0.7343	1.4121	1.6322	0.4845	0.1700	0.3857	0.8635
15	0.2805	1.0317	0.5765	1.3583	1.7272	0.4187	0.2901	0.2576	0.6288
16	0.2401	1.1612	0.4353	1.3555	1.6000	0.1481	0.1799	0.4223	0.4413
17	0.2500	1.0300	0.4400	1.2870	1.6500	0.0000	0.2000	0.4500	0.4500

AGE	1968	1969	1970	1971	1972	1973	1974	1975	1976
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0004	0.0014	0.0003	0.0001	0.0024	0.0013	0.0002	0.0001	0.0022
6	0.0024	0.0156	0.0208	0.0330	0.0268	0.0100	0.0044	0.0010	0.0048
7	0.0471	0.0138	0.1570	0.3263	0.1038	0.0883	0.0238	0.0148	0.0096
8	0.0947	0.2013	0.2574	0.3405	0.0611	0.1767	0.0841	0.0396	0.0197
9	0.1580	0.4326	0.3590	0.4097	0.1847	0.2082	0.1271	0.1728	0.0902
10	0.1872	0.6682	0.2406	0.5719	0.1507	0.2641	0.0937	0.3135	0.1114
11	0.2290	0.6727	0.4109	0.2837	0.2020	0.3458	0.2129	0.2027	0.1357
12	0.2626	0.8146	0.6973	0.7172	0.2102	0.5698	0.1553	0.1802	0.0644
13	0.4466	0.4967	0.5878	1.1053	0.3032	0.7866	0.3231	0.2833	0.1480
14	0.5571	1.5963	0.6912	2.9743	0.4472	0.7034	0.4937	0.4926	0.0409
15	0.6877	1.1496	0.9558	1.7847	0.0000	0.9937	0.5468	0.5430	0.3377
16	0.4080	1.1500	0.9500	1.7800	0.1852	1.0630	0.6850	0.9229	0.2318
17	0.4000	1.1500	0.0000	0.0000	0.0000	1.0000	0.6500	0.9200	0.2300

AGE	1977	1978	1979	1980	1981
1	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0001	0.0003	0.0002	0.0000	0.0020
5	0.0025	0.0037	0.0016	0.0010	0.0047
6	0.0053	0.0115	0.0076	0.0051	0.0024
7	0.0067	0.0424	0.0193	0.0123	0.0101
8	0.0189	0.0551	0.0367	0.0212	0.0197
9	0.0283	0.0591	0.0444	0.0359	0.0525
10	0.0984	0.0929	0.0514	0.0373	0.0530
11	0.1225	0.1893	0.0712	0.0445	0.0460
12	0.1062	0.1260	0.1070	0.0670	0.0615
13	0.0437	0.1894	0.0934	0.1275	0.1005
14	0.0648	0.1401	0.0807	0.1187	0.1572
15	0.0607	0.1248	0.0580	0.1030	0.1200
16	0.0628	0.0909	0.0528	0.1820	0.1000
17	0.0630	0.0900	0.0530	0.1820	0.1036

Table 7.--Estimated numbers of yellowfin sole (billions of fish) in the eastern Bering Sea, 1959-81, based on cohort analysis.

AGE	1959	1960	1961	1962	1963	1964	1965	1966	1967
1	2.040	1.620	0.931	1.407	1.108	1.047	1.320	1.519	2.394
2	2.308	1.810	1.437	0.826	1.248	0.983	0.928	1.171	1.347
3	2.826	2.047	1.605	1.275	0.733	1.107	0.871	0.823	1.039
4	1.029	2.506	1.815	1.424	1.130	0.650	0.976	0.773	0.730
5	1.382	0.912	2.223	1.599	1.263	1.003	0.565	0.865	0.685
6	1.856	1.226	0.809	1.947	1.406	1.119	0.871	0.501	0.767
7	1.865	1.640	1.063	0.696	1.596	1.223	0.945	0.771	0.444
8	1.565	1.632	1.342	0.793	0.376	1.383	0.959	0.832	0.670
9	1.234	1.336	1.282	0.792	0.363	0.273	1.006	0.809	0.697
10	0.923	0.989	0.950	0.579	0.366	0.233	0.190	0.809	0.624
11	0.625	0.670	0.588	0.324	0.256	0.241	0.148	0.147	0.570
12	0.377	0.419	0.320	0.174	0.114	0.168	0.151	0.104	0.097
13	0.213	0.245	0.165	0.098	0.045	0.063	0.105	0.104	0.058
14	0.118	0.138	0.084	0.059	0.021	0.016	0.042	0.074	0.056
15	0.063	0.079	0.044	0.036	0.013	0.004	0.009	0.031	0.045
16	0.038	0.042	0.025	0.022	0.008	0.002	0.002	0.006	0.022
17	0.019	0.026	0.012	0.014	0.005	0.000	0.002	0.002	0.003
SUM=	18.482	17.337	14.695	12.064	10.051	9.513	9.089	9.343	10.250

AGE	1968	1969	1970	1971	1972	1973	1974	1975	1976
1	2.779	3.693	5.662	6.117	3.542	2.390	5.964	6.791	5.461
2	2.123	2.465	3.275	5.022	5.425	3.141	2.120	5.289	6.023
3	1.195	1.883	2.186	2.905	4.454	4.812	2.786	1.880	4.691
4	0.921	1.060	1.670	1.939	2.576	3.950	4.268	2.471	1.668
5	0.648	0.817	0.940	1.481	1.719	2.285	3.504	3.785	2.192
6	0.608	0.574	0.724	0.833	1.313	1.521	2.024	3.107	3.356
7	0.668	0.538	0.501	0.629	0.715	1.134	1.336	1.787	2.753
8	0.358	0.565	0.471	0.380	0.402	0.572	0.921	1.157	1.562
9	0.501	0.289	0.410	0.323	0.240	0.336	0.425	0.751	0.986
10	0.480	0.379	0.166	0.254	0.190	0.177	0.242	0.332	0.560
11	0.401	0.353	0.172	0.116	0.127	0.145	0.120	0.195	0.215
12	0.308	0.283	0.160	0.101	0.077	0.092	0.091	0.086	0.141
13	0.059	0.210	0.111	0.071	0.044	0.056	0.046	0.069	0.064
14	0.028	0.034	0.113	0.055	0.021	0.029	0.022	0.030	0.046
15	0.021	0.014	0.006	0.050	0.002	0.012	0.013	0.012	0.016
16	0.021	0.009	0.004	0.002	0.007	0.002	0.004	0.006	0.006
17	0.012	0.012	0.000	0.000	0.000	0.006	0.001	0.002	0.002
SUM=	11.130	13.177	16.571	20.276	20.856	20.659	23.885	27.751	29.743

AGE	1977	1978	1979	1980	1981
1	7.389	2.674	0.000	0.000	0.000
2	4.843	6.554	2.372	0.000	0.000
3	5.342	4.296	5.813	2.104	0.000
4	4.161	4.738	3.810	5.155	1.866
5	1.479	3.690	4.201	3.379	4.572
6	1.940	1.308	3.261	3.720	2.993
7	2.963	1.711	1.147	2.870	3.283
8	2.418	2.610	1.455	0.998	2.514
9	1.358	2.105	2.191	1.244	0.867
10	0.799	1.171	1.759	1.859	1.064
11	0.444	0.642	0.946	1.482	1.588
12	0.167	0.349	0.472	0.782	1.258
13	0.118	0.133	0.273	0.376	0.648
14	0.049	0.100	0.098	0.220	0.293
15	0.039	0.041	0.077	0.080	0.174
16	0.010	0.033	0.032	0.064	0.064
17	0.004	0.008	0.027	0.027	0.048
SUM=	33.524	32.163	27.932	24.359	21.232

Table 8.--Estimated biomass (in 1,000 t) of yellowfin sole in the eastern Bering Sea by age (with totals for all ages and ages 7 and above), 1959-81, based on cohort analysis.

AGE	1959	1960	1961	1962	1963	1964	1965	1966	1967
1	10.	8.	5.	7.	6.	5.	7.	8.	12.
2	21.	16.	13.	7.	11.	9.	8.	11.	12.
3	51.	37.	29.	23.	13.	20.	16.	15.	19.
4	34.	83.	60.	47.	37.	21.	32.	26.	24.
5	77.	51.	124.	90.	71.	56.	32.	48.	38.
6	163.	108.	71.	171.	124.	98.	77.	44.	68.
7	209.	184.	119.	78.	179.	137.	106.	86.	50.
8	211.	220.	181.	107.	51.	187.	129.	112.	90.
9	196.	212.	204.	126.	58.	43.	160.	129.	111.
10	171.	183.	176.	107.	68.	43.	35.	150.	115.
11	131.	141.	124.	68.	54.	51.	31.	31.	120.
12	88.	97.	74.	40.	26.	39.	35.	24.	23.
13	56.	65.	43.	26.	12.	17.	28.	28.	15.
14	33.	39.	24.	16.	6.	5.	12.	21.	16.
15	19.	23.	13.	11.	4.	1.	3.	9.	13.
16	13.	15.	9.	8.	3.	1.	1.	2.	8.
17	7.	10.	4.	5.	2.	0.	1.	1.	1.
SUM	1491.	1492.	1273.	938.	723.	733.	711.	744.	735.
SUM 7+	1135.	1189.	971.	592.	461.	523.	540.	593.	562.

AGE	1968	1969	1970	1971	1972	1973	1974	1975	1976
1	14.	18.	28.	31.	18.	12.	30.	34.	27.
2	19.	22.	29.	45.	49.	28.	19.	48.	54.
3	22.	34.	39.	52.	80.	87.	50.	34.	84.
4	30.	35.	55.	64.	85.	130.	141.	82.	55.
5	36.	46.	53.	83.	96.	128.	196.	212.	123.
6	53.	51.	64.	73.	116.	134.	178.	273.	295.
7	75.	60.	56.	70.	80.	127.	150.	200.	308.
8	48.	76.	64.	51.	54.	77.	124.	156.	211.
9	80.	46.	65.	51.	38.	53.	68.	119.	157.
10	89.	70.	31.	47.	35.	33.	45.	61.	104.
11	84.	74.	36.	24.	27.	30.	25.	41.	45.
12	71.	66.	37.	24.	18.	21.	21.	20.	33.
13	16.	55.	29.	19.	12.	15.	12.	18.	17.
14	8.	9.	32.	15.	6.	8.	6.	8.	13.
15	6.	4.	2.	15.	1.	3.	4.	4.	5.
16	8.	3.	1.	1.	3.	1.	1.	2.	2.
17	4.	5.	0.	0.	0.	2.	0.	1.	1.
SUM	664.	675.	622.	666.	717.	890.	1071.	1314.	1534.
SUM 7+	489.	469.	353.	317.	273.	371.	456.	631.	895.

AGE	1977	1978	1979	1980	1981
1	37.	13.	0.	0.	0.
2	44.	59.	21.	0.	0.
3	96.	77.	105.	38.	0.
4	137.	156.	126.	170.	62.
5	83.	207.	235.	189.	256.
6	171.	115.	287.	327.	263.
7	332.	192.	128.	321.	368.
8	326.	352.	196.	135.	339.
9	216.	335.	348.	198.	138.
10	148.	217.	326.	344.	197.
11	93.	135.	199.	311.	334.
12	39.	81.	109.	181.	292.
13	31.	35.	72.	99.	171.
14	14.	28.	27.	62.	82.
15	12.	12.	23.	24.	51.
16	4.	12.	11.	23.	23.
17	2.	3.	10.	10.	17.
SUM	1783.	2029.	2224.	2432.	2593.
SUM 7+	1216.	1401.	1450.	1708.	2012.

simulation model predicts age specific abundance in future years through a population decay function:

$$N_{(i+1,j+1)} = N_{ij}\, e^{-(M+F)}$$

where N_{ij} = number of age i in year j

$N_{(i+1,j+1)}$ = number of age i in the following year.

The decay function projects numbers at age from a base year using estimates of natural (M) and fishing (F) mortality and recruitment.

The estimate of natural mortality used in the simulation was the same as that used in the cohort analysis (0.12). Two estimates of recruitment were used: 1.403 billion fish, which is the average recruitment at age 7 in 1959-81 from the cohort analysis, and 1.074 billion fish, which is the average abundance at age 7 in this same period of years, excluding the exceptionally strong year-classes of 1969, 1970, 1973, and 1974. These values are relatively conservative. For example, during the period of 1973-81 when population abundance was increasing rapidly, average recruitment at age 7 was 2.109 billion fish.

The simulations were carried out under four levels of fishing mortality corresponding to exploitation rates of 0.05, 0.10, 0.15, and 0.20. In the recent period of 1977-81, exploitation rates have averaged about 0.07 based on the estimates of abundance for that period from the cohort analysis and 0.06 based on abundance estimates from resource assessment surveys. A simulation was also run using a constant catch of 214,500 t, which is an estimate of maximum sustainable yield (MSY) for yellowfin sole (Bakkala et al. 1981).

The projections derived from these input data are given in Tables 9-12 and include estimates of abundance for ages 7-17 (ages fully recruited to research vessel catches), ages 8-17 (major ages taken by the commercial fishery), rates of exploitation (E) and fishing mortality (F), and estimated mean weight of individual fish in the fishable population.

The simulations indicate that population abundance will remain high through at least 1985 under most of the proposed conditions. The abundance of the fishable population (ages 8-17) may remain as high as 2.0 million t, if exploitation rates remain low (0.05) and recruitment is at the higher average level (1.403 billion). Even at an exploitation rate as high as 0.15 (Tables 9 and 10) or with a constant catch of 214,500 t (Tables 11 and 12) the exploitable population would be expected to range between 1.4 and 1.7 million t in 1985. Only if exploitation rates were allowed to reach 0.20 would the fishable stock decline fairly rapidly, falling to 1.2-1.3 million t by 1985 (Tables 9 and 10).

Following 1985, the simulations indicate that population abundance would continue to decline at the given levels of recruitment. The fishable population could decline to about 1.0 million t or less, if exploitation rates exceed 0.10 after 1985.

ECOSYSTEM SIMULATION OF LONG-TERM YIELD

Results presented thus far such as those from the cohort analysis and numeric simulation model are based on single species population dynamic models and do not account for the interactions of yellowfin sole with other components of the ecosystem. The catch levels suggested by these single species models may not be the most appropriate when consideration is given to their influence

Table 9.--Forecast of yellowfin sole abundance in the eastern Bering Sea, 1982-89, under varying levels of exploitation (E), with natural mortality (M) = 0.12, and recruitment the lower estimate for 1959-81. Projections are made for ages 7-17 (ages fully recruited to research vessel catches) and ages 8-17 (principal ages in commercial trawl catches).

	Estimated biomass						
Year	Ages 7-17 (1,000 t)	Ages 8-17 (1,000 t)	Recruits (millions)	Catch (1,000 t)	E 1/	F 2/	Mean individual fish weight (kg)
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,048.8	1,928.5	1,074.0	96.4	0.050	0.049	0.198
1983	2,069.3	1,949.0	1,074.0	97.5	0.050	0.049	0.208
1984	2,051.7	1,931.4	1,074.0	96.6	0.050	0.049	0.218
1985	2,010.8	1,890.5	1,074.0	94.5	0.050	0.049	0.227
1986	1,921.2	1,800.9	1,074.0	90.0	0.050	0.049	0.229
1987	1,754.8	1,634.5	1,074.0	81.7	0.050	0.049	0.222
1988	1,576.8	1,456.5	1,074.0	72.8	0.050	0.049	0.215
1989	1,514.9	1,394.6	1,074.0	69.7	0.050	0.049	0.222
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,048.8	1,928.5	1,074.0	192.8	0.100	0.107	0.192
1983	1,966.7	1,846.4	1,074.0	184.6	0.100	0.107	0.207
1984	1,861.1	1,740.8	1,074.0	174.1	0.100	0.107	0.217
1985	1,748.9	1,628.7	1,074.0	162.9	0.100	0.107	0.224
1986	1,612.2	1,491.9	1,074.0	149.2	0.100	0.107	0.224
1987	1,434.7	1,314.4	1,074.0	131.4	0.100	0.107	0.216
1988	1,270.6	1,150.3	1,074.0	115.0	0.100	0.107	0.208
1989	1,204.0	1,083.7	1,074.0	108.4	0.100	0.107	0.213
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,048.8	1,928.5	1,074.0	289.3	0.150	0.167	0.192
1983	1,866.7	1,746.4	1,074.0	262.0	0.150	0.167	0.207
1984	1,685.4	1,565.1	1,074.0	234.8	0.150	0.167	0.216
1985	1,520.5	1,400.2	1,074.0	210.0	0.150	0.167	0.221
1986	1,356.1	1,235.9	1,074.0	185.4	0.150	0.167	0.219
1987	1,181.6	1,061.3	1,074.0	159.2	0.150	0.167	0.210
1988	1,037.7	917.4	1,074.0	137.6	0.150	0.167	0.201
1989	975.7	855.4	1,074.0	128.3	0.150	0.167	0.204
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,048.8	1,928.5	1,074.0	385.7	0.200	0.232	0.192
1983	1,764.9	1,644.6	1,074.0	328.9	0.200	0.232	0.206
1984	1,517.0	1,396.7	1,074.0	279.3	0.200	0.232	0.214
1985	1,313.7	1,193.4	1,074.0	238.7	0.200	0.232	0.217
1986	1,136.5	1,016.2	1,074.0	203.2	0.200	0.232	0.214
1987	974.5	854.2	1,074.0	170.8	0.200	0.232	0.203
1988	854.1	733.8	1,074.0	146.8	0.200	0.232	0.194
1989	801.4	681.1	1,074.0	136.2	0.200	0.232	0.195

1/ E = Exploitation rate for fished population (ages 8-17).
2/ F = Fishing mortality.

Table 10.--Forecast of yellowfin sole abundance in the eastern Bering Sea, 1982-89, under varying levels of exploitation (E), natural mortality = 0.12, and recruitment the higher estimate for 1959-81. Projections are made for ages 7-17 (ages fully recruited to research vessel catches) and ages 8-17 (principal ages in commercial trawl catches).

Year	Estimated biomass Ages 7-17 (1,000 t)	Estimated biomass Ages 8-17 (1,000 t)	Recruits (millions)	Catch (1,000 t)	E [1]	F [2]	Mean individual fish weight (kg)
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,085.6	1,928.5	1,403.0	96.4	0.050	0.049	0.192
1983	2,145.5	1,988.4	1,403.0	99.4	0.050	0.049	0.205
1984	2,167.1	2,010.0	1,403.0	100.5	0.050	0.049	0.214
1985	2,164.7	2,007.6	1,403.0	100.4	0.050	0.049	0.221
1986	2,112.0	1,954.9	1,403.0	97.7	0.050	0.049	0.222
1987	1,980.0	1,822.9	1,403.0	91.1	0.050	0.049	0.216
1988	1,835.1	1,678.0	1,403.0	83.9	0.050	0.049	0.210
1989	1,803.0	1,645.9	1,403.0	82.3	0.050	0.049	0.217
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,085.6	1,928.5	1,403.0	192.8	0.100	0.107	0.192
1983	2,043.0	1,885.8	1,403.0	188.6	0.100	0.107	0.205
1984	1,974.3	1,817.1	1,403.0	181.7	0.100	0.107	0.213
1985	1,896.4	1,739.3	1,403.0	173.9	0.100	0.107	0.218
1986	1,790.7	1,633.5	1,403.0	163.4	0.100	0.107	0.218
1987	1,640.5	1,483.3	1,403.0	148.3	0.100	0.107	0.210
1988	1,501.1	1,344.0	1,403.0	134.4	0.100	0.107	0.204
1989	1,455.6	1,298.4	1,403.0	129.8	0.100	0.107	0.208
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,085.6	1,928.5	1,403.0	289.3	0.150	0.167	0.192
1983	1,942.9	1,785.8	1,403.0	267.9	0.150	0.167	0.204
1984	1,796.4	1,639.3	1,403.0	245.9	0.150	0.167	0.211
1985	1,661.9	1,504.8	1,403.0	225.7	0.150	0.167	0.214
1986	1,523.5	1,366.4	1,403.0	205.0	0.150	0.167	0.212
1987	1,370.4	1,213.3	1,403.0	182.0	0.150	0.167	0.204
1988	1,244.9	1,087.7	1,403.0	163.2	0.150	0.167	0.197
1989	1,197.5	1,040.4	1,403.0	156.1	0.150	0.167	0.200
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,085.6	1,928.5	1,403.0	385.7	0.200	0.232	0.192
1983	1,841.1	1,684.0	1,403.0	336.8	0.200	0.232	0.204
1984	1,625.8	1,468.7	1,403.0	293.7	0.200	0.232	0.209
1985	1,449.2	1,292.1	1,403.0	258.4	0.200	0.232	0.210
1986	1,293.4	1,136.3	1,403.0	227.3	0.200	0.232	0.207
1987	1,147.9	990.8	1,403.0	198.2	0.200	0.232	0.197
1988	1,040.8	883.6	1,403.0	176.7	0.200	0.232	0.190
1989	998.0	840.9	1,403.0	168.2	0.200	0.232	0.191

1/ E = Exploitation rate for fished population (ages 8-17).
2/ F = Fishing mortality.

Table 11.--Forecast of yellowfin sole abundance in the eastern Bering Sea, 1982-89, with constant catches of 214,500 t, natural mortality = 0.12, and recruitment the lower estimate for 1959-81. Projections are made for ages 7-17 (ages fully recruited to research vessel catches) and ages 8-17 (principal ages in commercial trawl catches).

Year	Estimated biomass Ages 7-17 (1,000 t)	Estimated biomass Ages 8-17 (1,000 t)	Recruits (millions)	Catch (1,000 t)	1/ E	2/ F	Mean individual fish weight (kg)
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,048.8	1,928.5	1,074.0	214.5	0.111	0.120	0.193
1983	1,944.5	1,824.3	1,074.0	214.5	0.118	0.128	0.207
1984	1,808.7	1,688.4	1,074.0	214.5	0.127	0.139	0.217
1985	1,658.4	1,538.1	1,074.0	214.5	0.139	0.154	0.223
1986	1,478.5	1,358.2	1,074.0	214.5	0.158	0.177	0.222
1987	1,258.6	1,138.3	1,074.0	214.5	0.188	0.216	0.213
1988	1,048.2	927.9	1,074.0	214.5	0.231	0.274	0.203
1989	906.3	786.0	1,074.0	214.5	0.273	0.334	0.203

1/ E = Exploitation rate for fished population (ages 8-17).
2/ F = Fishing mortality.

Table 12.--Forecast of yellowfin sole abundance in the eastern Bering Sea, 1982-89, with constant catches of 214,500 t, natural mortality = 0.12, and recruitment the higher estimate for 1959-81. Projections are made for ages 7-17 (ages fully recruited to research vessel catches) and ages 8-17 (principal ages in commercial trawl catches).

	Estimated biomass						
Year	Ages 7-17 (1,000 t)	Ages 8-17 (1,000 t)	Recruits (millions)	Catch (1,000 t)	1/ E	2/ F	Mean individual fish weight (kg)
1981	2,012.1	1,644.5	3,282.0	97.3	0.059	0.060	0.193
1982	2,085.6	1,928.5	1,403.0	214.5	0.111	0.120	0.192
1983	2,020.8	1,863.6	1,403.0	214.5	0.115	0.125	0.205
1984	1,925.9	1,768.8	1,403.0	214.5	0.121	0.132	0.212
1985	1,817.4	1,660.2	1,403.0	214.5	0.129	0.142	0.217
1986	1,677.3	1,520.1	1,403.0	214.5	0.141	0.156	0.216
1987	1,494.0	1,336.8	1,403.0	214.5	0.160	0.180	0.208
1988	1,316.2	1,159.0	1,403.0	214.5	0.185	0.212	0.200
1989	1,208.2	1,051.1	1,403.0	214.5	0.204	0.237	0.202

1/ E = Exploitation rate for fished population (ages 8-17).
2/ F = Fishing mortality.

on the stock size of yellowfin sole and the subsequent influence of this stock size on other species in the ecosystem. The Prognostic Bulk Biomass Model (PROBUB) developed by Laevastu and Favorite (1978) has been used to examine these interactions and can be used to estimate long-term equilibrium yields for yellowfin sole that are compatible with the overall marine ecosystem.

The PROBUB Model

PROBUB is a dynamic trophic model of the major components (marine birds, marine mammals, groundfish, pelagic fish, and benthic organisms) of the Bering Sea ecosystem. It is designed to evaluate the interrelations of these various components of the ecosystem. The model may be used to:

1. determine the sustainable biomass of the various marine ecological groups (with emphasis on fisheries resources).

2. assess the quantitative relationships between biomasses of the different ecological groups and the distribution of biomass with age among different species or groups; and

3. evaluate the stability of the ecosystem and seek levels of sustainable catches that will maintain stability.

The PROBUB model is described by Laevastu and Larkins (1981). The model determines predatory relationships and, consequently, the amount of each species or ecological group that must be present to sustain the various predators. The model computes changes in abundance and distribution of each of the species or species groups through monthly periods in five geographical subregions (Figure 6). The type of input data for PROBUB is described in Laevastu et al. (1980).

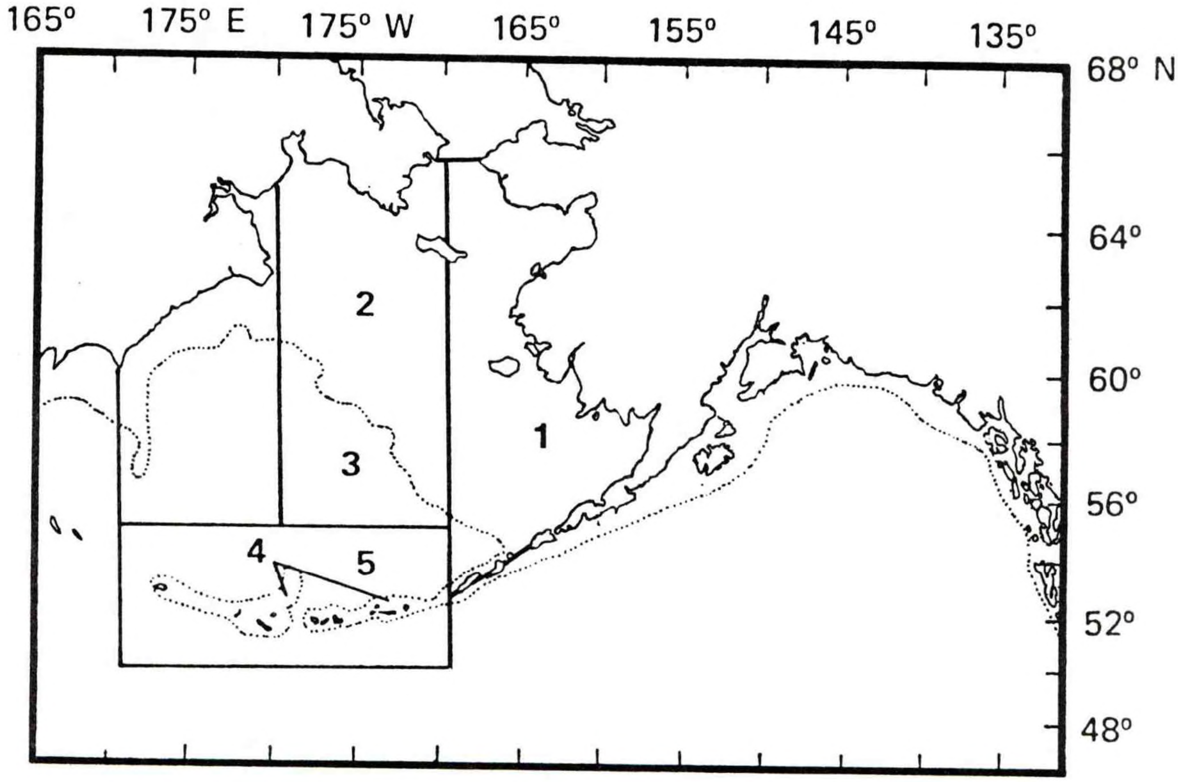


Figure 6.--Map of the Bering Sea showing delineation of the five geographical areas for ecosystem simulation. Dotted line shows the 200-m isobath.

Simulations

To estimate long-term sustainable yields for yellowfin sole, the PROBUB model was first used to simulate the dynamics of the Bering Sea ecosystem until it reached equilibrium. This initial simulation estimated equilibrium biomass of the various fish groups, given the estimated amount of apex (marine mammals and birds) predators and trophodynamic linkages among the various ecological groups. Biomass, growth, mortality, and other necessary input data used have been described by Laevastu and Larkins (1981).

After the ecosystem reached equilibrium, simulations were run to determine the effect of three levels of catch on the yellowfin sole population. Simulation series A assumes that annual catch levels for the major fisheries in the Bering Sea will remain constant at the 1980 level. These catch data, including estimates of catches discarded at sea and not reported, are tabulated in Table 13.

In simulation series B and C, the 1980 catches were increased for selected species by the following factors:

Species group	Series B factor	Series C factor
Greenland turbot, Pacific halibut	1.6	1.6
Flathead sole, arrowtooth flounder	1.4	1.4
Yellowfin sole, rock sole, Alaska plaice	1.4	2.0
Other flatfish	1.6	2.2
Pacific cod, saffron cod	1.0	1.6
Walleye pollock	1.4	1.2
Pacific ocean perch, other rockfish	0.8	1.0
Pacific herring	1.5	1.0
Atka mackerel	2.0	1.0
Squids	2.5	1.0

Table 13.--Reported 1980 catch data and estimated discards (in metric tons) of major fish and shellfish groups used for simulation of the Bering Sea ecosystem by the PROBUB model.

Species	Area 1	2	3	4	5	Total
	---------------------------- t	----------------------------				
Greenland turbot, halibut	13,981	11,272	3,180	2,728	699	31,860
Flathead sole, arrowtooth flounder	16,903	14,028	638	4,347	358	36,274
Yellowfin sole, rock sole, Alaska plaice	62,236	30,813	3,138	9,010	2,263	107,460
Other flatfish	7,171	4,440	714	2,163	467	14,955
Cottids	13,301	3,794	228	1,598	269	19,190
Pacific cod, saffron cod	46,667	21,959	9,403	14,913	7,675	100,617
Sablefish	2,563	2,418	1,560	2,035	519	9,095
Walleye pollock	466,686	404,569	242,457	117,452	275,064	1,506,228
Rockfish	9,269	5,017	4,582	4,621	6,036	29,525
Pacific herring	11,188	5,859	4,928	4,483	5,270	31,728
Capelin, smelt, sand lance	2,605	1,306	1,438	991	1,549	7,889
Atka mackerel	9,348	1,814	11,380	10,459	16,213	49,214
Salmon	40,805	4,716	4,818	6,014	27,477	83,830
Squid	9,400	5,406	39,105	7,950	45,719	107,580
Crabs	28,760	18,483	350	7,607	389	55,589
Shrimps	3,196	2,070	208	816	107	6,397

The model includes yellowfin sole as a component of a small flatfish group--yellowfin sole, rock sole (Lepidopsetta bilineata), and Alaska plaice (Pleuronectes quadrituberculatus). Yellowfin sole, however, makes up about 80% of the total catches of these three species. The levels of catch for yellowfin sole in the three simulation runs were, therefore, 86,000 t (simulation series A); 120,000 t (simulation series B); and 175,000 t (simulation series C).

Results

Equilibrium Biomass

Laevastu and Larkins (1981) have summarized results of simulations from the PROBUB model to show estimates of minimum and maximum equilibrium biomass of the major species of fish and shellfish in the eastern Bering Sea (Table 14). These estimates were computed as follows:

1. minimum equilibrium biomass was computed using the lowest estimated food requirements and highest estimated growth rates of predators, and

2. maximum equilibrium biomass was computed using the highest estimated food requirements and lowest estimated growth rates of predators.

Assuming that yellowfin sole made up about 80% of the small flatfish category, equilibrium biomass for yellowfin sole would range from 880,000 t to 1,328,000 t (Table 14).

Sustainable Yield

Changes in the biomass of the yellowfin sole population with the three simulated catch levels from an initial equilibrium level with respect to the ecosystem are shown in Table 15 and Figure 7. The results indicate that constant catches at any of the three levels will maintain the biomass of yellowfin

Table 14.--Equilibrium and mean exploitable biomasses of major groups of fish and shellfish in the eastern Bering Sea as estimated by the PROBUB model (from Laevastu and Larkins 1981, Table 9).

Species/ecological group designation	Estimated maximum equilibrium biomass (1,000 t)	Estimated minimum equilibrium biomass (1,000 t)
Halibut and Greenland turbot	585	400
Flathead sole, arrowtooth flounder	875	650
Yellowfin sole, rock sole, Alaska plaice	1,660	1,100
Other Flatfish	1,160	850
Cottids	4,438	4,000
Pacific cod	1,468	1,000
Sablefish	183	120
Walleye pollock	15,165	8,000
Rockfish	1,825	1,000
Pacific herring	2,327	1,500
Capelin	5,149	3,500
Atka mackerel	1,438	1,100
Salmon	(73)	(50)
Squid	2,310	1,200
Crab	1,225	800
Shrimp	1,792	900

Table 15.--Effects of three catch levels of yellowfin sole on the size of its population biomass.

Year	Simulation Run A Catch = 86,000 t	Simulation Run B Catch = 120,000 t	Simulation Run C Catch = 175,000 t
	1,000 t		
1	1154	1157	1157
2	1120	1114	1091
3	1163	1134	1066
4	1265	1206	1095
5	1309	1250	1106
6	1302	1215	1054
7			
8	1249	1144	977
9	1249	1118	950
10	1293	1138	979
11	1315	1155	1009
12	1282	1130	998

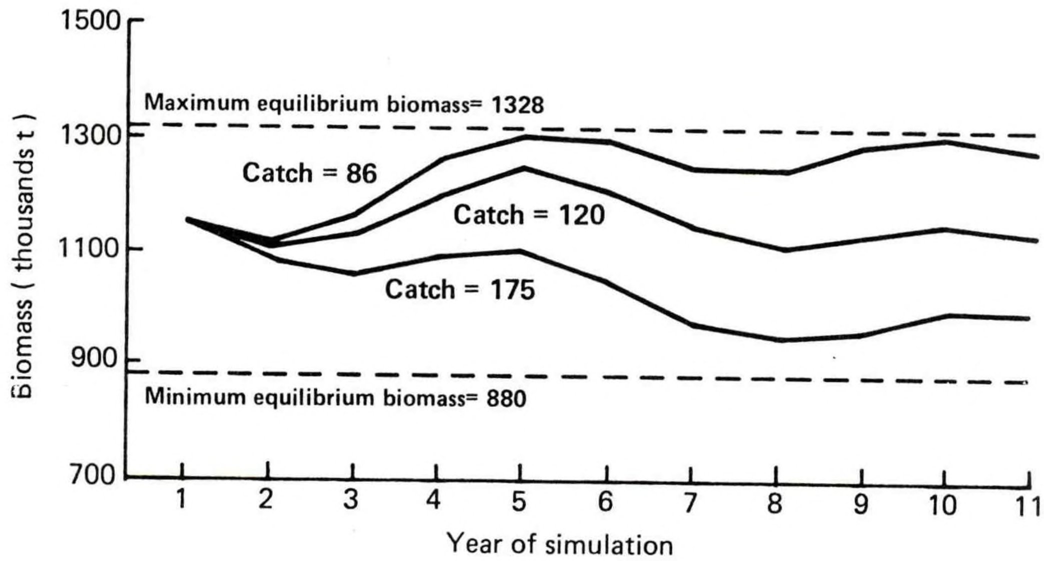


Figure 7.--Results of ecosystem simulation of the yellowfin sole biomass given three levels of yellowfin sole catch. Catch and biomass numbers are expressed in thousand metric tons.

sole within the bounds of its maximum and minimum equilibrium biomass. The 1980 catch of about 86,000 t would allow the population to increase toward the maximum equilibrium biomass. A higher catch (120,000 t) would cause little change while a still higher simulated catch (175,000 t) may reduce the population towards the minimum sustainable level.

The PROBUB model simulations indicate that intermediate levels of population abundance maintain ecosystem stability and at these levels of abundance, the yellowfin sole resource can sustain catches of 86,000-175,000 t. The population can be expected to fluctuate above and below the equilibrium biomass due to natural causes, as is the case presently. The current biomass of 2.0 million t or more is approximately twice the estimated equilibrium biomass. Advantage of these periods of high abundance can be taken by increasing catches beyond those possible under equilibrium biomass conditions.

DISCUSSION

Results from the cohort analysis and numeric population simulator are highly dependent on the value of natural mortality as well as levels of recruitment used. If natural mortality is greater than 0.12, then population abundance in 1959-81 would have been higher than shown by the cohort analysis (Tables 7 and 8). Conversely, projected abundance from the numeric population simulator may be overestimated if natural mortality is higher than 0.12 (Tables 9-12). The value of 0.12 simulates results from resource assessment surveys and was the most appropriate value according to a least squares analysis based on the method of Bledsoe and Lynde (1982). Examination of catch curves indicate that M increases with age rather than being constant. Had age specific M values been used, the population estimates in the earlier years examined in the cohort analysis would have been somewhat larger. Age specific rates have not yet been determined but are being studied.

Indications from the cohort analysis that natural mortality may be lower than the previously estimated 0.25 has implications in the determination of long-term sustainable yields. Current estimates of MSY, using a natural mortality value of 0.25, range from 169,000-260,000 t, with a mid-point of 214,500 t. If natural mortality was nearer to 0.12, the yield equation would indicate that MSY is only about half the above estimate, or 107,000 t.

Abundance estimates from resource assessment surveys are believed to be relatively accurate for the portion of the yellowfin sole population sampled. The bottom dwelling nature of the species and the rather uniform and static distribution of the population during late spring and summer months, when surveys are normally conducted, creates conditions that are conducive to estimating abundance from trawl assessment methods. The consistency of trends in abundance and duplication of results from year to year (Table 3, Figure 5) provides evidence of the reliability of assessment methods. These methods, however, underestimate the abundance of the total population to some degree because a portion of the population occupies shallow nearshore waters not sampled. Additionally, a catchability coefficient of 1:0 (all fish in the path of the trawl are caught) is assumed in deriving abundance estimates. If the catchability coefficient varies above (from herding affects of the trawl rigging) or below 1.0, then abundance of the sampled population would be inaccurately assessed. However, results of the cohort analysis (Table 8) are supportive of results from surveys indicating that abundance of the population is at least as high as 2.0 million t. Indications from age composition data and from the numeric population simulator are that abundance will remain high at least through the mid-1980's under moderate levels of exploitation (≤ 0.15).

Based on these findings, it is believed that the resource can sustain catches of at least 200,000 t annually until 1985. There is no indication from the projections that this level of exploitation would substantially reduce the abundance of the population within the next 4 yr.

The PROBUB ecosystem model suggests that the yellowfin sole population can be exploited at a sustainable level of about 175,000 t per year.

The results of this report, therefore, suggest that because of the present high level of abundance, the yellowfin sole resource can be exploited at about 200,000 t annually until at least 1985. At average levels of abundance, however, the resource may only sustain catches of 175,000 t or less annually.

REFERENCES CITED

Alverson, D. L., and M. I. Carney. 1975. A graphic review of the growth and decay of population cohorts. J. Cons. Int. Explor. Mer 36:133-43.

Alverson, D. L., and W. T. Pereyra. 1969. Demersal fish explorations in the northeastern Pacific Ocean--an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. J. Fish. Res. Board. Can. 26:1985-2001.

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. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Boulevard East, Seattle, WA 98112. (Submitted to the International North Pacific Fisheries Commission in October 1980.)

Bledsoe, C. J., and C. M. Lynde. 1982. A least squares technique for estimates of natural mortality and catchability. Unpubl. manuscr., Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Boulevard East, Seattle, WA 98112.

Fadeev, N. S. 1970. Promysel i biologicheskaia kharakteristika zheltoperoi kambaly vostochnoi chasti Beringova moria (The fishery and biological characteristics of yellowfin soles in the eastern part of the Bering Sea). Tr. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 70 (Izv. Tikhookean. Nauchno-Issled. Rybn. Khoz. Okeanogr. 7): 327-390. In Russian. (Transl. by Isr. Program Sci. Transl., 1972, p. 332-396 in P.A. Moiseev (editor), Soviet fisheries investigations in the northeastern Pacific, Part 5, avail. U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, VA, as TT 71-50127.)

French, R., R. Nelson, Jr., J. Wall, J. Berger, and B. Gibbs. 1981. Summaries of provisional foreign groundfish catches (metric tons) in the northeast Pacific Ocean and Bering Sea, 1980. Unpubl. rep., 188 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

French, R., R. Nelson, Jr., J. Wall, J. Berger, and B. Gibbs. 1982. Summaries of provisional foreign and joint-venture groundfish catches (metric tons) in the northeast Pacific ocean and Bering Sea, 1981. Unpubl. rep., 183 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Gunderson, D. R. 1980. Using r-k selection theory to predict natural mortality. Can. J. Fish. Aquat. Sci. 37:2266-2271.

International Pacific Halibut Commission. 1975. Items of information on the halibut fishery in the Bering Sea and the northeastern Pacific Ocean. Unpubl. manuscr., 37 p. International Pacific Halibut Commission, Post Office Box 5009, University Station, Seattle, WA 98105.

International Pacific Halibut Commission. 1980. Items of information on the halibut fishery in the Bering Sea and the northeastern Pacific Ocean. Unpubl. manuscr., 52 p. International Pacific Halibut Commission, Post Office Box 5009, University Station, Seattle, WA 98105.

Laevastu, T., and F. Favorite. 1978. Numerical evaluation of marine ecosystems. Part I. Deterministic Bulk Biomass Model (BBM). Processed Rep., 22 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Laevastu, T., and H. A. Larkins. 1981. Marine fisheries ecosystem. Fishing News Book, Ltd., Farnham, Surrey, England. 162 p.

Laevastu, T., and P. Livingston. 1980. Basic inputs to PROBUB model for the eastern Bering Sea and western Gulf of Alaska. NWAFC Processed Rep. 80-3, 28 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Pope, J.G. 1972. An investigation of the accuracy of virtual population analysis using cohort analysis. Int. Comm. Northwest Atl., Fish. Res. Bull. 9:65-74.

Smith, G.B., and R.G. Bakkala. Demersal fish resources of the eastern Bering Sea: spring 1976. U.S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF-754, 129 p.

Wakabayashi, K. 1974. Studies on resources of the yellowfin sole in the eastern Bering Sea. I. Biological characters. Unpubl. manuscr., 77 p. Far Seas Fisheries Research Laboratory, Fishery Agency of Japan, 1000 Orido, Shimizu 424, Japan.

Wakabayashi, K. 1975. Studies on resources of yellowfin sole in the eastern Bering Sea. Unpubl. manuscr., 22 p. Far Seas Fisheries Research Laboratory, Fishery Agency of Japan, 1000 Orido, Shimizu 424, Japan.

Wakabayashi, K., and R. Bakkala. 1978. Estimated catches of flounders by species in the Bering Sea updated through 1976. Unpubl. rep., 14 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. (Document submitted to the International North Pacific Fisheries Commission in October 1978).

Wakabayashi, K., R.G. Bakkala, and M.S. Alton, 1982. Methods of the U.S.-Japan demersal trawl survey. In R.G. Bakkala and K. Wakabayashi (editors), Results of cooperative U.S.-Japan groundfish investigations in the Bering Sea during May-August 1979. Unpubl. manuscr., 410 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Boulevard East, Seattle, WA 98112.

Wakabayashi, K., R. Bakkala, and L. Low. 1977. Status of the yellowfin sole resource in the eastern Bering Sea through 1976. Unpubl. rep., 45 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112. (Submitted to the International North Pacific Fisheries Commission in October 1977.)