CRDI
file
for Kodiak

Outer Continental Shelf Environmental Assessment Program

Final Reports of Principal Investigators

Volume 36 **December 1985**

Part 2 of 2

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
Office of Oceanography and Marine Assessment
Ocean Assessments Division
Alaska Office

"Outer Continental Shelf Environmental Assessment Program Final Reports of Principal Investigators" ("OCSEAP Final Reports") continues the series entitled "Environmental Assessment of the Alaskan Continental Shelf Final Reports of Principal Investigators."

It is suggested that sections of this publication be cited as follows:

Fredin, R.A. 1985. Northwest and Alaska Fisheries Center Processed Report 85-05: Pacific cod in the eastern Bering Sea: a synopsis. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2 (1986): 597-662

Pola, N.B., R.K. Miyahara, and A.F. Gallagher, Jr. 1985. Northwest and Alaska Fisheries Center Processed Report 85-08: Spatial and temporal extent of hydrocarbon contamination in marine species of Bristol Bay. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2 (1986): 663-710

Honkalehto, T. 1985. Northwest and Alaska Fisheries Center Processed Report 85-13: Recovery of three Bering Sea type fish populations from catastrophic larval mortality - a simulation approach. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2 (1986): 711-752

Livingston, P.A. 1985. Northwest and Alaska Fisheries Center Processed Report 85-12: Food habits of Bristol Bay Species which might be affected by oil development - a study on the variability in demersal and pelagic food habits. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2 (1986): 753-800

Fukuhara, F.M. 1985. Northwest and Alaska Fisheries Center Processed Report 85-11: Biology and fishery of southeastern Bering Sea red king crab (Paralithodes camtschatica, Tilesius). U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2 (1986): 801-982

Pola, N.B. 1985. Northwest and Alaska Fisheries Center Program Documentation No. 24: Modeling the biological impact of an oil spill; BIOS model. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2: 983-1038

Fukuhara, F.M. 1985. Northwest and Alaska Fisheries Center Processed Report 85-15: Estimated impacts of hypothetical oil spill accidents off Port Moller, Port Heiden and Cape Newenham on eastern Bering Sea yellowfin sole. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 36 Part 2 (1986): 1039-1128

OCSEAP Final Reports are published by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Oceanography and Marine Assessment, Ocean Assessments Division, Alaska Office, Anchorage, and primarily funded by the Minerals Management Service, U.S. Department of the Interior, through interagency agreement.

Requests for receipt of OCSEAP Final Reports on a continuing basis should be addressed to:

NOAA-OMA-OAD
Alaska Office
701 C Street
P. O. Box 56
Anchorage, AK 99513

The reports contained within this volume are from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and are individually available from that service.

OUTER CONTINENTAL SHELF

ENVIRONMENTAL ASSESSMENT PROGRAM

FINAL REPORTS OF PRINCIPAL INVESTIGATORS

Volume 36, Part 2

December 1985

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
Office of Oceanography and Marine Assessment
Ocean Assessments Division
Alaska Office

U.S. DEPARTMENT OF THE INTERIOR
Minerals Management Service
Alaska OCS Region
OCS Study, MMS 85-0107

Anchorage, Alaska

The facts, conclusions, and issues appearing in these reports are based on research results of the Outer Continental Shelf Environmental Assessment Program (OCSEAP), which is managed by the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, and funded (wholly or in part) by the Minerals Management Service, U.S. Department of the Interior, through an Interagency Agreement.

Mention of a commercial company or product does not constitute endorsement by the National Oceanic and Atmospheric Administration. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized.

The reports contained within this volume are from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA. Text has not been altered from that submitted as processed reports; some figures and charts have been enhanced to improve clarity in reproduction.

Outer Continental Shelf Environmental Assessment Program

Final Reports of Principal Investigators

VOLUME 36, PART 1 FEBRUARY 1986

CONTENTS

PACIFIC COD IN THE EASTERN BERING SEA: A SYNOPSIS

by

Reynold A. Fredin
Institute for Marine Sciences
University of Washington
and
Natural Resource Consultants

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

February 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Processed Report 85-05 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

TABLE OF CONTENTS

Table of Contents (cont'd.)

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Pacific cod (Gadus macrocephalus) is a relatively abundant and an economically important species of fish in the eastern Bering Sea. It ranked third in biomass among all species of fish in comprehensive demersal trawl surveys of the area in 1979 and 1980, exceeded only by walleye pollock and yellowfin sole. It was the first species of demersal fish to be commercially utilized in eastern Bering Sea, the original fishery having been a fleet of North American based sailing schooners accompanied by dory catcher boats which commenced handline fishing on a regular annual basis about 100 years ago and continued until 1950. Since the mid-1950's there has been, first, a widespread development of foreign trawl fishing activity for groundfish in the area, with catches of Pacific cod, although not a target species, reaching record highs by the early 1970's, and, within the past five years, a rapidly expanding U.S. trawl fishery, with vessels catching increasingly larger quantities of cod each year for domestic and foreign processing, the latter under joint venture arrangements. The species serves as the foundation for building a strong domestic fishery and processing industry around the groundfish resources of the eastern Bering Sea and Aleutian Islands.

Compared to the century of commercial fishing for Pacific cod in the eastern Bering Sea, biological research on the species in the area has a very brief history and, moreover, is lacking in comprehensiveness in certain respects. Little direct information is available regarding some important biological and life history aspects of Pacific cod in eastern Bering Sea. Thus, in preparing a synopsis of information on the species in the area, it is necessary to draw on findings from studies of Pacific cod throughout their range in the North Pacific Ocean and, where relevant, from studies of Atlantic cod, a closely related species. Even so, many gaps in our knowlege remain.

1. IDENTITY

The Pacific cod (Class Osteichthyes, Order Gadiformes, Family Gadidae, Genus *Gadus*, Species *macrocephalus*) is the only member of its genus represented in the eastern Bering Sea (Salveson and Dunn, 1976). It is distinguished from other North Pacific gadids (cod fishes) by the presence of three separate dorsal fins, anus located below the second dorsal fin, and a barbel below the lower jaw as long as or longer than the width of the eye (Hart, 1973). A detailed description of the species is given by Hart.

Several decades ago taxonomists disagreed as to whether the Pacific cod and Atlantic cod were different species or simply subspecies of the same species (Schultz and Welander, 1935; Svetovidov, 1948), but it is now generally accepted by researchers on North Pacific fish populations that the two are separate species, G. *macrocephalus* and G. *morhua*.

Other common names frequently used for Pacific cod are "cod," "true cod" and "gray cod."

2. DISTRIBUTION

a. Overall Distribution in the North Pacific Ocean.

On the North American coast Pacific cod inhabit waters over the continental shelf and the upper portion of the continental slope from Santa Monica Bay, California (about lat. 34°N), north to St. Lawrence Island in the northern Bering Sea (about lat. 63°N at long. 170°W) and throughout the Aleutian Islands (Figure 1). Cod also inhabit Norton Sound, but apparently only in small numbers (Wolotira et al, 1977). Along the coast of mainland Asia, they inhabit continental shelf and upper slope waters from the Gulf of Anadyr to the southern end of the

Korean Peninsula and along the west coast of Korea in the Yellow Sea to Port Arthur in China. They also occupy shelf and upper slope waters off the Kurile and Sakhalin Islands, the west coast of Japan in the Sea of Japan, and the Pacific coast of Japan from northern Hokkaido to Tokyo Bay (Bakkala et al, 1984). Moiseev (1953) indicates that an arc connecting the southernmost limits of the species' distribution in North America and Asia covers a distance of approximately 10,000 kilometers.

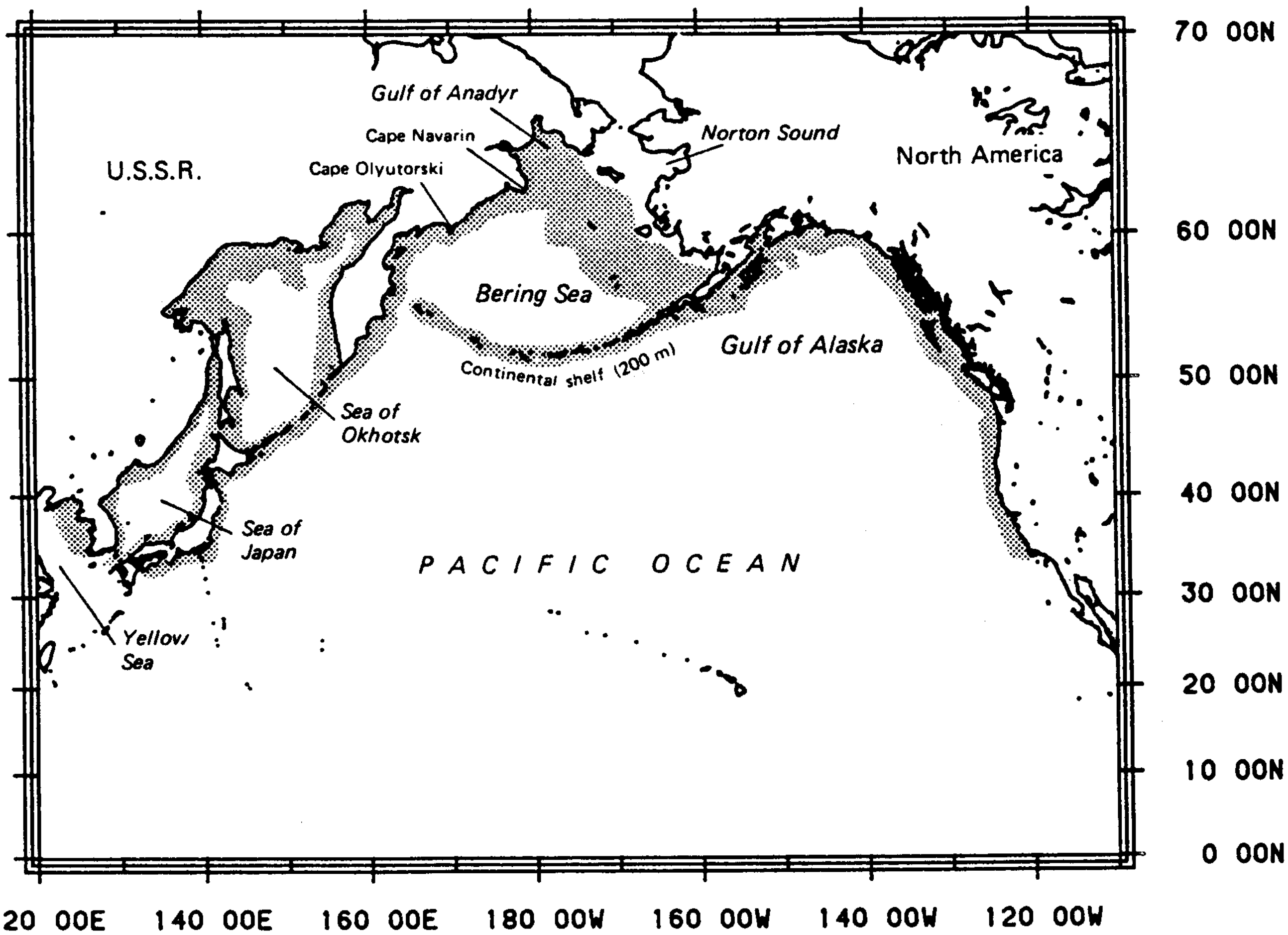


Figure 1.--Overall distribution of Pacific cod in the North Pacific Ocean. (From Bakkala et al., 1984.)

Average annual regional catches during 1968-77 suggest that the abundance of Pacific cod increases from south to north along both the Asian and North American sides of the North Pacific Ocean, peaking in the eastern Bering Sea (Figure 2). Catches during 1978-82 from four of the North American regions also suggest that cod abundance peaks in the eastern Bering Sea, with the Aleutians and Gulf of Alaska providing much larger catches than in earlier years:

Pacific cod catch (t)---1978-1982*

Year	Aleutians	E. Bering Sea	Gulf of Alaska	Canada
1978	3,295	42,543	12,160	6,750
1979	5,593	33,761	14,869	9,554
1980	5,788	45,861	35,439	8,703
1981	10,462	51,996	36,018	6,708
1982	11,526	55,040	33,563	4,808

*Sources: Aleutians and eastern Bering Sea data - Bakkala and Wespestad (1984); Gulf of Alaska data - Zenger (1983); Canada data - Smith (1979, 1980 and 1981) and Leaman (1982 and In press).

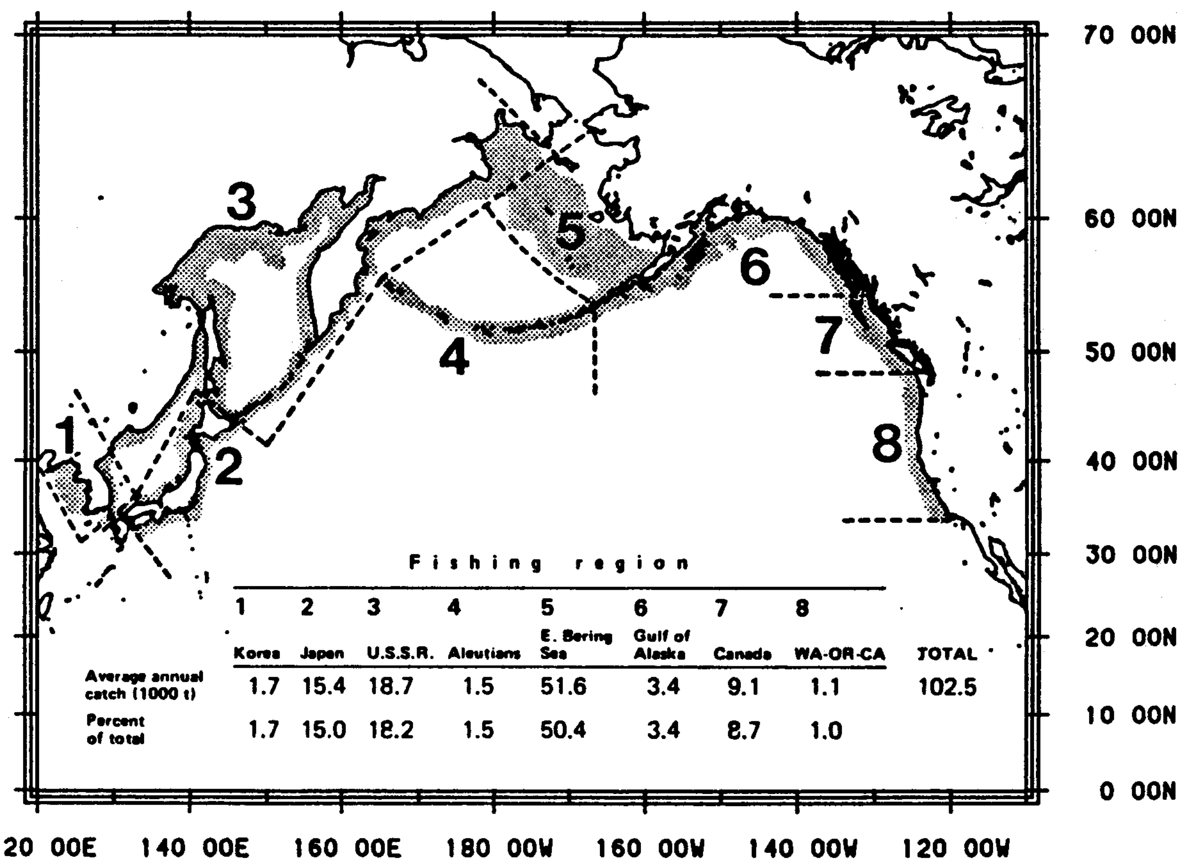


Figure 2.--Average annual catches of Pacific cod, in thousands of tons, by region of the North Pacific Ocean, 1968-77. (From Bakkala et al., 1984.)

b. Overall Distribution in Eastern Bering Sea.

The overall distribution of Pacific cod in the region delineated in Figure 2 as the eastern Bering Sea is probably best illustrated by the results of a comprehensive demersal trawl survey of groundfish resources carried out by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, during May-August of 1979. That survey provided the most extensive single-year coverage of the region to date and showed Pacific cod to be distributed over most of the continental shelf and slope from the Alaska Peninsula northward to St. Lawrence Island (Figure 3). Cod were generally absent in waters off the Alaska mainland out to the 30 m or 40 m depth contour from St. Lawrence Island south. As for nearshore waters north of St. Lawrence Island, trawl surveys during September-October 1976 and July-August 1979 in Norton Sound and adjacent waters indicated that cod occur in only negligible quantities (Wolotira et al, 1977, and Sample et al, unpubl. manusc.).

To the west and northwest of St. Lawrence Island a cooperative U.S.-Japan-U.S.S.R. demersal trawl survey in 1982 showed cod to be distributed from the continental slope well into the Gulf of Anadyr and along the Asian coast between Cape Navarin and Cape Olyutorski, much as indicated in Figure 1. Extent of intermixing of cod populations of the eastern and northwestern Bering Sea is not known, but tagging studies presently in progress are expected to provide detailed information on the matter and also on movements of cod between eastern Bering Sea, the Aleutians, and the western Gulf of Alaska.

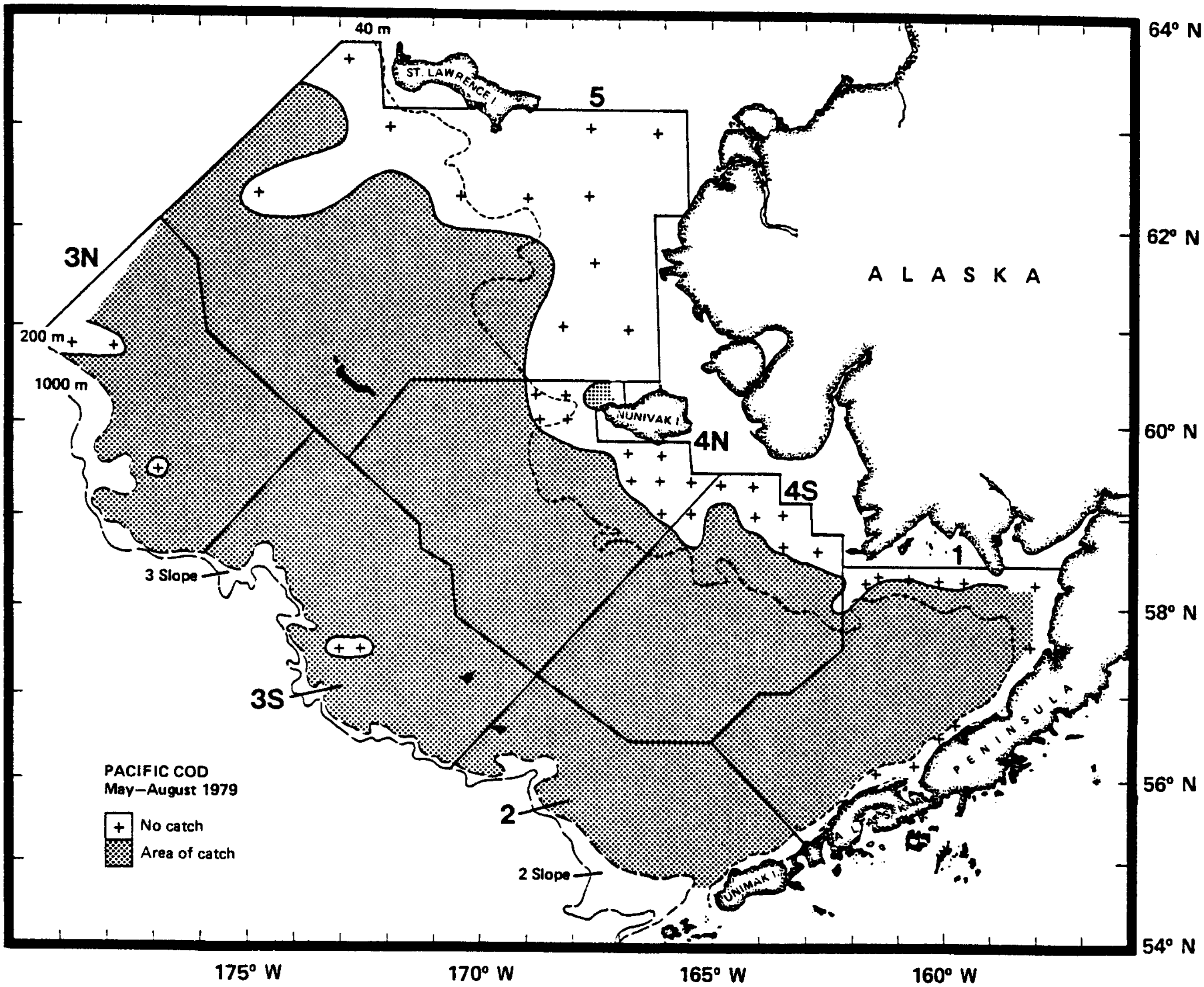


Figure 3.--Distribution of Pacific cod in eastern Bering Sea during May-August 1979. (From Bakkala et al., 1982.)

c. Distribution by Subarea Within the NWAFC Survey Area.

Estimates of abundance of Pacific cod obtained from NWAFC trawl surveys in May-August 1978-82 and June-August 1983 indicate that approximately 60 to 90 percent of the total number of cod in the survey area during a given summer are found in Subareas 1, 4N, 4S and 5, the remaining 10 to 40 percent in Subareas 2, 3N and 3S (Figure 4). Unweighted averages of annual percentages by subarea provide the following rankings with respect to cod abundance:

Subarea	Percent of total population in trawl survey area
1	30
4N	22
4S	18
3S	12
3N	7
2	6
5	3

The estimates of abundance likely would have been somewhat different in some subareas and years had there not been gaps in areal coverage (such as there were in Subareas 4S and 4N in 1978 and 1981 or in other subareas in one or more years), but the overall ranking of the subareas in regard to cod abundance probably would not be changed much. More serious errors may stem from one or more of the assumptions carried in making trawl survey (swept area) estimates of abundance, such as the assumption that the cod population is static (i.e., doesn't move from one sampling station or subarea to another) during the 3-4 months that the surveys are carried out and the assumption that the trawl sampling gear has a 100% capture efficiency (Pereyra et al, 1976 and Smith and Bakkala,1982). Magnitude of errors in population estimates revolving around the assumptions is not known.

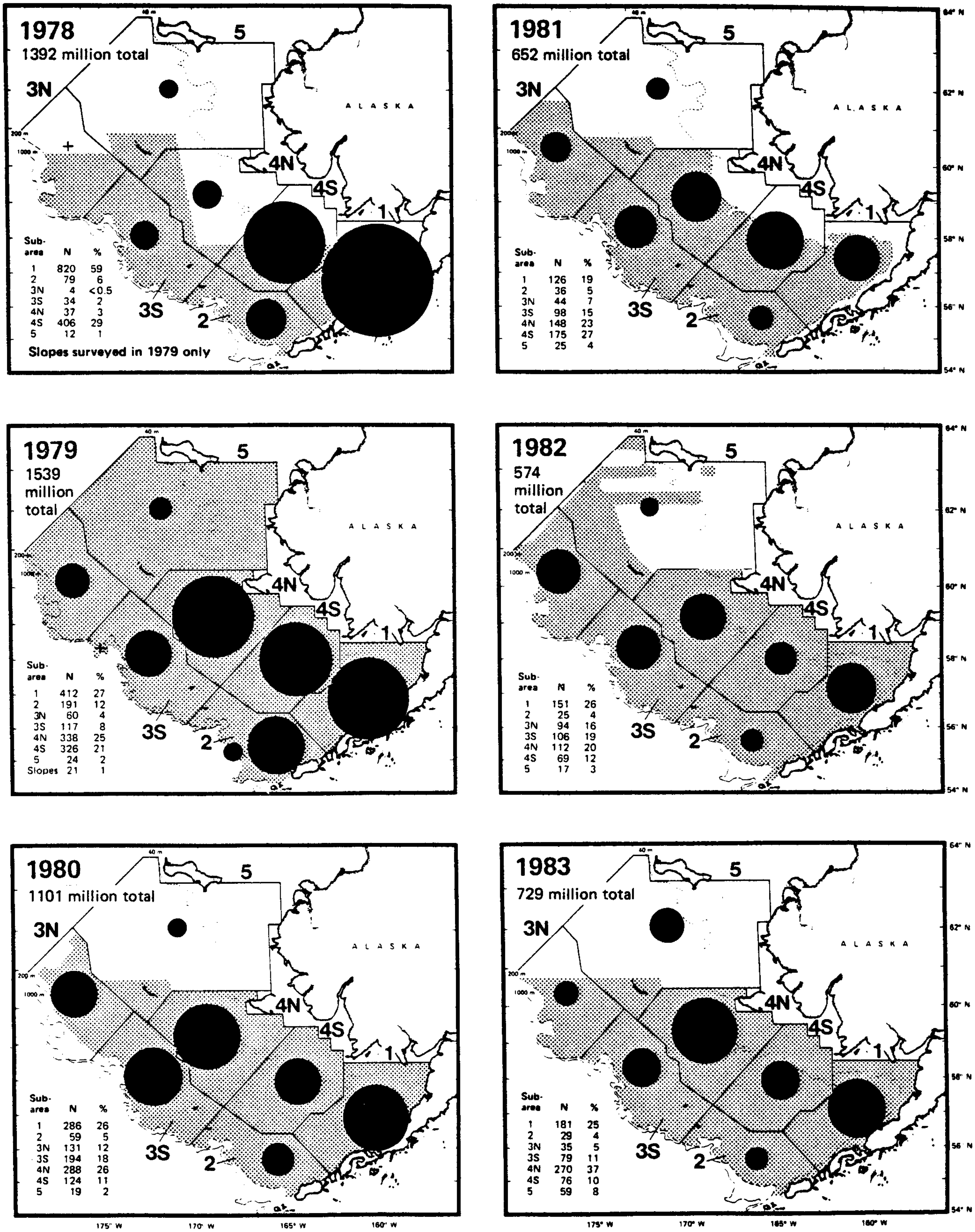


Figure 4.--Summer distribution of Pacific cod in the NWAFC trawl survey area in the eastern Bering Sea, 1978-1983, in millions of fish by subarea. (From NWAFC data files.)

d. <u>Variability in Distribution</u>.

The distribution of Pacific cod in the eastern Bering Sea varies between years and between seasons within years. The driving environmental variable behind the changes in distribution appears to be water temperature, with such biólogical factors as year-class abundance and age (size) composition, and probably spawning and feeding migrations, also playing important roles.

Between-year differences in distribution associated with water temperature are portrayed by Pereyra, Reeves, and Bakkala (1976), who compared distribution and relative abundance of Pacific cod in eastern Bering Sea during July-August of 1965-70 and 1971-75, sets of warm and cold years, respectively (Figure 5). In July-August of warm years cod occupied inner shelf waters from the Alaska Peninsula well to the north of Nunivak Island, but in cold years the population remained largely on the outer shelf and continental slope. In the relatively cold year of 1982, however, cod were found throughout eastern Bering Sea (Figure 6), indicating that distribution is influenced not only by water temperature but also by abundance. (As will be shown later, cod were much more abundant in 1982 than in the early 1970's.)

Seasonal changes in the distribution of cod are indicated by differences in the areas where they were found during a trawl survey in April-June 1976 (Figure 7) as compared to summer surveys (Figure 4). Catches during April, when ice cover was at its peak in 1976 and spring warming had yet to begin, are considered to depict winter distribution and May-June catches the spring distribution. Cod were concentrated on the outer continental shelf and along the shelf edge in April, whereas the May-June catches indicated a movement back to shallower waters. In appears from Figures 4 and 7 that cod move off the inner and central shelf regions as summer ends and winter approaches, concentrate

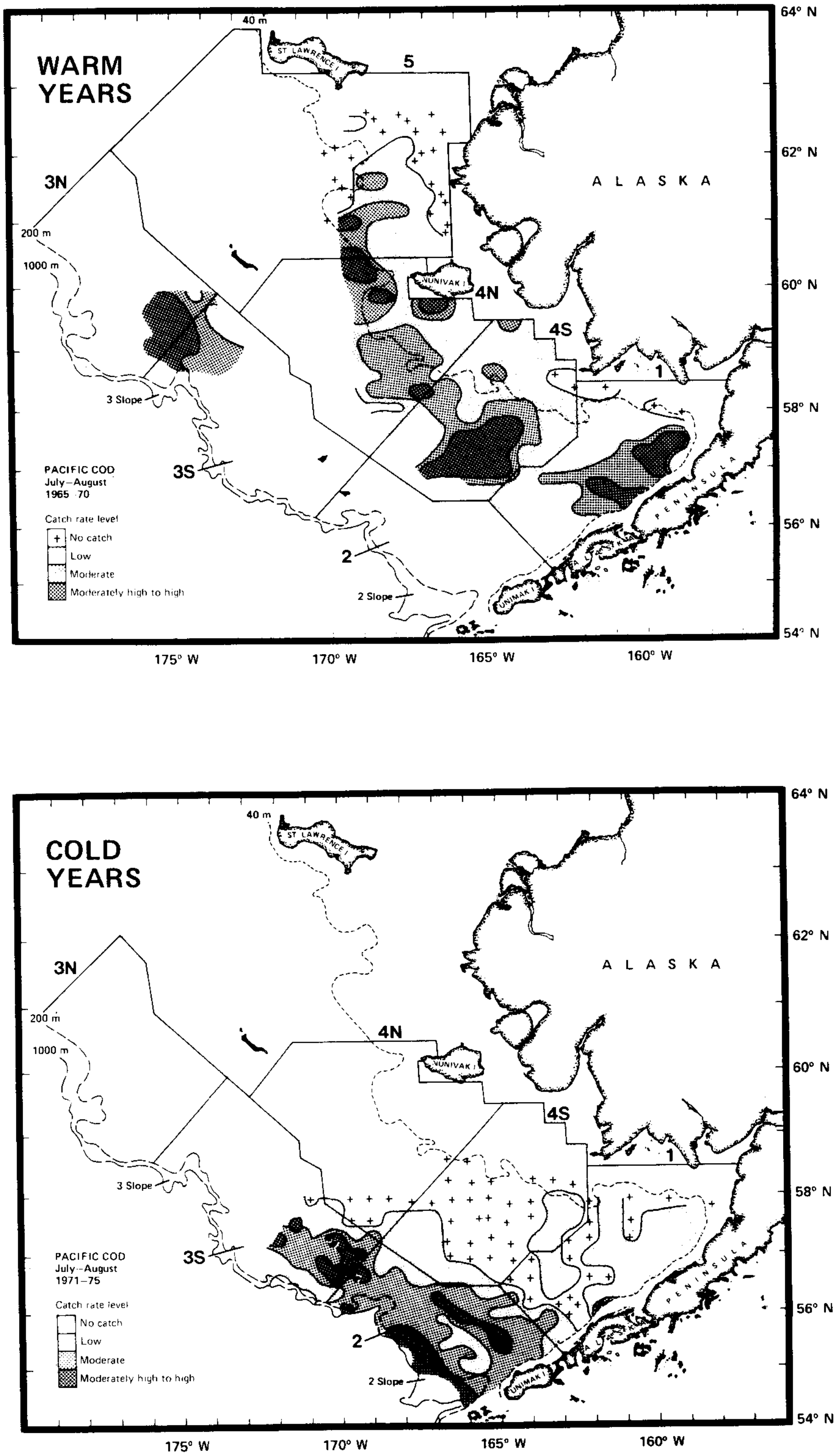


Figure 5. Distribution and relative abundance of Pacific cod in July-August 1965-70 and 1971-75 as shown by a composite of catch rates from demersal trawl surveys. (From Pereyra, Reeves, and Bakkala, 1976. Warm and cold years refer to relative climatic conditions in eastern Bering Sea during 1965-70 and 1971-75 as described by McLain and Favorite, 1976.)

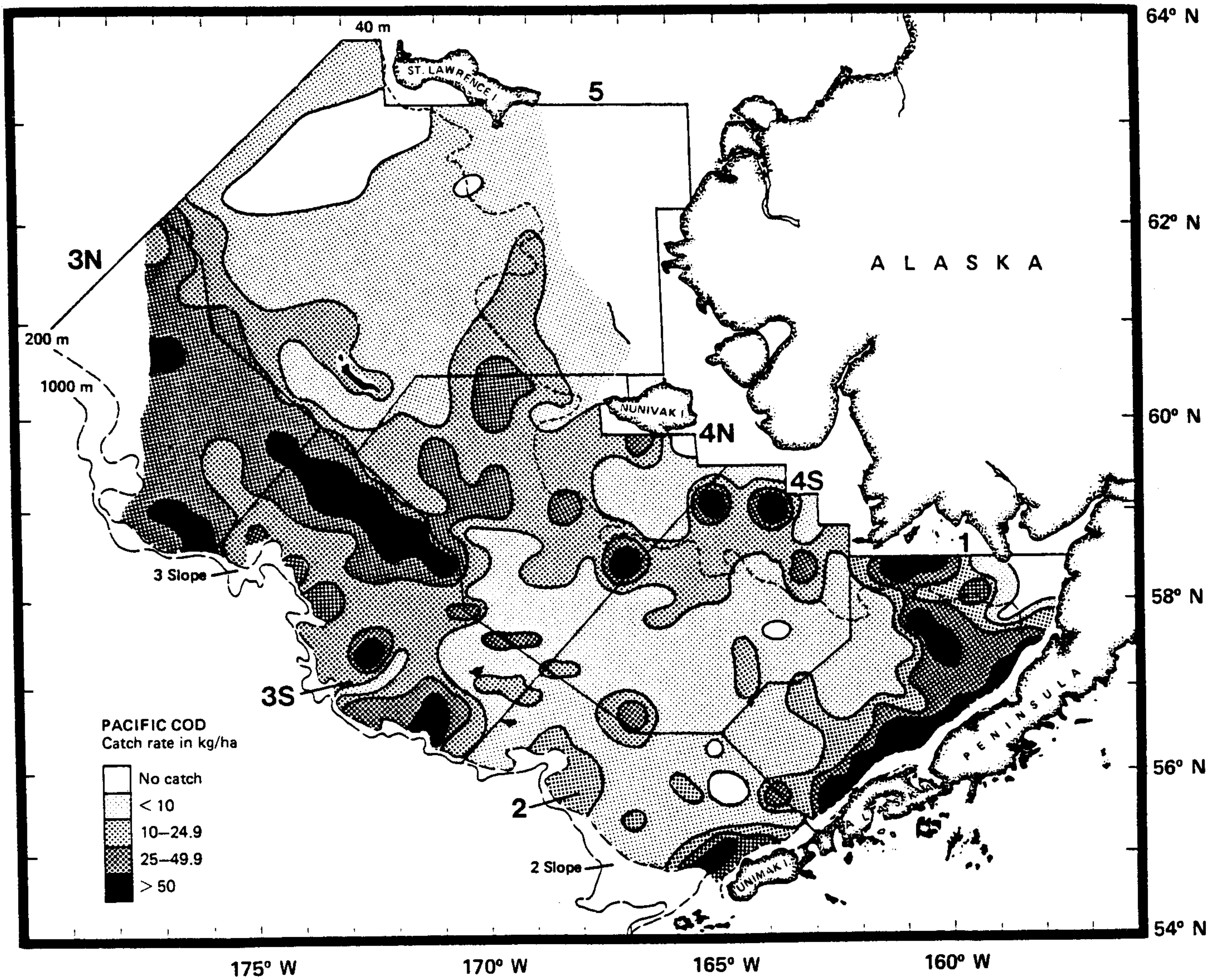


Figure 6.--Distribution of Pacific cod in the NWAFC trawl survey area in eastern Bering Sea during May-August 1982, (From NWAFC data files.)

in deeper water on the outer shelf and along the shelf edge during winter, migrate back toward the inner shelf as the ice pack recedes northward in the spring, and are broadly dispersed over much of the inner and central shelf, as well as the outer shelf and along the continental slope, during the summer.

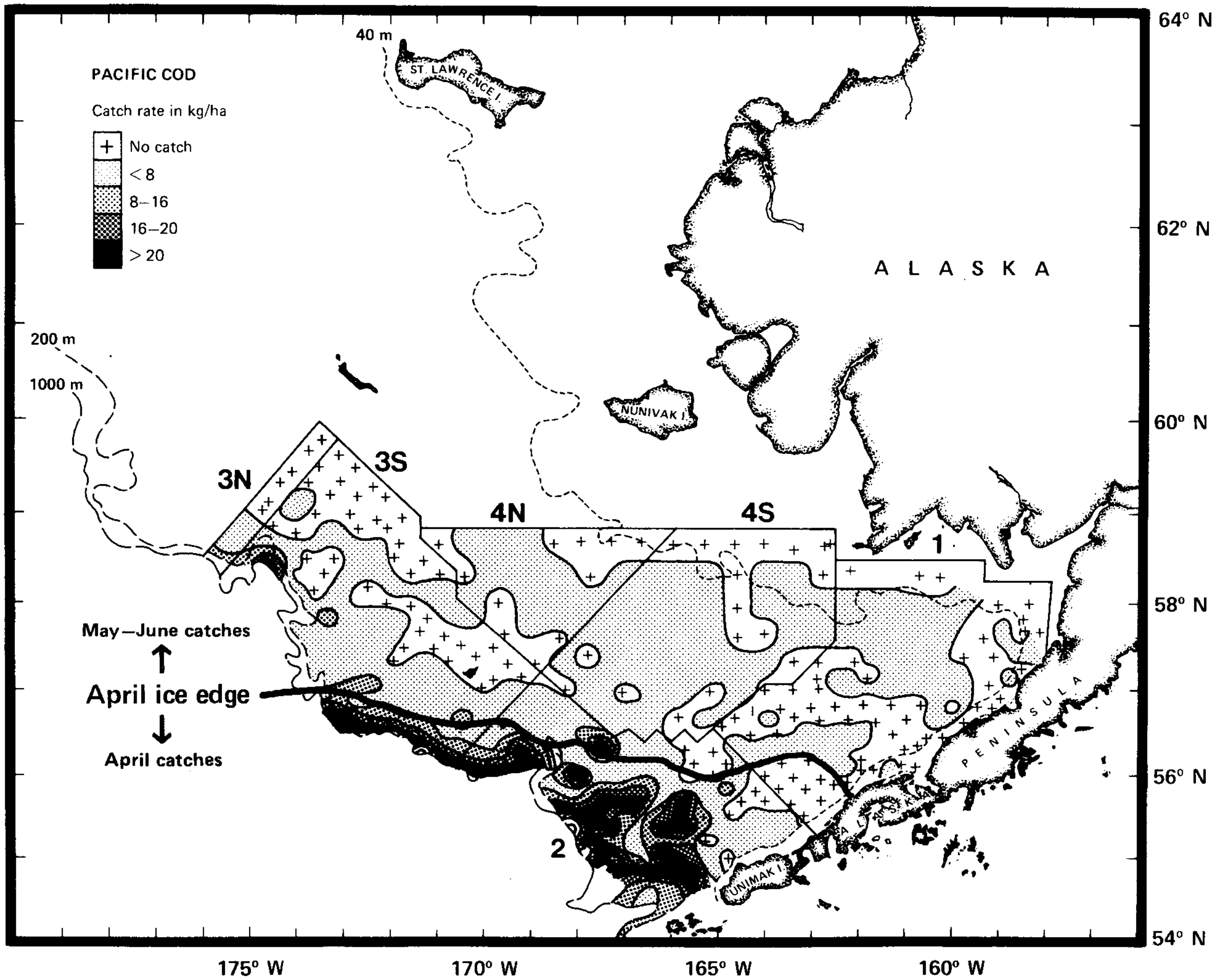


Figure 7.--Distribution of Pacific cod in eastern Bering Sea during April-June 1976 as indicated by NWAFC demersal trawl survey. (From Smith and Bakkala, 1982, and Bakkala, 1984.)

e. Distribution of Life History Groups.

(i) Spawning population. Musienko (1970) reported that cod populations around the Commander Islands and along the coast of Siberia from the general latitude of the Commanders northeasterly to the Gulf of Anadyr spawn during the period from January to May. On the basis of such evidence for cod populations in the western and northwestern Bering Sea, Bakkala (1984) concluded that spawning in the eastern Bering Sea can be expected to take place within the period of January to April. As to where Pacific cod spawn in eastern Bering Sea, normal development of fertilized eggs requires a water temperature greater than 0°C Mukhacheva and Zvyagina, 1960), with the optimum temperature for hatching and survival considered to be about 5°C (Teshima, 1983) and the optimum incubation temperature at 3-5°C (Musienko, 1970 and Yamamoto and Nishioka, 1952). Such temperature requirements preclude the inner continental shelf as an area for successful reproduction of Pacific cod, the bottom temperatures under ice cover there during winter being less than -1.5°C (Dodimead et al, 1962), and indicate that spawning takes place in the warmer waters on the outer continental shelf and slope or in protected bays and adjacent ice-free waters along the Alaska Peninsula and westward. Japanese longline vessels have taken spawning cod along the continental slope south of the Pribilofs from late January through March (Allen Shimada, pers. comm.), and U.S. fishermen have observed spawning from late December to April in bays and shallow near-shore waters in the eastern Aleutians and along the north side of Unimak Island to False Pass (Konrad Uri, pers. comm.).

(ii) Eggs and larvae. Pacific cod eggs are demersal, and none have been reported from the numerous ichthyoplankton surveys that have been carried out in eastern Bering Sea since 1955. Only five larvae, all taken in the central shelf region south of Nunivak Island, were reported (Waldron, 1981). Large numbers of larvae averaging 4-5 mm in April and 7-10 mm in May-June were collected during research vessel cruises in the Gulf of Alaska from Kodiak Island westward to Unimak Island during 1972-82 (Kendall, pers. comm.). Prevailing ocean currents could carry such larvae "downstream" through passes into the eastern Bering Sea.

(iii) Age 0 fish. During an August-October trawl survey in 1975, concentrations of small cod averaging 11-14 cm in length and considered to have been age 0 fish (young of the year) were encountered inside or near the 40 m depth contour from south of Nunivak Island into the outer reaches of Bristol Bay and along the north sides of the Alaska Peninsula and Unimak Island (Figure 8). It appears that cod are distributed in coastal waters from Unimak Island to the vicinity of Nunivak Island during the summer and early fall of their first year of life.

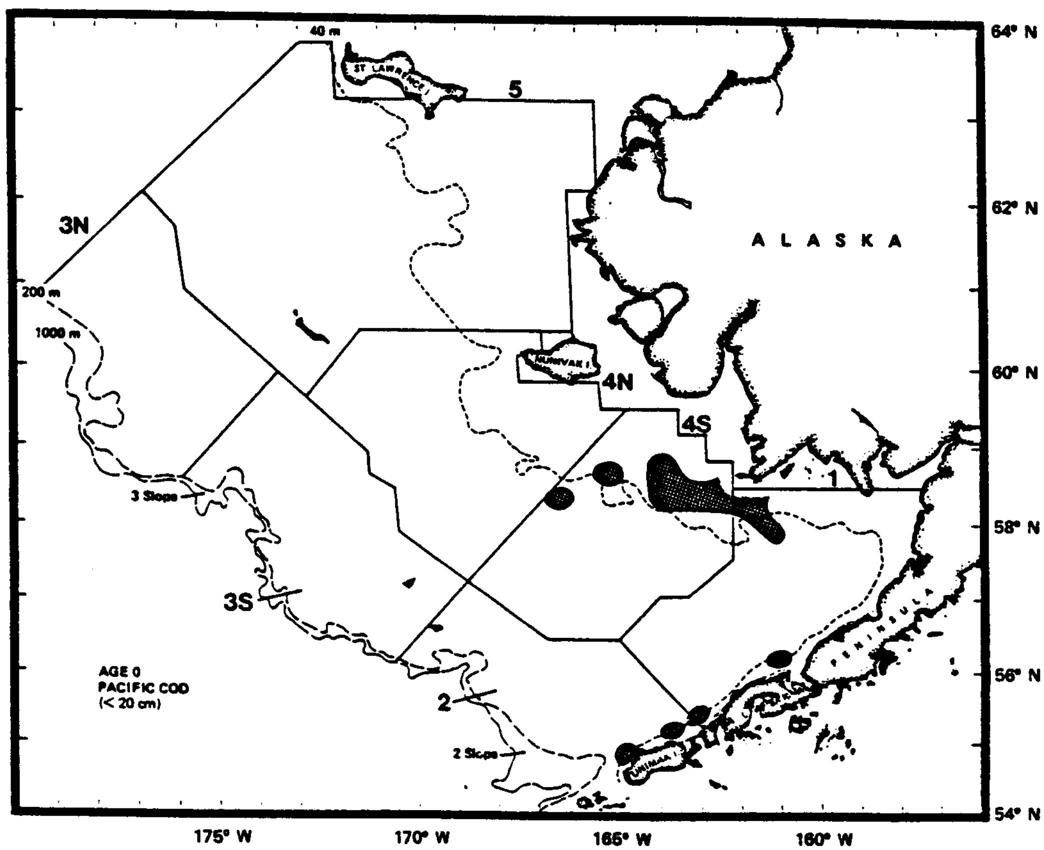


Figure 8.--Distribution of age 0 Pacific cod in the eastern Bering Sea as observed during NWAFC demersal trawl survey, August-October 1975. (From Bakkala, 1984.)

(iv) Age 1 and older fish. After the manner of Bakkala (1984), the distributions of age 1 and older cod in eastern Bering Sea during 1978-83 are based on length classes expected to represent specific ages, as follows: Age 1 - <28 cm, Age 2 - 28 to 38 cm, Age 3 - 39 to 50 cm, and Age 4 and older - >50 cm.

Bakkala (1984) shows some marked differences in the distribution of the age groups in 1979. Concentrations of age 1 fish were located in a continuous band along the north side of the Alaska Peninsula and northward near the 40 m depth contour to north of Nunivak Island. Age 2 cod were similarly distributed but tended to be in somewhat deeper waters in the central shelf region, extending to the north of St. Matthew Island. The distribution of age 3 cod was practically identical to that of age 2 fish except some concentrations of age 3 cod were found on the outer shelf and slope whereas age 2 fish were observed there only at low levels of abundance. The distribution of age 4 and older fish was distinctly different in that they were found almost exclusively on the outer shelf and slope. Thus there appeared to be an inshore to offshore progression in the distribution of age groups in 1979, with age 1 fish in inner shelf waters, ages 2 and 3 fish in central shelf waters, and age 4 and older fish in outer shelf and slope waters.

Distributions of the various age groups in 1983 (Figures 9a and 9b) suggest very little in the way of an inshore-offshore progression for ages 1 and 2 cod. The distribution of age 3 fish extended well onto the outer shelf but numerous concentrations were found near the 40 m depth contour on the inner shelf, where concentrations of younger fish were also found. Age 4 and older cod were observed throughout the survey area, and not almost exclusively on the outer shelf and slope, as was the case in 1979. Most of the larger concentrations of age 4 and older fish were observed near or inside the 40 m depth contour. Thus, and as Bakkala has pointed out (pers. comm.), there was not the marked inshore-offshore progression

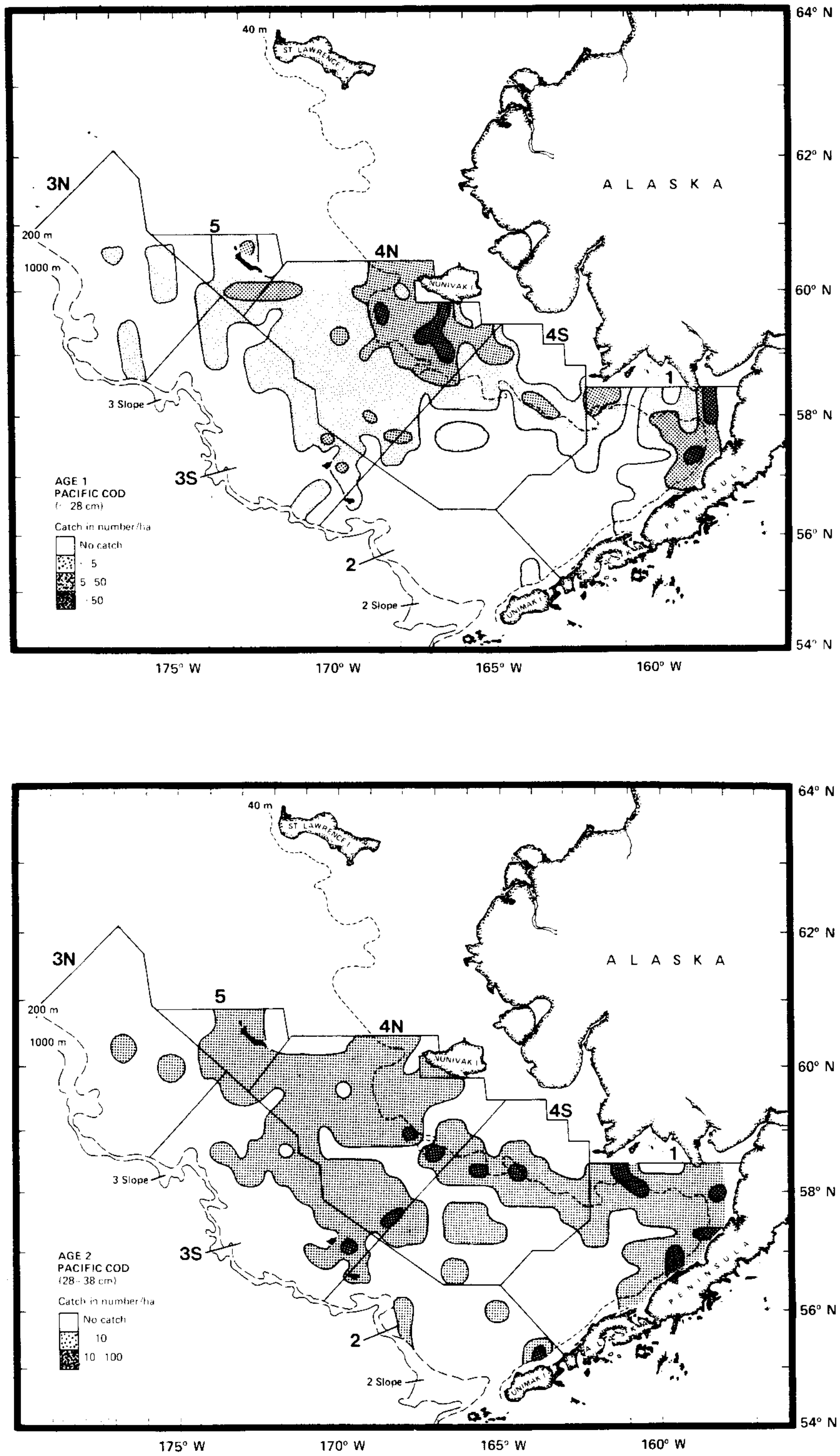


Figure 9a. Distributions of Age 1 and Age 2 Pacific cod in the NWAFC trawl survey area in eastern Bering Sea in 1983. (From NWAFC data files.)

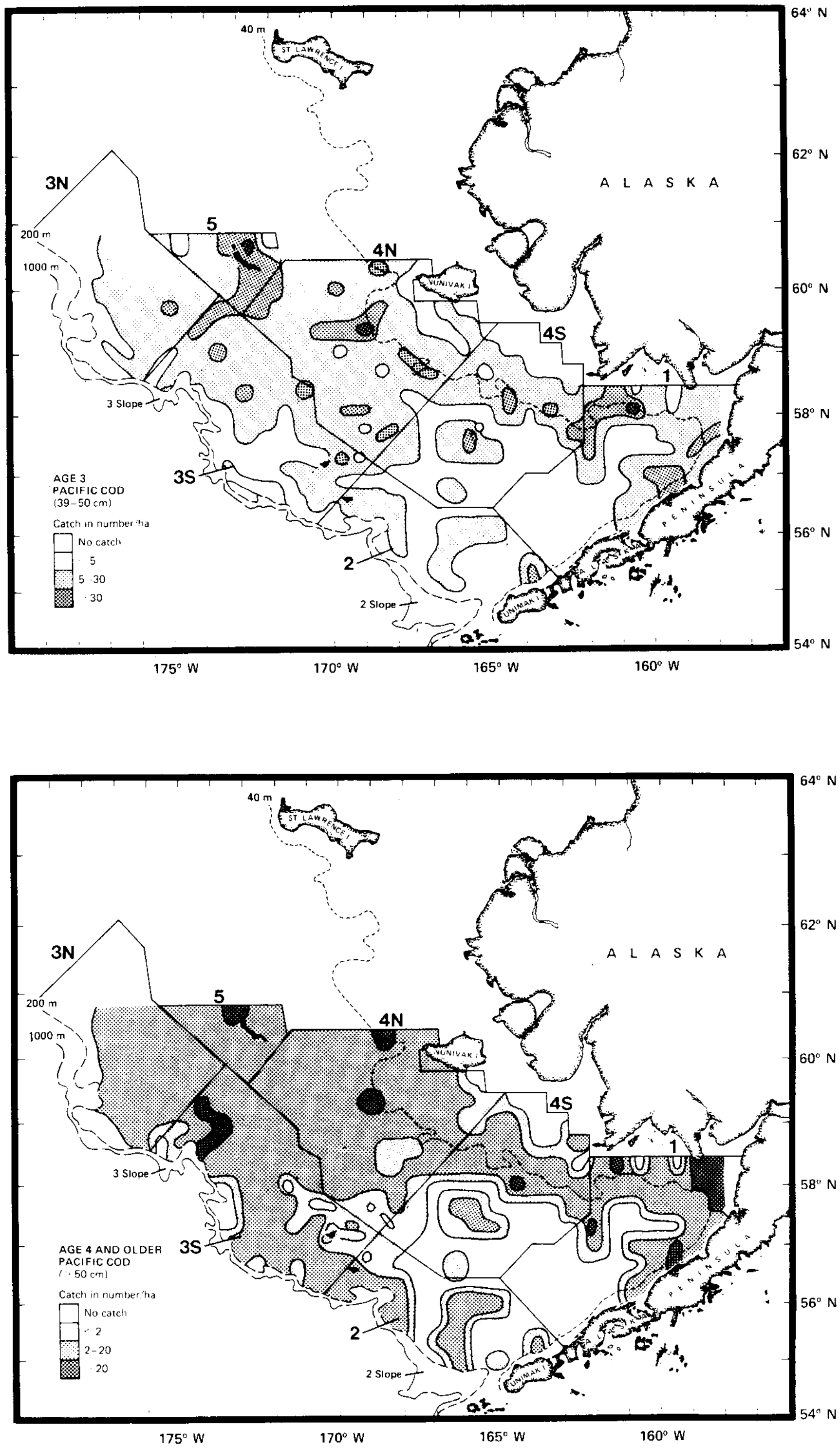


Figure 9b. Distributions of Age 3 and Age 4 Pacific cod in the NWAFC trawl survey area in eastern Bering Sea in 1982. (From NWAFC data files.)

in the distribution of cod with age in 1983 that there was in 1979. Although some of the ages 3 and 4 and older fish were found farther out on the shelf than the younger fish in 1983, most of them were mixed in with ages 1 and 2 fish on the inner shelf.

Annual distributions of the different age groups of cod by subarea in the NWAFC trawl survey area in eastern Bering Sea during the summers of 1978-83 are shown in Figures 10a-10d. Practically all of the age 1 cod and about 80% of the age 2 fish were found on the inner shelf, with Subareas 1, 4S and 4N being the key areas. The same subareas accounted for 50 to 80% of the age 3 fish, depending on the year. Percentage of the estimated total population of age 4 and older cod occurring in Subareas 1, 4S, and 4N varied from a low of 6% in 1978 to a high of 68% in 1983 and appears to have been fairly closely related to abundance.

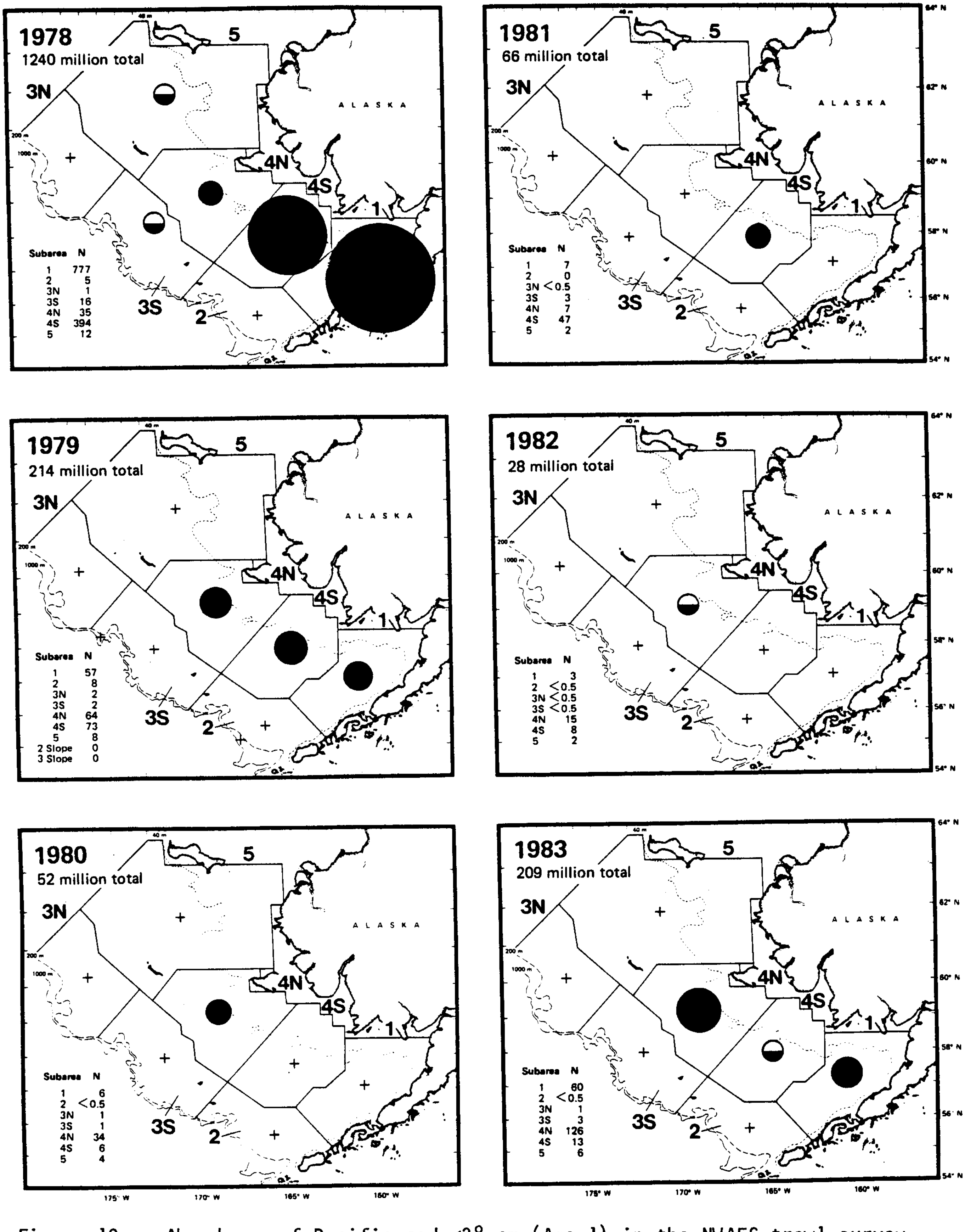


Figure 10a.--Abundance of Pacific cod <28 cm (Age 1) in the NWAFC trawl survey area in eastern Bering Sea during summers of 1978-83, in millions of fish by subarea. (From NWAFC data files.)

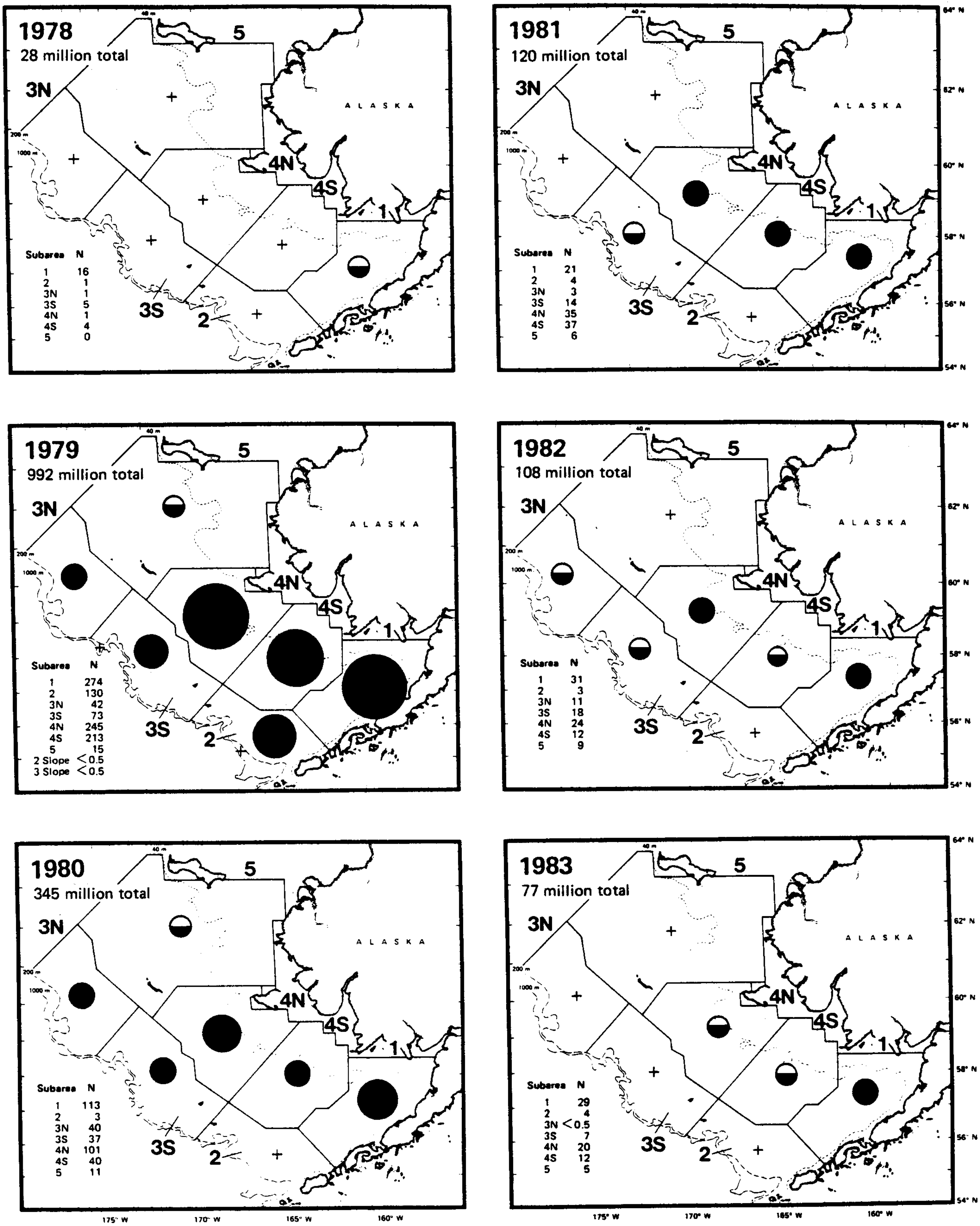


Figure 10b.--Abundance of Pacific cod 28-38 cm (Age 2) in the NWAFC trawl survey area in eastern Bering Sea during summers of 1978-83, in millions of fish by subarea. (From NWAFC data files.)

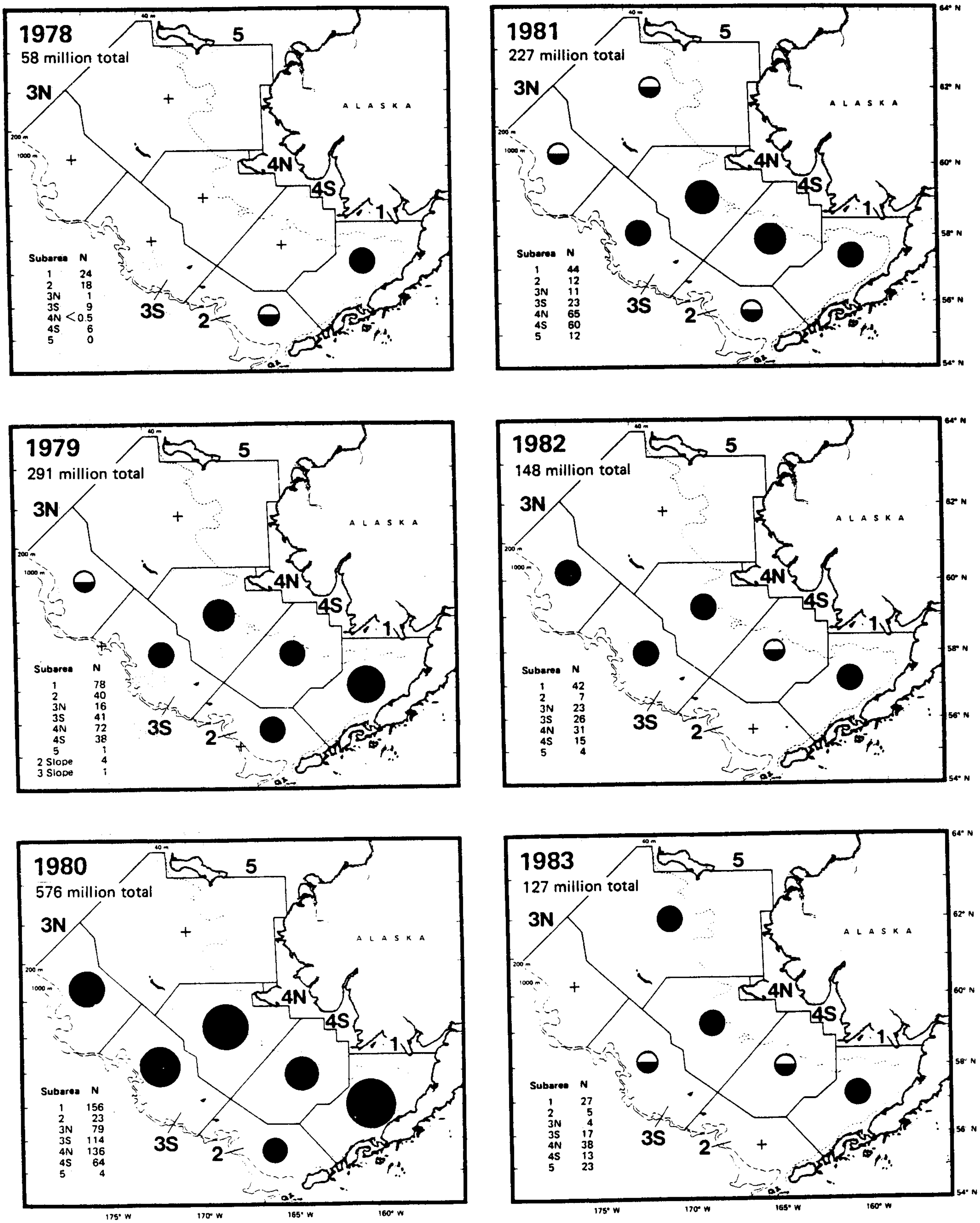


Figure 10c.--Abundance of Pacific cod 38-50 cm (Age 3) in the NWAFC trawl survey area in eastern Bering Sea during summers of 1978-83, in millions of fish by subarea. (From NWAFC data files.)

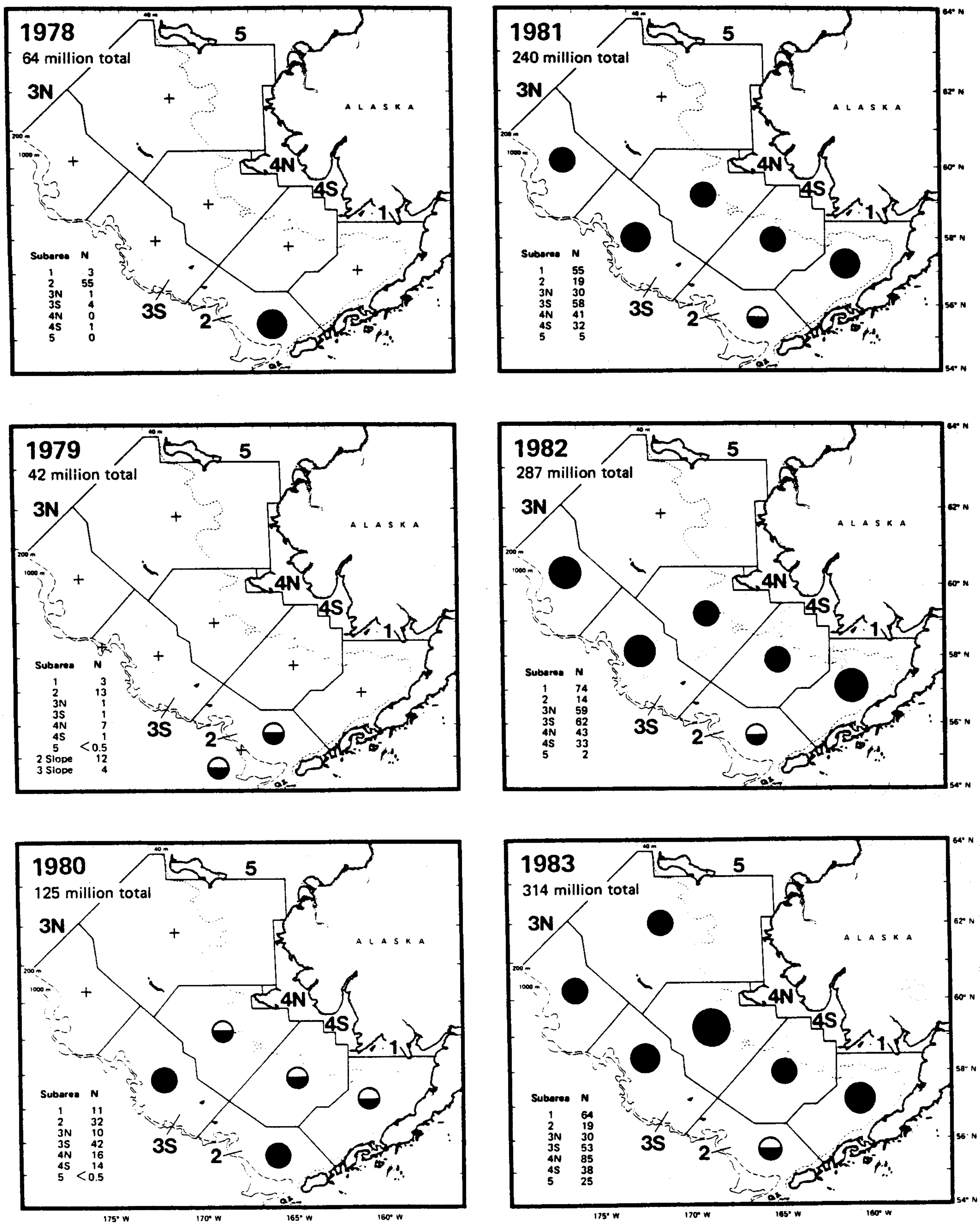


Figure 10d.--Abundance of Pacific cod >50 cm (Age 4 and older) in the NWAFC trawl survey area in eastern Bering Sea during summers of 1978-83, in millions of fish by subarea. (From NWAFC data files.)

3. BIOLOGICAL CHARACTERISTICS

a. Sex Ratios.

Bakkala (1984) reports that for eastern Bering Sea as a whole and for all age groups combined, females accounted for 51% of the total population of Pacific cod in 1976 and 48% in 1979. Samples collected during the 1980 trawl survey indicate that females accounted for 50.5% of the population in that year (Umeda and Bakkala 1983).

Population estimates by sex and size group in 1979 (Bakkala et al, 1982) and 1980(Umeda and Bakkala, 1983) show that the proportion of females generally increases with size class, as follows:

	Percent females by size class (cm)					
Year	10-19	20-29	30-39	40-49	50-59	≥60
1979	43.3	44.6	49.1	54.5	54.3	45.6
1980	44.0	44.4	47.7	51.0	58.0	61.6

The overall sex ratio and size-specific differences for cod in eastern Bering Sea are similar to findings reported by Vershinin (unpubl. MS) for cod in the Anadyr-Navarin region in the northwestern Bering Sea, where the sex ratio is nearly 1:1 and males dominate in the younger age groups, females in the older age groups. Vershinin ascribes the age-specific differences in sex ratio to the earlier maturity of males and their entry into the fishery at a younger age than females.

b. Fecundity.

Fecundity of Pacific cod in eastern Bering Sea has yet to be determined, but Figure 11, taken from Thomson (1962), provides a clue as to what it might be for different sizes of fish, assuming that the fecundity-length relationship for the species is constant. If that is the case, cod of slightly over 50 cm in length in eastern Bering Sea would be expected to produce approximately 0.5 million eggs, 60 cm cod 1.2 million eggs, 80 cm fish 3.25 million eggs, and 90 cm cod a little over 5 million eggs. The eggs are 1 mm in diameter.

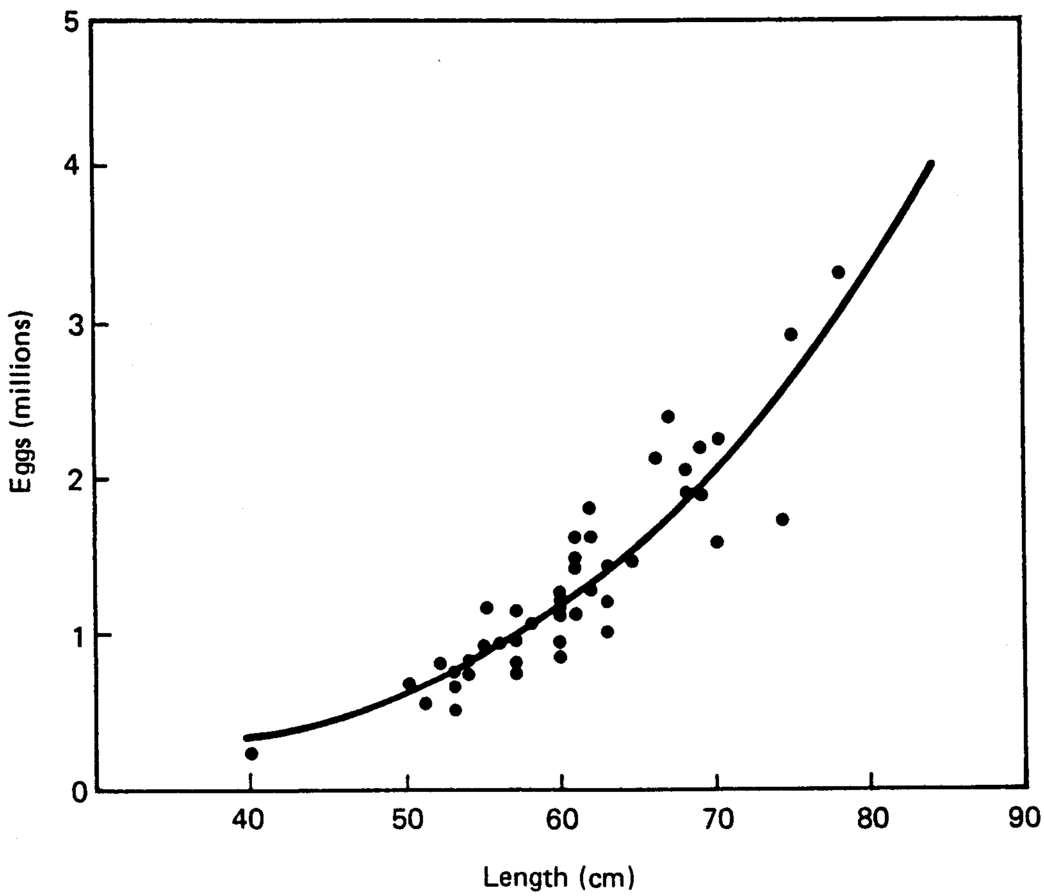


Figure 11.--Fecundity of Pacific cod from Hecate Strait. The solid line is the calculated regression: $\log_{10}$ fecundity (in thousands) = 3.64658 $\log_{10}$ fish length (in cm) - 3.41209. (From Thomson, 1962.)

c. Egg development.

The eggs of Pacific cod are demersal and, during early development, slightly adhesive (Hart, 1973 and Zhang, 1981). Time of development is highly temperature dependent as illustrated in Figure 12. Temperatures resulting in maximum hatching success have been variously reported as 3-5°C (Musienko, 1970), 3-6°C (Yamamoto and Nishioka, 1953), 1-8°C (Mukhacheva and Zvyagina, 1960) and 5°C (Teshima, 1983).

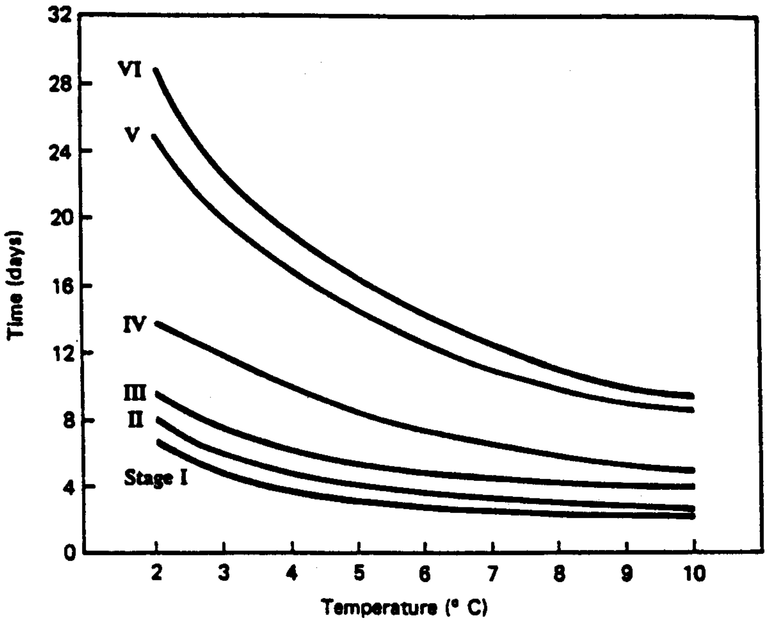


Figure 12.--Number of days required for Pacific cod eggs to reach six developmental stages when held at constant temperatures of 2 to 10°C. (From Forrester and Alderdice, 1966.)

d. Larval Development and Early Growth of Juveniles.

Hart (1973) reported the length of newly hatched larvae as 4.5 mm, which is practically identical to the 4 and 5 mm lengths reported by Musienko (1970) and Zhang (1981), respectively, for larvae after yolk sac absorption. Zhang also gave lengths of larval and juvenile cod in a natural environment in Korea over a 6-month period:

Time after hatching	Total length in mm
At hatching	3.6
30 days	10-13
2 mos	15-25
3 mos	23-40
4 mos	40-70
5 mos	60-90
6 mos	80-110

Zhang's data suggest that the abundant small cod on the inner continental shelf of eastern Bering Sea during the August-October 1975 trawl survey, which averaged about 11 cm in length in Subarea 4S and 14 cm in Subarea 1 (Pereyra et al, 1976), were approximately 6 to 8 months old.

e. Growth.

Growth of Pacific cod in eastern Bering Sea has not been well defined because of problems in aging the fish in the region. Counts of annual rings on scales appear to give unreliable results (Bakkala, 1984) and modal analyses of length frequency data using the method of MacDonald and Pitcher (1979) may not accurately separate certain age groups due to overlapping of lengths of fish of adjacent ages. In spite of its shortcomings, and because a more satisfactory alternative aging procedure has yet to be developed, NWAFC scientists presently use the latter method for aging cod in eastern Bering Sea.

Length-at-age data automatically generated for each year's length frequency by the modal analysis method of aging provide a composite age-length relationship for cod sampled during the 1978-83 trawl surveys in eastern Bering Sea. Means and ranges of estimated modal lengths at age for the six years of sampling are shown in Figure 13.

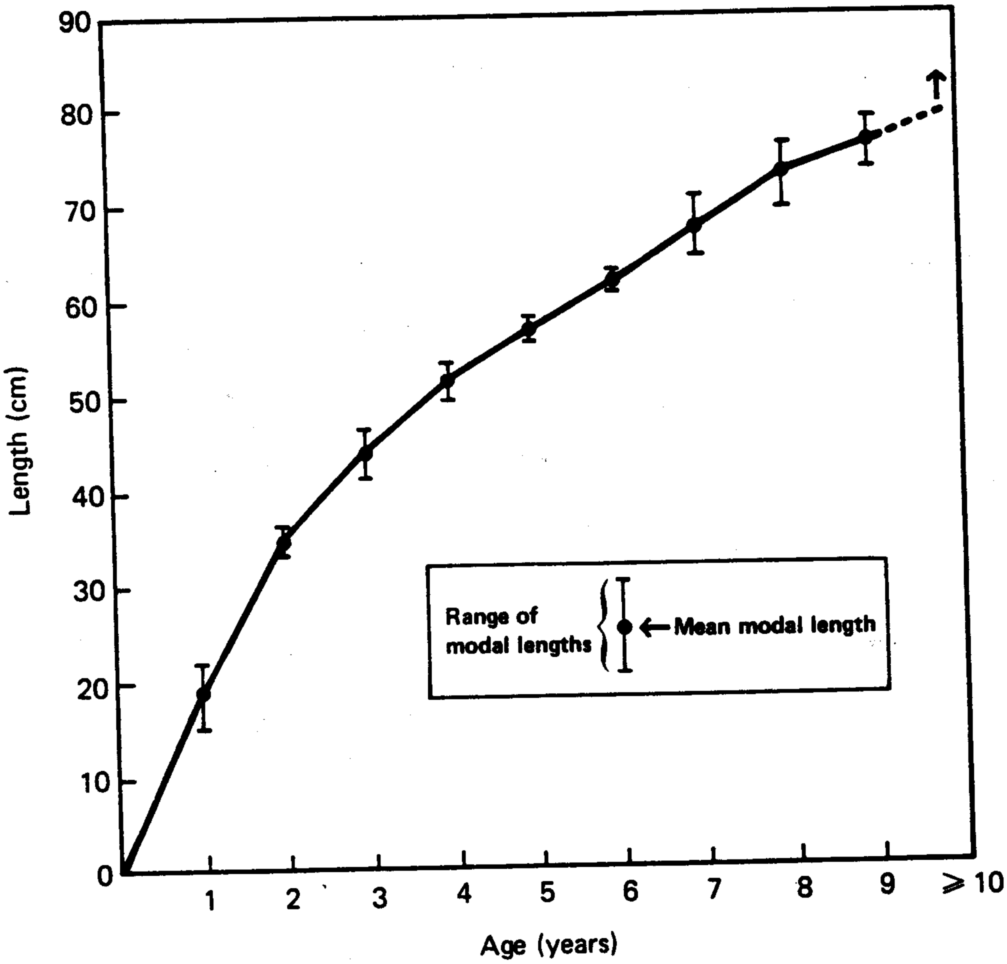


Figure 13.--Age-length relationship for Pacific cod in eastern Bering Sea as aged by modal analyses of length frequencies, 1978-83. (From Shimada, pers. comm.)

f. Size at maturity.

An analysis by Teshima (unpublished manuscript) indicates that sexual maturity of Pacific cod in eastern Bering Sea is first reached by both sexes when their body length is slightly over 50 cm; that the length at which 50 percent of the fish are mature is 60 cm for males, 62 cm for females; and that both sexes mature at a larger size than cod from Hecate Strait, but at a smaller size than those off the west coast of Kamchatka (Figure 14).

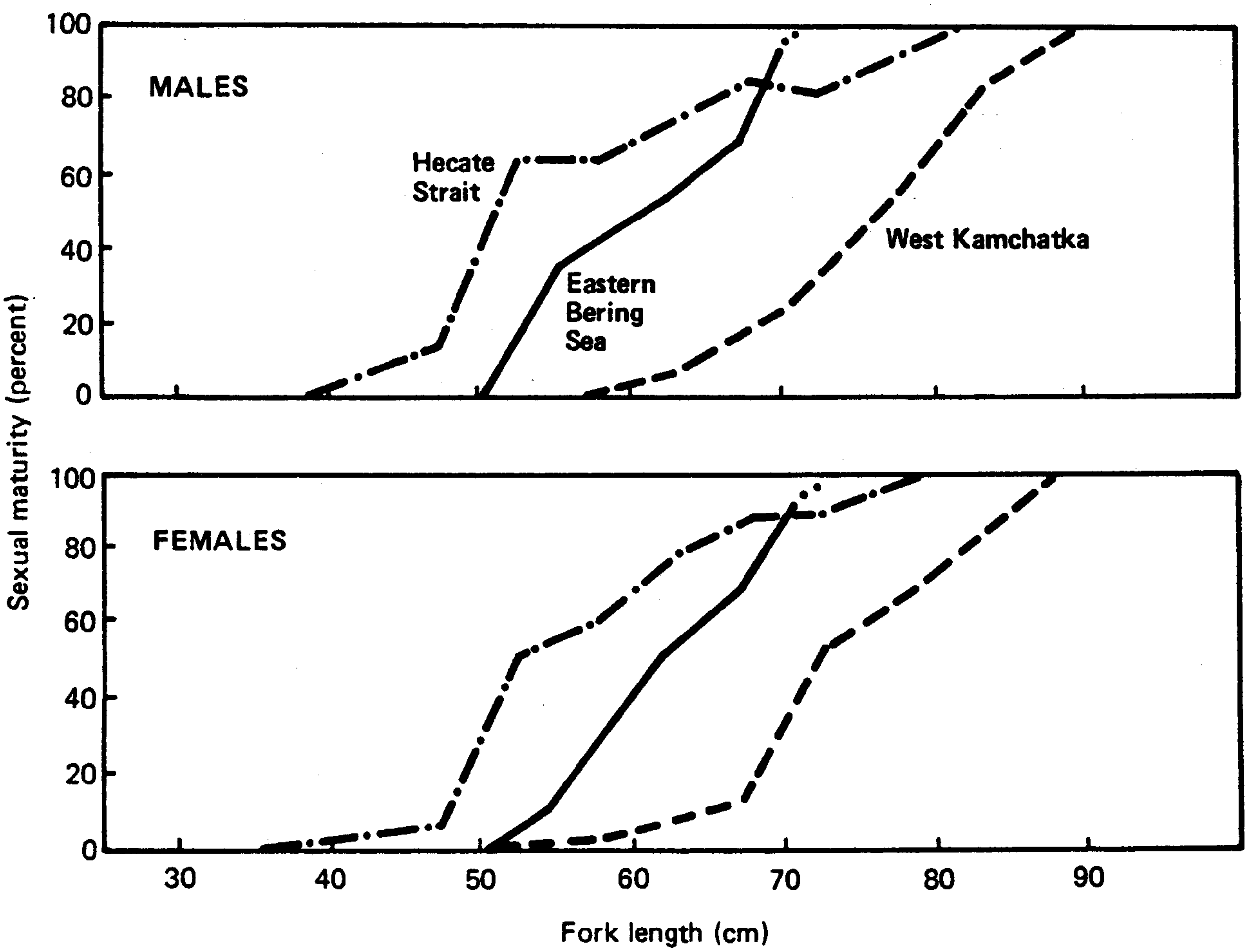


Figure 14.--Relationship between sexual maturity and body length for Pacific cod in eastern Bering Sea and Hecate Strait and off the west coast of Kamchatica. (From Teshima, unpublished manuscript.)

g. Size and age at entry into fisheries.

Length compositions of Pacific cod taken in the Japanese trawl and longline fisheries in eastern Bering Sea during 1978-83 indicate that cod enter the trawl fishery when they are about 30 cm in length and the longline fishery at approximately 40 cm (Figure 15). In most years cod taken in the longline fishery are 5 to 10 cm longer than those caught in the trawl fishery. The difference in size composition can be attributed primarily to differences in area of fishing, with gear selectivity probably also playing a role.

Comparison of the length frequency distributions of cod taken in NWAFC trawl surveys with the distributions for the Japanese fisheries during 1978-81, years when the 1977 year class predominated in the survey catches as 1, 2, 3, and 4-year-old fish successively, indicates that cod enter the Japanese trawl fishery at 3 years of age and the longline fishery mainly as 4-year-olds (Figure 15). (Assignation of cod to the 1977 year class is based on information on larval development and growth of young of the year linked to a backcalculation from modal lengths of fish sampled during the 1978 and 1979 trawl surveys.)

h. Natural Mortality.

The instantaneous rate of natural mortality (M) of Pacific cod in eastern Bering Sea is not known, nor has the rate been directly estimated for any cod population in the North Pacific Ocean except the stock in Hecate Strait in Canadian waters. For that population, Ketchen (1964) indicates that M lies in the range of 0.83 to 0.99, the midpoint of which is 0.9. If cod in Canadian waters have a much shorter lifespan than elsewhere, as Ketchen (1961) suggests, it can be assumed that M for the eastern Bering Sea population is substantially less than 0.9.

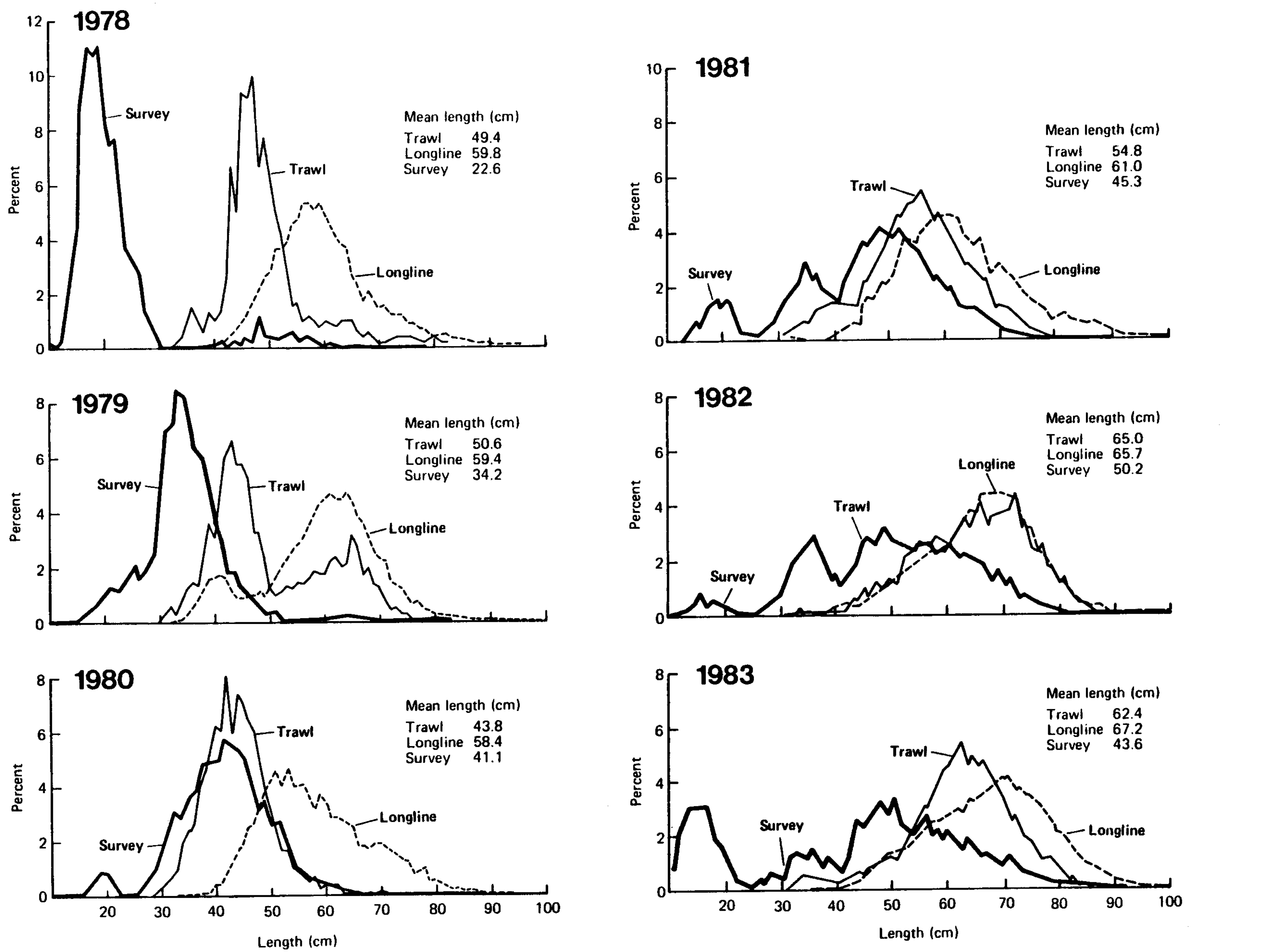


Figure 15.--Length composition of Pacific cod in NWAFC trawl surveys and Japanese trawl and longline fisheries in the eastern Bering Sea, 1978-1983. (From Bakkala, 1984, and NWAFC data files.)

i. Length-weight relationship

From samples of approximately 3,500 fish measured and weighed in the course of trawl surveys during 1975-1981, June and Shimada (pers. comm.) have determined the length-weight relationship for Pacific cod in eastern Bering Sea to be as shown in Figure 16. Their estimates of weights for fish of different lengths are 30 to 60% greater than those reported by Niggol (1982).

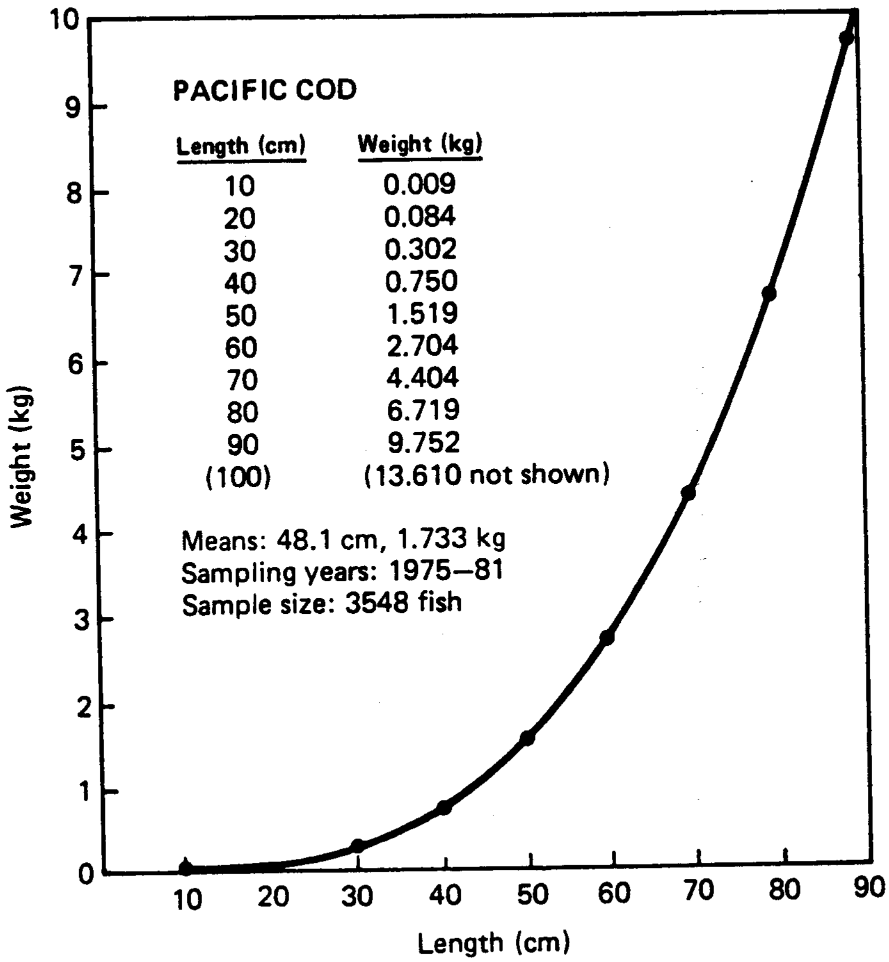


Figure 16.--Length-weight relationship for Pacific cod in eastern Bering Sea, sexes combined, (From June and Shimada, pers. comm.)

j. Feeding habits.

Krivobok and Tarkovskaya (1964) reported that cod from the southeastern Bering Sea contained large numbers of pollock (*Theragra chalcogramma*), Pacific herring (*Clupea harengus pallasi*), smelt (Osmeridae), capelin (*Mallotus villosus*), flatfish (Pleuronectidae), eel pouts (Zoarcidae), crab, shrimp, octopus, mollusk, and other fish, but they gave no specific quantities. Similar prey species were found in stomachs of cod sampled during NWAFC's trawl survey in eastern Bering Sea in June-July of 1980, with the principal species varying between sectors of the survey area (Figure 17). Snow crab predominated among food items in the southeast sector; pollock, snow crab, and miscellaneous invertebrates (including clams, hermit crab, and snails) in the central sector; and shrimp and pollock in the northwest sector. For the overall area sampled, unweighted averages of frequency of occurrence indicate that the four most important prey items were snow crab (23.7%), pollock (22.4%), miscellaneous invertebrates (19.1%), and shrimp (16.6%).

June (pers. comm.) has estimated the minimum and maximum daily consumption of five species of crab prey by Pacific cod in eastern Bering Sea during the summer (June-August) of 1981. His estimates of minimum daily consumption are as follows:

Species of crab	Number consumed per day (1000's)	Weight consumed per day (m.t.)
Red king	100	122.9
Blue king	39	11.8
Tanner - opilio	4,093	106.8
Tanner - bairdi	10,069	32.1
Korean horsehair	2,265	4.9

Estimates of maximum daily consumption are approximately ten times the minimum estimates.

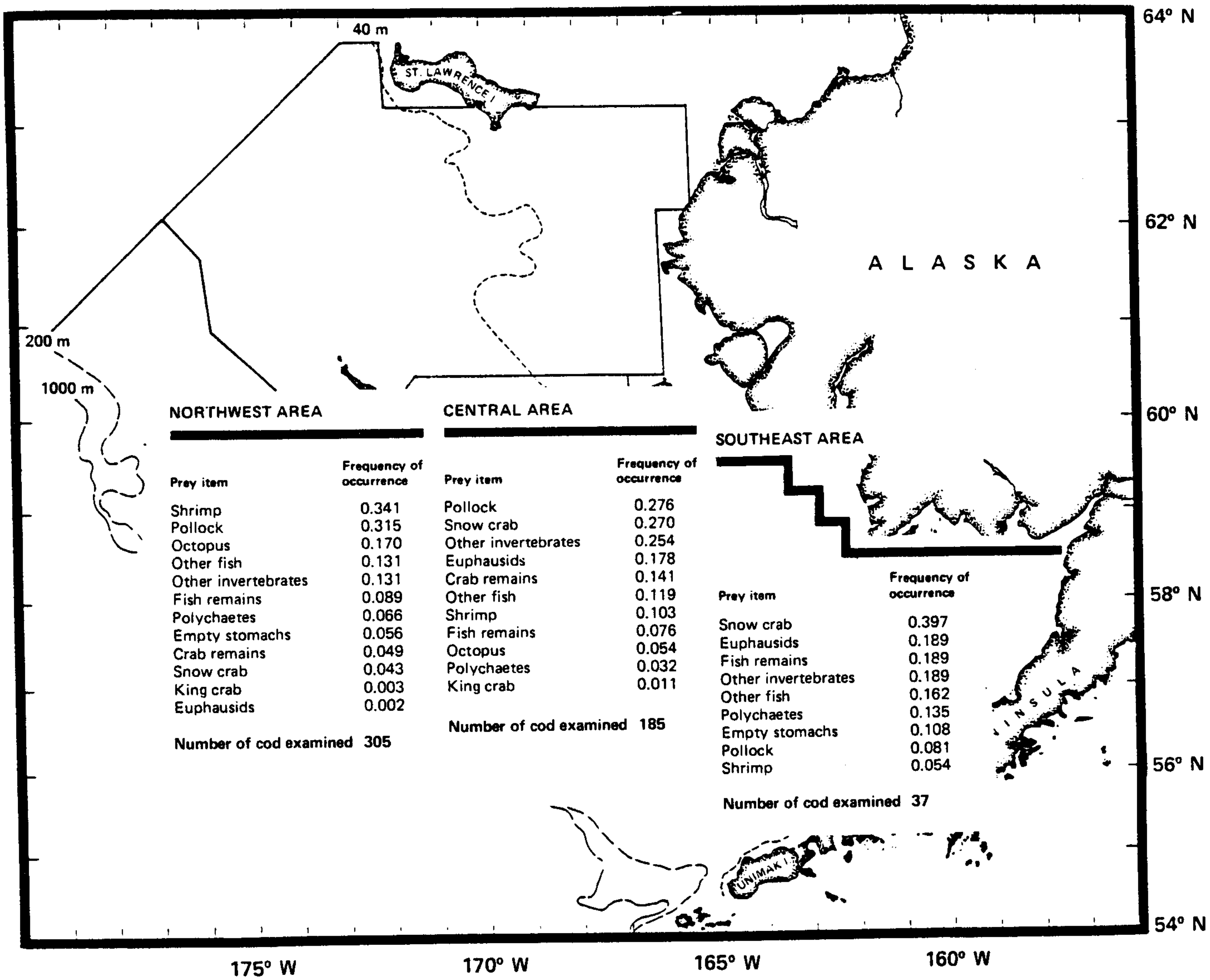


Figure 17.--Frequency of occurrence of prey items taken by Pacific cod in three sectors of the eastern Bering Sea, June-July, 1980. (From Bakkala, 1984.)

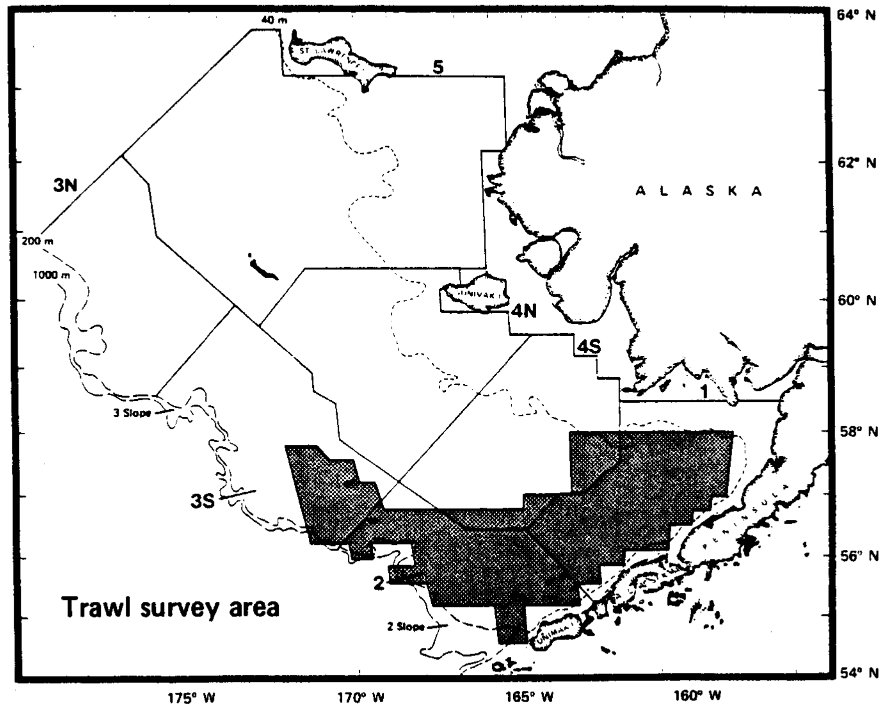
In regard to predation on red king crab by cod, all of the crabs in cod stomachs for which sex could be determined were females. Connecting such evidence with June's estimates of daily consumption and, as will be shown subsequently, indications of a major increase in cod abundance beginning in the late 1970's, it appears that predation by Pacific cod may be the principal cause of the sharp decline in abundance of red king crab in eastern Bering Sea in recent years.

Cannibalism does not seem to be a significant aspect of feeding by Pacific cod in eastern Bering Sea. By way of contrast, Daan (1983) estimates that cannibalism by Atlantic cod in the North Sea exercised a mortality of 5% on 2-year-old cod in 1981, and he indicates that the numbers of cannibalized young-of-the-year and 1-year-old cod exceeded the number of 2-year-olds meeting a similar fate by factors of nearly 150 and 10, respectively.

4. ABUNDANCE

Catch per unit effort (CPUE) data for Pacific cod in an area in southeast Bering Sea where NWAFC has conducted annual demersal trawl surveys of groundfish populations since 1973 indicate that after several years at a relatively stable and low level of abundance the size of the cod population began to increase in 1978 and by 1983 was 4-5 times the 1973-77 level of abundance (Figure 18). Recruitment of the exceptionally strong 1977 year class into the population undoubtedly contributed greatly to the increase, but it is possible that some of the difference between the 1973-77 and 1979-83 levels of abundance is due to improvements in survey methods over the years, including those accruing from experience.

CPUE's from the Japanese longline fishery also point to a major increase in the cod population in recent years, a doubling to tripling of abundance between 1977-79 and 1980-82 (Figure 19). The increase, however, lags by a couple of years



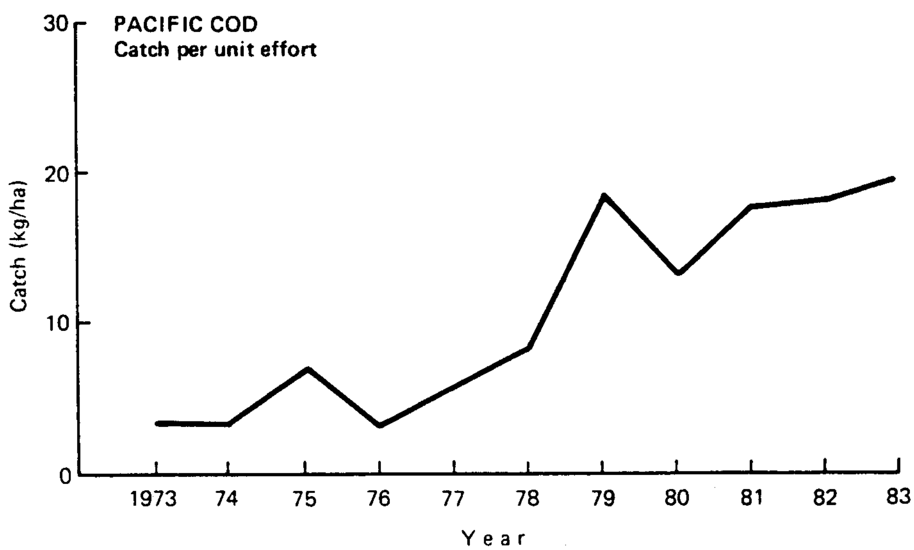


Figure 18.--Relative abundance of Pacific cod in southeast Bering Sea as indicated by catch per unit effort data from NWAFC demersal trawl surveys, 1973-1983. (From Bakkala and Wespestad, 1984.)

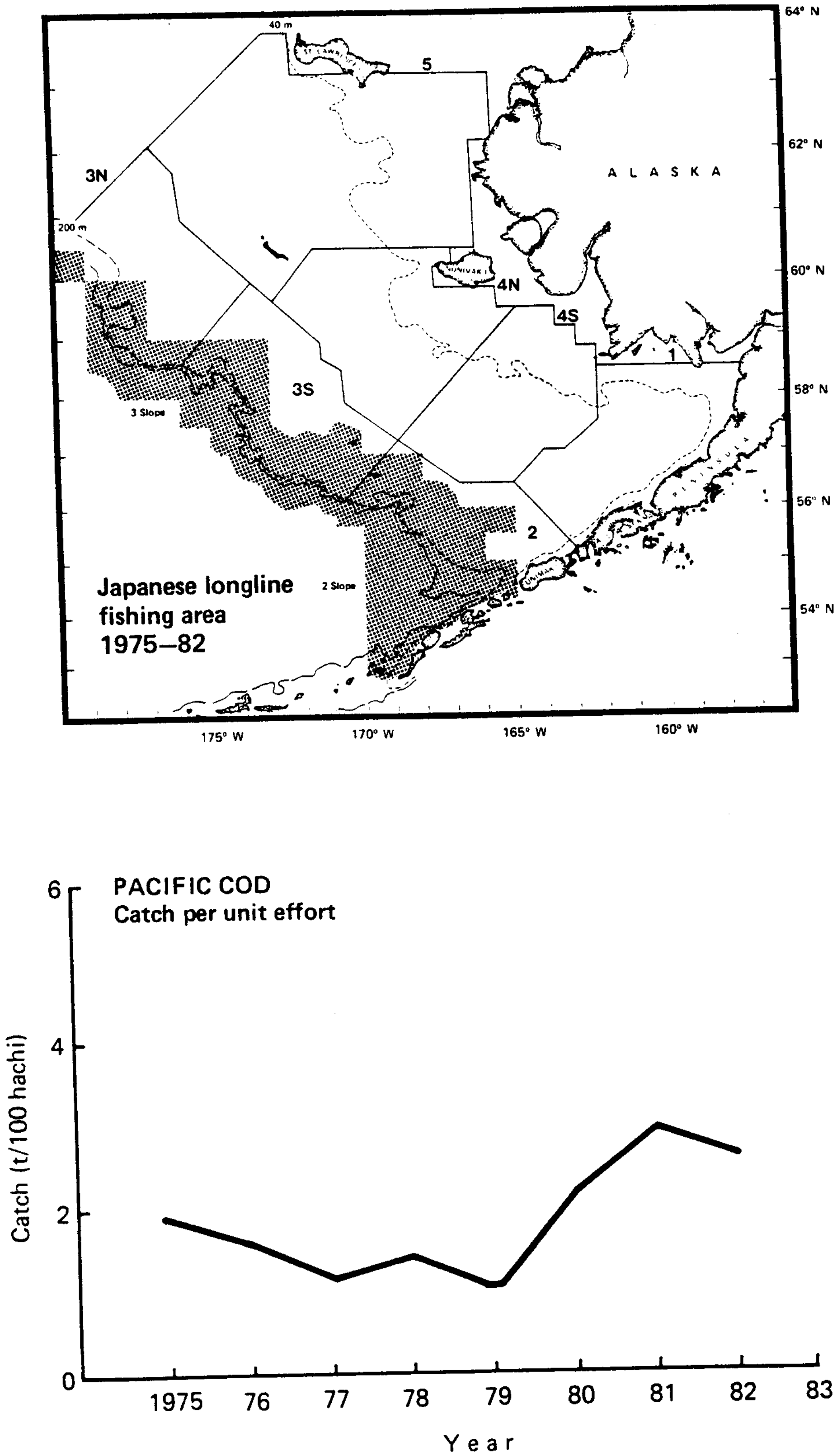


Figure 19.--Relative abundance of Pacific cod in the Japanese longline fishing area in eastern Bering Sea as indicated by catch per unit effort data from the fishery, 1975-1982. (Area of fishing from NWAFC data file. CPUE data are from Bakkala and Wespestad, 1984.)

the increase shown by the trawl survey data in Figure 18 because cod recruit to the longline fishery at a later age in life than they first appear in the surveys.

Based on estimates derived from large-scale trawl surveys, the biomass of Pacific cod in eastern Bering Sea increased from approximately 300 thousand tons in 1978 to more than 1.1 million tons in 1983 (Figure 20). Since the 1978 survey did not include sampling in large portions of subareas 3N, 4N and 4S, the biomass estimate for that year probably is on the low side relative to 1983. Nevertheless, there is little doubt that cod biomass increased markedly between 1978 and 1983.

Bakkala and Wespestad (1984) have projected the biomass of Pacific cod in eastern Bering Sea in 1984-86 to be as follows:

	Thousands of t	
Year	Age 2 and above	Age 3 and above
1984	688	581
1985	462	356
1986	385	278

Assumptions carried in the projections include a natural mortality coefficient of 0.5, recruitment at age 2 of 190 million fish in each of the three years, and annual catches ranging from 111 to 232 thousand tons. It remains to be seen how accurate the projections might be, but the following comparison of projections (age 2 and over) and survey estimates (all ages) of biomass for 1979-83 suggests that there may be considerable differences between projected values and survey estimates of biomass for 1984-86:

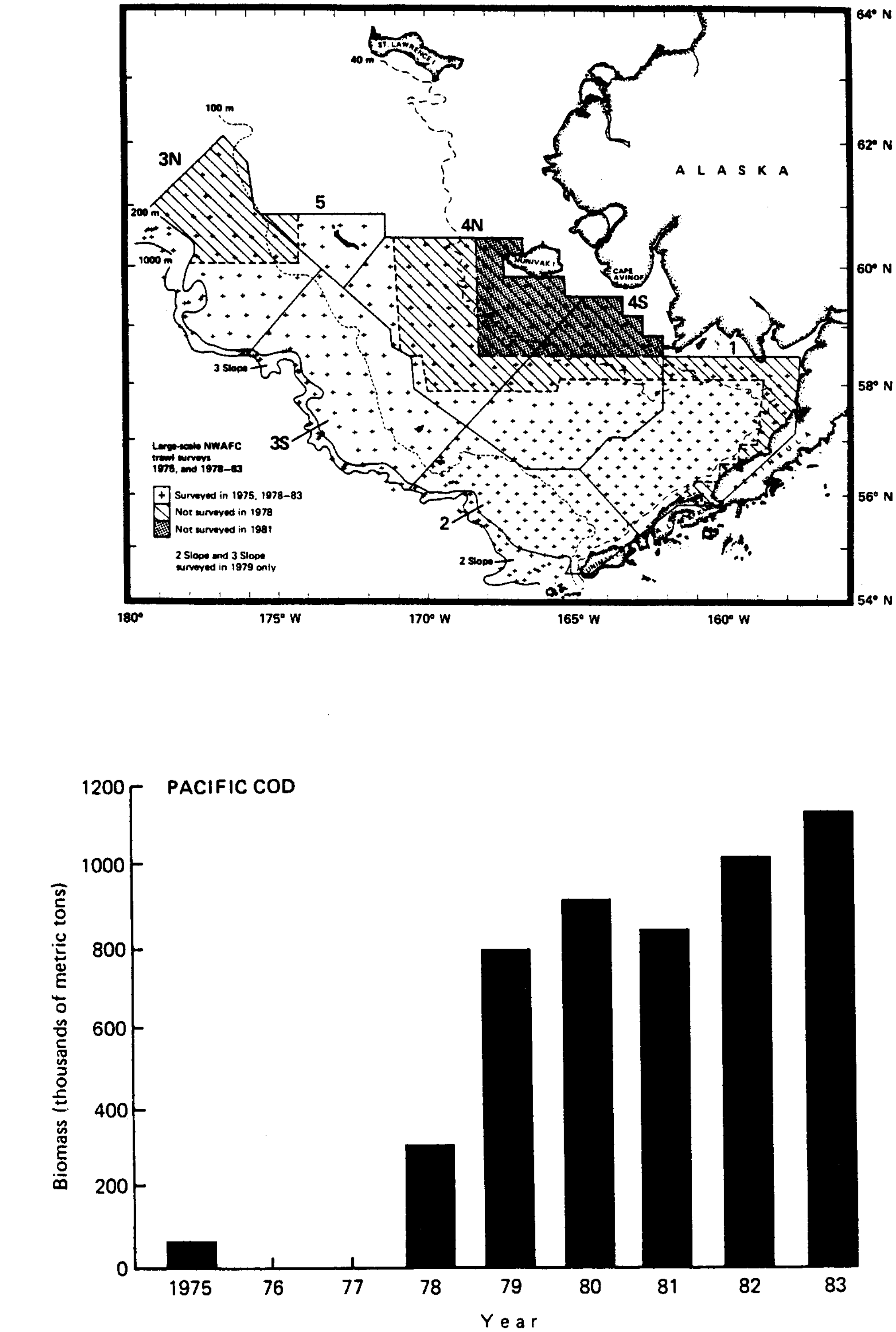


Figure 20.--Estimates of biomass of Pacific cod in eastern Bering Sea as derived from large-scale trawl surveys by NWAFC in 1975 and 1978-83. (From Bakkala and Wespestad, 1984.)

	Thousands of t		
Year	Projected biomass, age 2 and above	Survey estimates of biomass, all ages	Projection/survey estimate, %
1979	966	792	121
1980	1,271	913	139
1981	1,267	840	151
1982	1,100	1,013	109
1983	882	1,126	78

Notwithstanding differences between projections and survey estimates of biomass, which of course could be a consequence of errors in either or both, it appears that the abundance of cod in eastern Bering Sea will diminish significantly from the current level as the lifespan of the 1977 year class, which accounted for about one-third of the estimated total biomass in 1983, comes to an end.

5. COMMERCIAL CATCH

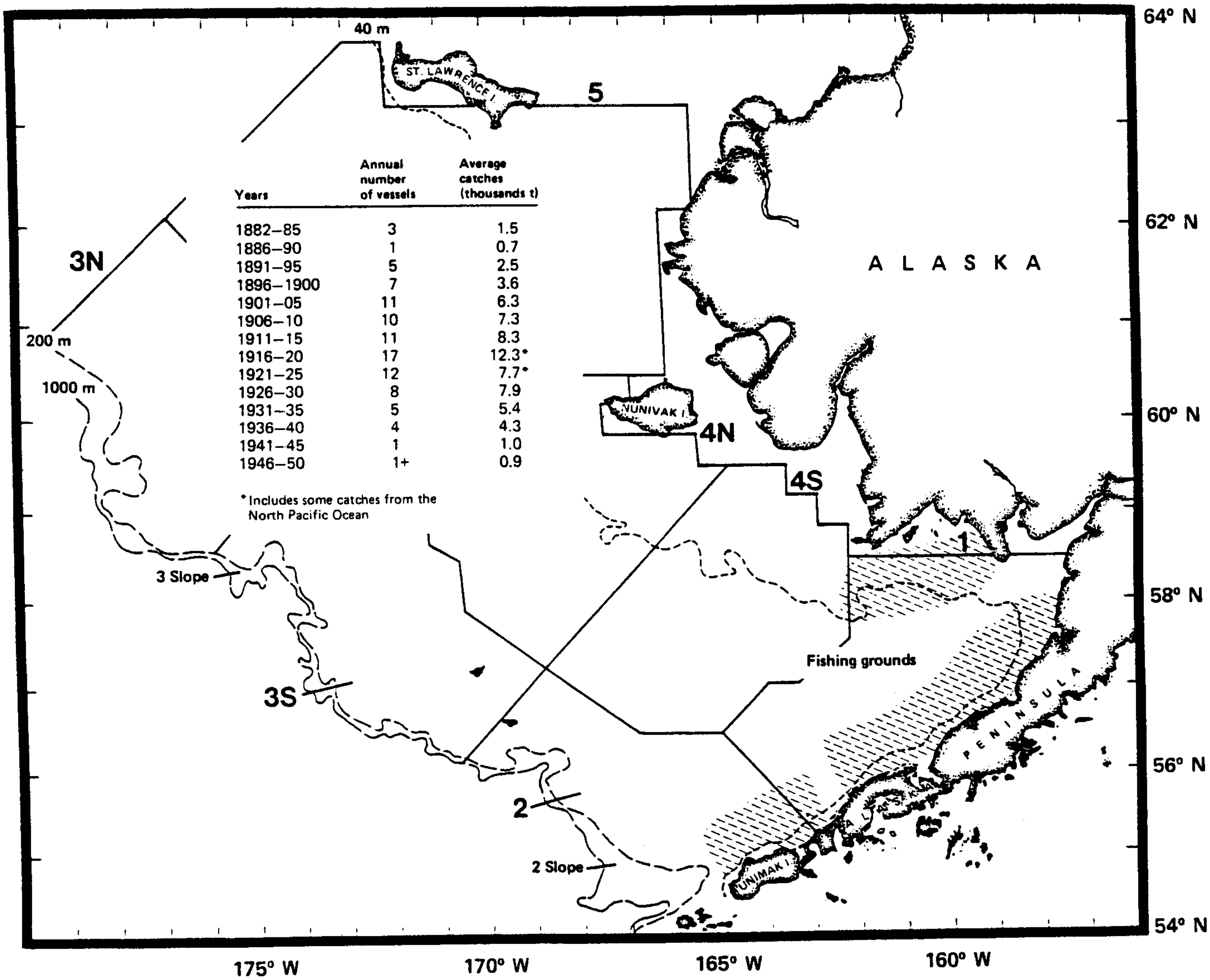
a. North American Fishery - 1882 to 1950

After beginning on a regular annual basis in the early 1880's, the North American schooner - dory catcher boat fishery for Pacific cod in eastern Bering Sea developed slowly over a 20-year period, reached its peak around the time of World War I, and then gradually declined until the fishery terminated in 1950 (Figure 21). Fishing took place during May-August at depths of 25 to 100 m on cod banks along the north side of Unimak Island and the Alaska Peninsula and between Capes Constantin and Newenham. Maximum annual catch was 14,000 t.

b. Foreign Fisheries

A Japanese mothership fleet operated in the eastern Bering Sea between 1933 and 1941, targeting first on pollock and then on yellowfin sole, with cod probably being taken as a by-catch and included in the 1,100 to 2,800 t of species other than pollock and flatfish caught annually (Forrester et al, 1978; and Bakkala, 1984).

After a hiatus of a dozen years during and following World War II, Japanese vessels resumed fishing for groundfish in eastern Bering Sea in 1954. They were joined by trawling vessels of the U.S.S.R. in 1958, Republic of Korea in 1967, Taiwan in 1974, Poland in 1979, and the Federal Republic of Germany in 1980. Yellowfin sole was the target species of the Japanese fishery through the early 1960's and of the Soviet fishery through 1970. In 1963 and 1971, respectively, pollock became the target species for the two fisheries, and it has been the main species sought by vessels of the other nations. Pacific cod have not been a target species of the trawl fisheries except when concentrations are found during the course of fishing for other species, but they have been a target of the Japanese longline fishery at times (Bakkala, 1984).



Years	Annual number of vessels	Average catches (thousands t)
1882–85	3	1.5
1886–90	1	0.7
1891–95	5	2.5
1896–1900	7	3.6
1901–05	11	6.3
1906–10	10	7.3
1911–15	11	8.3
1916–20	17	12.3*
1921–25	12	7.7*
1926–30	8	7.9
1931–35	5	5.4
1936–40	4	4.3
1941–45	1	1.0
1946–50	1+	0.9

*Includes some catches from the North Pacific Ocean

Figure 21.--Area fished by the North American schooner-dory catcherboat fishery for Pacific cod in eastern Bering Sea and average annual catches and number of vessels, 1882-1950. (From Cobb, 1927, and Pereyra et al., 1976.)

Annual catch of cod increased from slightly over 200 t in 1958 (the first year that any foreign nation reported cod catches separately from other species) to nearly 14,000 t in 1963 and then to 70,000 t in 1970. From that peak it fell to an average annual catch of 50,000 t during 1971-76 and 35,000 t during 1977-82 (Table 1). Most of the cod have been taken on the outer continental shelf each year (Bakkala, 1984 and Low, 1974). Distribution of trawl catches is much more widespread than longline catches, as shown by average annual catches during 1978-82 (Figure 22).

c. U.S. Fisheries --Recent Years.

A U.S. domestic trawl fishery and joint venture fisheries, the latter involving U.S. catcher boats delivering catches to processing vessels of other nations, recently began operations in eastern Bering Sea. Areas fished are shown in Figure 23. Combined catches of Pacific cod by these fisheries increased from less than 1,000 t in 1979 to nearly 49,000 t in 1983, accounting for more than one-half of the all-nation catch in the latter year (Table 1).

Table 1.--Commercial catches (t) of Pacific cod in eastern Bering Sea, 1958-82, by nations. (From Bakkala, 1984; Bakkala and Wespestad, 1984; and NWAFC data files.)

	Foreign fisheries					U.S. fisheries			
Year	Japan	USSR	ROK 2/	Other nations 3/	Total	Joint ventures 4/	Domestic 5/	Total	All-nation catch
1958	223	- 1/			223				223
1959	3,632	-			3,632				3,632
1960	5,679	-			5,679				5,679
1961	6,883	-			6,883				6,883
1962	10,347	-			10,347				10,347
1963	13,641	-			13,641				13,641
1964	13,408	-			13,408				13,408
1965	14,719	-			14,719				14,719
1966	18,200	-			18,200				18,200
1967	32,064	-	-		32,064				32,064
1968	57,902	-	-		57,902				57,902
1969	50,351	-	-		50,351				50,351
1970	70,094	-	-		70,094				70,094
1971	40,568	2,486	-		43,054				43,054
1972	35,877	7,028	-		42,905				42,905
1973	40,817	12,259	-		53,386				53,386
1974	45,915	16,547	-	-	62,462				62,462
1975	33,322	18,229	-	-	51,551				51,551
1976	32,009	17,756	716	-	50,481				50,481
1977	33,141	177	-	2	33,320		15	15	33,335
1978	41,234	419	859	-	42,512		31	31	42,543
1979	28,532	1,956	2,446	47	32,981		780	780	33,761
1980	27,334	7	6,346	1,371	35,058	8,370	2,433	10,803	45,861
1981	27,570		6,147	2,481	36,198	7,410	8,388	15,798	51,996
1982	17,380		8,151	647	26,178	9,312	19,550	28,862	55,040
1983	31,256		10,185	65	41,506	14,362	34,315	48,677	90,183

1/ Dash indicates fishing but catches of cod not reported.
2/ Republic of Korea.
3/ Taiwan, Poland, and West Germany.
4/ Joint ventures between U.S.-ROK and U.S.-USSR.
5/ U.S. vessels delivering to domestic processors.

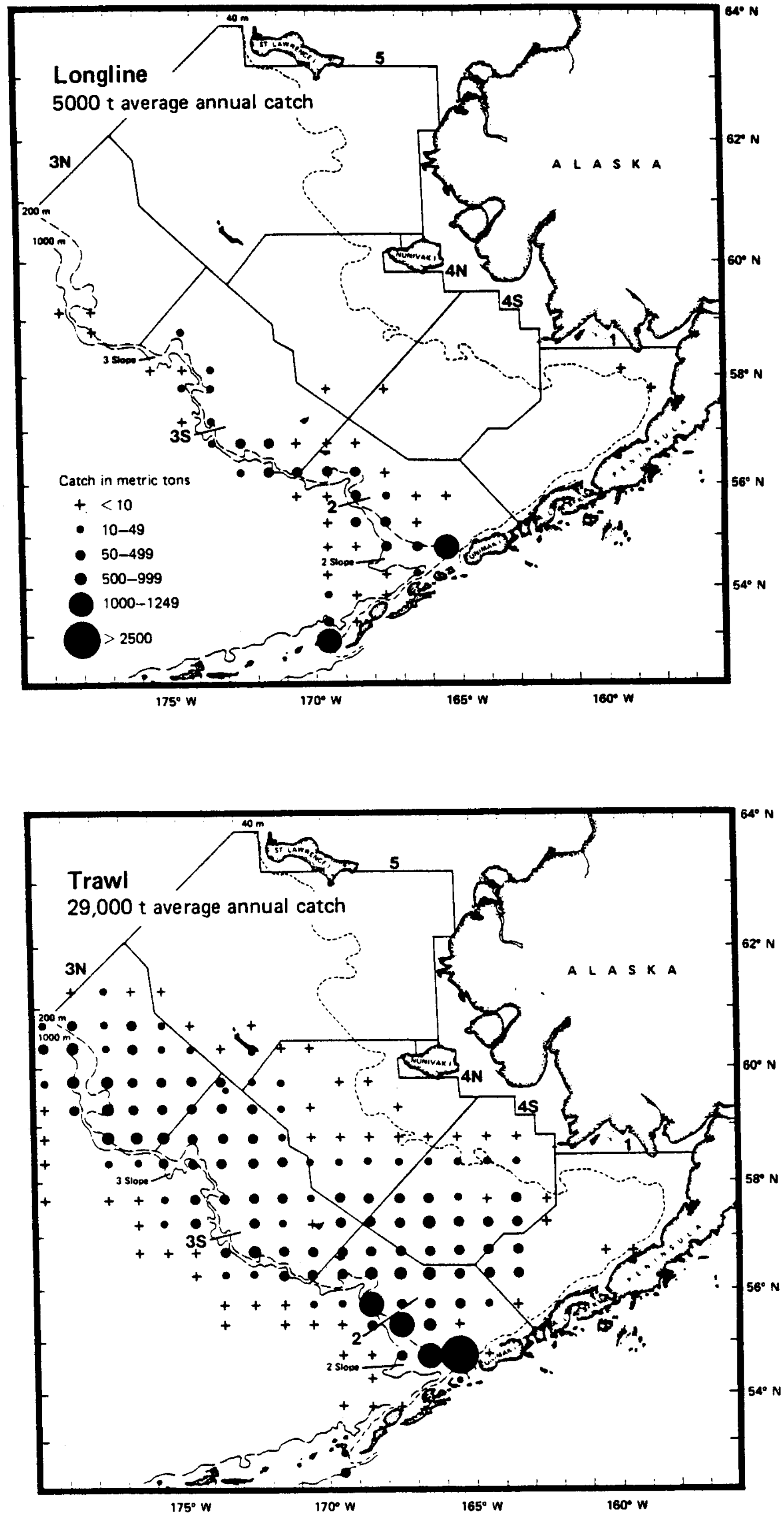


Figure 22.--Distribution of average annual catches of Pacific cod by foreign trawl and longline fisheries in eastern Bering Sea during 1978-82, as reported by fishing nations and U.S. observers. (From NWAFC data files.)

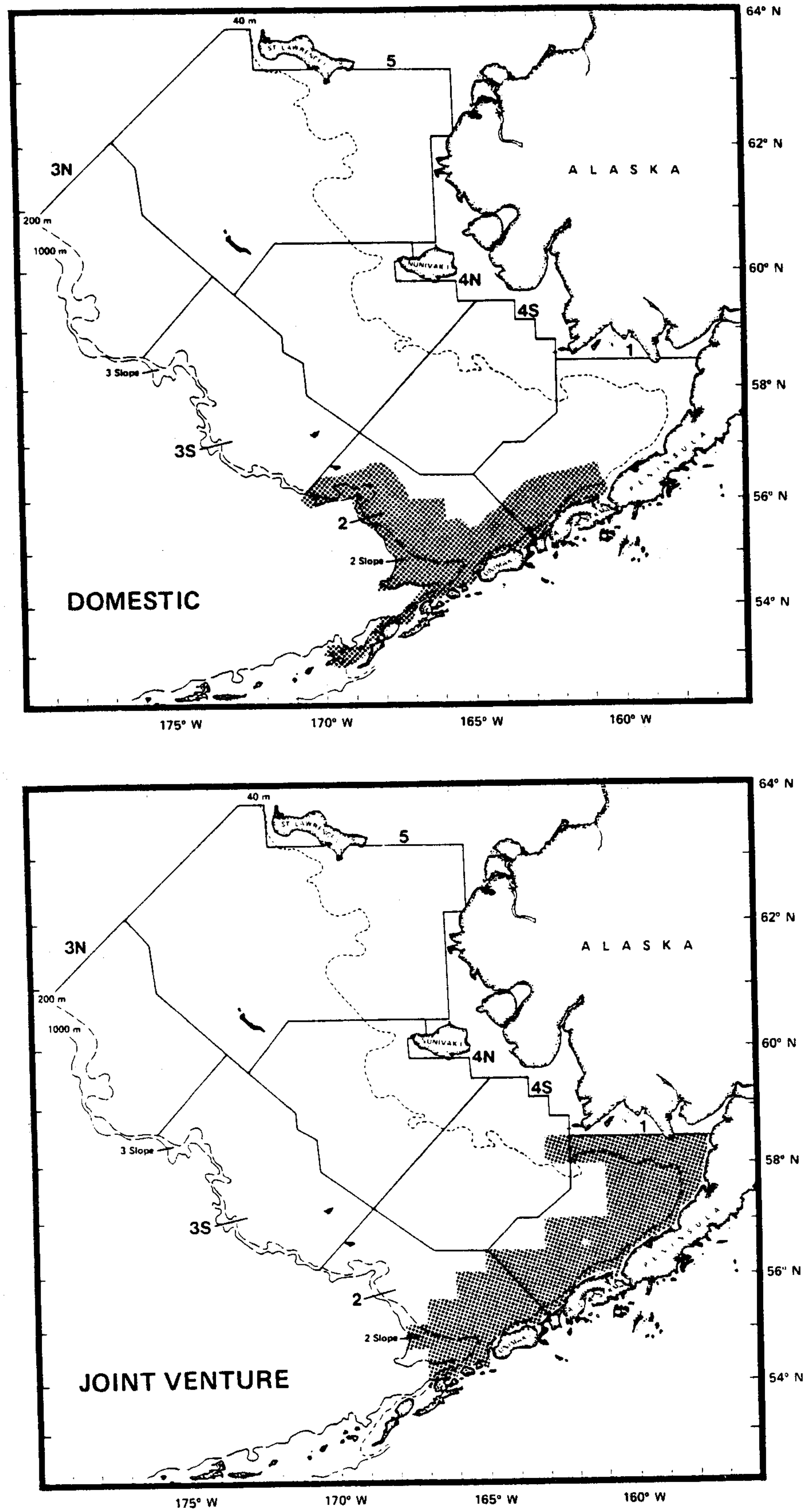


Figure 23.--Areas fished for Pacific cod in eastern Bering Sea by U.S. vessels connected with domestic and foreign (joint venture) processing operations. (R. Nelson and S, Hughes, pers. comm.)

6. MANAGEMENT

Measures employed in regulating domestic and foreign fisheries for groundfish in eastern Bering Sea prior to enactment of the U.S. Fishery Conservation and Management Act (FCMA) of 1976 included gear restrictions, licensing of vessels and fishing gear, time-area closures, requirements for reporting of catches or landings, and quotas for some species in some years. A detailed summary of the historical regulations is given in the Fishery Management Plan (FMP) for the Groundfish Fishery in the Bering Sea/Aleutian Islands Area (Figure 24) prepared by the North Pacific Fisheries Management Council in October 1983. The FMP also describes in full the current management regime for the domestic and foreign fisheries for groundfish (excluding Pacific halibut) under the provisions of the FCMA.

Four priority objectives dictate the philosophy of management for the groundfish fishery in the region:

(1) Provide for the rational and optimal use, in a biological and socio-economic sense, of the region's fisheries resources as a whole;

(2) Minimize the impact of groundfish fisheries on prohibited species (including halibut, herring, salmonids, shrimps, scallops, snails, king crab, Tanner crab, Dungeness crab, corals, surf clams, horsehair crab and lyre crab) and continue the rebuilding of the Pacific halibut resource;

(3) Provide for the opportunity and orderly development of domestic groundfish fisheries, consistent with (1) and (2) above; and

(4) Provide for foreign participation in the groundfish fishery, consistent with all three objectives above, to take the portion of the total allowable catch (TAC) not utilized by domestic fishermen.

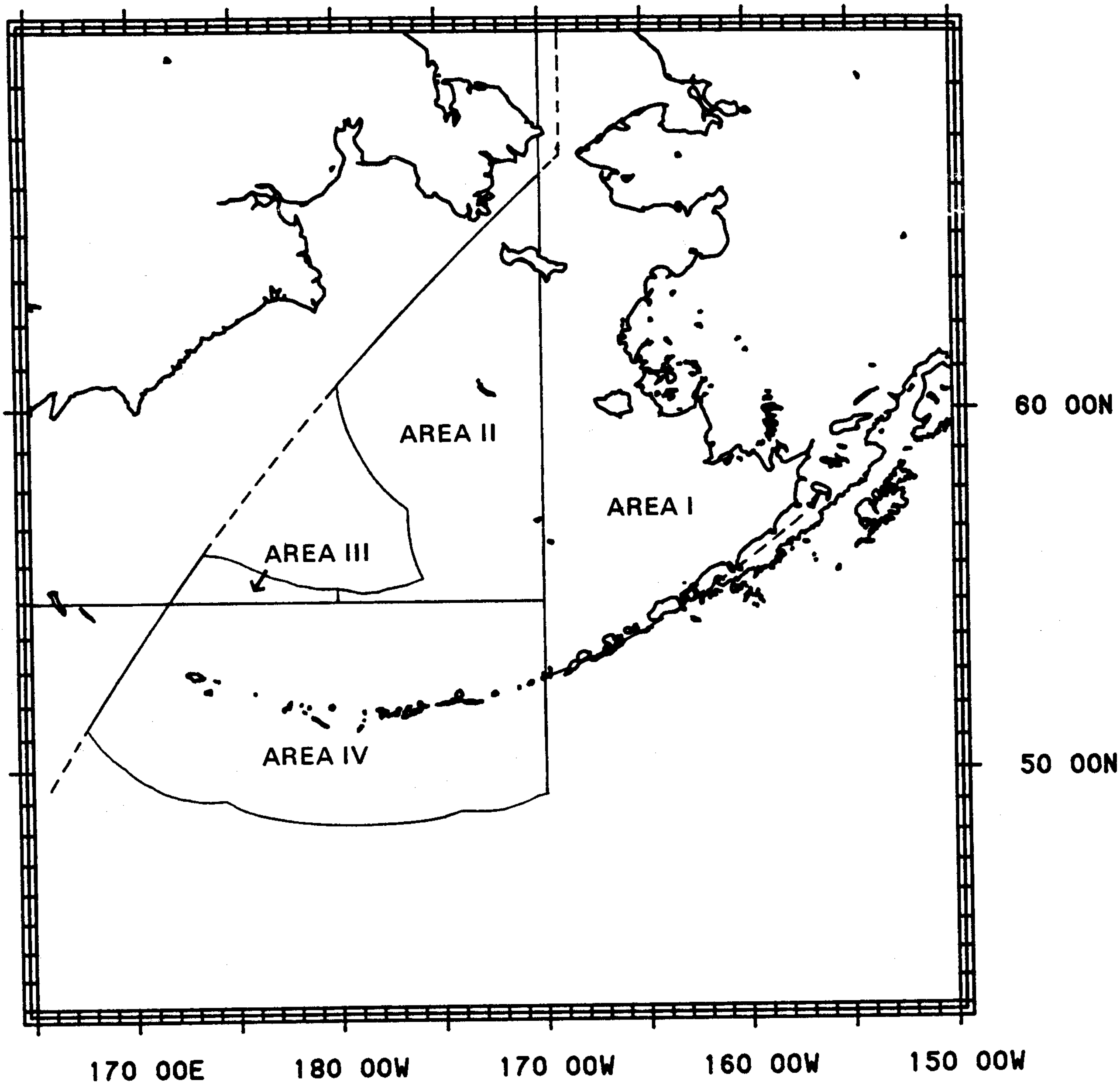


Figure 24.--Fishing areas in the Bering Sea and Aleutian Islands as established by the North Pacific Fisheries Management Council.

In connection with the last two objectives the proportion of the TAC of Pacific cod from the Bering Sea/Aleutian Islands area allocated to U.S. fisheries increased from zero in 1977 to 55% in 1982 (Table 2). The proportion of the TAC allocated to U.S. fisheries is expected to become much greater in the near future.

Table 2.--Allocation of total allowable catches (t) of Pacific cod in the Bering Sea/Aleutian Islands area, 1977-82 (from Fishery Operations Branch, NMFS, Alaska Region).

		Allocations			
Year	TAC	U.S. fisheries	Foreign fisheries	Reserves[a/]	% U.S.
1977	58,000	-	58,000	-	0
1978	70,500	-	58,070	12,430	0
1979	58,000	-	56,500	1,500	0
1980	70,700	22,265	48,435	-	31
1981	78,700	27,232	51,468	-	35
1982	78,700	43,265	35,435	-	55

a/ Set aside for unexpected expansion of U.S. fisheries, possible operational problems of domestic and foreign fleets, adjustment of TAC according to stock conditions during the fishing year, or subsequent apportionment.

7. THE RESOURCE IN RELATION TO OIL DEVELOPMENTS IN BRISTOL BAY

Simulation studies of the uptake and depuration of petroleum hydrocarbons in selected marine species resulting from exposure to oil-contaminated water and sediments and the consumption of oil-contaminated food following hypothetical oil spills off Port Heiden on the Alaska Peninsula (Gallagher and Pola, 1984) provide an indication of the possible consequences of oil developments in the Bristol Bay ecosystem as they relate to the Pacific cod resource and fishery in eastern Bering Sea. The studies involve two accident scenarios, one a well blowout lasting five days and releasing 20,000 barrels of Prudhoe Bay crude oil per day for a total spill of 100,000 bbl, the other a tanker accident resulting in a spill of 200,000 bbl of refined automotive diesel fuel within a 24-hour period. The distribution of oil in a 15 m surface layer and in a 10 cm bottom layer was estimated over a 10,000 km^2 area for the blowout scenario, and a 4,352 km^2 area in the case of the tanker accident scenario. Concentrations of oil in the water in the surface layer (water soluble fractions, or WSF) and in the bottom layer (on-bottom fractions, or TARS) were measured in parts per billion over a period of 30 days following the hypothetical blowout or accident.

Findings from Gallagher and Pola's simulation study of oil concentrations in water can be summarized as follows:

Scenario 1-a: Blowout, WSF. Maximum concentration was 0.1 to 1.0 ppm, lasting approximately 17 days after the blowout and contaminating less than 3% of the study area, that is, less than 300 km^2.

Scenario 1-b: Blowout, TARS. Maximum concentration also was 0.1 to 1.0 ppm, beginning about two weeks after the blowout and lasting 8 days, contaminating a maximum of 3% of the study area.

Scenario 2-a: Accident, WSF. Maximum concentration exceeded 5 ppm, but for only 4 days following the accident and contaminating less than 2% of the study area, that is, approximately 50 km^2. Concentrations of 1-5 ppm contaminated up to 10% of the study area (about 450 km^2) for about 12 days following the spill, and concentrations of 0.1 to 1.0 ppm contaminated up to 22% of the area (nearly 1,000 km^2) for 15 days immediately after the spill.

Scenario 2-b: Accident, TARS. Maximum concentration also exceeded 5 ppm, lasting nearly 2 weeks beginning 4 days after the spill and contaminating about 5% of the study area (about 225 km^2). Concentrations of 1-5 ppm, lasting for 4 weeks after the spill, contaminated up to 19% of the study area (about 825 km^2), and concentrations of 0.1-1.0 ppm lasted throughout the 30 days of the simulation study, contaminating 28% of the area (1,200 km^2).

A point of reference for relating the foregoing findings to the impact that a well blowout or tanker accident might have on the Pacific cod resource in eastern Bering Sea is given by Moore and Dwyer (1974) who estimated the concentrations of soluble aromatic derivatives causing mortalities of finfish in their larval and adult stages of life: 0.1-1.0 ppm for larvae and 5-50 ppm for adults. For purposes of this study, it is assumed that concentrations of 5-50 ppm are lethal for cod of 4 years of age and over, with concentrations of 1-5 ppm causing mortalities of cod of ages 1-3, which are referred to here as sub-adults.

Spawning populations. Relatively little is known about the distribution of spawning populations of Pacific cod in eastern Bering Sea, but evidence at hand indicates that spawning takes place in areas far removed from the three sites selected for simulation studies of oil spills: off Port Moller, Port Heiden, and Cape Newenham. It appears that an oil spill or well blowout at any one of the three offshore sites would have little, if any, effect on spawning adults.

Eggs and larvae. Not enough is known about the distribution of Pacific cod eggs and larvae in eastern Bering Sea to make a quantitative determination of the impact that a well blowout or tanker spill off Port Moller, Port Heiden, or Cape Newenham might have on their development or survival, or the abundance of the year class that they represent. The worst-case scenario indicated by Gallagher and Pola's simulation studies (Scenario 2-b) shows that an area of 1,200 km^2 would be contaminated with oil of sufficient concentration to be lethal to cod larvae. Such an area undoubtedly represents only a small fraction of the total area where cod larvae are to be found in eastern Bering Sea.

Sub-adults. Under Scenario 2-b, an oil spill from a tanker accident in Subarea 1, which encompasses 84,000 km^2, would contaminate about 825 km^2 of the subarea for a 4-week period with oil concentrations of 1-5 ppm. Assuming that sub-adult cod are evenly distributed throughout the subarea without moving in or out of the contaminated area during the 4-week period when the concentration of oil is assumed to be lethal, it is estimated that about 1% of the population of ages 1-3 cod in Subarea 1 would be killed as a result of a 200,000 bbl spill caused by a tanker accident. Based on the average annual abundance of ages 1-3 cod in the NWAFC trawl survey area in eastern Bering Sea during 1978-83 (Figure 10), a 1% mortality in Subarea 1 translates into about 0.3% mortality for the trawl survey area as a whole.

Adults. Under the same scenario as described for sub-adult cod and employing similar assumptions, it is estimated that slightly less than 0.3% of the total population of age 4 and older cod in Subarea 1 would be killed as a result of the oil spill. Such a loss would represent 0.05% of the total population of age 4^+ cod in the eastern Bering Sea, as indicated by trawl survey estimates of abundance during 1978-83.

Judging from trawl survey estimates of abundance of age 1 and older cod in the different subareas of eastern Bering Sea during 1978-83, the impact of an oil spill from a tanker accident (Scenario 2-b) off Cape Newenham in Subarea 4S on the total abundance of sub-adult and adult cod would be expected to be less (by 40%) than a corresponding spill in Subarea 1. In neither case would the kill of sub-adult and adult cod be detectable in trawl survey estimates of abundance. The estimated error of the point estimate of 727 million cod in the population in 1983 (Figure 10) was $\pm 22\%$, about fifty times greater than the estimated percentage kill of age 1 and older cod that would be attributable to a very large oil spill in Subarea 1.

Although not suffering a mortality due to a well blowout or tanker spill, a segment of the cod population would be tainted through the consumption of oil-contaminated food. Gallagher and Pola estimate that a well blowout would result in the tainting of up to 2% of the biomass in the spill area, a tanker accident up to 30%. As depuration proceeds, that is, the purging of hydrocarbons from contaminated fish over time, the percentage of tainted fish decreases. Extrapolation of data given by Gallagher and Pola on percent biomass tainted in relation to the number of days after the start of a spill suggests that it would take about 60 days for Pacific cod to be taint-free, which in turn suggests that the spill area would have to be closed to fishing for approximately two months to avoid the catching of tainted fish. The closed area would represent only a minor fraction of the total area where fishing for cod could be continued, unaffected by tainted fish.

REFERENCES

Bakkala, R. G.

1984. Pacific cod of the eastern Bering Sea. Int. North Pac. Fish. Comm., Bull. 42.

Bakkala, R. G., T. M. Sample, M. S. Bohle, J. A. June, A. M. Shimada and Y. Umeda.

1982. Data report: 1979 demersal trawl survey of the eastern Bering Sea continental shelf and slope. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC 30, 200 p.

Bakkala, R. G. and V. G. Wespestad.

1984. Pacific cod. In R. G. Bakkala and L. L. Low (editors): Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1983. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-53, 189 p.

Bakkala, R., S. Mishima, S. Westrheim, C. Zhang, and E. Brown.

1984. Distribution of Pacific cod (Gadus macrocephalus) in the North Pacific Ocean. Int. North Pac. Fish. Comm., Bull. 42.

Bohle, Michael S., and R. G. Bakkala.

1984. Data report: 1978 bottom trawl survey of eastern Bering Sea groundfish. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC 55, 164 p.

Cobb, J. N.

1927. Pacific cod fisheries. Rep. U.S. Comm. Fish., 1926, append. 7:305-499. (Doc. 1014.)

Daan, N.

1983. Analysis of the cod samples collected during the 1981 stomach sampling project. Unpubl. manusc. (Document submitted to ICES, Demersal Fish. Comm., 1983.)

Dodimead, A. J., F. Favorite, and T. Hirano.

1962. Salmon of the North Pacific Ocean. Part II. Review of oceanography of the subarctic Pacific region. Int. North Pac. Fish. Comm. Bull. 13:195 p.

Forrester, C. R. and D. F. Alderdice.

1966. Effects of salinity and temperature on embryonic development of Pacific cod (*Gadus macrocephalus*). J. Fish. Res. Board Can. 23:319-340.

Forrester, C. R., A. J. Beardsley, and Y. Takahashi.

1978. Groundfish, shrimp, and herring fisheries in the Bering Sea and Northeast Pacific -- historical catch statistics through 1970. Int. North Pac. Fish. Comm., Bull. 37, 147 p.

Gallagher, A. F. and Nancy B. Pola.

1984. The uptake and depuration of petroleum hydrocarbons in marine species: a simulation study of the uptake and depuration of petroleum hydrocarbons and its effect on selected marine species in the Bristol Bay ecosystem. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA. Processed Rpt. 84-16, 68 pp.

Hart, J. L.

1973. Pacific fishes of Canada. Fish. Res. Board Can., Bull. 180, 740 p.

Kennedy, W. A.

1970. Reading scales to age Pacific cod (*Gadus macrocephalus*) from Hecate Strait. J. Fish. Res. Board Can. 27:915-922.

Ketchen, K. S.

1961. Observations on the ecology of the Pacific cod (*Gadus macrocephalus*) in Canadian waters. J. Fish. Res. Board Can. 18:513-558.

1964. Preliminary results of studies on growth and mortality of Pacific cod (*Gadus macrocephalus*) in Hecate Strait, British Columbia. J. Fish. Res. Board Can. 21:1051-1067.

Krivobok, M. N. and O. I. Tarkovskaya.

1964. Chemical characteristics of yellowfin sole, cod, and Alaska pollock of the southeastern part of the Bering Sea. Tr. Vses. Nauchno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 49 (Izv. Tikhookean. Nauchno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 51):257-271. (Transl. in Soviet Fisheries Investigations in the Northeast Pacific, Part II, p. 271-286, by Israel Program Sci. Transl., 1968, avail. Natl. Tech. Inf. Serv., Springfield, VA, as TT67-51204.)

Leaman, J. E.

1982. Catch and effort statistics of the Canadian groundfish fishery on the Pacific coast in 1981. Can. Tech. Rep. Fish. Aquat. Sci. No. 1124. 90 p.

In press. Catch and effort statistics of the Canadian groundfish fishery on the Pacific coast in 1982. Dept. Fish. and Oceans, Fish. Res. Branch, Pac. Biol. Sta., Nanaimo, B.C.,Canada V9R 5K6.

Low, L. L.

1974. A study of four major groundfish fisheries of the eastern Bering Sea. Ph.D. Thesis, Univ. Wash., Seattle, 240 p.

McLain, D. R. and F. Favorite.

1976. Anomalously cold winters in the southeastern Bering Sea, 1971-75. In Goulet, J. R., Jr. (ed). The environment of the United States living marine resources 1974. U.S. Dep. Commer., NOAA, NMFS, MARMAP Contr. No. 104. 38 p.

Moiseev, P. A.

1953. Cod and flounders of far eastern seas. Izv. Tikhookean. Nachno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 40:287 p. (Transl. Fish. Res. Board Can., Transl. Ser. 119, 596 p.)

Mukhacheva, V. A., and O. A. Zvyagina.

1960. Development of the Pacific cod *Gadus morhua macrocephalus* Til. Acad. Nauk. SSSR Tr. Inst. Okeanol. 31:145-165. (Transl., Fish. Res. Board Can., Nanaimo, B.C.)

Musienko, L. N.

1970. Reproduction and development of Bering Sea fishes. Tr. Vses. Nauchno-issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 70 (Izv. Tikhookean. Nauchno-issled. Inst. Rybn. Khoz. Okeanogr. 72):166-224. (Transl. in Soviet Fisheries Investigations in the Northeastern Pacific, Part V, p. 161-224, by Israel Program Sci. Transl., 1972, avail. Natl. Tech. Inf. Serv., Springfield, VA, as TT71-50127.)

Niggol, K.

1982. Data on fish species from Bering Sea and Gulf of Alaska. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-29. 125 p.

Pereyra, W. T., J. E. Reeves, and R. G. Bakkala.

1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Processed Rep., 619 p., Northwest and Alaska Fisheries Center, Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd., Seattle, Wash. 98112.

Salveson, S. J. and J. R. Dunn.

1976. Pacific cod (Family Gadidae). In: Pereyra, Reeves, and Bakkala. 1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Processed Rep., 619 p., Northwest and Alaska Fisheries Center, Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd., Seattle, Wash. 98112.

Schultz, L. P. and A. D. Welander.

1935. A review of the cods of the northeastern Pacific with comparative notes on related species. Copeia 1935(3):127-139.

Smith, G. B. and R. G. Bakkala.

1982. Demersal fish resources of the eastern Bering Sea: Spring 1976. U.S. Dep. Commer., NOAA Tech. Rpt. NMFS SSRF-754, 129 p.

Smith, J. E.

1979. Catch and effort statistics of the Canadian groundfish fishery on the Pacific coast in 1978. Fish. and Mar. Serv., Tech. Rep. No. 891. Dept. Fish and Ocean, Fish and Mar. Serv., Resource Serv. Br., Pac. Biol. Sta., Nanaimo, B.C., Can. 82 p.

1980. Catch and effort statistics of the Canadian groundfish fishery on the Pacific coast in 1979. Can. Tech. Rep. Aquat. Sci. No. 961, 90 p.

1981. Catch and effort statistics of the Canadian groundfish fishery on the Pacific coast in 1980. Can. Tech. Rep. Aquat. Sci. No. 1032, 90 p.

Svetovidov, A. N.

1948. Gadiformes. In: Fauna of USSR. Izdatel'stvo Akad. Nauk., Moscow-Leningrad, 9(4), 222 p. (Transl. Israel Prog. Sci., Transl. 1962, 232 p. Avail. Natl. Tech. Inf. Serv., Springfield, VA, as OTS 63-11071.)

Teshima, K.

1983. Relationships between catch per hour trawled of Pacific cod and water temperature in the eastern Bering Sea. Unpubl. manusc.

Thomson, J. A.

1962. On the fecundity of Pacific cod (Gadus macrocephalus) from Hecate Strait, British Columbia. J. Fish. Res. Board Can. 19(3):497-500.

Umeda, Y. and R. Bakkala.

1983. Data report: 1980. Demersal trawl survey of the eastern Bering Sea and continental shelf. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-49. 175 p.

Vershinin, V. G.

1983. Cod biology and fishing in Anadyr-Navarin area of the Bering Sea. Abstract of unpubl. manusc.

Waldron, K. D.

1981. Ichthyoplankton. In: D. W. Hood and J. A. Calder (editors), The Eastern Bering Sea Shelf: oceanography and resources, Vol. 1, p. 471-493. Univ. Wash. Press., Seattle.

Wolotira, R. J., Jr., T. M. Sample, and M. Morin, Jr.

1977. Demersal fish and shellfish resources of Norton Sound, the southeastern Chukchi Sea and adjacent waters in the baseline year 1976. Processed Rep., 292 p. Northwest and Alaska Fisheries Center, Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Yamamoto, G. and C. Nishioka.

1952. The development and rearing of hatched larvae of North Pacific cod (Gadus macrocephalus Tilesius). Japan Sea Reg. Fish. Res. Lab., Spec. Publ., 1952:301-308. (Transl. Fish. Res. Bd. Can., Transl. Ser. 402, 18 p.)

Zenger, H. H., Jr.

1983. Pacific cod. In: G. Stauffer (editor) et al: Condition of the groundfish resources of the Gulf of Alaska as assessed in 1983. Processed Rep., 190 p. Northwest and Alaska Fisheries Center, Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd., Seattle, Wash. 98112.

Zhang, Chang Ik.

1981. Pacific cod of South Korean waters. (Document submitted to the annual meeting of the Int. North Pac. Fish. Comm., Vancouver, Can., Oct. 1981.) Northwest and Alaska Fisheries Center, Natl. Mar. Fish. Serv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

SPATIAL AND TEMPORAL
EXTENT OF HYDROCARBON
CONTAMINATION IN MARINE SPECIES
OF BRISTOL BAY

by

Nancy B. Pola, Robert K. Miyahara
and
Arthur F. Gallagher, Jr.

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

April 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Processed Report 85-08 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure 10.--Area covered by tainting (contamination >5 ppm) of a demersal fish species from a model run with no migrations (solid line) and with migrations of 5, 10, and 15 km/day. Migration directions are as in Figure 2.

Figure 11.--Contamination of a pelagic fish (Species 1) at day 10 from model runs with no migrations and with migrations of 5 km/day. Contours of 5, 10, 50, and 100 ppm are drawn. Original source of the oil is marked "•" and area covered by 1.0 ppm WSF at day 10 is shaded.

Figure 12.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid for migrations of 5 and 10 km/day and migration angle of 45° (in the direction of the oil movement).

Figure 13.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid for migrations of 5 and 10 km/day and migration angle of 225° (in the opposite direction of the oil movement).

Figure 14.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid with no migrations.

INTRODUCTION

The potential biological contamination resulting from a hypothetical Bering Sea oil spill, and the effect of fish migrations on the distribution of the contamination, are simulated by BIOS (Biological Impact of an Oil Spill), a multispecies biomass-based ecosystem model. BIOS was developed at the request of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) as part of their eastern Bering Sea oil impact study (Swan 1984, Gallagher 1984). Uptake of oil contaminants, from exposure to contaminated water and sediments as well as from consumption of contaminated food, is simulated for 16 fish species groups (Table 1). Two oil spill scenarios (Table 2) were modelled at each of three locations in Bristol Bay: offshore of Cape Newenham, Port Heiden, and Port Moller (Figure 1). Gridded values of hydrocarbon concentrations dissolved or in suspension in the water column (referred to here as the water soluble fraction, WSF) were provided by Rand Corporation in conjunction with Science Applications, Inc. (see Laevastu and Fukuhara 1984a). The fraction of oil reaching the bottom and entering the sediments (referred to here as TARS) was calculated with a simulation model developed by Laevastu and Fukuhara (1984b).

The simulation techniques for hydrocarbon uptake and depuration are described in Gallagher and Pola (1984) and will not be discussed in detail here. The concentrations of hydrocarbons within the fish (referred to here as contamination) are calculated in parts per million (ppm; mg hydrocarbon per kg biomass). This report examines the magnitude and spatial extent of contamination over the model grid simulated with and without fish migrations of various speeds and directions. In addition, the contamination of migrating fish beyond the bounds of the model grid is traced until depuration

Table 1.--Species groups in the BIOS model.

No.	Species
1	Herring juveniles
2	Herring adults
3	Pollock juveniles
4	Pollock adults
5	Pacific cod juvenile
6	Halibut juveniles
7	Yellowfin sole juveniles
8	Other flatfish juveniles
9	Yellowfin sole adults
10	Other flatfish adults
11	Pacific cod adults
12	King and Bairdi crab juveniles
13	King and Bairdi crab adults
14	Mobile epifauna
15	Sessile epifauna
16	Infauna

Table 2.--Hypothetical oil-spill scenarios.

Scenario	Oil type	Volume	Duration	Grid size
Blowout	Prudhoe Bay crude	20,000 bbl/day	15 days	50 x 50
Accident	Automotive diesel	200,000 bbl	10 days	32 x 34

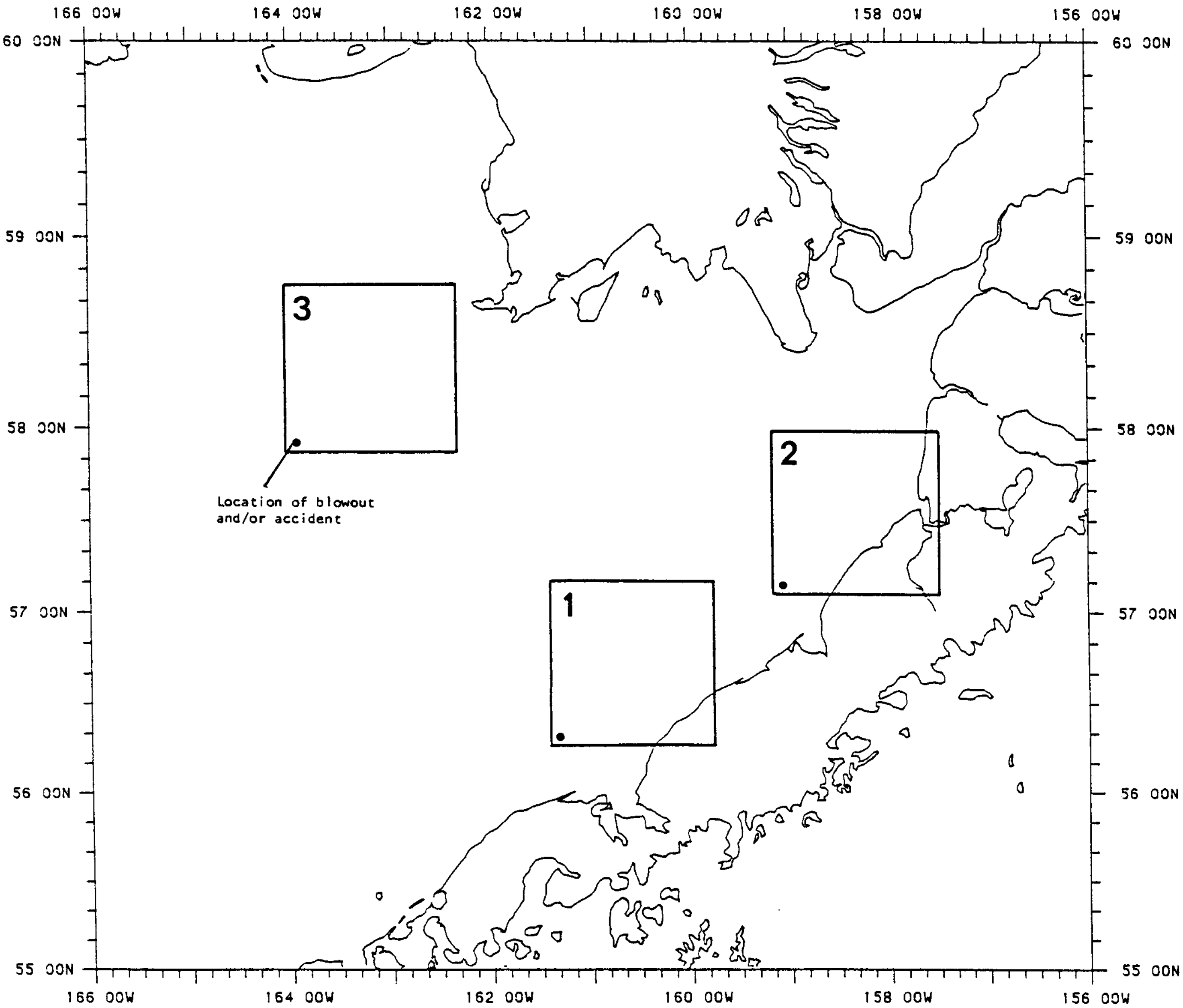


Figure 1.--Locations of hypothetical oil spill scenarios.

below detectable levels of contamination (defined as <5 ppm) is complete. The model does not allow avoidance of oil by fish, in an attempt to maximize the biological impact of the hypothetical oil spills.

METHODS

Model Formulations

The amount of contamination in a fish species (C_f) at any time step (t_d) is computed in the BIOS model as:

$$C_f(t_d) = \frac{k_1 C_o(t_d)}{k_2} (1-\exp(-k_2)) + C_f(t_d-1)\exp(-k_2) \tag{1}$$

where C_o is the external oil concentration, k_1 is the uptake rate, and k_2 is the depuration rate. Equation 1 is a finite-difference approximation to the single compartment model discussed by Wilson (1975) and Moriarty (1975), and reviewed by Connell and Miller (1981). Uptake of contaminants is assumed to be equally divided between uptake from exposure to oil in the water or sediments and uptake from consumption of contaminated food (Teal, 1977). C_f refers to the total amount of hydrocarbons in the fish; no attempt has been made to partition the contamination within the fish (gut, liver, muscle, etc.), and no information was provided by Rand Corporation as to the chemical composition of the oil at each time step.

Equation 1 can be rewritten as:

$$C_f(t_d) = C_U + C_D \tag{1a}$$

where C_U is the amount of contamination taken up by a fish species at simulation time step t_d and C_D is the amount accumulated over previous time steps, after depuration. The external oil concentration includes both oil in the water column (WSF) and in the sediments (TARS); the relative effect of each component is determined by the proportion of pelagic or demersal food in the species' diet. The uptake of contamination is computed in the model as:

$$C_U = (F_p B_p C_{WSF} + F_d B_d C_{TARS})\ (1-\exp(-k_2)) \tag{2}$$

where F_p and F_d are the fractions of pelagic and demersal food, respectively, in a species' diet, B_p and B_d are the pelagic and demersal bioconcentration factors, and C_{WSF} and C_{TARS} are the napthalene fractions of the oil concentrations in the water column and in the sediments, respectively. A detailed discussion of assumptions and parameters in equations 1 and 2 is given in Gallagher and Pola (1984).

The BIOS model functions include optional fish migration. The biomass of each species group is assumed constant over all gridpoints (see the following section); migrations are therefore simulated in the model by the advection of contamination through the grid. The amount of contamination leaving gridpoint (n,m) in the x-direction is:

$$R_{x,n,m} = (G_x t|U|)/L \tag{3}$$

and in the y-direction is:

$$R_{y,n,m} = (G_y t|V|)/L \tag{4}$$

where t is the migration time step, L is the grid spacing, U and V are the migration velocity components, and G_x and G_y are contamination gradients:

$$G_x = [C(t)_{n,m+j} - C(t)_{n,m}] \tag{5}$$

$$G_y = [C(t)_{n+i,m} - C(t)_{n,m}] \tag{6}$$

The subscripts i and j are defined as:

$$i = \begin{cases} i & , \quad V < 0 \\ 0 & , \quad V = 0 \\ -1 & , \quad V > 0 \end{cases}$$

$$j = \begin{cases} -1 , & U < 0 \\ 0 , & U = 0 \\ 1 , & U > 0 \end{cases}$$

such that the gradients G_x and G_y are taken in the "upstream" direction. The contamination is then redistributed over the grid:

$$C(t+1)_{n,m} = C(t)_{n,m} - R_{x,n,m} - R_{y,n,m} \tag{7}$$

$$C(t+1)_{n,m+j} = C(t)_{n,m+j} + R_{x,n,m} \tag{8}$$

$$C(t+1)_{n+i,m} = C(t)_{n+i,m} + R_{y,n,m} \tag{9}$$

The migration time step, t, is restricted by the stability criterion:

$$t|U^*| < L \tag{10}$$

where U* is the maximum migration speed in km/day. That is, for a migration speed of 15 km/day and grid spacing of 2 km, t < .13 days. In the present analysis, a migration time step of .0625 days was used, and migrations were performed 16 times during each daily model time step.

Any contamination leaving the grid is saved on disk to be used as input to the submodel OUTMIG, which traces the spatial extent of contamination until depuration to less than 5 ppm, the level used as the threshold for the detection of tainting in fish. The OUTMIG submodel uses a grid with twice the dimensions of the BIOS grid (e.g., for the accident scenario, a grid size of 64 x 68 is used). The BIOS model grid occupies one quadrant of the OUTMIG grid; the specific quadrant is dependent upon the migration direction (Figure 2). As contamination leaves the BIOS grid, it enters the first adjacent row and column of the OUTMIG grid. Migrations in OUTMIG are calculated as in the main BIOS model (i.e., using equations 3 - 9); however, since the oil spill is restricted to the area of the BIOS model grid, there is no uptake of contaminants (equation 2) in the OUTMIG submodel.

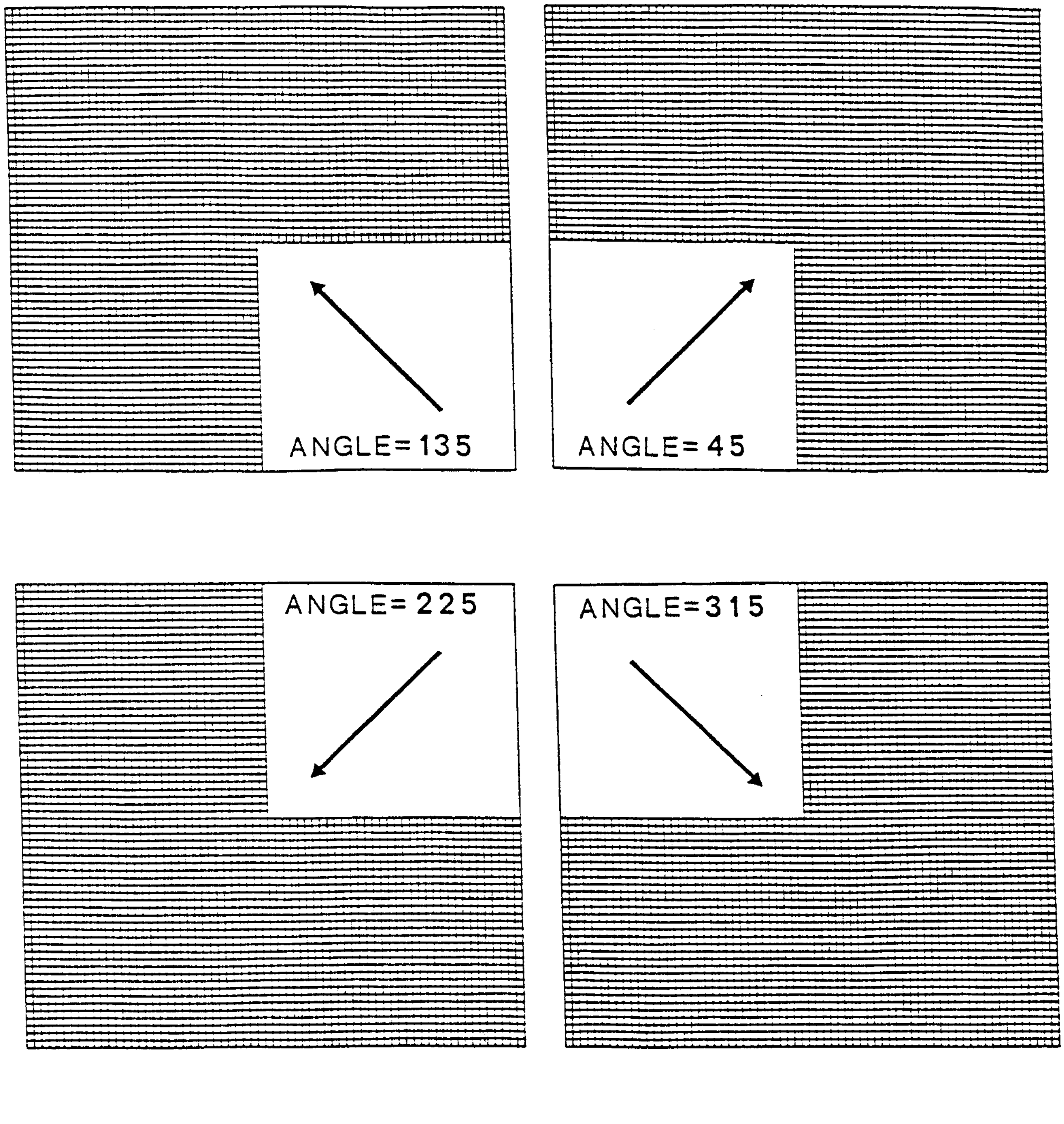


Figure 2.--Migration directions and corresponding grids used in the OUTMIG submodel.

Both the BIOS model and the OUTMIG submodel were run for 50 days. The oil concentrations provided by Rand Coporation were computed for 10 days in the accident scenario and for 15 days in the blowout scenario (Table 2). At model time steps greater than those limits, the oil concentrations in the water column were decayed at a constant rate:

$$WSF(t_d)_{n,m} = WSF(t_d - 1)_{n,m} e^{-k} \tag{11}$$

where a decay rate (k) of 0.3 was estimated from the Rand data.

Model Parameterization

Model calculations are performed at each model gridpoint during each daily time step. Grid size for the accident scenario is 32 x 34 and for the blowout scenario is 50 x 50 (Table 2); grid spacing for each scenario is 2 km. Since 1975 (in some cases, since 1972), survey data have been collected at regular intervals at consistent locations in the Bering Sea. Station spacing for survey cruises is 20 n mi (34.04 km). The biological data cannot be adequately resolved to the 2 km model grid spacing; therefore, the biomass for each species group is assumed constant over all gridpoints. Biomass values (kg/km^2) used for each location are shown in Table 3 (see Table 1 in Gallagher and Pola (1984) for a description of assumptions used in the biomass calculations). When the migration option is selected in the model, it is assumed that fish (i.e., contamination) leaving the model grid are replaced by the equivalent biomass (at zero contamination) entering the grid at the opposite ("upstream") side.

Species-specific migration speeds and directions are input to the BIOS model. Most available literature on migrations of fish stocks in the Bering

Table 3.--Species biomass (kg/km^2) at each simulation location.

Species number	Location		
	Port Moller	Port Heiden	Cape Newenham
1	1409	521	1551
2	1121	414	1234
3	3708	2322	3261
4	11007	6893	9679
5	424	279	307
6	730	330	240
7	722	482	711
8	2004	1472	1650
9	800	534	789
10	2004	1472	1650
11	861	461	681
12	664	222	432
13	1654	553	1078
14	5970	4995	6075
15	13930	11655	14175
16	19150	13750	19250

Sea are based on seasonal distribution patterns (Thorsteinson and Thorsteinson 1984; Pereyra et al. 1976; Bakkala and Smith 1978); minimum migration speeds are computed as the mean distance between seasonal locations divided by the time between seasons. Information on migration speeds from tagging-recapture studies is contradictory. Harden Jones (1968) gives a value of 3 body lengths per second (bl/s) as the maximum sustainable speed for fish between 10 and 100 cm length (i.e., maximum sustainable speeds are 25.9 - 259.2 km/day). Walker et al. (1978) calculated average ground speeds for plaice that moved more than 15 km in the duration of their tracking experiment; values were between 16 and 40 km/day (mean 24.39 km/day). Arnold (1981), in another tagging-recapture study of plaice, calculated a mean ground speed of 0.3 km/h (7.2 km/day), and Harden Jones (1981) in the same publication listed plaice speeds of between 38 and 95 cm/sec (33 - 82 km/day). Table 4 (adapted from Harden Jones 1977) summarizes results from several tagging-recapture studies. Migration speeds range from 1 - 185 km/day and no direct relationship between fish length and migration speed is evident from these data. In the present study various migration speeds and directions were used and differences in the resulting contamination fields were examined. The oil slick moved toward the northeast at approximately 3 km/day. Migration speeds of 5, 10, and 15 km/day were input into the model. Migration directions used were 45° (i.e., moving approximately in the same direction as the oil spill), 135° (moving across the spill toward the northwest), 225° (moving toward the source of the spill), and 315° (moving across the spill to the southeast); all angles are measured relative to due east (see Figure 2). The effects of beaching of oil were not addressed; therefore, in the present analysis, all grid boundaries are open.

Species	Mean length (cm)	Speed		Author
		km/day	bl/sec	
Sole	30	7-16	0.28 - 0.53	Anon. (1965)
Plaice	35	1-7	0.06 - 0.23	Bannister (unpub.)
Herring	25	4-30	0.20 - 1.40	Bolster (1955)
Mackerel	35	16-23	0.54 - 0.77	Bolster (1974)
Sockeye salmon	70	9-22	0.15 - 0.36	Harden Jones (1968)
Cod	80	6-28	0.09 - 0.40	Trout (unpub.)
Albacore	77	26-44	0.39 - 0.66	Clemens (1961)
Bluefin	250	93-185	0.43 - 0.86	Mather et al. (1977)

Table 4.--Migration speeds calculated from tagging-recapture studies.

Conflicting values for the minimum detectable level of contamination (threshold level of tainting) are also given in the literature. Howgate et al. (1977) give a threshold value of 10 l/kg (between 8 and 10 ppm, depending on the density of the oil); Rice (1981) states that "experienced tasters can detect 10-30 ppm crude oil in cooked or raw fish fillets". However, a literature review by Solomon and Mills (1982) gives a value of 0.4-0.5 ppm as the lowest detectable level of oil in fish. In a study by Brandal et al. (1976), a panel of experienced tasters found tainting in Atlantic salmon, *Salmo salar*, with a contamination level of 0.5 ppm. In the latter example however, only the aromatic hydrocarbons (primarily benzene and napthalene) were measured; in addition, the 0.5 ppm refers to the contamination within the muscle tissue only, rather than the level of contamination within the entire organism (as computed by the BIOS model). The threshold of 5 ppm used in the present study, therefore, is considered reasonable and slightly conservative.

RESULTS

Oil Concentrations

Gridded subsurface oil concentrations (WSF) for two hypothetical oil-spill scenarios at three locations in the Bering Sea (Figure 1; Table 2) were provided by Rand Coporation. Maximum WSF concentrations (ppm) for all six simulated oil spills are given in Table 5. Maxima are the same order of magnitude at the 3 locations for each scenario; however, maxima differ by an order of magnitude between scenarios. The similarity of contoured WSF concentrations among locations is illustrated in Figures 3 (Port Moller and Cape Newenham) and 4 (Port Heiden) five, ten, twenty, and thirty days after the onset of the

Table 5.--Maximum subsurface oil concentrations for each simulated oil spill.

	Maximum WSF (ppm)		
Scenario	Pt. Moller	Pt. Heiden	Cape Newenham
Accident	9.04	8.98	9.58
Blowout	0.34	0.30	0.29

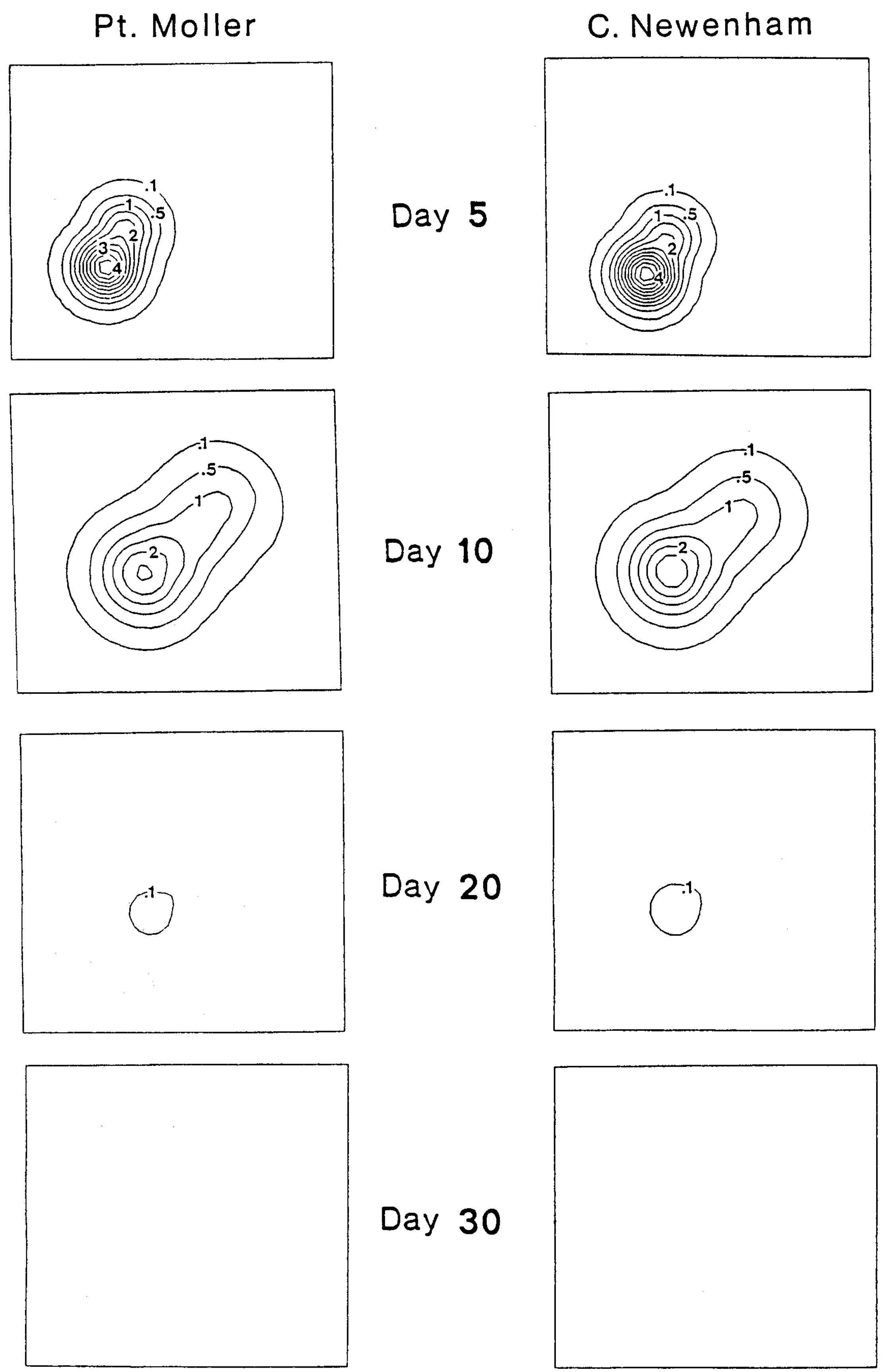


Figure 3.--Concentrations of oil in the water column (WSF) at Port Moller and at Cape Newenham. Contour interval is 0.5 ppm and the 0.1 ppm contour is included.

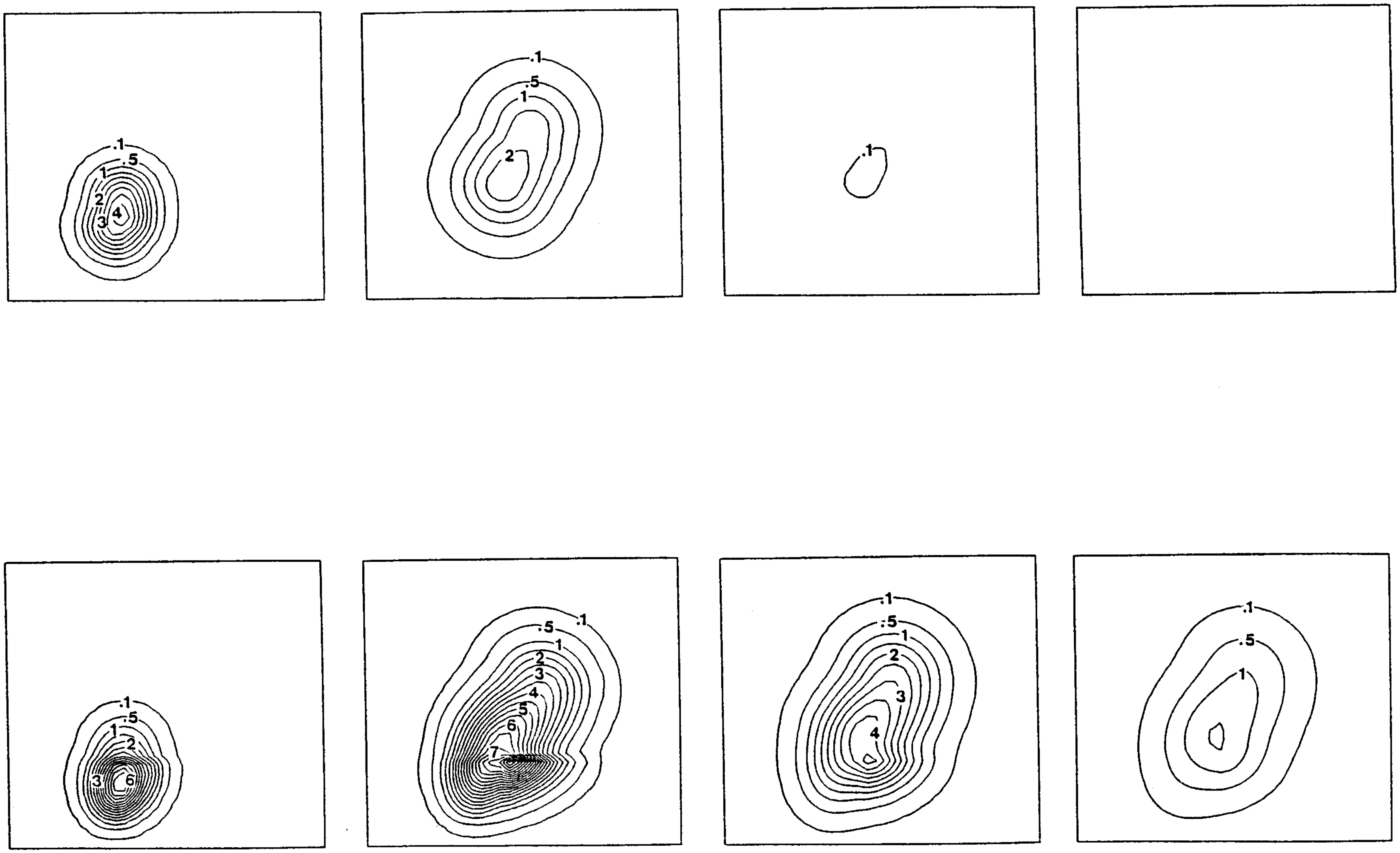


Figure 4.--Concentrations of oil in the water column (WSF) and in the sediments (TARS) at Port Heiden. Contour interval is 0.5 ppm and the 0.1 ppm contour is included.

oil spills (accident scenario). Concentrations are less than 1.5 ppm at all locations after 20 days; after 30 days, concentrations are everywhere less than 0.001 ppm (1.0 ppb). To avoid unnecessary repetition of results, therefore, only Port Heiden will be discussed. Concentrations of oil in the sediments (TARS), which are computed by the model of Laevastu and Fukuhara (1984b) using WSF concentrations as input, are also shown for the Port Heiden accident scenario in Figure 4. TARS reach a maximum of 10.1 ppm by day 10, and remain at levels above 1.5 ppm 30 days after the onset of the simulation.

Contours for the blowout scenario are not shown, since WSF concentrations are everywhere below 0.5 ppm (Table 5). Spatial coverage of oil in the blowout scenario is also much less than in the accident scenario. Time series of total area (km^2) covered by oil concentrations greater than 1.0 ppm, 0.1 ppm, 0.01 ppm, and 0.001 ppm (1.0 ppb) are shown in Figure 5 for both the accident (upper panel) and blowout (lower panel) scenarios. Maximum area covered and the duration of coverage for each concentration level are summarized in Table 6. In the blowout scenario, the maximum areal extent of oil concentrations, even at levels as low as 0.001 ppm, is less than 700 km^2, while in the accident scenario, over 300 km^2 are covered by concentrations above 1.0 ppm. This disparity is in part a result of the different types of oil spills simulated: the diesel fuel of the accident scenario is more water soluble than the Prudhoe Bay crude oil of the blowout scenario. In addition, at our request, winds, tides, and temperatures for the accident scenario were selected so as to maximize the amount of oil in the water column. Approximately 32,000 tonnes of oil (at 0.89 g/cm^3 density) were released in the blowout scenario and 20,000 tonnes (at 0.83 g/cm^3 density) were released in the accident

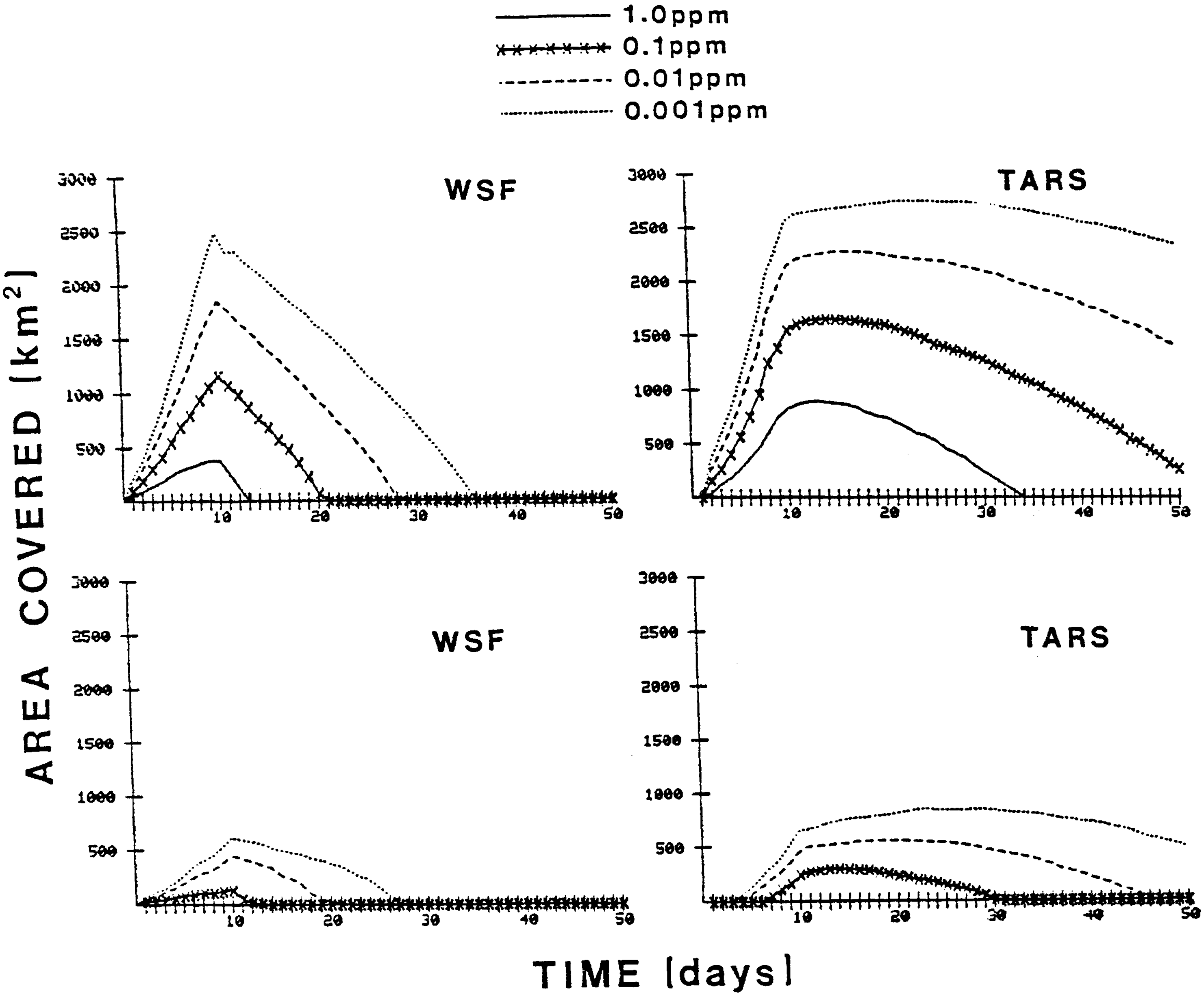


Figure 5.--Time series of total area covered (km^2) by WSF and by TARS at concentrations greater than 1.0 ppm, 0.1 ppm, 0.01 ppm, and 0.001 ppm for the accident (upper) and blowout (lower) scenarios.

Table 6.--Maximum spatial coverage (km^2) and maximum duration (days) of various levels of subsurface (WSF) and bottom (TARS) oil concentrations at Port Heiden.

Oil conc. (ppm)	Accident				Blowout			
	WSF		TARS		WSF		TARS	
	area	duration	area	duration	area	duration	area	duration
>1.0	380	13	752	33	0	0	0	0
>0.1	1160	21	1548	>50	132	12	248	24
>0.01	1844	28	2140	>50	444	20	460	43
>0.001	2480	36	2560	>50	616	27	652	>50

scenario. Of these totals, 81% of the fuel oil, but less than 1% of the crude oil, entered the water column as WSF. Figure 6, from Gallagher and Pola (1984), shows the percent of biomass contaminated (as simulated by BIOS) for selected species in the accident and blowout scenarios. Most species are untainted in the blowout scenario and tainting, when it occurs, affects less than 4% of the Port Heiden biomass (e.g., less than 0.01% of the Bering Sea adult herring biomass; see Table 7). Subsequent results on fish contamination and migrations will therefore only be presented for the accident scenario.

Fish Contamination

The relative effect of either WSF or TARS on each fish species in the BIOS model is proportional to the fraction of pelagic or demersal food in the species' diet (F_p and F_d in equation 2) and dependent upon the toxicity of either oil type. Oil toxicity is primarily due to napthalenes; the WSF concentrations from the diesel accident were estimated to be 50% napthalene and TARS were estimated to be 10% napthalene (Gallagher and Pola 1984). This difference is reflected in the contrast between contamination of a pelagic species (Species 1, juvenile herring; F_p = 1.00) and a demersal species (Species 13, adult crabs; F_p = 0.10, F_d = 0.90) from a model run with no migrations shown in Figure 7. Contours of 5, 10, 50, and 100 ppm are drawn; results are shown 5, 10, 20, and 30 days after the oil spill. The area covered by WSF (for Species 1) or TARS (for Species 13) greater than 1.0 ppm is shaded in each figure. Totals of area (km^2) covered by each level of contamination for 50 daily model time steps are given in Table 8. The pelagic species is more quickly contaminated and reaches higher levels of contamination than the demersal species, even though concentrations of TARS reach higher levels than

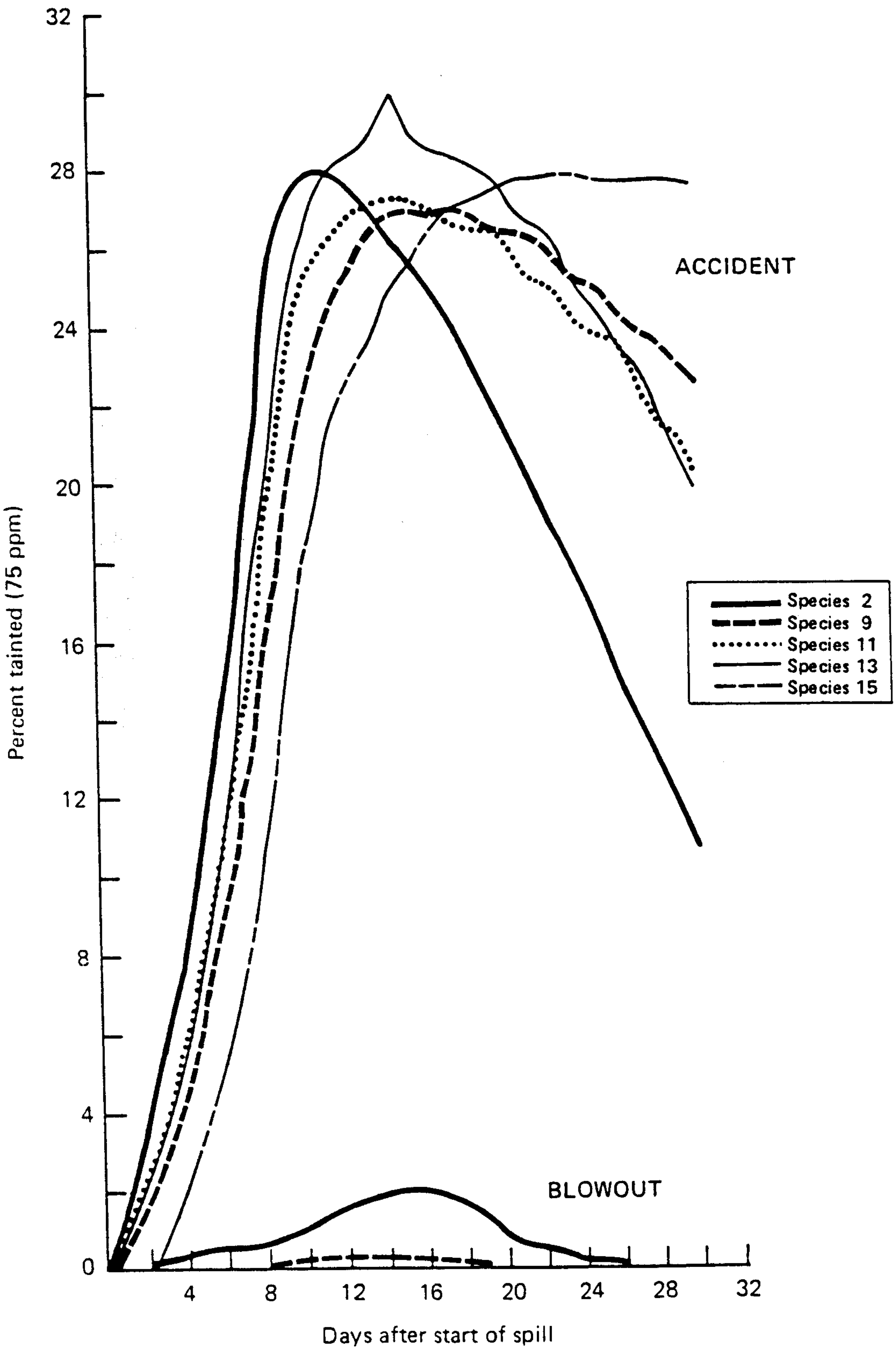


Figure 6.--Percent of biomass within the BIOS model grid contaminated in the accident and blowout scenarios (from Gallager and Pola 1984).

Table 7.--Percent of Bering Sea biomass (from DYNUMES model) in accident scenario study area.

Species number	Location		
	Pt. Moller	Pt. Heiden	C. Newenham
1	0.505	0.187	0.556
2	0.505	0.187	0.556
3	0.471	0.295	0.414
4	0.471	0.295	0.414
5	0.577	0.379	0.418
6	1.220	0.551	0.401
7	0.902	0.602	0.888
8	1.141	0.838	0.939
9	0.900	0.601	0.888
10	1.141	0.838	0.939
11	0.577	0.309	0.456
12	0.806	0.269	0.524
13	0.804	0.268	0.524
14	0.416	0.348	0.424
15	0.416	0.348	0.424
16	0.604	0.433	0.607

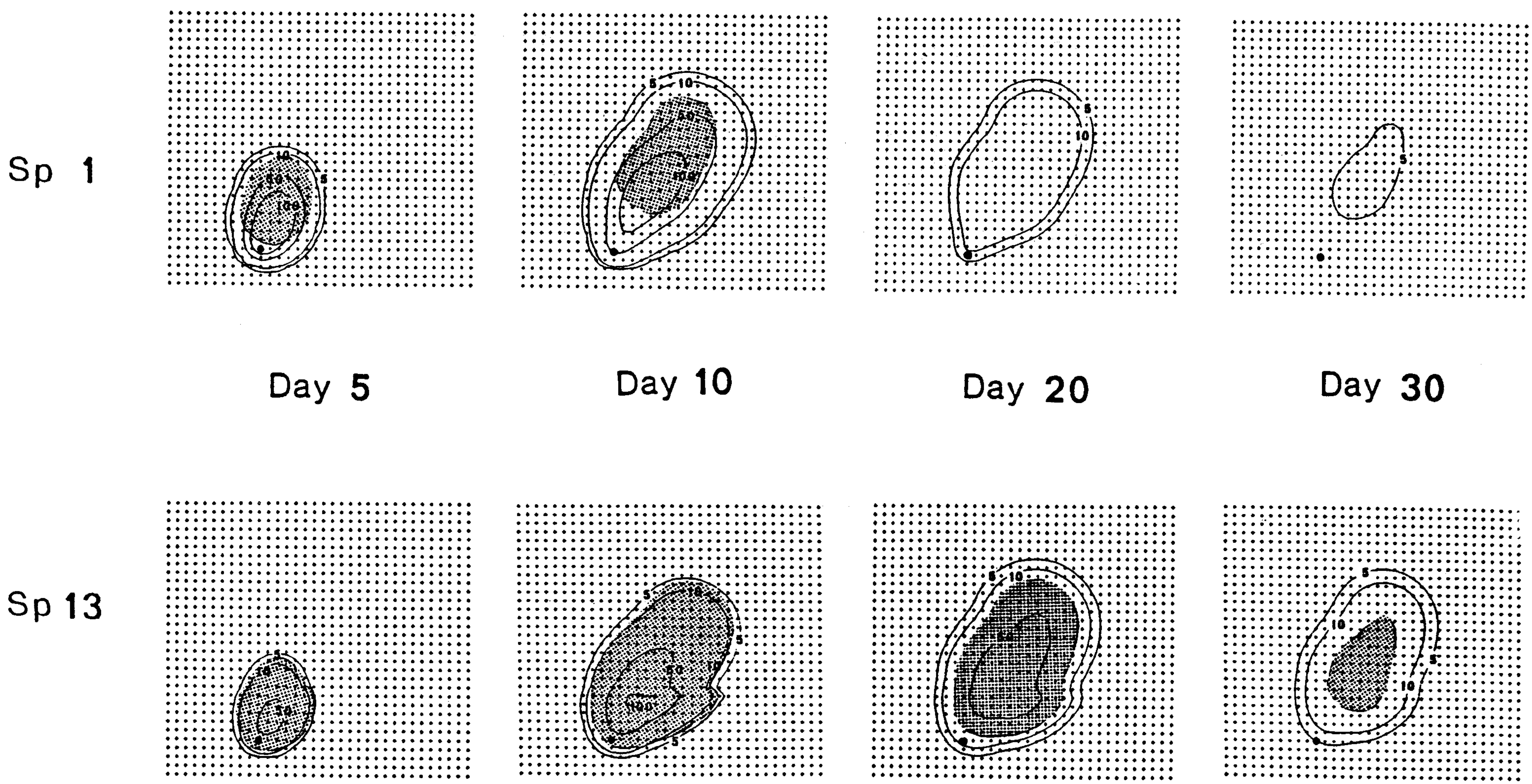


Figure 7.--Contamination of a pelagic (Species 1) and a demersal (Species 13) species group from a model run with no migrations. Contours of 5, 10, 50, and 100 ppm are drawn.

Table 8.--Area covered (km^2) by contamination, Port Heiden accident scenario, no migration.

	Species 1				Species 13			
	Contamination (ppm)				Contamination (ppm)			
Day	>5	>10	>50	>100	>5	>10	>50	>100
1	72	56	24	4	24	8	0	0
2	144	120	60	32	80	52	0	0
3	240	208	96	48	144	96	0	0
4	356	292	140	80	228	160	8	0
5	468	392	192	96	320	232	40	0
6	616	512	248	116	424	324	68	0
7	764	632	304	144	564	428	92	0
8	968	792	360	148	736	544	124	0
9	1080	900	412	152	904	684	156	4
10	1212	988	452	168	1020	788	216	20
11	1224	1020	472	152	1108	868	268	24
12	1232	1036	452	136	1144	920	292	32
13	1216	1012	424	104	1192	960	328	32
14	1188	976	376	56	1228	976	356	32
15	1152	936	328	20	1236	1000	364	28
16	1100	880	268	0	1240	1008	368	20
17	1068	856	192	0	1240	1004	352	16
18	1036	792	116	0	1244	996	336	12
19	972	744	52	0	1240	976	320	8
20	924	684	4	0	1220	960	292	4
21	868	604	0	0	1188	952	272	0
22	820	552	0	0	1168	932	220	0
23	744	476	0	0	1152	916	196	0
24	688	400	0	0	1148	884	156	0
25	604	340	0	0	1128	860	112	0
26	540	248	0	0	1104	832	80	0
27	472	152	0	0	1068	784	24	0
28	388	76	0	0	1040	760	0	0
29	324	8	0	0	1016	732	0	0
30	224	0	0	0	968	696	0	0
31	128	0	0	0	940	640	0	0
32	48	0	0	0	904	592	0	0
33	0	0	0	0	864	568	0	0
34	0	0	0	0	824	516	0	0
35	0	0	0	0	780	448	0	0
36	0	0	0	0	748	412	0	0
37	0	0	0	0	692	372	0	0
38	0	0	0	0	648	304	0	0
39	0	0	0	0	588	248	0	0
40	0	0	0	0	548	180	0	0
41	0	0	0	0	488	116	0	0
42	0	0	0	0	440	64	0	0
43	0	0	0	0	384	16	0	0
44	0	0	0	0	324	0	0	0
45	0	0	0	0	268	0	0	0
46	0	0	0	0	192	0	0	0
47	0	0	0	0	136	0	0	0
48	0	0	0	0	92	0	0	0
49	0	0	0	0	28	0	0	0
50	0	0	0	0	0	0	0	0

concentrations of WSF (Figure 4). The maximum daily contamination of the two species are shown in Figure 8 along with the maximum daily concentrations of WSF and TARS. The largest WSF concentration, 9.0 ppm, occurs on the first day; the largest TARS concentration, 10.1 ppm, occurs on day 10. The greatest contamination of the pelagic species is on day 5 and that of the demersal species is on day 14 (i.e., maximum uptake lags maximum oil in each case by 4 days). Although the pelagic species reaches contamination levels almost twice that of the demersal species (208.1 ppm vs 129.7 ppm), tainting of the demersal species (contamination >5 ppm) continues 17 days after the pelagic species has depurated below detectable levels, due to the longer residence time for TARS than for WSF.

Effects of Migrations

The effects of fish migrations on the level of contamination within the fish and on the spatial extent of contaminated fish were examined. The area covered by tainted fish (contamination >5 ppm) for each migration speed and direction, as well as for the case of no migration, is shown for Species 1 (juvenile herring; pelagic) and Species 13 (adult crabs; demersal) in Figures 9 and 10, respectively. In all cases, migration reduced the total area covered by tainted fish. Coverage for both species groups was least, but the duration of tainting was longest, at the slowest migration speed (5 km/day). Tainting lasted 5 to 8 days longer for the 5 km/day migrations than for the case of no migration.

The duration (in days) of fish contamination at levels above 5, 10, 50 and 100 ppm is given in Table 9 for the pelagic (upper) and demersal (lower) species. Contamination at all levels remains for the longest period of time for migrations of 5 km/day. Migration (at all speeds and directions) increases

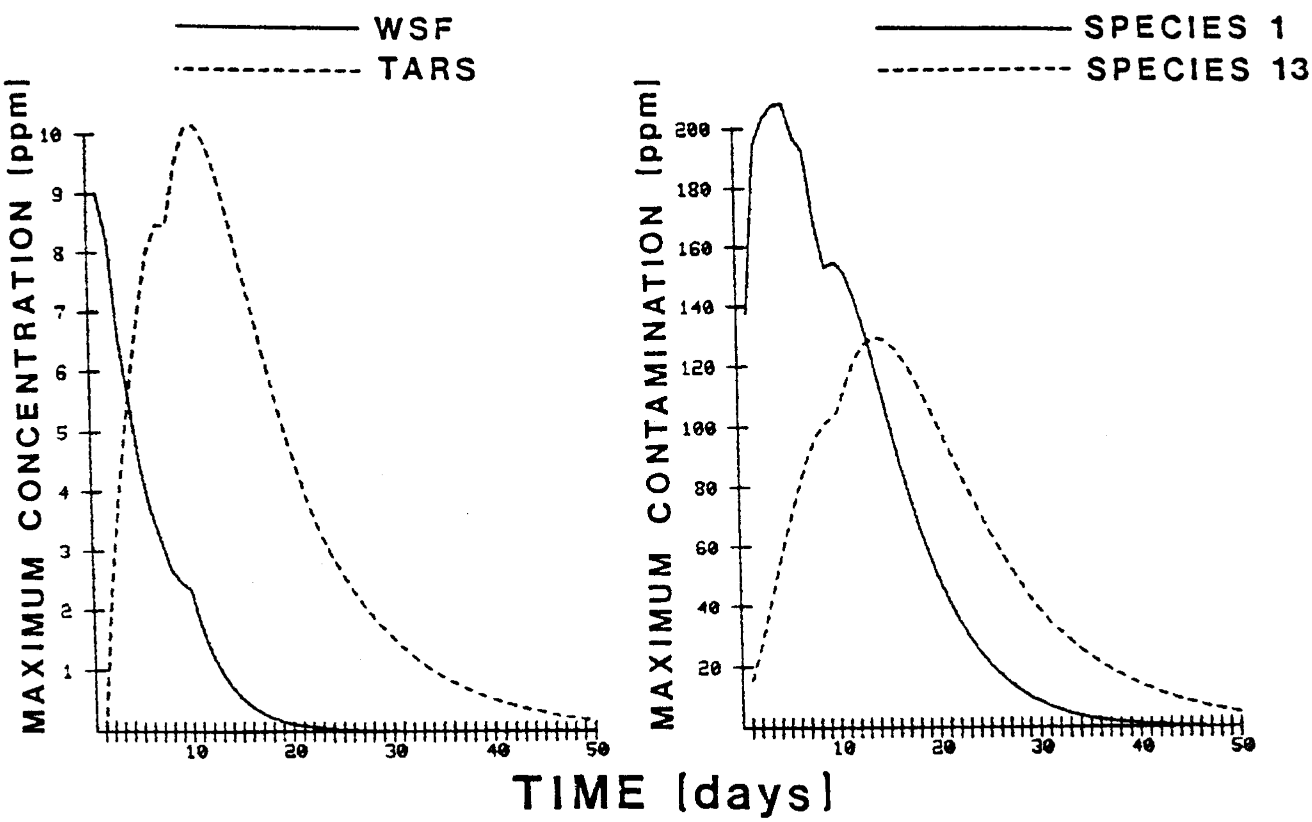


Figure 8.--Maximum concentrations of WSF and TARS and maximum contamination of Species 1 (pelagic) and Species 13 (demersal) each daily model time step.

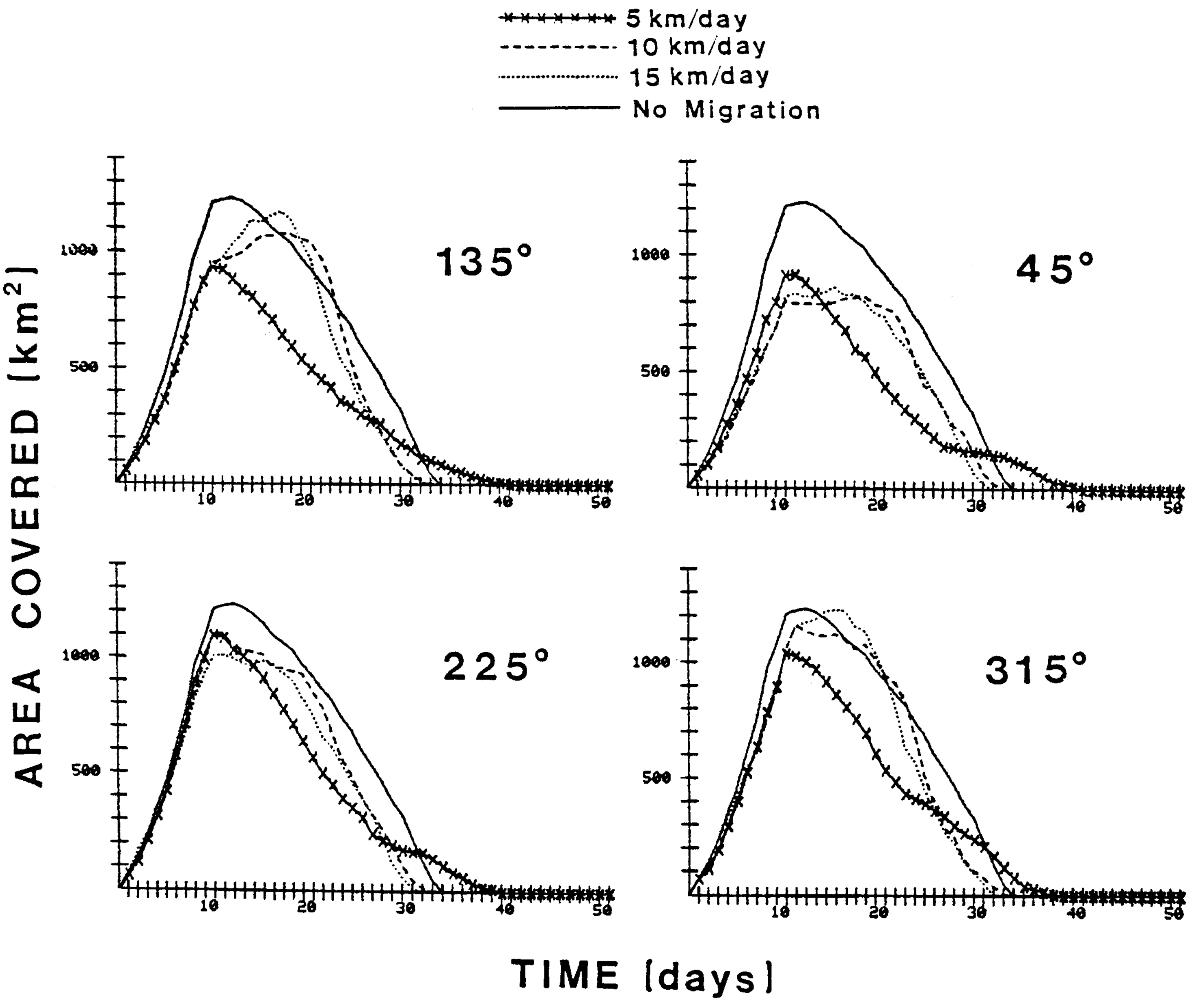


Figure 9.--Area covered by tainting (contamination >5 ppm) of a pelagic fish species from a model run with no migrations (solid line) and with migrations of 5, 10, and 15 km/day. Migration directions are as in Figure 2.

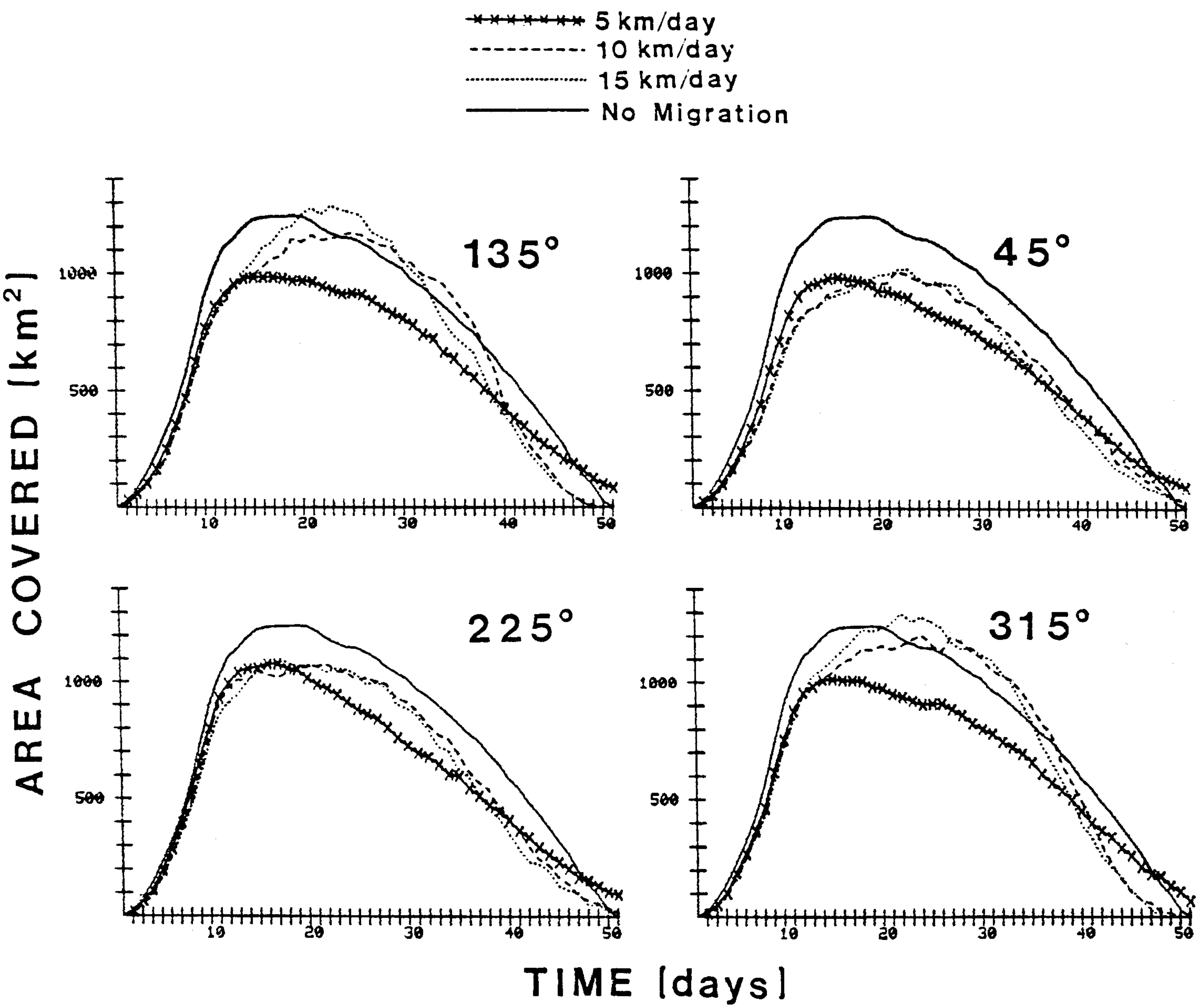


Figure 10.--Area covered by tainting (contamination >5 ppm) of a demersal fish species from a model run with no migrations (solid line) and with migrations of 5, 10, and 15 km/day. Migration directions are as in Figure 2.

		Contamination Level			
Speed	Angle	>5	>10	>50	>100
No Migration		32	29	20	15
5	135	40	38	28	25
	45	39	36	28	25
	225	38	35	27	23
	315	37	35	26	22
10	135	31	30	21	19
	45	32	30	23	21
	225	31	29	22	20
	315	32	30	24	18
15	135	31	29	23	19
	45	30	29	22	20
	225	30	28	22	20
	315	31	28	23	18

Speed	Angle	>5	>10	>50	>100
No Migration		49	43	24	12
5	135	56	52	35	26
	45	54	50	35	26
	225	54	50	33	25
	315	54	48	33	24
10	135	49	43	28	20
	45	51	47	34	25
	225	51	46	33	22
	315	48	42	28	21
15	135	48	43	29	21
	45	51	48	35	27
	225	51	47	34	25
	315	47	42	28	21

Table 9.--Duration (days) of various levels of contamination for Species 1 (upper) and Species 13 (lower), with and without migrations.

the duration of the higher (>50 and >100) levels of contamination.

The effect of migration of the pelagic species is illustrated in Figure 11, where contours of 5, 10, 50, and 100 ppm contamination are shown for day 10 in the case of no migration and with migrations of 5 km/day in four directions (angles are relative to due east). The initial source of the oil is marked by a solid dot in each figure and the area covered by WSF greater than 1.0 ppm is shaded. The contamination field in each case is extended in the direction of migration. When migrating in the direction of the movement of the oil (~45°), fish take up contamination, but can then depurate as they leave the oil-spill area. On the other hand, fish migrating toward the original source of the oil (225°) are exposed to more oil over a longer period of time.

It was shown in Figure 10 that the total area covered by tainted fish was actually reduced by migrations. The distortion of the contamination field caused by migrations, however, can increase the affected fishing area. This is illustrated in the results for Species 1 from the OUTMIG submodel shown in Figures 12 through 14. In each figure, grid points with tainted fish (contamination >5 ppm) are marked. Results shown for days 5, 10, 20, and 30 with migrations of 5 and 10 km/day at 45° (Figure 12) and 225° (Figure 13) can be compared with results with no migration (Figure 14). As the contaminated fish migrate through the grid and beyond, the length of the area of tainting increases. For example, in the case of migration at 10 km/day at an angle of 225° (Figure 13), tainted fish occupy a strip extending 76 km to the southwest of the original source of the oil by day 20. A circle of this radius has an area of over 18,000 km^2, whereas the area of tainting on day 20 in the case of no migrations can be contained in a circle with a

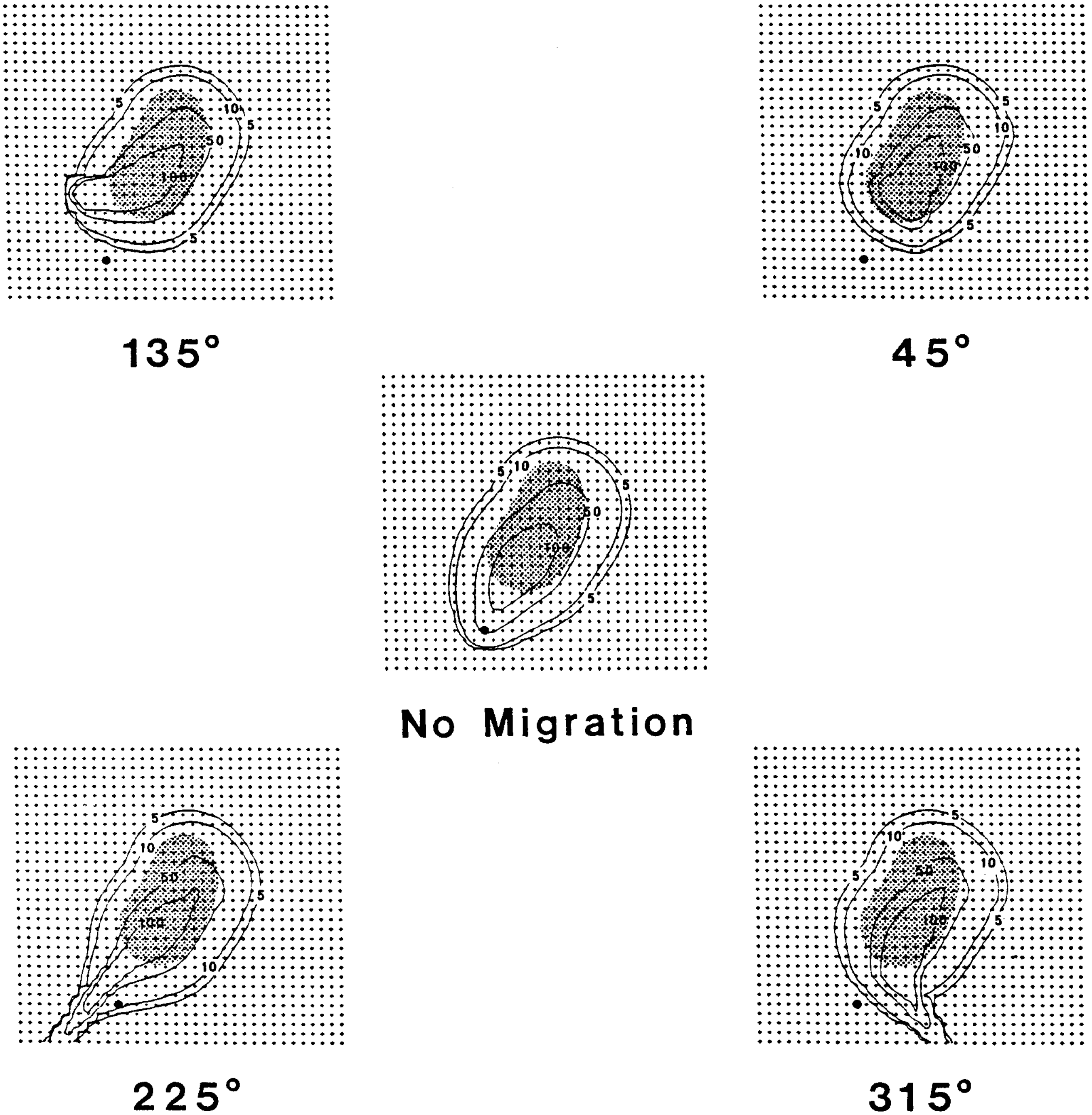


Figure 11.--Contamination of a pelagic fish (Species 1) at day 10 from model runs with no migrations and with migrations of 5 km/day. Contours of 5, 10, 50, and 100 ppm are drawn. Original source of the oil is marked "●" and area covered by 1.0 ppm WSF at day 10 is shaded.

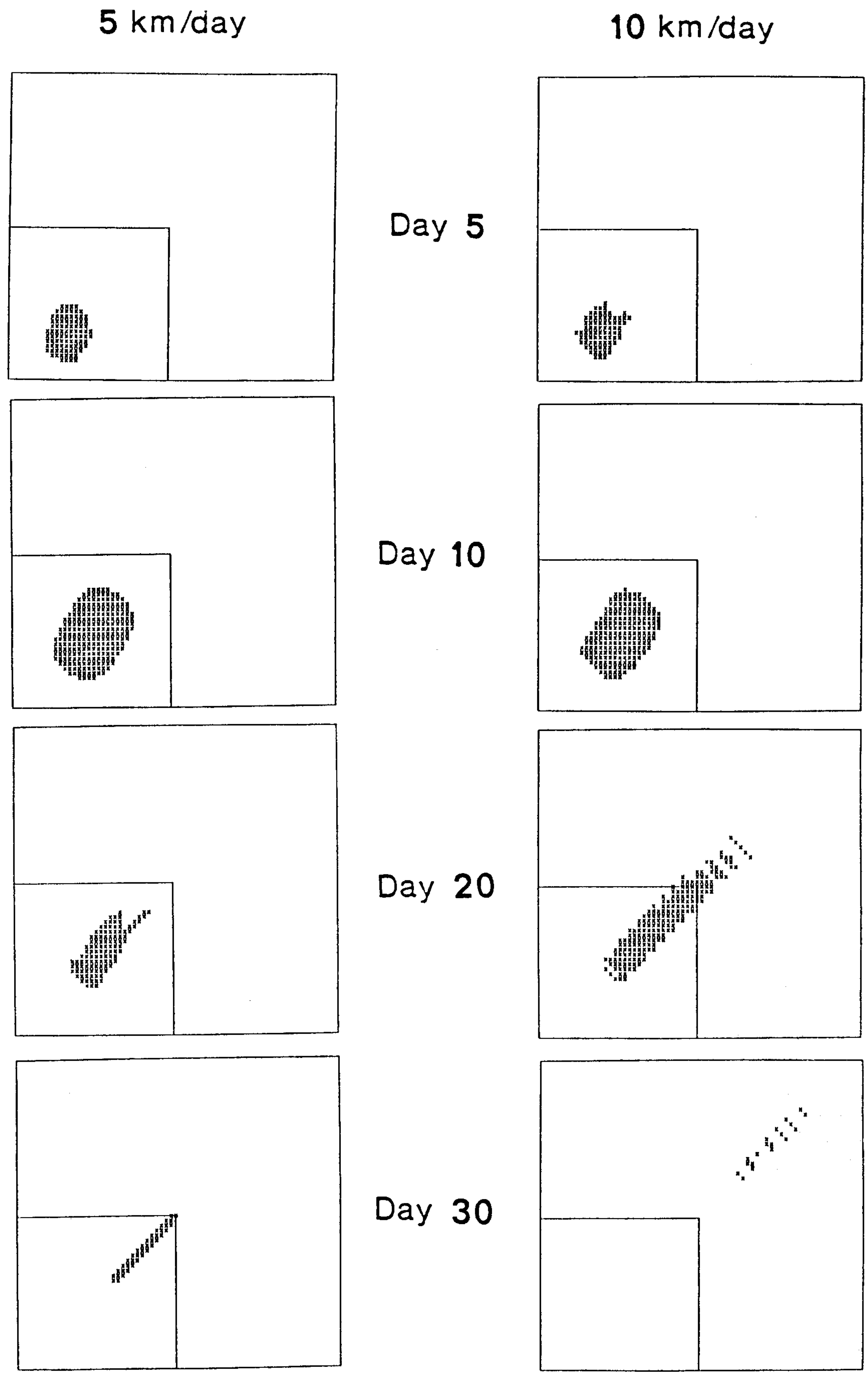


Figure 12.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid for migrations of 5 and 10 km/day and migration angle of 45° (in the direction of the oil movement).

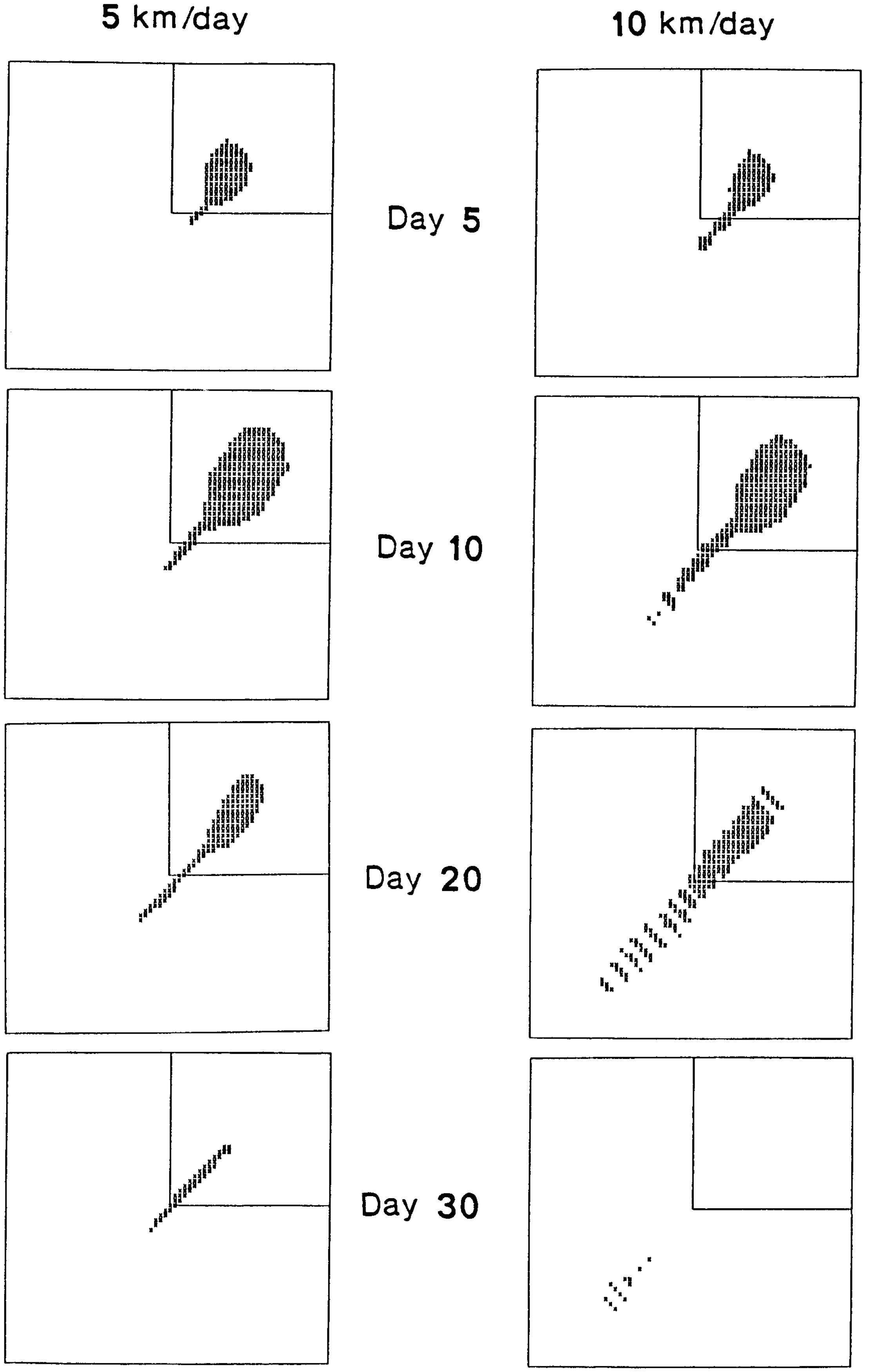


Figure 13.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid for migrations of 5 and 10 km/day and migration angle of 225° (in the opposite direction of the oil movement).

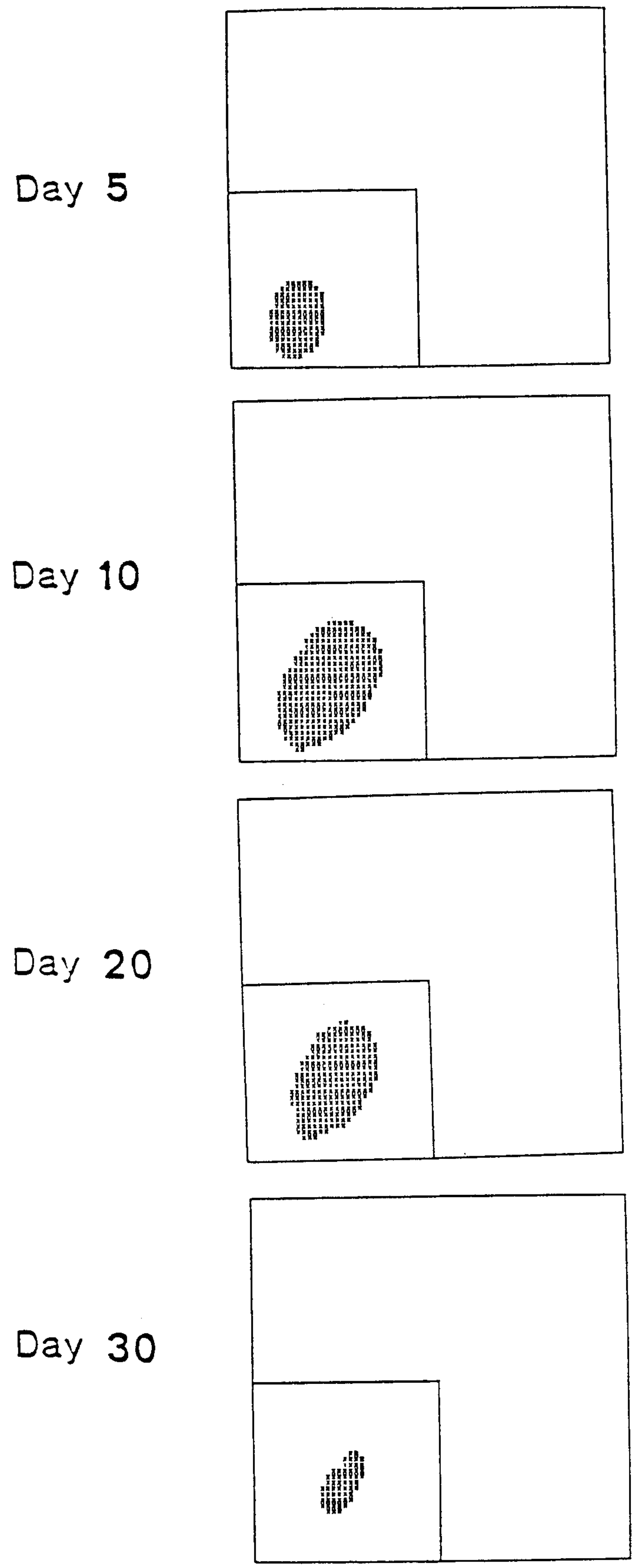


Figure 14.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid with no migrations.

radius of 25 km (i.e., less than 2,000 km^2). This is not to suggest that 18,000 km^2 of the Bering Sea should be closed to fishing in the event of an oil spill.* It does demonstrate, however, that tainted fish migrating through an oil spill area can travel well beyond the bounds of the oil before depurating.

SUMMARY AND DISCUSSION

The BIOS model was developed to evaluate potential effects of an oil spill on the eastern Bering Sea ecosystem. Due to a lack of accurate quantitative data on many of the processes involved in an oil spill, the model was kept as simple and generic as possible. Biological contamination was simulated as a combined function of uptake and depuration. Uptake of contaminants was assumed to be equally divided between uptake from the water or sediments and uptake from contaminated food. The latter was simulated as a function of the relative pelagic or demersal species in a fish's diet. Migration of fish was simulated by the advection of contamination through the model grid and beyond.

Concentrations of oil in the water column (WSF) for the well blowout scenario were everywhere below 0.5 ppm and had a minimal simulated effect on the ecosystem. WSF concentrations for the accident scenario were an order of magnitude larger (maximum 9.0 ppm). Computed concentrations of oil in the sediments (TARS) reached a maximum of 10.1 ppm and remained in the area up to 50 days.

Results for a pelagic-feeding species (juvenile herring) and a demersal-feeding species group (adult crabs) were presented. Maximum contamination of both species occurred 4 days after the corresponding maximum oil concentrations.

Contamination of the pelagic species reached a maximum of 208.1 ppm (approximately twice the maximum of the demersal species). Maximum area covered by tainted fish in the simulation with no migrations was less than 2,000 km^2.

Migrations of 5, 10, and 15 km/day were simulated in each of four directions: moving with the oil (45°), moving toward the source of the oil (225°), or northwest (135°). Migrations increased the duration of higher levels of contamination (>50 and >100 ppm), due to the movement of already contaminated fish through higher concentrations of oil. In addition, migrations extended the distance from the source of the oil at which tainted fish could be found.

The assumptions and simplifications of the model could be improved with more accurate data on rates of uptake and depuration of oil, transfer of contamination through feeding, detectable levels of contamination, and avoidance of oil by fish. Laboratory and field studies using realistic oil concentrations could be designed to address many of these problems. Until more accurate quantitative data is available, however, the qualitative results of a model such as BIOS can provide insights to many of the interactive processes involved in an oil spill.

REFERENCES

Arnold, G. P.

1981. Movement of fish in relation to water currents. In Aidley, D. J., (ed) Animal Migration. Cambridge Univ. Press, pp 55-79.

Bakkala, R. G. and G. B. Smith.

1978. Demersal fish resources of the eastern Bering Sea: Spring 1976. Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, WA, Processed Rep., 233 pp.

Brandl, P. O., O. Grahl-Nielsen, T. Neppelberg, K. H. Palmork, K. Westrheim, and S. Wilhelmsen.

1978. Oil - tainting of fish, a laboratory test on salmon and saithe, ICES C. M. 1976/E:33. Unpub. MS.

Connell, D. W., and G. J. Miller.

1981. Petroleum hydrocarbons in aquatic ecosystems - behavior and effects of sublethal concentrations: Part 1. CRC critical reviews in environmental control 2(1):37-104.

Gallagher, Arthur F., Jr.

1984. Documentation of the biological impact of an oil spill model, BIOS. Part 2: Fish feeding and contamination through consumption - Subroutine FEDOIL. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA., Program Documentation No. 22, 21 pp.

Gallagher, A. J., Jr. and N. B. Pola.

1984. The uptake and depuration of petroleum hydrocarbons in marine species: A simulation study of the uptake and depuration of petroleum hydrocarbons and its effect on selected marine species in the Bristol Bay ecosystem. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA, Processed Rep. 84-16, 68 pp.

Harden Jones, F. R.

1968. Fish Migration, Edward Arnold (publishers), London, 325 pp.

Harden Jones, F. R.

1977. Performance and behaviour on migration. In: Steele, J. H., (ed.) Fisheries Mathematics, Academic Press, London, pp 145-170.

Harden Jones, F. R.

1981. Fish migration: strategy and tactics. In Aidley, D. J., (ed.) Animal Migration. Cambridge Univ. Press, pp 139-165.

Howgate, P., P. R. Mackie, K. J. Whittle, J. Farmer, A. D. McIntyre, and A. Ebeftheriou.

1977. Petroleum tainting in fish. P. 143-146. In: A. D. McIntyre and K. J. Whittle (eds.) Petroleum Hydrocarbons in the Marine Environment. Conseil. Int. pour l'Explor. Mer, Vol. 171.

Laevastu, T., and F. Fukuhara.

1984a. Quantitative determination of the effects of oil development in the Bristol Bay region on the commercial fisheries in the Bering Sea. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA., Processed Rep. 84-06, 73 pp.

Laevastu, T., and F. Fukuhara.

1984b. Oil on the bottom of the sea. A simulation study of oil sedimentation and its effects on the Bristol Bay ecosystem. ICES Document, C. M. 1984/E:6. Mar. Environ. Quality Committee, 19 pp.

Moriarity, F.

1975. Organochlorine Insecticides: Persistent Organic Pollutants. Academic Press, London, 302 pp.

Pereyra, W. T., J. E. Reeves, and R. G. Bakkala.

1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, WA, Processed Rep., 619 pp.

Rice, S. D.

1981. Review: Effects of oil on fish. Natl. Academy of Sci. Workshop on Petroleum in the Environment, Nov. 1981. NMFS, Auke Bay, 34 pp.

Solomon, F. and M. L. Mills. [eds.]

1982. Potential impacts of oil spills on fisheries resources under department of fisheries jurisdiction, summarized from WDF - sponsored testimony on the proposed cross sound Northern Tier pipeline. Prog. Rep. 168, Dept. of Fish., State of Wash. 66 pp.

Swan, Nancy Pola.

1984. Biological Impact of an Oil Spill (BIOS) model documentation. Part 1: Fish migrations and exposure to contamination. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA., Program Documentation No. 21, 17 pp.

Teal, John M.

1977. Food chain transfer of hydrocarbons. In: Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms (D. A. Wolfe, Ed.), pp 71-77.

Thorsteinson, F. V., and L. K. Thorsteinson.

1982. Finfish Resources. Chapter 6 In M. J. Hameedi, [ed.] The St. George Basin environment and possible consequences of planned offshore oil and gas development. Proceedings, of a Synthesis meeting. U.S. Dept. Commerce, NOAA, Office of Marine Pollution Assessment.

Walker, M. G., F. R. Harden Jones, and G. P. Arnold.

1978. The movement of plaice (Pleuronectes platessa L.) tracked in the open sea. J. Cons. int. Explor. Mer, 38(1), pp 58-86.

Wilson, K. W.

1975. The laboratory estimation of the biological effects of organic pollutants. Proc. R. Soc. Lond. B., 189:459-477.

RECOVERY OF THREE BERING SEA TYPE FISH POPULATIONS FROM CATASTROPHIC LARVAL MORTALITY - A SIMULATION APPROACH

by

Taina Honkalehto
Compass Systems, Inc.

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

April 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Processed Report 85-13 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Figure 11. Atka mackerel--total exploitable biomass responses, including interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case I (see text): Linear relationship between spawning stock and recruits.

Figure 12. Pacific ocean perch--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

Figure 13. Walleye pollock--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

Figure 14. Atka mackerel--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

ABSTRACT

One approach towards elucidating fish stock and recruitment relationships is to simulate how changes in early stage mortality affect the exploitable stock biomass. Predation, starvation and pollution are known contributors to early larval mortality. This study examines the effects of losses due to oil contamination on recruitment to exploitable biomass. Simulation methods are used to project larval mortalities caused by possible accidental release of oil through time for three commercial Bering Sea fish stocks, Atka mackerel (*Pleurogrammus monopterygius*), walleye pollock (*Theragra chalcogramma*) and Pacific ocean perch (*Sebastes alutus*). Two hypothesized relationships between adult and new recruit biomass are used. Case I models annual recruit biomass (Age 1) as a proportion of the previous year's reproducing adult biomass. Assuming no density dependence, a catastrophic mortality of all Age 1 fish permanently lowers exploitable biomass for all three species. Perch biomass declines the least and mackerel the most, although losses to the latter species are obscured by its high interannual recruitment variation. In Case II, with no spawning stock and recruitment relationship, recruit biomass is a proportion of the long term mean biomass. Under these conditions, populations respond to loss of all Age 1's by first declining, then returning to near pre-oil spill biomass after the year class cycles through. Results of early mortality on each species are discussed in light of life history differences between species. Ideas for further use of the

simulation are also presented.

INTRODUCTION

"...it seems to me that even though there be governing causes of mortality that may result in a true law of mortality, any group of lives studied is so heterogeneous, due to differences in...climate, race, physical characteristics, etc. that any formula must in practice be considered merely to be a generalization of what is actually happening." (Elston,1923 p.68)

Current fisheries research continues to tackle the problem of the relationship between spawning stock and subsequent recruits as an important key to effective stock management. Increased understanding of stock and recruit relationships will arise from ongoing studies of larval stage mortality and growth but progress is slow due to high spatial and temporal variability. Meanwhile, model simulation of larval mortality and resulting effects on recruitment can aid in delineating the expected range of response to environmental perturbation.

Early mortality in marine fish has been attributed to consumption by predators (Lebour, 1923; Theilacker and Lasker, 1974; Hunter, 1976; Alvarino, 1980; McGowan and Miller, 1980; Frank and Leggett, 1983; and additional references in Hunter 1981;1983), starvation (Hunter and Kimbrell, 1980; Beyer and Laurence, 1980) as well as to marine pollution (Nelson-Smith, 1972; Kuhnhold, 1972; Rosenthal and Alderdice, 1976; Kuhnhold et.al., 1978; IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN,1977; additional references in Bax, 1985). The purpose of this study was to simulate the impact of catastrophic first year mortality due to oil contamination in marine fish, and to project biomass losses to the exploitable stock through time. A stock as used in this paper refers to a group of fish spawning in the same place and time; no allowance has been made for discrete spawning units. Thus the catastrophic loss applies to all potential recruits to that stock.

DESCRIPTION OF THE MODEL

A biomass-based, single species simulation model was programmed to run on a Columbia PC to study the impacts of losses of fish eggs and larvae on subsequent year class strengths. Three commercially important Bering Sea fish species with dissimilar life history patterns (Table 1) were selected to demonstrate potential stock biomass responses to catastrophic first year mortality following an (hypothetical) oil spill. Stable population age structures for Atka mackerel, walleye pollock and Pacific ocean perch corresponding to long-term mean data from Niggol (1982) and Bakkala and Low (1983) were used (Table 2). For convenience, each species was initially ascribed 100 units of biomass. Oil loss effects on exploitable biomass were analyzed by first deriving a general simulation, then running separate simulations with data from each species. Each set of simulations contrasted two hypothesized relationships between recruit and adult biomass. The first case modelled recruit biomass as a proportion of the previous years' spawner biomass; the second assumed no spawner and recruit relationship. Interannual recruitment variability was determined empirically for each

Table 1. Model Inputs: Life history parameters of Bering Sea Pacific ocean perch, Atka mackerel and walleye pollock.

SPECIES	TYPICAL LIFESPAN (years)	EXPLOITABLE AGES	REPRODUCTIVE AGES	SPAWNING MODE	SPAWNING SEASON	COEFFICIENT OF VARIATION (recruits)	HABITAT (adults)	FECUNDITY (eggs)	SOURCES
PACIFIC OCEAN PERCH	20	11-20	6-20	ovoviviparous	Mar.-May	0.23	demersal	27,000 - 180,000	Niggol 1982 Bakkala & Low 1983
WALLEYE POLLOCK	12	3-12	3-12	oviparous	Mar. -June	0.47	semi-demersal	186,000 - 600,000	Niggol 1982 Bakkala & Low 1983
ATKA MACKEREL	7	2-6	3-7	oviparous	June -Aug.	0.95	pelagic	5000 - 43,000	Niggol 1982 Macy et.al. 1978 Bakkala & Low 1983

Table 2. Model Inputs: Growth coefficents (G), stable age structure in 100 biomass units (B), and mortality coefficients (M) for Pacific ocean perch, Atka mackerel and walleye pollock. (Niggol, 1982).

SPECIES	INPUT	AGE CLASSES 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PACIFIC OCEAN PERCH	B	5.2	6.8	9.7	9.6	9.1	8.5	7.8	7.4	6.7	5.9	4.9	4	3.4	2.8	2.3	2.3	1.6	1.1	0.7	0.4
	G	1.38	0.95	0.512	0.37	0.306	0.258	0.254	0.174	0.153	0.155	0.103	0.084	0.076	0.061	0.054	0.035	0.019	0.004	-0.01	
	M	1.12	0.6	0.52	0.42	0.38	0.34	0.32	0.28	0.28	0.3	0.28	0.25	0.26	0.27	0.28	0.31	0.36	0.44	0.59	
WALLEYE POLLOCK	B	6.6	12	13.6	14.2	13	11.5	9.7	7.6	5.3	3.4	2.1	1								
	G	1.398	0.686	0.554	0.385	0.264	0.144	0.112	0.087	0.077	0.059	0.047									
	M	0.8	0.56	0.513	0.47	0.385	0.322	0.354	0.451	0.513	0.517	0.752									
ATKA MACKEREL	B	29.7	26.5	19	12	7.2	3.8	1.8													
	G	0.569	0.312	0.162	0.107	0.067	0.5														
	M	0.71	0.65	0.62	0.6	0.7	0.78														

species and entered into the model.

CHARACTERISTICS OF SELECTED SPECIES

Atka mackerel

Atka mackerel are distributed across the North Pacific east of 165 W and north of 44 N (Figure 1). Though primarily pelagic, adult mackerel aged three or four begin moving inshore to spawn during May. Spawning peaks in summer in the straits between the Aleutian Islands, as females deposit sticky egg masses on kelp fronds or on stones. Each female produces three or four batches of eggs at 5-7 day intervals at preferred water temperatures of around 5-8 C. After a 40-45 day incubation period during which they would be especially susceptible to smothering or contamination from oil, newly hatched, planktotrophic larvae are dispersed with currents in the open ocean. They display some vertical migration; more larvae reside in the upper layers of the water column at night than during the day (Macy et.al., 1978).

Walleye pollock

Walleye pollock are one of the most abundant north Pacific fish. They are semi-demersal and inhabit deep waters of the north Pacific and Bering Sea to off central California (Figure 2). Walleye pollock prefer slightly colder temperatures than Atka

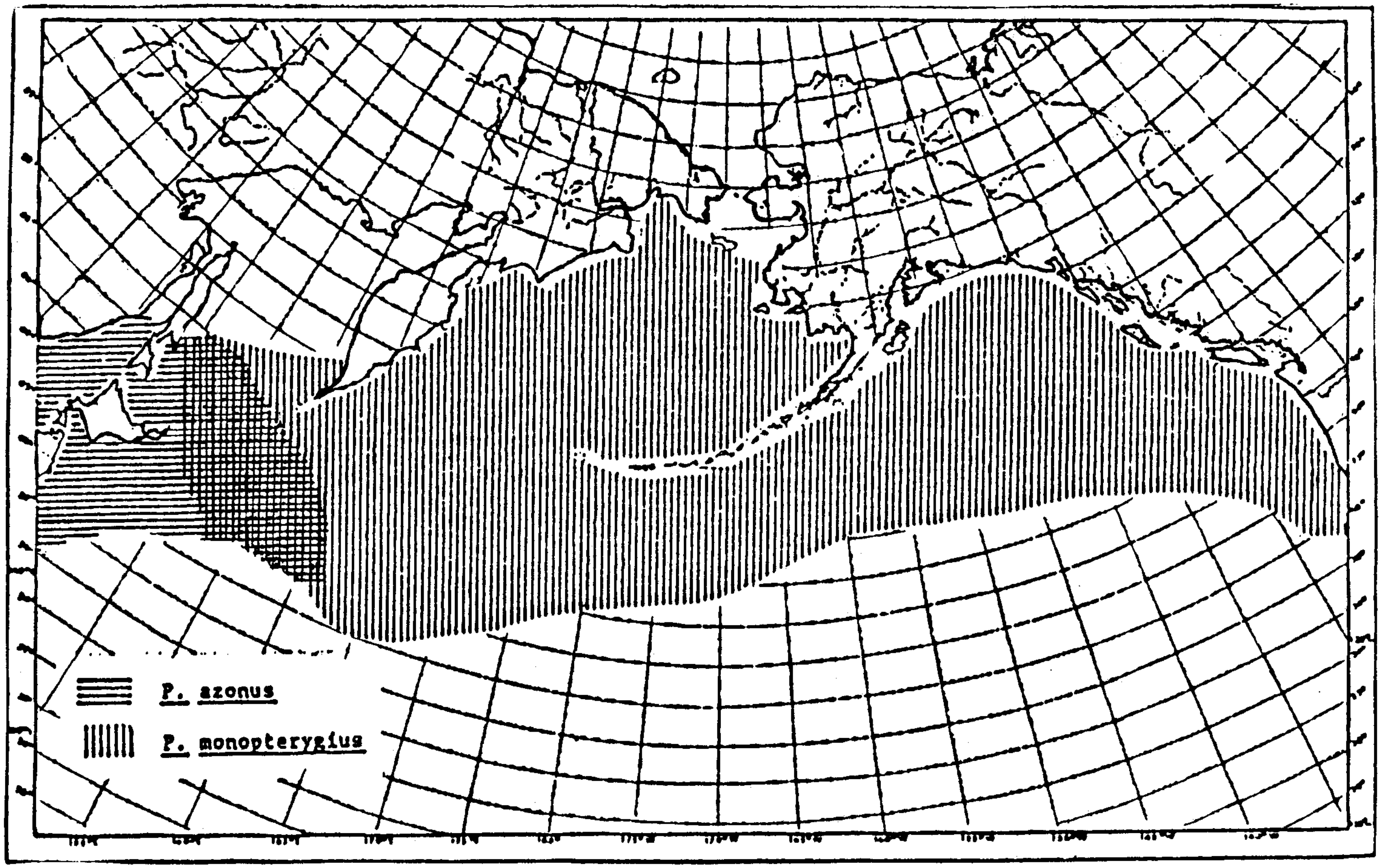


Figure 1. Presumed range of *Pleurogrammus monopterygius* and *P. azonus* in the North Pacific and Bering Sea. Both species are found further inshore than the map indicates (from Macy et.al., 1978).

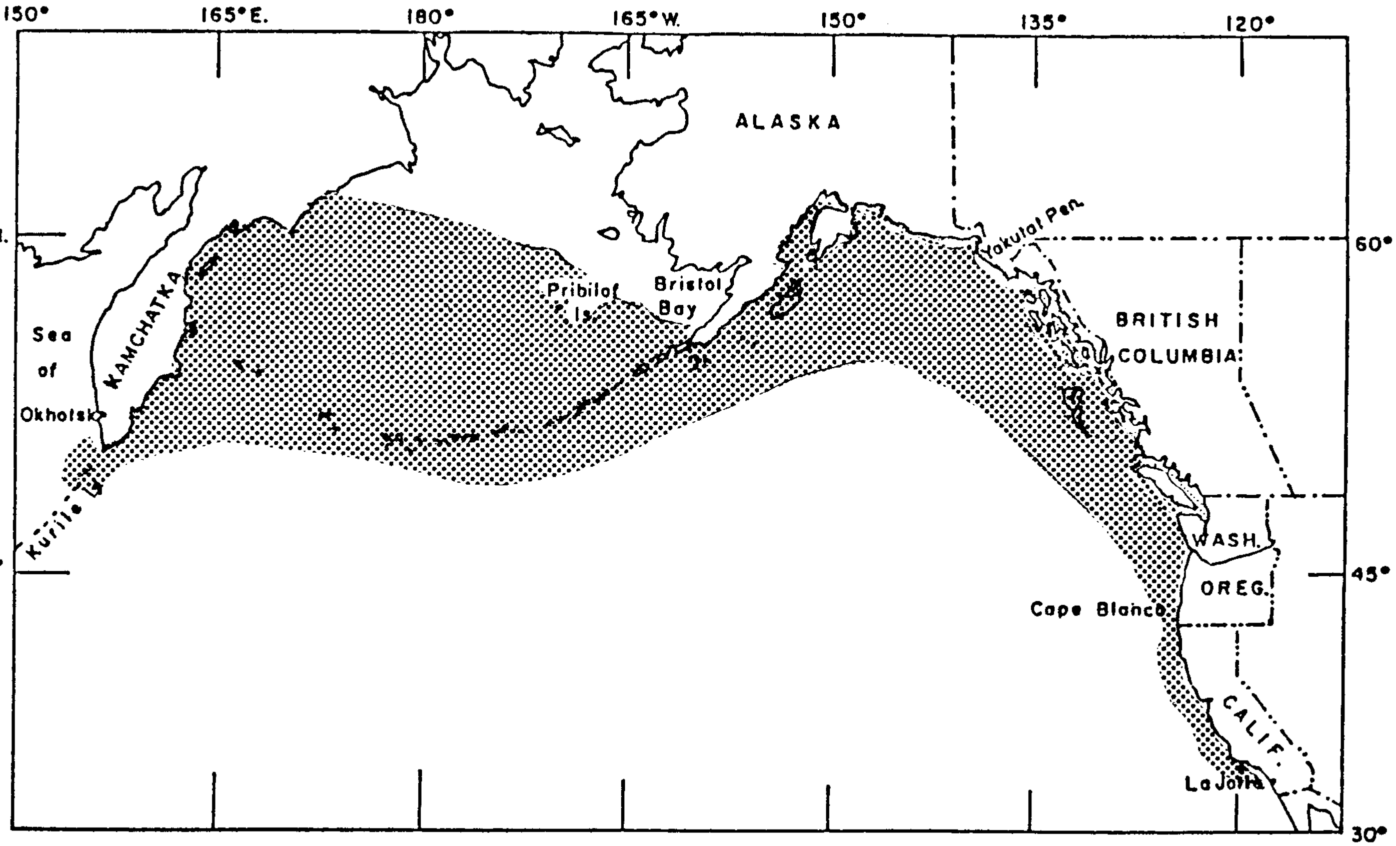


Figure 2. Distribution of walleye pollock, *Theregra chalcogramma* (Smith, 1981), modified.

mackerel, with optima between 2-5 C. Most of the population winters offshore, then migrates to spawning grounds on the southeastern Bering Sea continental slope and Gulf of Alaska shelf west and northwest of Unimak Island between February and May. During the spawning season which peaks in late April, three to four year (+) females release eggs that concentrate in the surface waters and hatch in about twelve days (at 6-7 C). Newly hatched larvae have been observed drifting offshore with local current systems which may promote larval survival. By age 1, walleye pollock achieve their broad oceanic distribution (Kasahara, 1961; Serobaba, 1975; Smith, 1981; Norcross and Shaw, 1984).

Pacific ocean perch

Pacific ocean perch were once a dominant ichthyofaunal component in the north Pacific (Major and Shippen, 1970; Gunderson, 1976). However, heavy fishing during the past two decades has reduced their numbers. Their trans-Pacific range (Figure 3) includes open ocean habitat as well as rocky bottomed gullies, caves and submarine depressions along the outer continental shelf and upper slope between 180 to 460 m. Bering Sea stocks of Pacific ocean perch mature at 6-7 years of age. They mate during January and February in Bristol Bay, southwest of the Pribilof Islands and in the Gulf of Alaska. Between March and May, females migrate to deep water (around 400 m) and release

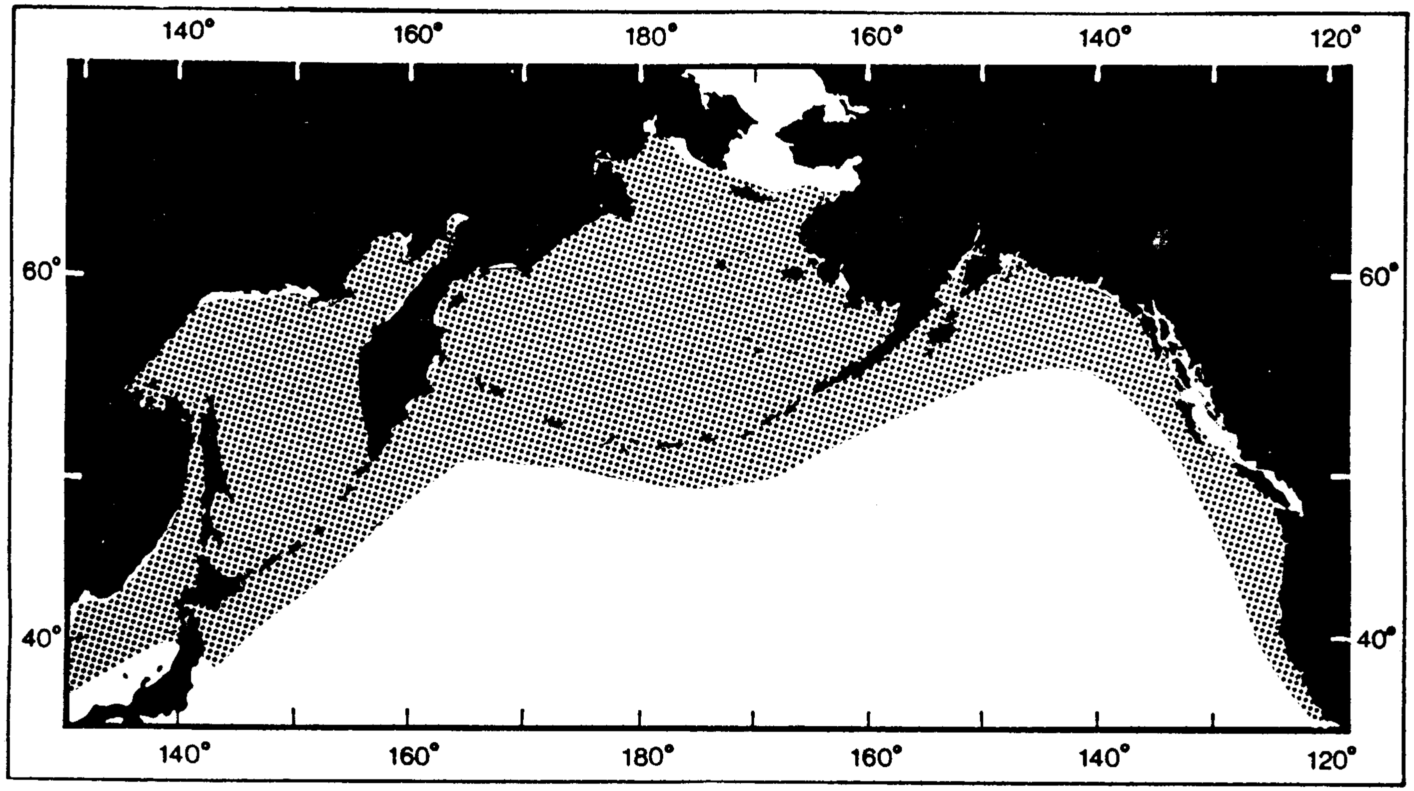


Figure 3. Distribution of Pacific ocean perch, *Sebastes alutus* (Major and Shippen, 1970), modified.

pelagic larvae in spawning episodes lasting three or four hours. Emergent larvae, 6-8 mm in length, remain pelagic for up to five years and feed on copepods and other crustaceans (Laevastu, pers. comm.). After two years, they develop demersal habits.

COMPUTATIONS

Yearly biomass changes in the stocks were simulated as follows:

$$B_{i+1,t+1} = B_{i,t} \, e^{G_i (B_{i,0} / B_{i,t}) - M_i} \tag{1}$$

where

i - year class; i = (1,20) for Pacific ocean perch
(1,7) for Atka mackerel
(1,12) for Walleye pollock
t - time (year); t = 0 at start of simulation
B - biomass units; initially 100 units in population
G - empirical growth coefficient
M - mortality coefficient (natural + fishing mortality)
e - natural constant (2.71828...)

Since the mortality schedule relating recruits to prior adult biomass is poorly known for most species (Cushing, 1971; Hunter, 1976; Gunderson, 1976), recruitment was simulated for both maximum effect and minimum effect cases under the assumption that actual population responses would lie somewhere between the two. In Case I, the maximum effect of oil losses on subsequent years' exploitable stock biomass was simulated assuming direct linear proportionality between stock and recruits (ages 0-1) biomass. Thus in years following the oil spill, the affected year class contributed zero biomass towards the exploitable stock. Case II assumed that recruited biomass was independent of parental biomass, representing the control of recruit biomass via an environmental "window" that allowed only a prescribed number of larvae to successfully recruit no matter how many were spawned in a given year (Hempel, 1965). Recruit biomass was determined as the proportion of the equilibrium spawner biomass necessary to sustain that equilibrium biomass. Recruit biomass for year (t+1) was computed in year (t) for each case as follows:

Case I: Maximum effect of oil losses possible

$$R_{t+1} = S_{.t} * p \tag{2}$$

Case II: Minimum effect (environmental window)

$$R_{t+1} = S_{.0} * p \tag{3}$$

where

t, t+1 - time (years), and 0 denotes equilibrium year

. - denotes summation over mature age classes unique to each species:

Pacific ocean perch	=	11- 20
Atka mackerel	=	3- 7
Walleye pollock	=	3- 12

R - biomass recruited, based on a starting population biomass of 100 units

S - reproductive stock (no. of units) in a given age class, during a given year, (t)

p - species specific, empirically determined proportionality constant relating equilibrium population biomass to recruit biomass

Using empirical growth, mortality and biomass distribution data (Table 1), equations (1) and either (2) or (3) were computed for each species in one hundred year time series. Growth and mortality coefficients were adjusted slightly, if necessary, until each population maintained a stable biomass over successive years. Justification for using a stable biomass model was presented in Laevastu and Larkins (1981, p.98). In year 1 of the study, each fish population had an age and biomass structure that totaled 100 units. Later age and biomass structures do not necessarily sum to 100.

Once the equilibrium population structure was obtained, early mortality due to an oil spill was simulated by setting first year fish biomass in year fifteen (R(15,1)) equal to zero. Population responses to oil contamination losses were graphed both for individual year classes within species and for total exploitable biomass between species.

Annual recruitment variability due to unexplained fluctuations in the environment, predator and prey populations, adult fertility and other changing factors was included in the second set of simulations using a random number generator. For each species, a normally distributed, interannual coefficient of variation of recruits was matched to that obtained from available data (Bakkala and Low, 1983; Chikuni, 1975). Total exploitable biomass responses to 100% recruitment failure in year fifteen were then graphed for each species using Case I and Case II recruitment regimes. Density-dependent growth and mortality were omitted from the simulations for simplicity and because few relevant empirical data exist to support their inclusion (Gunderson, 1976).

RESULTS

Individual Year Class Effects

Responses of representative year classes to catastrophic loss of recruits under Case I and prior to inclusion of interannual recruitment variability, are illustrated in Figures 4-7. The first simulation (Figures 4-6) shows different between species responses: Atka mackerel declined the most, and Pacific ocean perch the least. An example of individual year class responses to 100% mortality of recruits and Age 2's (Figure 7) was included for comparison with Figures 4-6. For Atka mackerel, the effect of losing all of the two youngest year classes in one year was much greater than losing just one year class.

Total Exploitable Biomass Effects

Total exploitable biomasses, the percent of each species utilized by commercial fisheries, were computed and their responses to 100% mortality of Age 0-1's were compared (Figure 8) prior to inclusion of interannual recruitment variability in the simulations. Atka mackerel biomass fell the most within a year of the oil kill, yet the population increased slightly before stabilizing. Pacific ocean perch declined the least, and showed no change until nearly a decade after the catastrophic event. Walleye pollock biomass fell nearly as rapidly as mackerel and

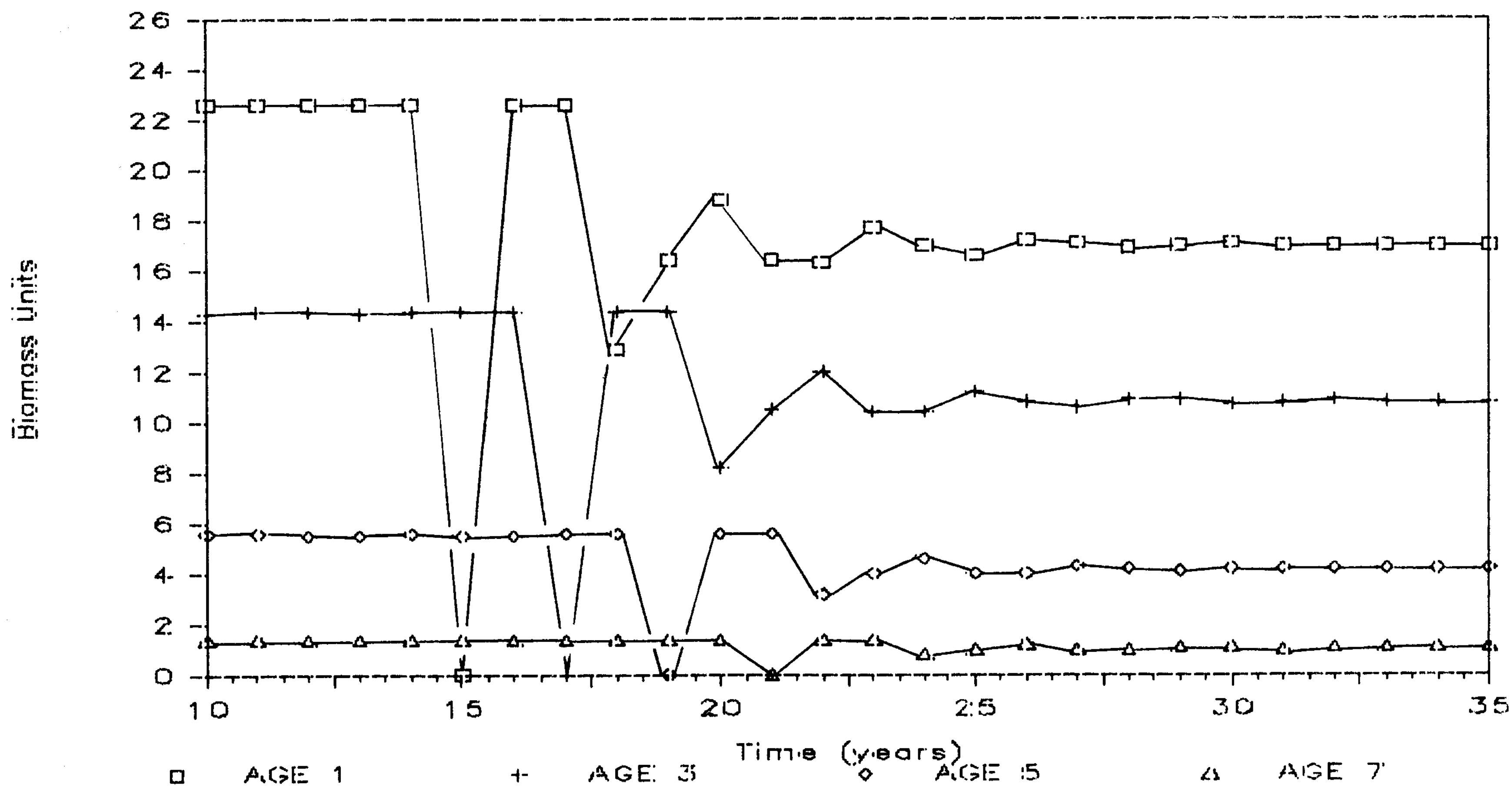


Figure 4. Effect of 100% mortality of Age 1 (0-1 year old) Atka mackerel in one year on the equilibrium biomass of selected year classes over time.

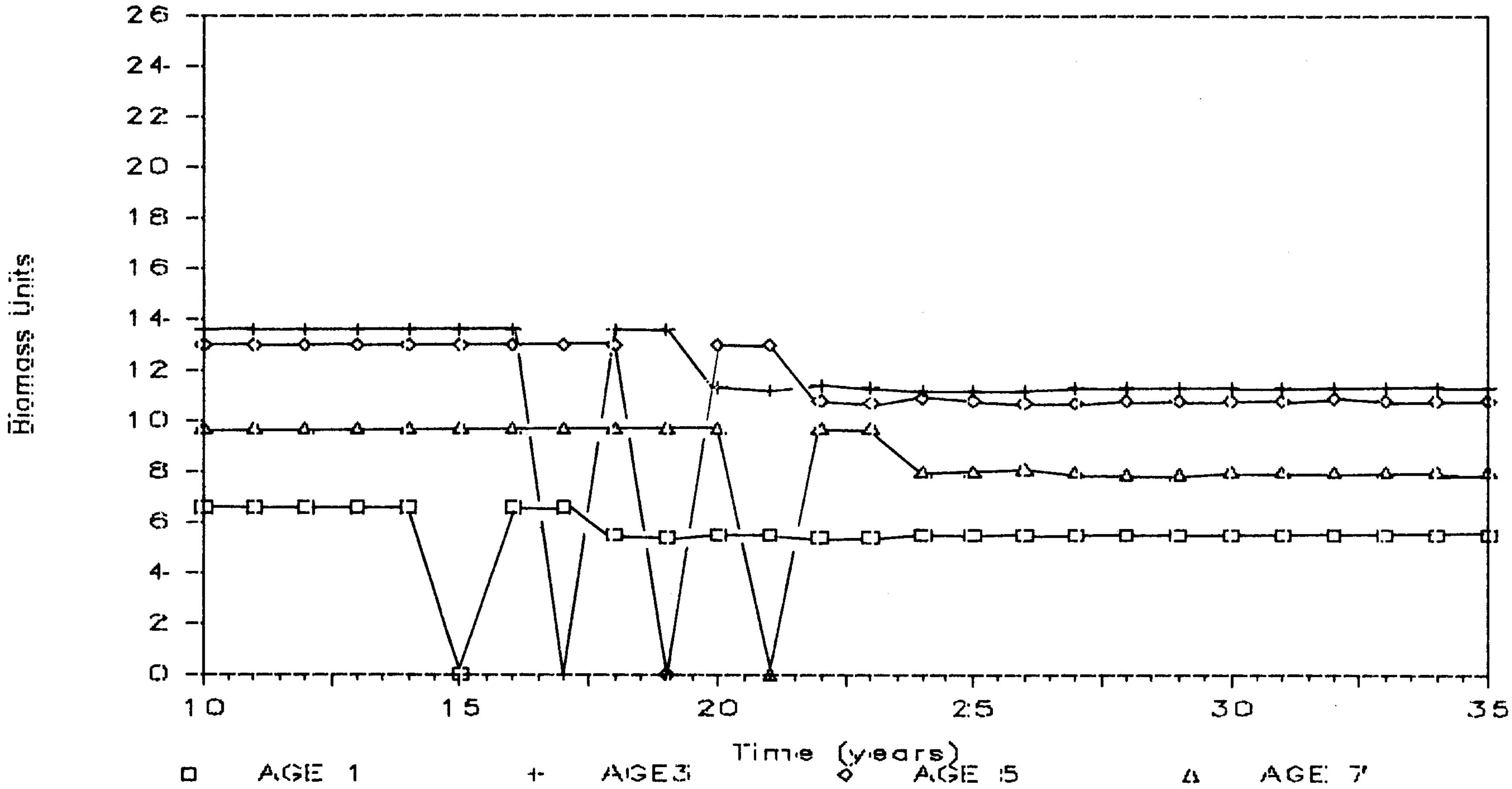


Figure 5. Effect of 100% mortality of Age 1 (0-1 year old) walleye pollock during one year on the equilibrium biomass of selected year classes.

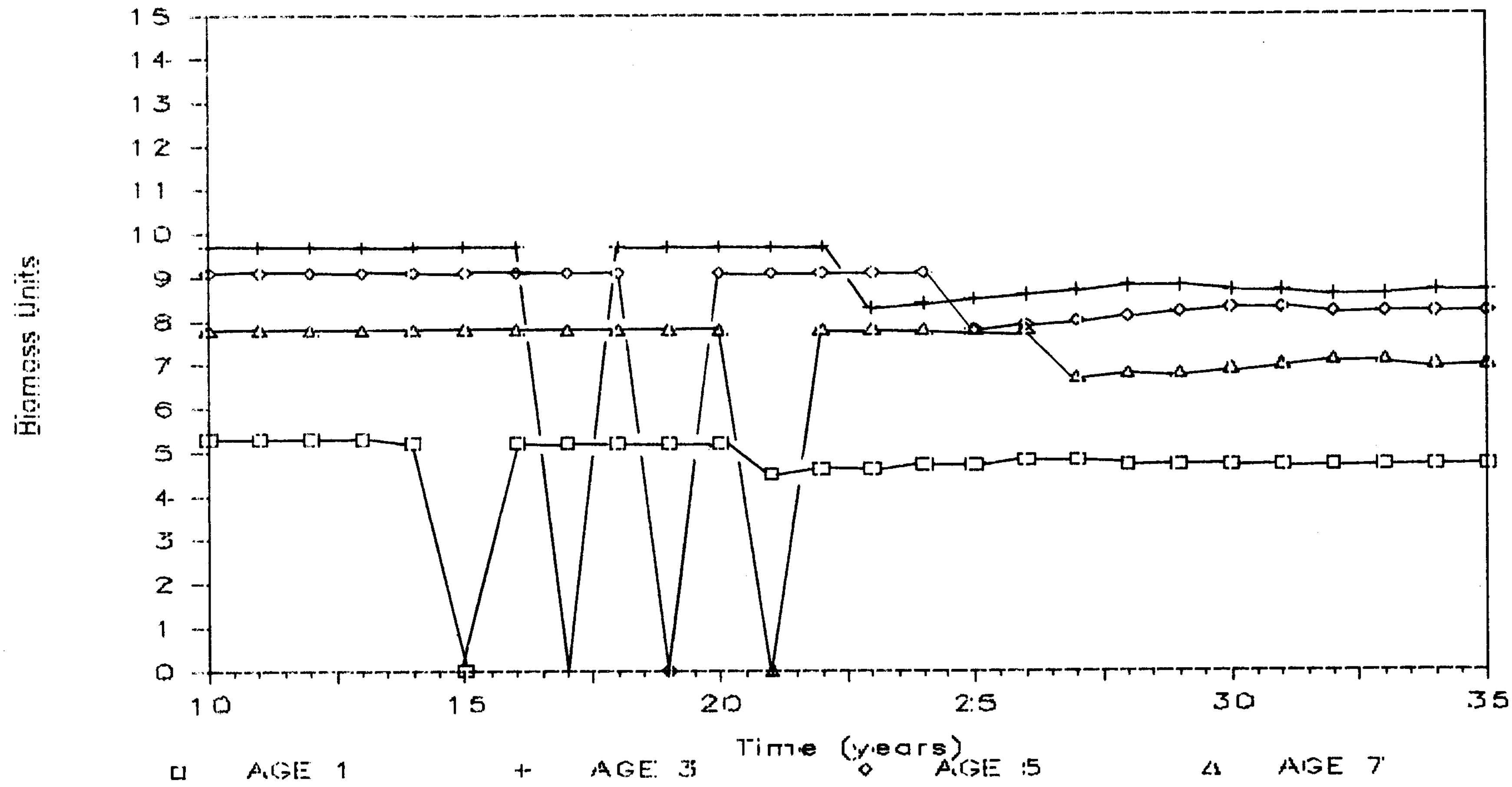


Figure 6. Effect of 100% mortality of Age 1 (0-1 year old) Pacific ocean perch in one year on the equilibrium biomass of selected year classes.

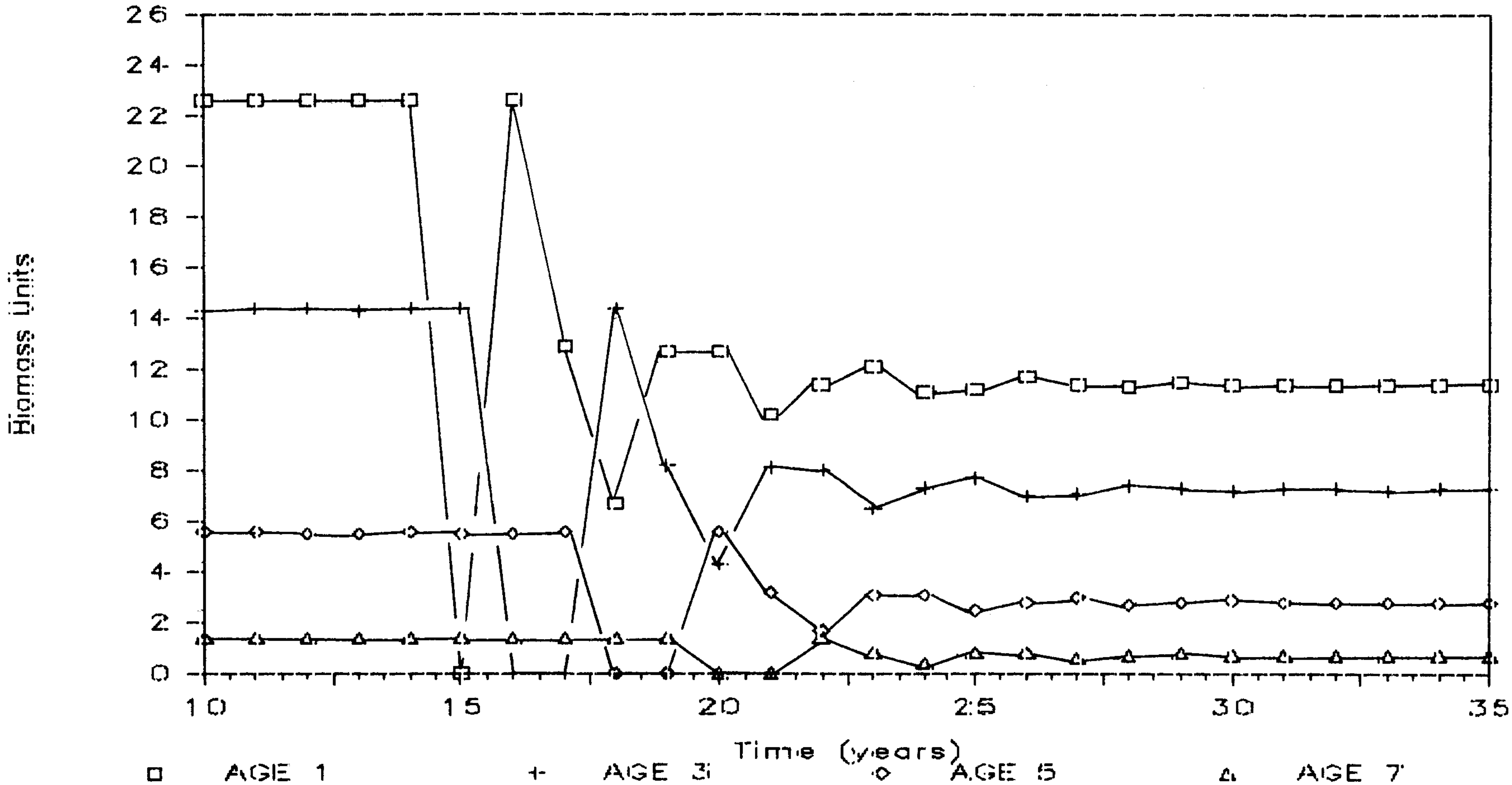


Figure 7. Population responses of Atka mackerel to catastrophic oil induced losses of Age 1 and Age 2 (1-2 year old) fish in a single year.

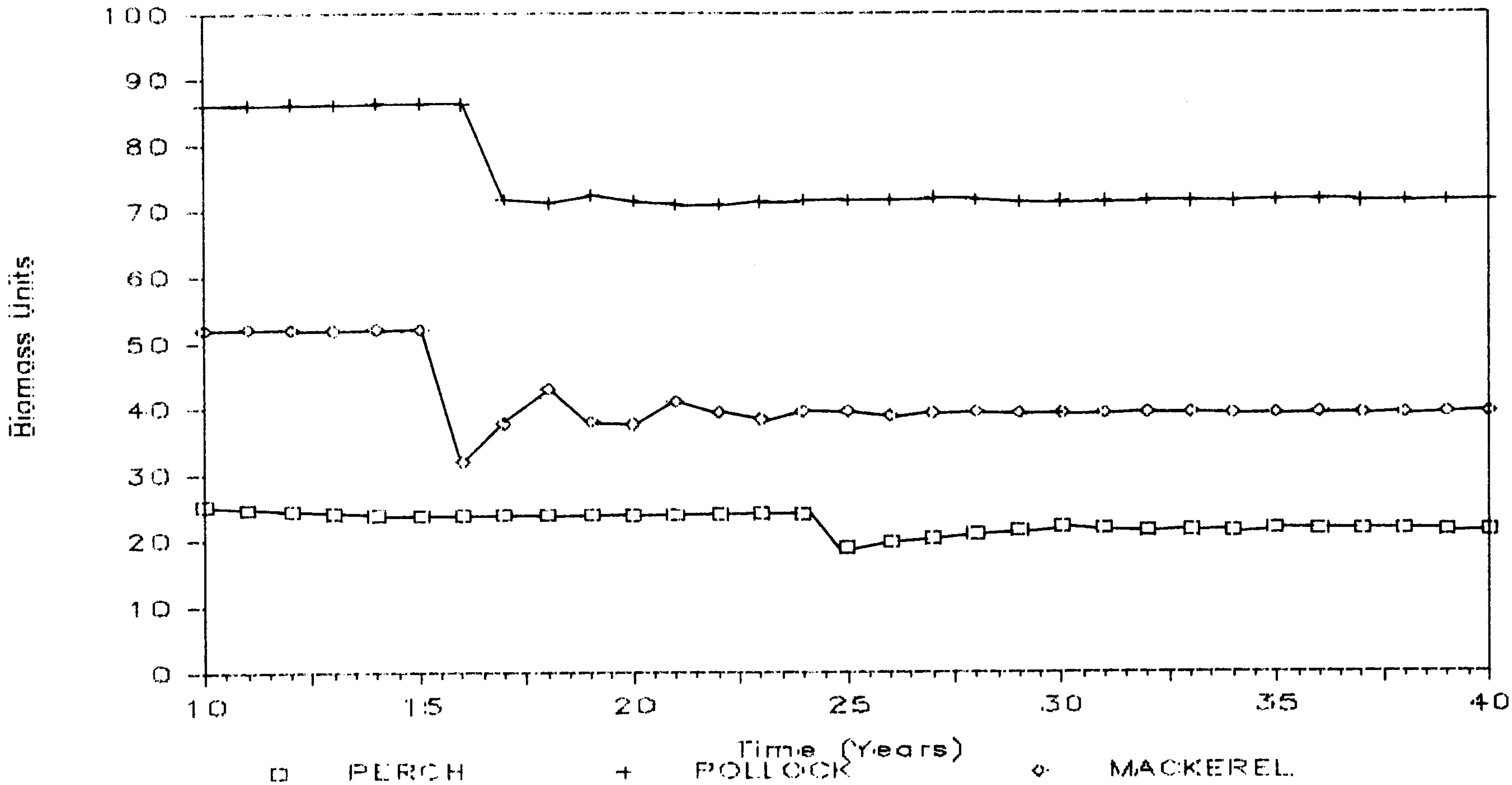


Figure 8. Total exploitable biomass responses of perch, pollock and mackerel to 100% loss of Age 1's in year 15.

did not rebound at all during successive years.

The two final sets of simulations included a normally distributed interannual random component of recruitment computed from recent fisheries data for each species. Results for Case I with linear dependence of recruitment on parent stock size are shown in Figures 9-11. Seed random numbers were used two times--with and without a simulated oil spill--for each species. Figure 9 shows that losses due to oil in year 15 do not affect the exploitable perch biomass until ten years later (year 25), and that the total percent biomass affected is low. Pollock respond more quickly to oil losses and display a periodic biomass curve. Mackerel show a reduced biomass from oil losses that is somewhat masked by the amplitude of its normally high interannual recruitment fluctuations (Figure 11).

Results from Case II simulations with recruitment based on the equilibrium stock showed that effects of oil losses appeared with the first year class exploited by the fishery and diminished as a function of the longevity of the species involved (Figures 12-14).

DISCUSSION AND CONCLUSIONS

Predation, starvation, natural environmental and man-made factors leading to early mortality in marine fish populations still require extensive investigation. As mentioned, literature

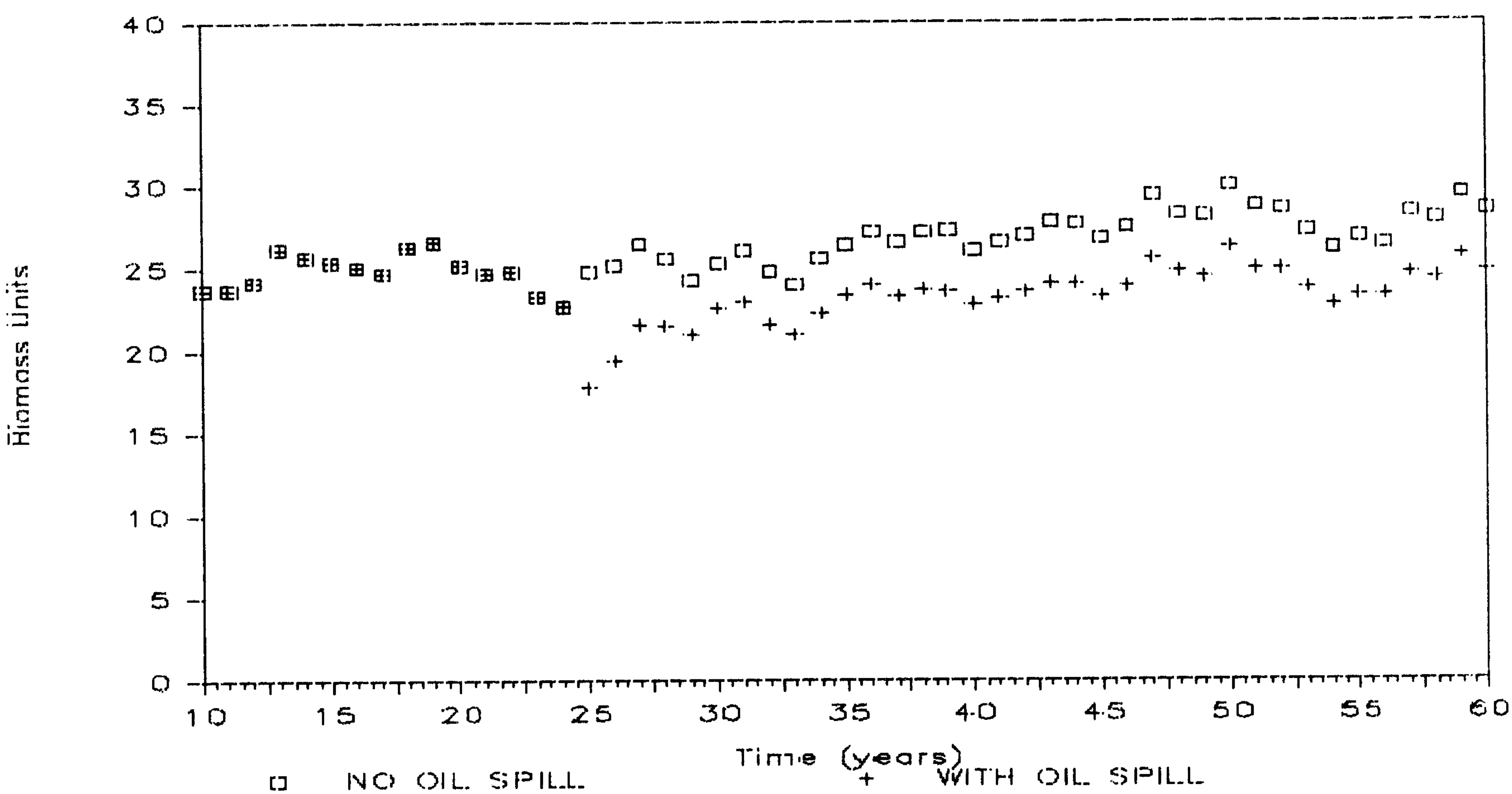


Figure 9. Pacific ocean perch--total exploitable biomass responses, including interannual recruitment variability, to losses due to oil in year 15. Case I (see text): linear relationship between spawning stock and recruits.

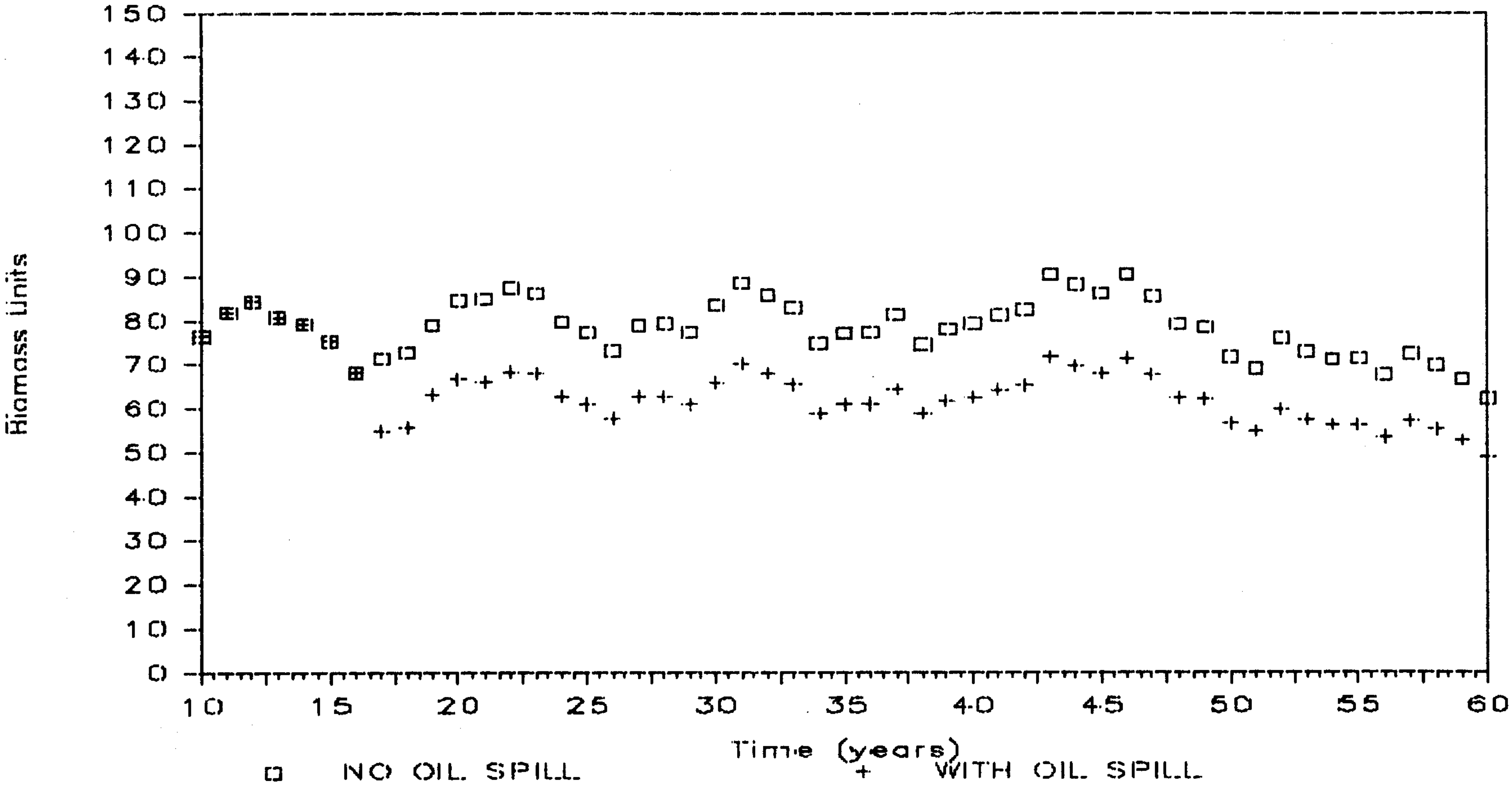


Figure 10. Walleye pollock--total exploitable biomass responses, including interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case I (see text): Linear relationship between spawning stock and recruits.

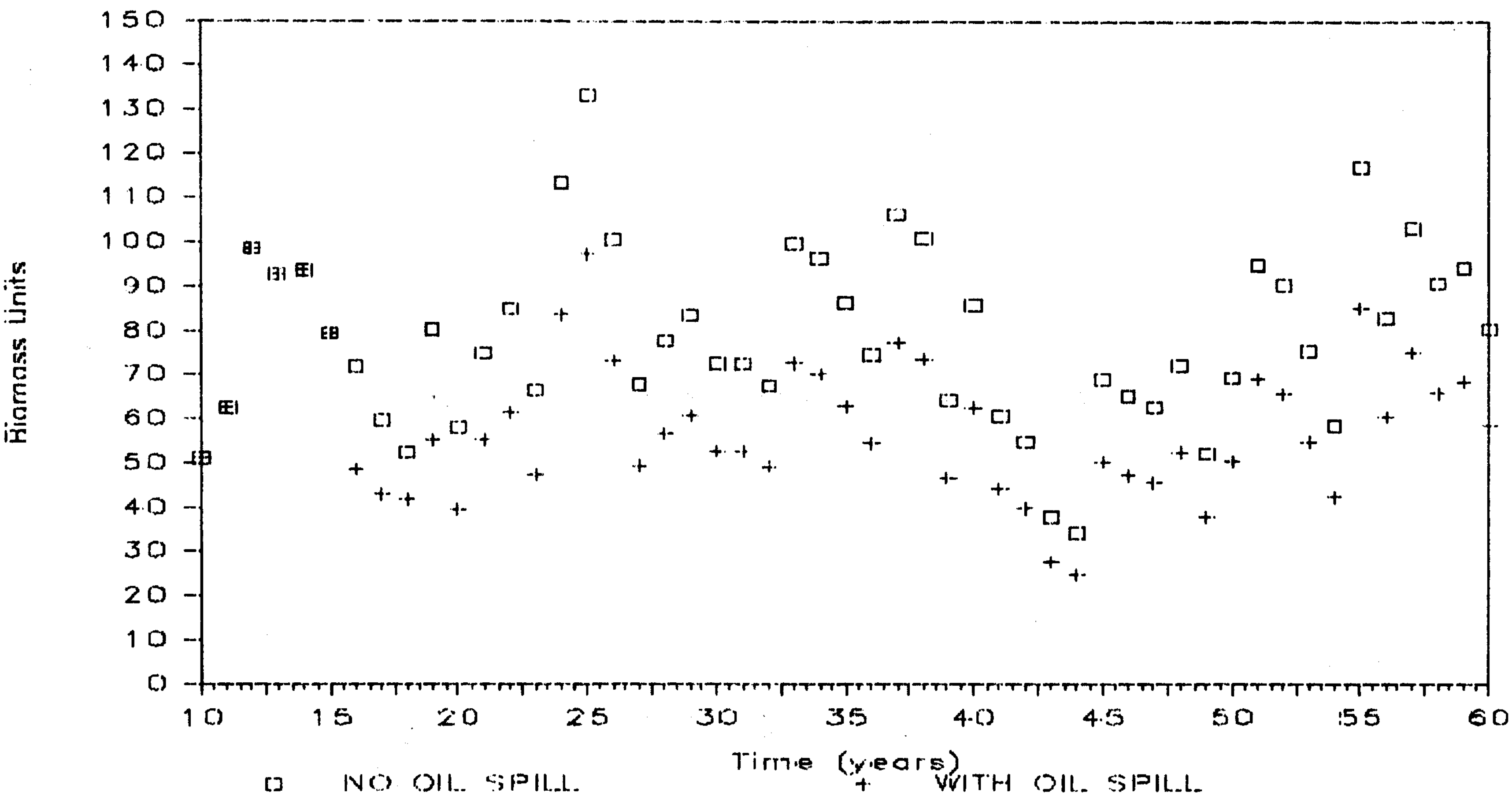


Figure 11. Atka mackerel--total exploitable biomass responses, including interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case I (see text): Linear relationship between spawning stock and recruits.

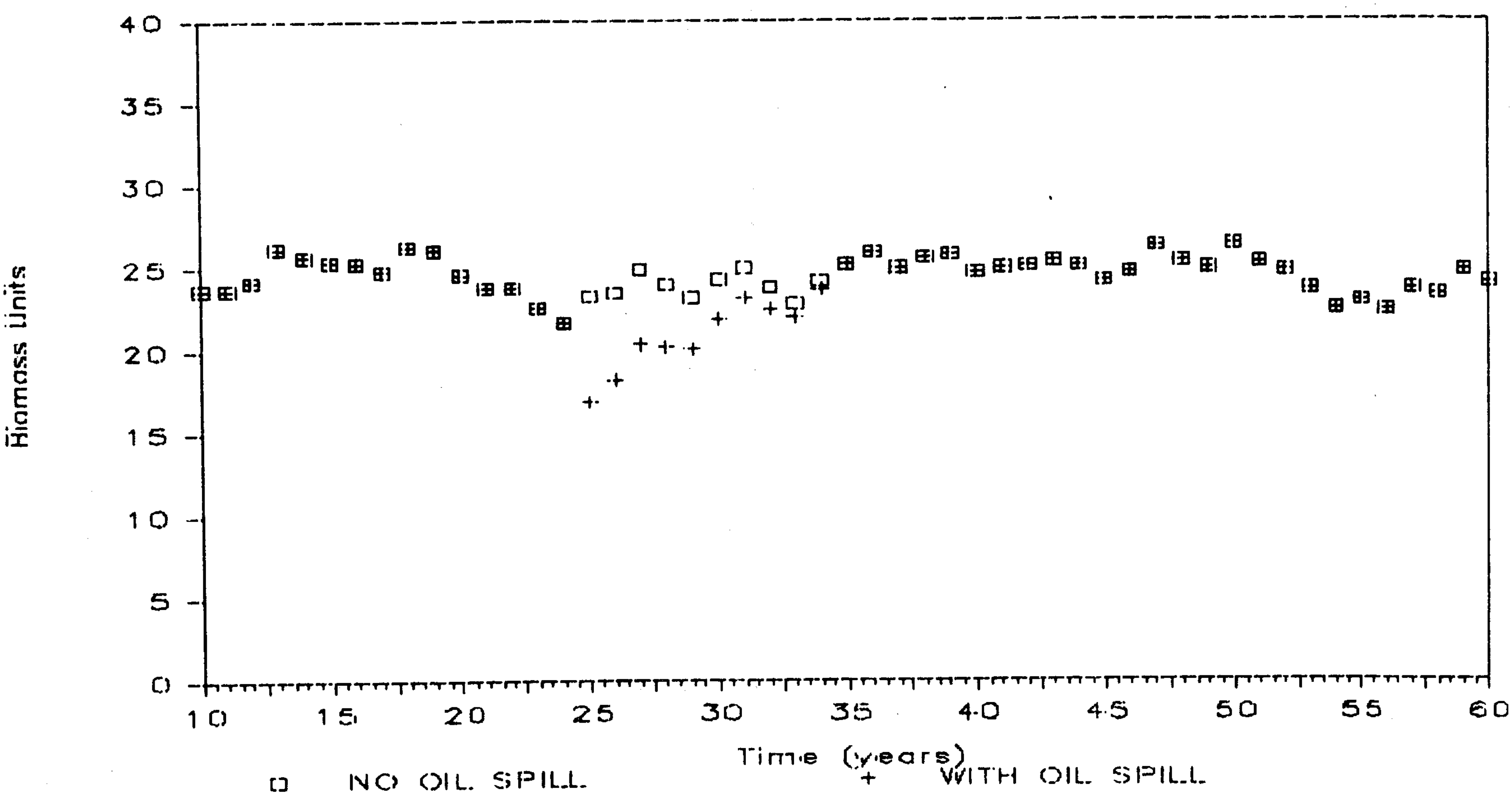


Figure 12. Pacific ocean perch--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

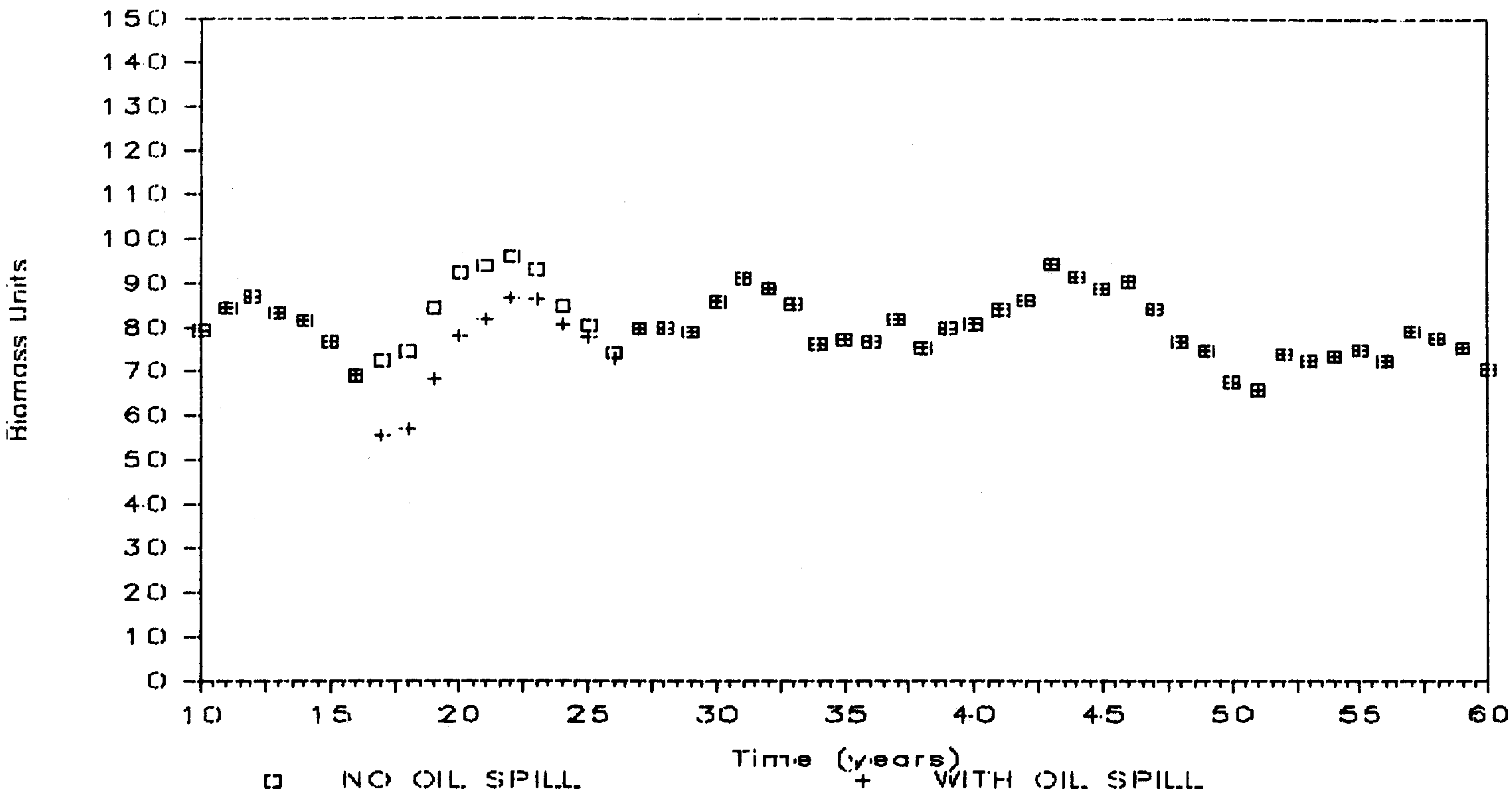


Figure 13. Walleye pollock--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

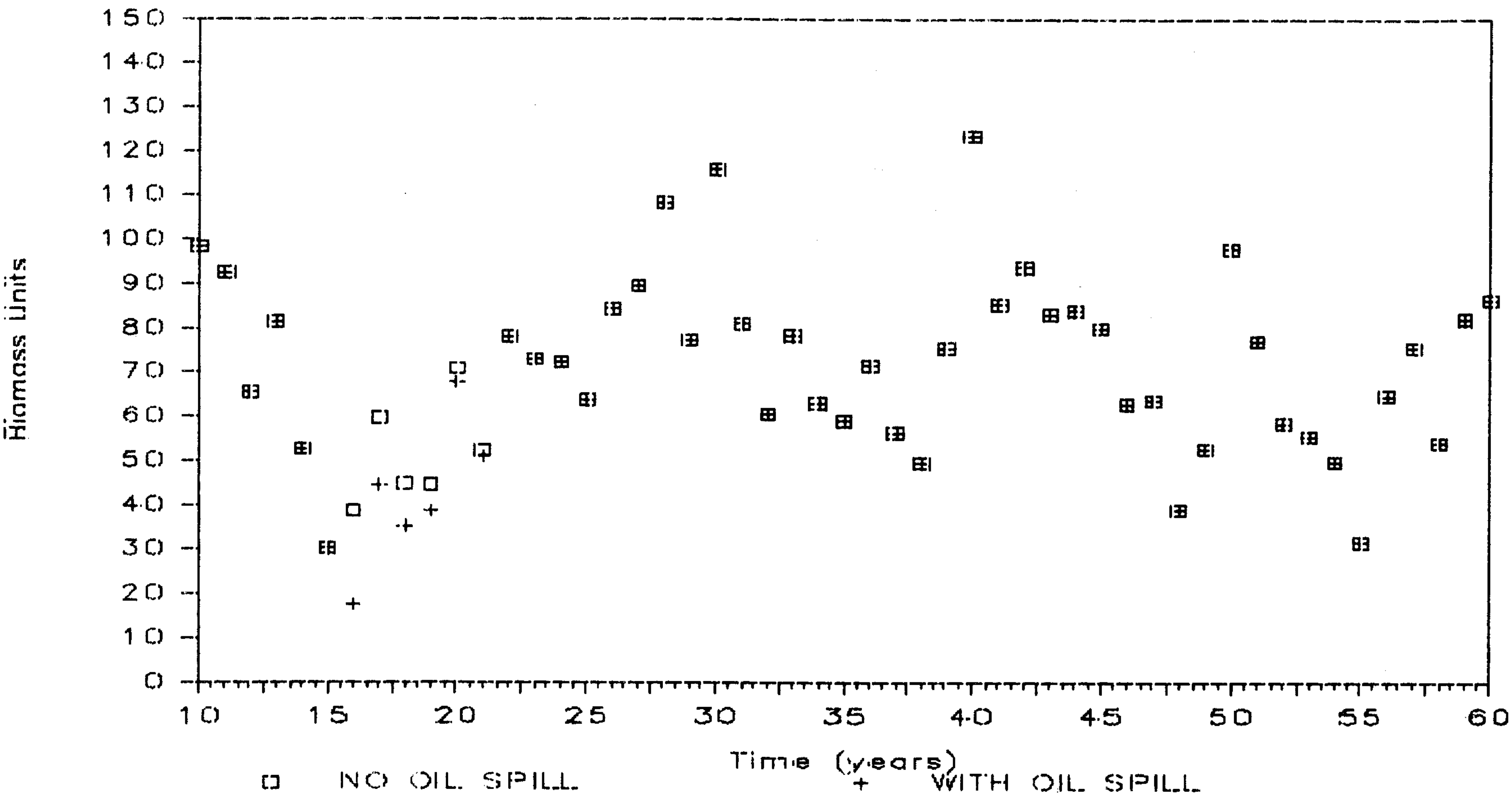


Figure 14. Atka mackerel--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

currently available quantifying relative importance of these mortality factors is sparse. Rather than attempting to model first year mortality processes per se, this study assumes a mechanism for early mortality (oil contamination), computes recruit biomass that is sensitive (Case I) and non-sensitive (Case II) to previous-year adult biomass, and tracks the impact of low-biomass year classes through time. It is instructive in estimating different species' responses to catastrophic population phenomena other than fishing mortality.

Previous work on population dynamics of marine fish populations has emphasized individual year class fluctuations. Combining year classes from a particular stock into total exploitable biomass damps out individual responses, distributing effects of perturbations through time (Laevastu and Larkins, 1981). In this study, the effects of oil induced losses of recruits to important commercial Bering Sea fish stocks were considered from the total exploitable biomass point of view with the following assumptions: (1) death of Age 0-1's was modelled, as oil contact potential would be highest during the pelagic phases of perch and pollock larvae and during oceanward transport of mackerel larvae (Kasahara, 1961; Gunderson, 1976) and (2) the worst case scenario of 100% mortality (catastrophic) was modelled, as true oil-related mortality after contact is poorly known for any species (Samuels and Ladino, 1984). Actual mortality would be considerably less than 100%, and would more likely range from 1 to 10%, even in a major oil spill (Laevastu, pers. comm.).

Simulated pollock, mackerel and perch populations with twelve, seven and twenty year classes, respectively, responded differently to catastrophic oil losses. These results are attributable to differences in life history characteristics among the three species.

Pacific ocean perch embody two inherently stabilizing traits, longevity and adult demersality (Nikol'skii, 1962; Laevastu and Larkins, 1981). Fecundity and interannual recruitment variability are low, and the number of recruits may be sensitive to stock size (Gunderson, 1976). Thus in nature, this stock probably behaves more like a Case I (see Figure 9, this report) simulation than Case II. The absolute percent biomass loss to the population would be damped by numerous year classes. However, some form of compensatory growth (density-dependent) would be required to elevate the population back to its pre-oil spill biomass.

Walleye pollock biomass, when perturbed by catastrophic oil losses, fluctuated moderately. A cyclical pattern became evident in runs with different seed random numbers (Figure 10). This corresponded well to Laevastu and Larkins' results (1981) which they attributed to cannibalism among the older pollock year classes. Not enough information existed to catagorize pollock as either Case I or Case II fish. In the former simulation, recovery of the stock would require compensatory growth. If they behave as in Case II (Figure 13) recovery would occur in about ten years.

The relatively short-lived, pelagic Atka mackerel undergo large interannual recruitment variability (Macy et.al.1978; Ronholt, 1983). They most likely behave as in the Case II simulation (Figure 14). Since interannual recruitment fluctuations are on the same scale as fluctuations due to oil losses, the long-term average mackerel population biomass would appear little changed after oil-caused deaths occurred. In the short term, however, because Age 1's and 2's make up such a large proportion of the total biomass, losses would be swift and acute. Recovery under a Case II scenario would take five to six years.

Some similar responses among the three populations were also noted. In Case I simulations, all three species stabilized at lower exploitable biomass levels that, without inclusion of compensatory density-dependence in the simulation, never returned to original levels. When recruitment was made independent of parent stock size (Case II) exploitable biomass always returned to original levels after a number of years equivalent to the number of different exploitable cohorts in the stock.

Finally, with the inclusion of density-dependent growth and/or mortality (Samuels and Ladino,1984), the simulations presented here could be used to model other mortality factors affecting fish larvae in the ocean such as predation, starvation and anomalous environmental conditions once more data on larval fish biology and distribution become available.

ACKNOWLEDGEMENTS

I thank N. Bax and T. Laevastu for their inspiration and for critical review of this manuscript. This study was funded by the Northwest and Alaska Fisheries Center, NOAA grant No. 84-ABC-098, Dr. T. Laevastu, COTR.

REFERENCES CITED

Alvarino, A.
1980. The relation between the distribution of zooplankton predators and anchovy larvae. CalCOFI Rep. 21:150-160.

Bakkala, R.G. and L. Low.
1983. Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1982. NOAA Tech. Mem. NMFS F/NWC-42. March 1983.

Bax, N.J.
1985. Simulations of the effects of potential oil spill scenarios on juvenile and adult sockeye salmon *Oncorhynchus nerka* migrating through Bristol Bay, Alaska. NWAFC Processed Rept. 85-03 Seattle, WA.

Beyer, J.E. and G.C. Lawrence.
1980. A stochastic model of fish growth. Ecol. Modelling 8:109-132.

Chikuni, S.
1975. Biological study on the population of the Pacific ocean perch in the North Pacific. Bulletin Far Seas Fisheries Research Lab. 12:1-119. [in Japanese, English summary]

Cushing, D.H.
1971. The dependence of recruitment on parent stock in different groups of fishes. J. Cons. Int. Explor. Mer. 33:340-362.

Frank, K.T. and W.C. Leggett.
1983. Multispecies larval fish associations: accident or adaptation? Can. J. Fish. Aquat. Sci. 40:754-762.

Gunderson, D.R.
1976. Population biology of Pacific Ocean perch *Sebastes alutus* stocks in the Washington-Queen Charlotte Sound region, and their response to fishing. Ph.D. dissertation, Univ. of Washington, Seattle WA 140p.

Hempel, G.
1965. On the importance of larval survival for the population dynamics of marine food fish. CALCOFI Rep. X:13-32.

Hunter, J.R.
1976. Report of a colloquium on larval fish mortality studies and their relation to fishery research. NOAA Tech. Rep. NMFS Circ. 395.

Hunter, J.R.
1981. Feeding ecology and predation of marine fish larvae. In: Marine Fish Larvae: morphology, ecology and relation to fisheries, R. Lasker [ed.] University of Washington Press, Seattle pp.34-77.

Hunter, J.R.
1983. Commentary: On the determinants of stock abundance. In: From Year to Year: Interannual variability of the Environment and Fisheries of the Gulf of Alaska and the Eastern Bering Sea. W.S. Wooster [ed.] UW, Seattle, WA.

Hunter, J.R. and C. Kimbrell.
1980. Early life history of Pacific mackerel,*Scomber japonicus*. Fishery Bulletin U.S. 78(1):89-101.

IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN.
1977. Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), Impact of oil on the marine environment. Rep. & Studies, GESAMP, 6:250p.

Kasahara, H.
1961. Fisheries resources of the North Pacific Ocean. Part I. H.R.MacMillan Lectures in fisheries. Inst. of Fisheries UBC Vancouver, B.C.

Kuhnhold, W.W.
1972. The influence of crude oils on fish fry. In: Marine Pollution and Sea Life. M. Ruvio [ed.] Fishing News (Books) Ltd. (FAO) London. pp.315-318

Kunhold, W.W., D.Everich,J.J. Stegeman, J.Lake and R.E. Wolke.
1978. Effects of low levels of hydrocarbons on embryonic, larval and adult winter flounder. In: The proceedings of the conference on assessment of ecological impacts of oil spills. June 14-17. Keystone CO. Amer. Inst. Biol. Sci.

Laevastu, T. and H.A. Larkins.
1981. Marine Fisheries Ecosystem: its quantitative evaluation and management. Fishing News Books Ltd. Farnham, England. 162p.

Lebour, M.V.
1923. The food of plankton organisms. II. J. mar. biol. Ass. UK. 13:70-92.

Macy, P.T., J.M. Wall, N.D. Lampsakis, J.E. Mason.
1978. Resources of non-salmonid pelagic fishes of the Gulf of Alaska and Eastern Bering Sea. Part I.Introduction. General fish resources and fisheries. US Dept. of Commerce. NOAA, NMFS, NWAFC. Seattle WA.

Major, R.L. and H.H. Shippen.
1970. Synopsis of biological data on Pacific ocean perch *Sebastodes alutus*. FAO species synopsis no. 79. Circular 347. US Dept. Commerce, NOAA.

McGowan, J.A. and C.B. Miller.
1980. Larval fish and zooplankton community structure. CalCOFI Rep. 21:29-36.

Nelson-Smith, A.
1972. Oil Pollution and Marine Ecology. Elek, Ltd. London. 260p.

Niggol, K.
1982. Data on fish species from Bering Sea and Gulf of Alaska. NOAA Technical Memorandum. NMFS F/NWC - 29.

Nikol' skii, G. V.
1962. On some adaptations to the regulation of population density in fish species with different types of stock structure. pp.265-282 in E.D. LeCren and M.W. Howgate, [eds.] The exploitation of natural animal populations.

Norcross, B.L. and R.F. Shaw.
1984. Oceanic and estuarine transport of fish eggs and larvae: A review. Trans. Am. Fish. Soc. 113:153-165.

Ronholt, L. L.
1983. Atka mackerel. In: R. G. Bakkala and L. Low [eds.] Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1982. NOAA Tech. Memorandum NMFS F/NWC-42. 1983. pp.163-177.

Rosenthal, H. and D.F. Alderdice.
1976. Sublethal effects of environmental stressor, natural and pollutional, on marine fish eggs and larvae. J. Fish. Res. Bd. Can. 33:2047-65.

Samuels, W.B. and A. Ladino.
1984. Calculations of seabird population recovery from potential oilspills in the mid-Atlantic region of the United State. Ecol. Modelling 21(1):63-84.

Serobaba, I.I.
1975. Spawning ecology of the walleye pollock *Theragra chalcogramma* in the Bering Sea. J. Ichthyol. 14:544-552.

Smith, G.B.
1981. The biology of the walleye pollock. In: D.W. Hood and J.A. Calder [eds.] The eastern Bering Sea Shelf: Oceanography and Resources. Vol. I. U.S. Govt. Print Office, Wash. D.C. pp. 527-551.

Theilacker, G.H. and R. Lasker.
1974. Laboratory studies of predation by euphausiid shrimps on fish larvae. pp. 287-299 in J.M.S. Blaxter [ed.] The early life history of fish. Springer Verlag. Berlin. 765p.

FOOD HABITS OF BRISTOL BAY

SPECIES WHICH MIGHT BE

AFFECTED BY OIL DEVELOPMENT

A STUDY ON THE VARIABILITY

IN DEMERSAL AND PELAGIC FOOD HABITS

by

P. A. Livingston

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

April 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Processed Report 85-12 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Simulation modeling efforts have shown that one of the consequences of oil spill events on the Bering Sea fauna is contamination of fishes via uptake of oil (Gallagher and Pola 1984). Oil uptake by fishes and invertebrates occurs through passive uptake processes (adsorption and absorption) and the ingestion of oil contaminated food. Contamination was shown to be more persistent, lasting at least two weeks longer, in fishes consuming demersal food items because of the longer residence time of weathered oil in the demersal habitat (Pola and Miyahara 1985). Laevastu and Fukuhara(1985) in their review of studies on oil sedimentation in the sea conclude that very high concentrations of oil can accumulate in the nepheloid layer near the bottom and later in sediments and may possibly persist in the sediments for years. Thus, species which utilize demersal food items are more likely to be impacted in the long-term by oil spill events than species which consume pelagic food. It becomes important to outline the existing knowledge of patterns of demersal versus pelagic habitat utilization by marine fish species to determine likelihoods of oil spill impact on these species. In order to extrapolate oil spill modelling results to other seasons or areas it is necessary to understand the variability in demersal versus pelagic food components in marine fish species by season, area, and fish size.

It is the purpose of this study to summarize data regarding the food habits of the marine fish and invertebrate species used in the BIOS (Biological Impact of an Oil Spill) Model. Differences in food habits by fish size, season, and area in the Bering Sea will be discussed particularly with reference to changes in pelagic versus demersal food habits. This should provide an indication of the likely impact on these species from oil spills occurring in different areas and times in the eastern Bering Sea. The species included in this report are sockeye salmon, Pacific herring, walleye pollock, Pacific cod, Pacific halibut, yellowfin sole, rock sole, flathead sole, arrowtooth flounder, Alaska plaice, and king and Tanner crabs. New data will be presented for walleye pollock, Pacific cod, yellowfin sole, flathead sole and arrowtooth flounder. Other evidence for food habit trends are obtained from the literature.

SAMPLE COLLECTION AND PROCESSING

Specimens were collected during 1983 and 1984 in the eastern Bering Sea by U.S. observers aboard foreign fishing vessels and by U.S. scientists aboard research vessels participating in resource assessment surveys of the area. Stomachs of Pacific cod, walleye pollock, yellowfin sole, arrowtooth flounder, and flathead sole were taken from bottom and midwater trawl samples of variable tow duration. The 5436 stomach samples which were obtained came mostly from the middle shelf to slope areas of the eastern Bering Sea in depths of 45m to 200m (Table 1).

Individual fish were first checked for signs of regurgitation, i.e., food items in mouth or gill plates or flaccid stomach and discarded if any such signs were noted. Stomachs from the remaining fish were excised and placed individually into muslin bags with a specimen label containing fish fork length, sex, and station information. All samples were preserved in a 10:1 seawater/formaldehyde mixture.

Stomachs were analyzed individually in the laboratory. Prey items were identified to the lowest practical taxon and damp weight to the

Table 1.--Stomach sampling dates, areas, and depths for five groundfish species in the eastern Bering Sea and the respective sample sizes.

Species	Sampling dates	Area	Depth interval (m)	No. stomachs
Arrowtooth flounder (*Atheresthes stomias*)	Mar-Oct 1983-84	Outer shelf, slope	65-200+	825
Pacific cod (*Gadus macrocephalus*)	Sep-Jan 1983-84	Middle-outer shelf, slope	50-200+	184
Flathead sole (*Hippoglossoides elassodon*)	Jun-Sep 1984	Middle-outer shelf	45-125	271
Walleye pollock (*Theragra chalcogramma*)	Jul-Jun 1981-83	Middle-outer shelf, Aleutian Basin	45-200+	3098
Yellowfin sole (*Limanda aspera*)	Feb-Aug 1984	Inner-outer shelf	45-125	1058
				5436

nearest milligram and number of each prey taxon were recorded. Length measurements of fish and crab prey were taken when enough remained of the items to permit measurement.

FOOD HABITS OVERVIEW OF KEY PREDATORS
General Prey Types

Pacific cod

Figure 1 shows the main categories of food consumed by Pacific cod sampled in autumn and winter in the eastern Bering Sea. Crab and fish constituted the major portion of cod's diet by weight. Most of the crab consumed was Tanner crab (*Chionoecetes* sp.) and the major fish prey was the walleye pollock . Other fish consumed were from the families Zoarcidae, Cottidae, Stichaeidae, Cyclopteridae, and Pleuronectidae. Cod also consumed a variety of invertebrates including crangonid and pandalid shrimp, anemones, squid, polychaetes, and small epibenthic crustaceans.

Other studies of Pacific cod food habits in the eastern Bering Sea produced similar results. Shimada and June (1982) sampled extensively throughout the eastern Bering Sea and discovered pollock dominated the diet by weight (28%) and other fish, Tanner crab, king crab (*Paralithodes* sp.) and shrimp were also important food items. Mito (1974) and Feder (1978) found pollock, tanner crab, and shrimp as the most predominant items in the diet of Pacific cod.

Similar prey types were consumed by cod in the Gulf of Alaska. Jewett (1978) found that pandalid shrimp occurred most frequently in the diet of cod sampled near Kodiak Island and that pollock and Tanner crab were the next most frequently occurring prey. In southeast Alaska, Clausen (1980) reported that pollock and herring constituted the bulk of

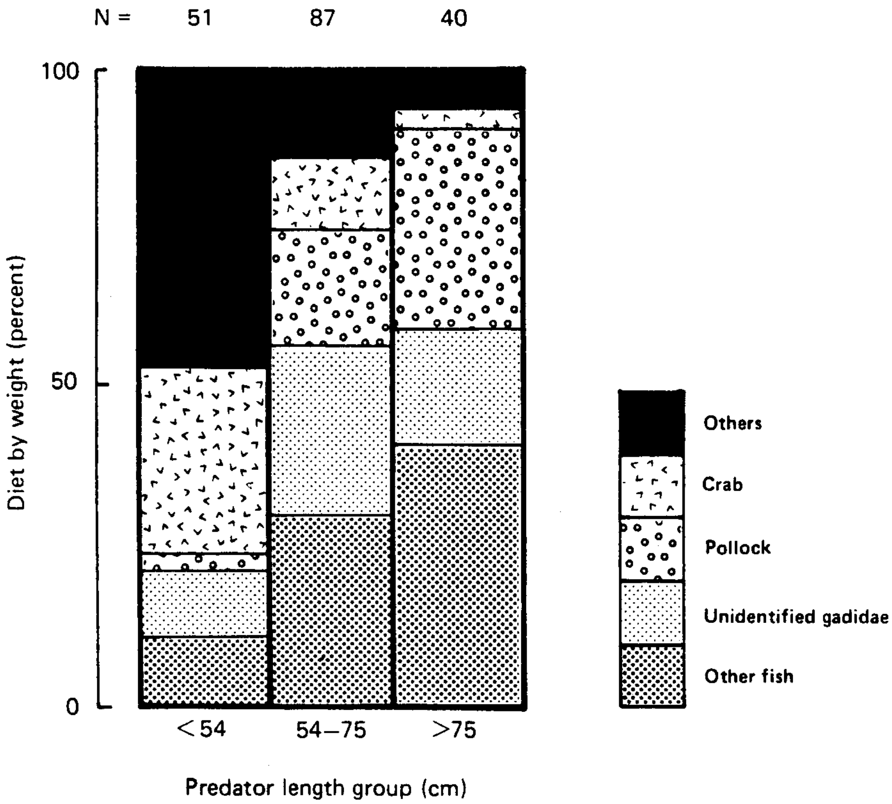


Figure 1.--Percentages by weight of main food items consumed by cod sampled in autumn and winter in the eastern Bering Sea.

cod's diet (40% by volume) and tanner crab and shrimp made up most of the remainder.

Allen (1984) summarized the feeding behavior of Pacific cod. He described cod as a benthopelagivore that is a searcher-pursuer. Results from the above studies support this observation that the main prey types of cod are benthic invertebrates and pelagic fish which requires a search and pursuit prey capturing behavior.

Arrowtooth flounder

Figure 2 shows the percentages by weight of main food items consumed by arrowtooth flounder sampled in spring through autumn in the eastern Bering Sea. Pollock dominated the diet, constituting as much as 67% by weight of prey consumed by arrowtooth flounder. Other fish were also important prey and included Zoarcidae, Macrouridae, Cottidae, Stichaeidae, Ammodytidae, and Pleuronectidae. As much as 25% by weight of the diet was squid, mainly *Berryteuthis* sp., and up to 26% by weight of prey consumed were crustaceans (pandalid shrimp and euphausiids).

The only other detailed analysis of arrowtooth flounder food habits in the eastern Bering Sea was performed by Mito (1974). He found flounder consuming mostly pollock (56-100% by weight) and shrimp (1-38% by weight). Smith et al. (1978) sampled arrowtooth flounder in the Gulf of Alaska and reported unidentified fish (23% by weight), pollock (10% by weight) and euphausiids (37% by weight) as the main dietary components. Off northern California, arrowtooth flounder ate mostly fish (47% by weight), the majority of which were flatfish. Also important in the diet were pandalid shrimp (38% by weight) and euphausiids (7% by weight)(Gotshall 1969).

Allen (1982) characterizes large-mouthed flatfishes with symmetrical mouths like the arrowtooth flounder as sight-feeders which are oriented

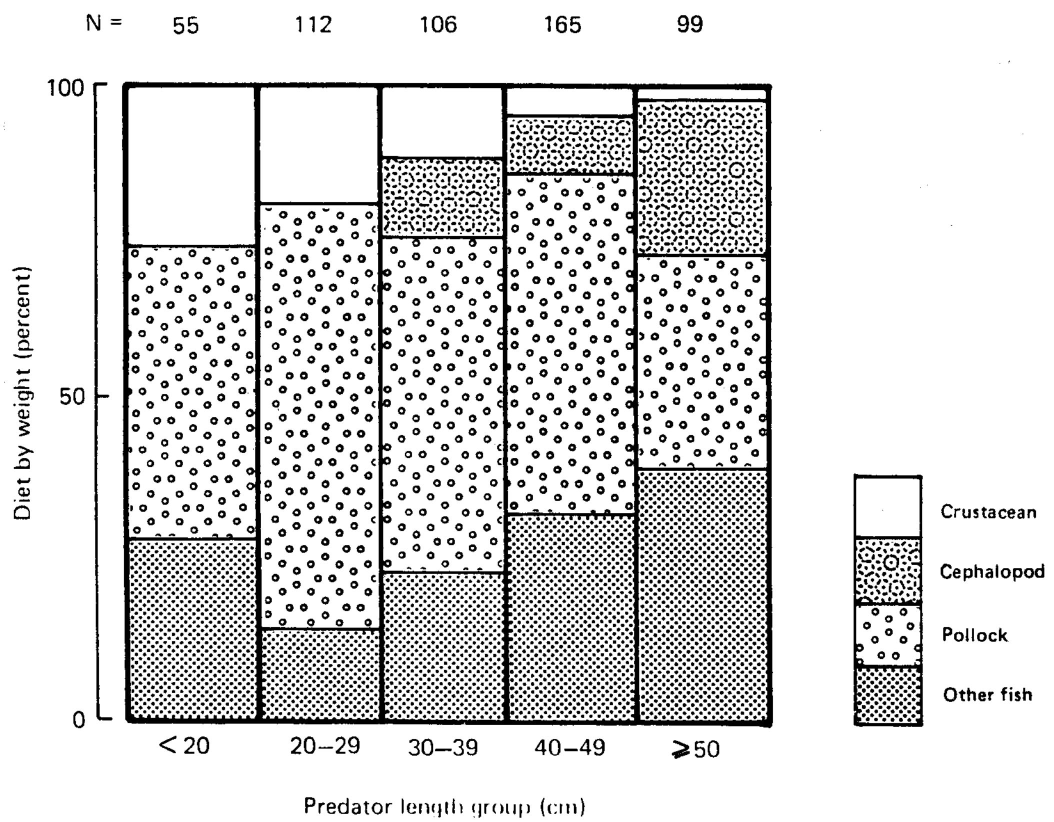


Figure 2.--Percentages by weight of main food items consumed by arrowtooth flounder sampled in spring, summer, and autumn in the eastern Bering Sea.

up in the water column when foraging for prey. The presence of pelagic fish and euphausiids or nektonic benthopelagic crustaceans such as shrimp in the arrowtooth flounder diet support these observations.

Flathead sole

Figure 3 shows the percentages by weight of main food items consumed by flathead sole sampled in summer in the eastern Bering Sea. Epibenthic crustacea, which includes shrimp and crab, constitute from 10 to 60% of the diet by weight. Brittle stars are also an important prey item forming up to 72% of the diet by weight. Other lesser important dietary components include polychaetes, echiuroids, and molluscs. Fish formed from 0-22% of the diet by weight, the major portion of which was pollock.

Mito's (1974) study of flathead sole's diet in the eastern Bering Sea classified flathead sole as a mostly benthic feeder. Ophiuroids (brittle stars) at times formed up to 98% by weight of the diet. Pandalid shrimp (up to 47% by weight), Tanner crab (up to 23% by weight) and pollock (up to 15% by weight) were the other major dietary components. Skalkin (1963) called flathead sole in the eastern Bering Sea a benthic and nektonic feeder based on its consumption of benthic brittle stars and nektonic shrimp, euphausiids, and hyperiid amphipods. Similarly, Mineva (1964) found flathead sole consuming mostly brittle stars, along with shrimp, amphipods, fishes, and molluscs. In the Gulf of Alaska, flathead sole ate euphausiids, brittle stars, pandalid shrimp and juvenile pollock (Smith et al. 1978). In the coastal waters of Washington state, Miller (1970) reported flathead sole consumed mostly fish (39% by weight) and mysids (36% by weight). Shrimp, clams, and polychaetes formed the remainder of the diet.

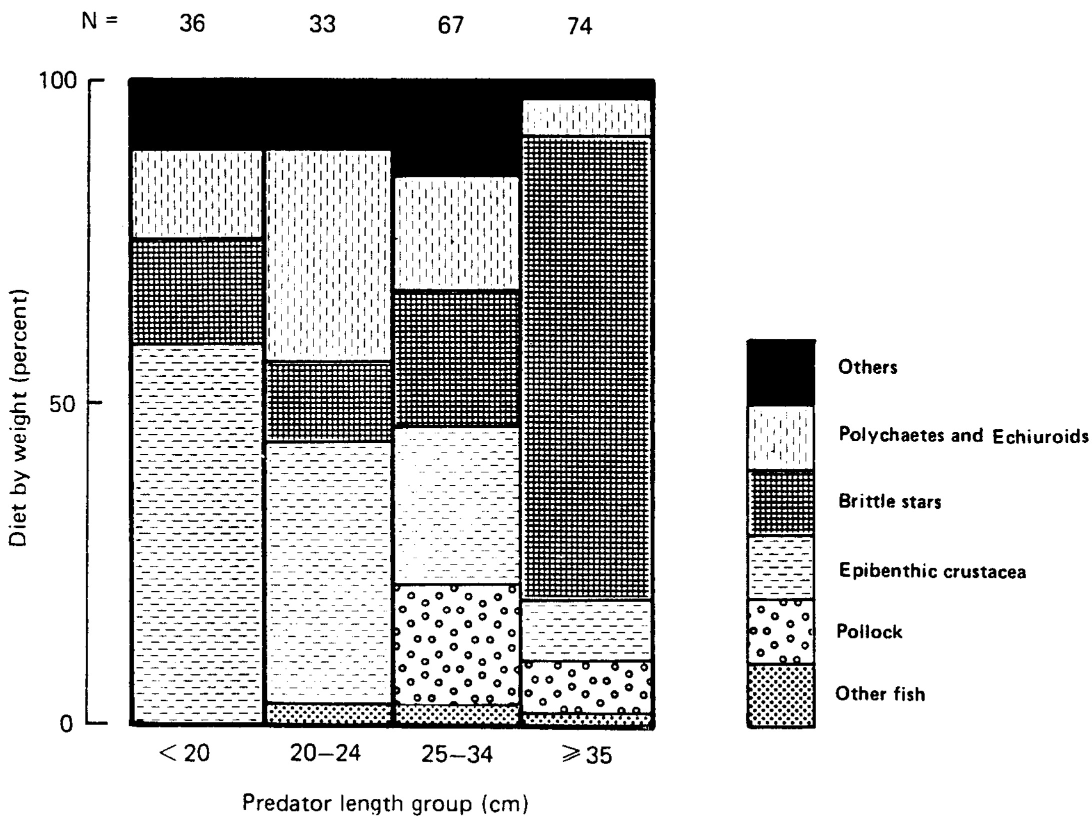


Figure 3.--Percentages by weight of main food items consumed by flathead sole sampled in summer in the eastern Bering Sea.

Allen (1984) classified flathead sole as a benthopelagivore that uses ambush, search, and pursuit techniques for food gathering. The above results support this observation in that flathead sole uses benthic and pelagic foods for prey. Some of these prey are sessile requiring searching behavior while others are more motile requiring ambush or pursuit behavior for capture.

Walleye pollock

Table 2 (from Dwyer 1984)shows the major prey items found in walleye pollock collected from the eastern Bering Sea. Euphausiids (13% by weight) and fish (48% by weight) were the main consumed prey. The major fish consumed was walleye pollock. Other prey items consumed included copepods, amphipods, and larvaceans.

Other studies have also reported juvenile pollock and euphausiids as major prey items of pollock (Takahashi and Yamaguchi 1972; Mito 1974; Bailey and Dunn 1979). Pandalid shrimp is also consumed by pollock in certain areas (Feder 1977). Allen (1984a) classifies pollock as a pelagivore which pursues it prey. The above findings substantiate this observation in that pollock consume pelagic juvenile pollock, euphausiids and copepods.

Pacific halibut

Most food habit studies on Pacific halibut show its main prey to be fish, crab, shrimp and molluscs. Fish consumed include sandlance (Smith et al. 1978), pollock (Mito 1974), and crab(Feder 1977)(mainly Tanner crab). Allen (1984b) notes that Pacific halibut feed mostly on nektonic and motile epibenthic fish. Although its life mode is benthic it obtains prey primarily from the water column and partly from the bottom. Allen (1984b) classifies halibut as an ambusher-pursuer that feeds mostly on active prey.

Table 2. Major prey items found in the stomachs of pollock collected from the eastern Bering Sea. All items which showed a percent frequency of occurrence (% F.O.)>10% are included. IRI = Index of Relative Importance (Pinkas et al. 1971)

Prey Organism	% F.O.	Mean No./ Stom.	% No.	Mean Wt./ Stom. (g)	% Wt.	IRI
Thecosomata	16.8	6.8	2	0.02	<1	42
Calanus cristatus	14.9	19.5	6	0.11	2	117
Calanus sp.	10.7	34.5	11	0.06	1	128
Calanoida (unident.)	23.8	54.1	17	0.12	2	457
Parathemisto sp.	25.6	5.5	2	0.02	<1	52
Thysanoessa inermis	17.6	7.4	2	0.21	3	95
Euphausiacea (unident.)	30.2	18.2	6	0.72	10	481
Larvacea	11.4	87.1	28	0.31	4	372
Theragra chalcogramma	10.3	0.4	<1	2.92	41	420
Osteichthyes (unident.)	13.7	0.7	<1	0.52	7	101

Alaska plaice and Rock sole

The main food item of Alaska plaice appears to be infaunal polychaetes (Skalkin 1963; Mineva 1968; Allen 1984a). Minor food items include amphipods, bivalve molluscs, shrimp, and echiuroids. Allen (1984a) classifies plaice as a benthivore which stalks and extracts prey on or associated with the bottom.

Rock sole consume similar prey types. Polychaetes, clams and brittle stars are major prey items while amphipods and even fish are minor prey items (Feder 1977; Mito 1974; Rogers et al. 1979; Smith et al. 1978). Allen (1984a) also classifies rock sole as a benthivore. He reports that rock sole is a searcherstalker which extracts and excavates for prey on the sea bottom.

Yellowfin sole

Yellowfin sole utilizes a more diverse set of prey items than Alaska plaice and rock sole. It consumed not only molluscs, polychaetes, brittle stars, and amphipods but also euphausiids, shrimp, and sand dollars. Some studies have reported fish (Feder 1977; Rogers et al. 1979; Wakabayashi 1974) and crab larvae (Haflinger 1983) as prey items (Table 3). Allen classifies yellowfin sole as a benthopelagivore which actively searches and pursues its prey.

King and Tanner crab

King crab consume mostly bivalve molluscs, echinoderms and crustaceans (McLaughlin and Hebard 1961; Feder 1977). Cunningham (1969) reports that echinoderms comprise most (49% by weight) of the adult diet while molluscs (37% by weight) form the remainder (Table 4).

Tanner crab have similar diet of which bivalves, crustaceans, and polychaetes are the main food items (Feder 1978, 1979, 1981). Fish is

Table 3. Major prey items of yellowfin sole by life history stage, season, and area.

<u>Food Habits</u>

Life history stage	Reference	Season	Area	Food Items (% by weight
Larvae (2-10 mm) Limanda limanda	Last, 1980	Su	North Sea	90% copepodites, 10% decapod zoea.
Juveniles	Rogers et al. 1979	Sp, Su	Kodiak I.	22% fish (cottids), 20% poly chaetes, 18% crab, 14% clams.
Adults 100-200 mm	Wakabayashi, 1974	Su	Bering Sea	polychaetes, amphipods, echiuroids.
201-300 mm				polychaetes, bivalves, echiuroids, gadids, osmerids, amphipods.
301+ mm				Mostly bivalves and echiuroids.
Adults	Skalkin, 1963	Sp, Su	SW of Cape Newenham	mysids, euphausiids (30-50 m depth) polychaetes, molluscs (50-65 m depth).

Table 4. Major prey items of king crab by life history stage, season, and area.

Food habits

Life history stage	Reference	Season	Area	Food items (% by weight)
Pelagic larvae	Incze, pers. comm.	Sp, Su	Bristol Bay	copepod nauplii, copepodites, cirripedia larvae.
Benthic juveniles	Takeuchi, 1968	Su		polychaetes, seaweed.
Adults	Cunningham, 1969	Su	Bristol Bay	49% echinoderms, 37% molluscs, 10% crustaceans, polychaetes.

also a prey item but may possibly be consumed only as dead carcasses lying on the sea bottom. Feder (1977, 1978) calls both king and Tanner crabs scavengers in describing their main food gathering behavior.

Pacific herring

Table 5 shows some of the main food items of Pacific herring; copepod eggs, copepods, algae, and euphausiids. Fish fry and amphipods are also consumed occasionally (Rumyantsev and Darda 1970). It appears herring utilize the pelagic environment exclusively for food gathering.

Sockeye salmon

Table 6 outlines the major prey consumed by sockeye salmon. Fish, copepods, and euphausiids dominate the diet. Other prey itmes include pelagic crab larvae, amphipods and pteropods. Similar to herring, sockeye salmon feeds exclusively on pelagic prey.

Size Related Feeding Trends

Pacific cod

Figure 1 also shows changes in major prey items of Pacific cod with increasing cod size. Cod appears to consume more invertebrate prey and particularly crab at smaller (<54 cm) sizes and changes to more of a fish-feeder as it grows in length. By the time cod are >75 cm in length, their diet consists mostly of fish (90% by weight).

Most other studies found identical changes in diet with cod size. Shimada and June (1982) report that the percentage of pollock by weight in cod's diet increased from about 15% in cod <45cm to up to 60% in cod >65cm in length. Mito (1974) found cod <50cm long ate more shrimp and crab while cod >50cm consumed mostly pollock. He noted that the proportion of 1+ aged pollock consumed increased with increasing cod size while the proportion of 0-age pollock decreased in the diets of larger cod. This

Table 5. Major prey items of Pacific herring by life history stage, season, and area.

Food habits

Life history stage	Reference	Season	Area	Food items (% by weight)
Larvae 9-20 mm	Wailes, 1963	Sp	British Columbia	40% invertebrate eggs, 40% diatoms, 20% copepods nauplii.
Larvae 9-20 mm	Barraclough, 1967	Sp, Su	British Columbia	90% copepod nauplii, 10% eggs and algae.
Juveniles 20-100 mm	Barraclough, 1967	Su	British Columbia	phytoplankton, copepod eggs, copepods, amphipods, larvaceans.
Adults 100+ mm	Wailes, 1963	Su, F, Sp	British Columbia	euphausiids, copepods.
Adults	Dudnik and Usol'tsev 1968	Su	Bering Sea	euphausiids, calanoid copepods, Sagitta.
Adults	Barraclough, 1967	Sp, Su	British Columbia	90% copepods, 10% amphipods, euphausiids, brachyura larvae, and invert. eggs.

Table 6. Major prey items of sockeye salmon by life history stage, season and area.

Food habits

Life history stage	Reference	Season	Area	Food items (% by weight)
Smolts	Manzer, 1969	Su	British Columbia	48% copepods, 24% fish, 14% larvaceans, 5% decapods, 4% insecta, 3% amphipods.
Smolts	Straty, 1974	Su	Bristol Bay	Sandlance larvae, euphausiid larvae, copepods, cladocera, pteropods, decapod larvae, other fish larvae, invert. eggs, insects.
Adults	Kanno and Hamai, 1971	Su	E. Bering Sea shelf	43% euphausiids, 27.7% fish, 25.1% amphipods.
Adults	Nishiyama, 1974	Su	Bristol Bay	70% euphausiids, 20% fish larvae, 10% crab zoea, amphipods and pterapods.

predator-prey size relationship was reported to be linear in that as cod size increased the maximum pollock size which was consumed increased in a linear fashion. Clausen (1980) and Jewett (1978) observed similar trends in the Gulf of Alaska. Crab and shrimp dominated in cod <50 or 60 cm while cod between 50-70 cm or 60-70 cm had a transitional diet and cod >70 cm consumed mostly fish. Thus cod have a definite change in diet with increasing size; swithching from a predominantly crustacean and other invertebrate diet to a fish dominated diet when cod reach a length of between 50 to 70 cm.

Arrowtooth flounder

Figure 2 shows trends in food items consumed by arrowtooth flounder of various size groups. No major changes occur in percentages by weight of various prey items in the diet. Cephalopod consumption appears to replace crustaceans (euphausiids and shrimp) in arrowtooth flounder of increasing length. The percentages of fish other than pollock (which are mostly deep-water fishes) increase slightly while the percentage of pollock decreases slightly with increasing arrowtooth flounder length. These trends may not be related directly to size but rather to depth of sampling; larger flounder may be captured in deeper water than smaller flounder and where squid and deep-water fish are more available.

Similar to the present study, Mito (1974) found all sizes of arrowtooth flounder consuming mostly pollock. He also noted increasing prey pollock length with increasing flounder length. The results of Shuntov (1970), Smith et al. (1978) and Mikawa (1963) are somewhat different to those above. Their studies all report increasing amounts of predation on fish and decreasing amounts of euphausiids consumed as arrowtooth flounder increase in length. Thus, it appears arrowtooth flounder are predominantly a fish feeder but at smaller sizes may consume more euphausiids and other crustaceans. The maximum size of prey fish consumed also increases with arrowtooth flounder length.

Flathead sole

Figure 3 shows the proportions of various prey items in the diet of flathead sole of different size groups. Flathead sole <25 cm appear to consume mostly epibenthic crustacea such as crab and shrimp along with polychaetes, echiuroids and brittle stars. Sole >25 cm consumed more brittle stars and pollock. The percentages of brittle stars in the diet increased from 16% by weight in sole <25 cm to 72% by weight in sole >35 cm in length.

Mito (1974) reports no clear trends in diet with flathead size. However Smith et al. (1978) note that flathead sole >30 cm in length caught in deeper waters of the Gulf of Alaska consumed mostly brittle stars while flathead sole <30 cm long captured in shallower water consumed more euphausiids. Miller (1970) stated flathead sole's diet changed from mostly mysids when sole were <18cm to shrimps when sole were 18-26 cm long and finally to fishes and clams when sole were >26cm long. Thus, there are some size-related feeding trends in flathead sole as larger sole tend to consume more fish and brittle stars than smaller sole. There might be some confounding of predator size with depth of capture, though, as larger flathead sole may be caught in deeper waters where brittle stars and juvenile pollock may be more available.

Walleye pollock

Figure 4 (from Dwyer 1984)shows the changes in major prey items consumed by pollock with increasing pollock length. Most notable is the

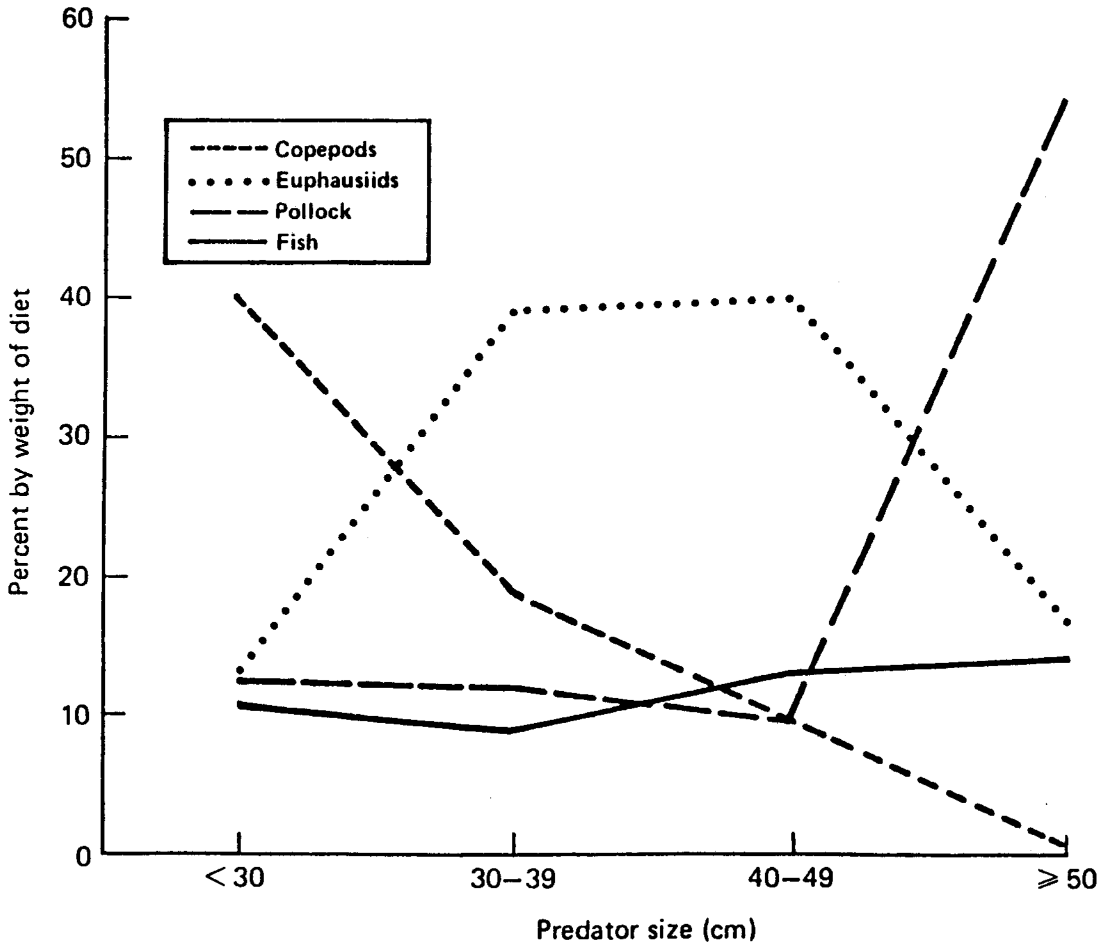


Figure 4. Percent by weight of major prey categories in the diet of pollock, by fish size. ("Fish" refers to all fish prey which was not positively identified as pollock.)

increase in cannibalism with length; small pollock (<50 cm) consume only 10% by weight of prey pollock and pollock larger than 50 cm consume mostly pollock (more than 50% by weight of the diet). There is an opposite trend in the consumption of copepods which decreases with increasing pollock length. Euphausiids are consumed mostly by pollock which are 30-49 cm long. The consumption of other fish is fairly constant over all pollock size groups (around 10% by weight of the diet).

Takahashi and Yamaguchi (1972), Mito (1974) and Bailey and Dunn (1979) found similar size related dietary trends. Pollock <50 cm consumed mostly euphausiids and copepods while pollock >50 cm consumed mostly pollock, herring, and euphausiids. Pollock in the Gulf of Alaska do not appear to cannibalize but instead consume pandalid shrimp (Feder 1977; Smith et al. 1978).

Pacific halibut

Pacific halibut also appear to change their diet with increasing size. Smith et al. (1978) found juveniles in the eastern Bering Sea had shrimp occurring in their stomachs about as frequently as fish. Novikov (1964) found crustaceans occurring in almost all (89%) stomachs of halibut <30 cm while the percent frequency of occurrence of fish increased with increasing size; from 61% in halibut 30-60cm long to 87% in halibut >90 cm long. Thus, halibut appears to switch from an epibenthic crustacean diet to a fish diet with increasing size.

Alaska plaice and Rock sole

Adult plaice appear to consume the same food items regardless of size (Skalkin 1963; Mineva 1964). Similar results have been noted for a similar species the European plaice, <u>Pleuronectes platessa</u>, which feed primarily on polychaetes and bivalves at sizes >5 cm (see Allen 1984a).

Rock sole also exhibit little change in diet with size. The dominant food of most adults is polychaetes (Mito 1974; Smith et al. 1978). Rock sole of the smaller sizes (20-30 cm) may consume more amphipods (Mito 1974) and larger rock sole include fish such as sandlance in their diet (Smith et al. 1978).

Yellowfin sole

As Table 3 shows yellowfin sole change their feeding habits with increasing size. Wakabayashi (1974) noted that juveniles <20 cm consumed polychaetes and amphipods but with increasing size also included fish and bivalves in their diet. Unpublished NWAFC data indicate, however, that at least 80% of the diet by weight for juvenile and adult yellowfin sole (14-33 cm) in Bristol Bay in spring was bivalves. Small amounts of polychaetes, echinoderms, and crustaceans were also consumed by all size classes.

King and Tanner crabs

As Table 4 shows king crab switch from consuming copepods when they are pelagic larvae to polychaetes as benthic juveniles and finally to echinoderms, molluscs, crustaceans, and polychaetes as adults. Pearson et al. (1984) found that the softs tissue contained in juvenile king crab stomachs was predominantly polychaetes, sand dollars, and clams.

Tarverdiyeva (1981) described the change in food habits with size in Tanner crab. His data show some difference in frequency of occurrence of the major prey items; molluscs, polychaetes, crustaceans, and echinoderms between Tanner crab of 24-60 mm carapace widths and 61-161 mm carapace widths. Polychaetes and decapod crustaceans occurred more frequently in larger Tanner crab while echinoderms and amphipods occurred more frequently in small crab. Feder (1978), however, shows little difference in frequency of occurrence of prey types among various sizes of Tanner crab in Cook Inlet. Crabs of all sizes consumed clams, barnacles, and pagurid crabs.

Pacific herring

Table 5 shows differences in food items consumed by herring of various sizes. It appears that juvenile herring consume smaller food items such as phytoplankton, copepod eggs, copepods and amphipods. Adults usually consume more euphausiids although copepods still remain in the diet and at times may still be predominant in the stomach contents.

Sockeye salmon

Table 6 shows differences in food consumption between sockeye smolts and adults. Smolts consume small prey such as fish larvae, invertebrate larvae and eggs, and copepods. Adults consume mostly euphausiids and fish. Small portions of the diet are composed of crab zooea, amphipods and pteropods.

EASTERN BERING SEA FOOD HABITS
Area and Season Trends

Pacific cod

The cod taken for the present study were sampled from the central (165° W longitude to 171° W longitude) and northwest (westward of 171° W longitude)regions of the eastern Bering Sea and pollock, tanner crab, and other fish were the main food items. Pollock were consumed by cod in both these areas. Shimada and June (1982) sampled during summer and found that the frequency of occurrence of pollock in cod stomachs increased from 8% in southeastern Bering Sea (eastward of 165° W longitude) to 27%

in the central area and 32% in the northwest. They also noted that the occurrence of euphausiids decreased from the southeast to the northwest and that cod consumed sandlance, flatfish, and king crab in the southeast region and pollock and Tanner crab in the central and northwest regions. Similarly, Mito (1974) in the autumn, Feder (1978) in spring and Allen (1984) sampled cod in the deeper waters (>70m) of the central region and reported pollock, Tanner crab, and shrimp as the main prey items. Thus, cod appear to have definite area trends in diet composition; more pollock and tanner crab are consumed in the central and northwest regions while other fish, king crab and euphausiids are consumed in the southeast with no real seasonal change in diet evident from any of the studies.

Arrowtooth flounder

Stomach samples from arrowtooth flounder taken for the present study were obtained around the Pribilof Islands and to the northwest of the Pribilof Islands at depths ranging from 65 m to more than 200 m. Pollock, euphausiids, cephalopods, and bathypelagic fish were the main food items. Pollock were consumed by arrowtooth flounder at virtually all shelf stations sampled and many of the slope sampling sites. Larger arrowtooth flounder were obtained mostly from foreign commercial fishing vessels which were fishing in the deeper slope waters of the northwest region so the increasing percentages of cephalopods and bathypelagic fish in the diet of larger arrowtooth flounder are probably due to the increased availability of those prey in the slope region of the eastern Bering Sea. The only other detailed study of arrowtooth flounder food habits in the eastern Bering Sea was by Mito (1974) who sampled southeast of the Pribilof Islands in waters about 200 m in depth. His study reported mostly pollock and shrimp in the stomach contents. Mikawa (1963) and Shuntov (1970) both note a decrease in stomach content of arrowtooth flounder sampled in winter. They claim arrowtooth flounder feeds mostly during summer and autumn. Thus, arrowtooth flounder also has area trends in diet as fish captured in deep slope waters consume more cephalopods and bathypelagic fishes than those captured in waters over the shelf.

Flathead sole

Flathead sole were obtained during summer from the central and northwest shelf regions of the eastern Bering Sea in depths from 45 m to 125 m for this study. The main food items were shrimp, crabs, and brittle stars. Pollock were consumed by flathead sole only at a few stations which were located northwest of the Pribilof Islands. Mito (1974) sampled the slope region in autumn just south of the Pribilof Islands and Mineva (1964) sampled flathead sole northwest of the Pribilof Islands. Both reported similar trends; brittle stars, shrimp and fish were the main dietary items. Mineva (1964) also reported that flathead sole do feed during winter but only small amounts compared to summer feeding. Skalkin (1963) noted that as sampling of flathead sole moved further inshore in the eastern Bering Sea, planktonic crustaceans such as hyperiid amphipods and euphausiids replaced brittle stars and pandalid shrimp in the diet. Thus, flathead sole appear to consume more brittle stars and fish with increasing depth and more euphausiids inshore.

Walleye pollock

Dwyer (1984) outlined seasonal and area differences in diet for walleye pollock. In spring, euphausiids and copepods were consumed by most pollock while only small amounts of prey pollock were consumed by fish >50 cm. In summer, copepods were the most dominant prey item for smaller pollock while euphausiids and prey pollock were consumed by larger pollock. Copepods disappeared from the diets in autumn and the main prey items for all pollock size groups were pollock and euphausiids. By winter, fish <30cm were consuming mostly euphausiids while pollock 30-44 cm long contained mostly fish (gadids and myctophids). The largest pollock size group (>50 cm) consumed mostly fish the majority of which was pollock. Seasonal changes in mean stomach content weights were also observed with lowest amounts in winter and highest in the summer. Some differences were observed in pollock diet among the Aleutian Basin area, the area northest of the Pribilofs, and the area southeast of the Pribilofs. Cannibalism was never observed in the Aleutian Basin. Average stomach content weight varied among areas with the southeast area having the greatest stomach content weight (1.1% of the body weight) followed by the northest area (0.7% body weight) and finally the Aleutian Basin with the lowest value of 0.4% body weight. Cannibalism was most important in the southeast region during autumn and winter and in the northwest during summer.

Pacific halibut

Novikov (1964) compared halibut's diet between the southeast and northwest regions of the eastern Bering Sea. The main difference was in the type of fish consumed; in the northwest pollock occurred most frequently in stomachs while in the southeast flatfishes such as yellowfin sole occurred more frequently. Crustaceans also occurred more frequently in the northwest than in the southeast. Intensity of feeding changed seasonally being lower in winter than in summer. Novikov (1964) also noted that young halibut continue feeding through the winter while large halibut cease feeding during this season.

Alaska plaice and Rock sole

Allen (1984a) summarized the literature on Alaska plaie and noted that seasonal changes in diet have been reported. Echinoderms were more important in spring while molluscs and polychaetes predominated in summer. Winter feeding was almost nonexistent. It was mentioned that seasonality in diet may be due to plaice's seasonal migration through different depth zones.

Rock sole also change their feeding intensity seasonally. The most intensive feeding occurs in spring and summer while feeding ceases almost completely in winter. Some seasonal changes in prey items were also noted by Allen (1984a); gammarid amphipods and crustaceans dominating spring and summer diets but polychaetes were more important in autumn. Skalkin (1963) noted changes in family of polychaetes consumed by season but it is not clear whether region of sampling also varied seasonally.

Yellowfin sole

Seasonal changes in stomach content weight occur in yellowfin sole with feeding ceasing almost completely in winter. Unpublished NWAFC data indicate frequency of occurrence of polychaetes, bivalves, sand dollard, shrimp, euphausiids, and amphipods is high in the southeast area. In the northwest, however, brittle stars occur most frequently followed by polychaetes, crustceans, and molluscs, Fadeev (1972) noted that certain areas in the Bering Sea, such as the Cape Newenham area, are poor in benthic organisms and thus yellowfin sole in those areas may consume more pelagic prey. Skalkin (1963) reports crustaceans in the diet of yellowfin sole sampled inshore (30-50 m), mostly polychaetes in waters 50-65 m, molluscs at 6580 m and brittle stars at depths greater than 75 m. Thus, there does appear to be a trend in yellowfin sole's diet with depth with more brittle stars in deep waters and crustaceans and polychaetes in shallower waters.

King and Tanner crab

There are little seasonal data available for comparison of king crab diets. Feder (1978) sampled in spring and reported bivalves occuring most frequently in the diet. McLaughlin and Hebard (1961) report a similar trend in summer.

Tanner crab diets by Bering Sea area were discussed by Tarverdiyeva (1981). In the western Bering Sea, Tanner crab consumed mostly sea urchins. He found Tanner crab consuming primarily bivalve molluscs near the Pribilof Islands. Decapods and sea urchins were the secondary foods. Further north near St. Matthew Island, polychaetes, bivalves and decapod crustaceans were all important prey items.

Data regarding seasonal changes in stomach fullness are not available for either species.

Pacific herring

Rumyantsev and Darda (1970) noted seasonal changes in stomach filling in Pacific herring. Stomach fullness was low in spring and increased to maximum values in June and July. Feeding continued into autumn but was not as vigorous as in summer. Dudnek and Usol'tsev (1964) report herring captured in the southeast area of the Bering Sea consume mostly euphausiids and copepods and that foraging continued until November.

Sockeye salmon

Kanno and Hamai (1971) report changes in sockeye salmon's diet with area. Squid was 95% of the diet by weight in the western and central

Bering Sea. Euphausiids (43% by weight), fish (28% by weight), and amphipods (25% by weight) were the amin prey items in the south and central Bering Sea. Further inshore in Bristol Bay, Nishiyama (1974) found euphausiids (70% by weight) as the dominant prey, with fish and crustaceans forming the remainder of the diet.

In the inner portion of Bristol Bay, sockeye smolts have been found with empty stomachs. Feeding seems to have commenced though, by the time smolts reach Port Moller.

DISCUSSION

The fish and crab diets reported here show a variety of trends regarding the pelagic versus demersal nature of the diet. Some of the fishes utilize strictly demersal food items as prey such as Alaska plaice and rock sole. Others such as Pacific cod and flathead sole use demersal and pelagic animals for food. Finally, most of the pelagic fishes consume only pelagic prey. Some fishes exhibited size related differences in the pelagic versus demersal nature of the diet. Fish such as cod and flathead sole feed more demersally as juveniles and switch to pelagic fishes as adults.

Seasonal trends in diet appeared mainly to be in the amount and not the type of food consumed by predators. There was general agreement among the studies cited here that fish feed most heavily in summer and autumn, almost none at all in winter, and small amounts in spring. There were area differences in prey consumed but it appeared that although different prey items were eaten the basic pelagic or demersal nature of the diet did not change. The only exception was in the Soviet literature which reports the Bering Sea to be poor in benthos in some areas (particularly

Cape Newenham) where demersally feeding fishes may consume more pelagic prey.

Since the main differences in benthic versus pelagic diets are by predator species and predator size, the diets must be categorized by the degree of demersal feeding of predators by species and size in order to speculate on the effect of oil on various fishes via uptake of benthic prey. Table 7 shows such a summarization based on the results from feeding studies cites in this paper. All species except Pacific herring and sockeye salmon have a demersal component in their diet. Juveniles of some species feed more demersally such as Pacific cod, flathead sole, Pacific halibut, and yellowfin sole. Finally, some groups feed strictly in the demersal habitat both as juveniles and adults: Alaska plaice, rock sole, and king and Tanner crabs.

Areas in the eastern Bering Sea likely to be impacted most by demersal oil fractions would be those areas where demersally feeding fish are most abundant. Walters and McPhail(1982) summarized community structure in the eastern Bering Sea and concluded the areas with the highest density of fish and invertebrates were the inner (southeast) and central shelf regions. The most abundant species in these areas are yellowfin sole, Tanner crab, king crab, Alaska plaice, rock sole and Pacific cod. These areas thus appear to be dominated by demersally feeding fishes whereas the outer shelf and sole regions contain more walleye pollock, large Pacific cod and pelagically feeding flounders such as Greenland halibut and arrowtooth flounder. There is still a high abundance of Tanner crab in these outer shelf regions though, which could suffer if weathered oil was present on the bottom.

Seasons of greatest impact via uptake of demersal food would be those seasons where feeding level (or amount of food ingested) is at its highest level. Summer is the season of greatest food intake for all the groups discussed here and autumn is next in terms of most food intake. In spring fishes feed little and winter most groups cease feeding entirely.

Thus, there are several groups of fishes and invertebrates which are strict demersal feeders both as juveniles and as adults. Areas of highest abundance of these groups in the eastern Bering Sea are the inner (southeast) and central shelf. The season of greatest feeding activity by these groups in summer. The impact of oil on the bottom would then be greatest for the demersal groups inhabiting those regions during summer.

Table 7.--Categorization of the pelagic versus demersal nature of the diets of 10 predator species groups by predator size in the eastern Bering Sea. (Predators which feed strictly pelagically = 0, predators which obtain <25% of their food from the bottom = 1, predators which obtain 25-49% of their food from the bottom = 2, predators which obtain 50-74% of their food from the bottom = 3, and predators which obtain ≥75% of their food from the bottom = 4.)

Predator	Size group	
	Juveniles	Adults
Pacific cod	4	1
Arrowtooth flounder	1	1
Flathead sole	4	3
Walleye pollock	1	1
Pacific halibut	3	1
Alaska plaice and rock sole	4	4
Yellowfin sole	4	3
King and Tanner crab	4	4
Pacific herring	0	0
Sockeye salmon	0	0

Literature Cited

Allen, M.J. 1982. Functional structure of soft-bottom fish communities of the southern California shelf. Ph.D. Thesis, Univ. California, San Diego, 577 pp.

Allen, M.J. 1984a. Functional organization of demersal fish communities of the eastern Bering Sea shelf. (Unpubl. manuscr.) NOAA, NMFS, NWAFC, 7600 Sand Point Wy., N.E, Seattle, Washington 98115.

Allen, M.J. 1984b. Niche segregation of nearshore soft-bottom fishes in a subarctic, warm-temperate, and tropical environment. (Unpubl. manuscr.). NOAA, NMFS, NWAFC, 7600 Sand Point Wy. NE, Seattle, Washington 98115. 44 pp.

Armstrong, D.A. et al. 1981. Distribution and abundance of decapod crustacean larvae in the S.E. Bering Sea with emphasis on commercial species. Ann. Rept. Env. Assess. of the Alaska Cont. Shelf V.II, pp 365-596.

Bailey, K.M. and J.R. Dunn. 1979. Spring and summer foods of walleye pollock, Theragra chalcogramma, in the eastern Bering Sea. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 77:304-308.

Barraclough, W.E. 1967. Data Record. Number, size, and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia, April 25-29, 1966. Fish. Res. Board Can. MS Rep. Ser. 922, 926, 928, 940.

Clausen, D.M. 1980. Summer food of Pacific cod, Gadus macrocephalus, in coastal waters of southeastern Alaska. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 78:968-973.

Cunningham, D. 1969. A study of the food and feeding relationships of the Alaskan king crab, Paralithodes camtschatica. M.S. Thesis, San Diego State College. 78 pp.

Dudnik, Y.I. and E.A. Usol'tsev. 1968. The herrings of the eastern part of the Bering Sea. In: Soviet fisheries investigations in the northeast Pacific, Pt. II, pp 236-240. Ed: P.A. Moiseev.

Dwyer, D.A. 1984. Feeding habits and daily ration of walleye pollock (Theragra chalcogramma) in the eastern Bering Sea. M.S. Thesis, Univ. Wash. Seattle, Washington, 102 pp.

Fadeev, N.S. 1972. The fishery and biological characteristics of yellowfin soles in the eastern part of the Bering Sea. In: Soviet fisheries investigations in the northeast Pacific, Pt. V, pp 332-396. Ed: P.A. Moiseev.

Feder, H.M. 1977. The distribution, abundance, diversity, and biology of benthic organisms in the Gulf of Alaska and the Bering Sea. In: Environmental Assessment of the Alaskan Continental Shelf, Annual Reports 8:366-712. U.S. Dep. Commer., Natl. Oceanic Atmos. Admin., Environ. Res. Lab., Boulder, Colo.

Feder, H.M. 1978. Distribution, abundance, community structure, and trophic relationships of the nearshore benthos of the Kodiak shelf, Cook Inlet, northeast Gulf of Alaska and the Bering Sea. In: Environmental Assessment of the Alaskan Continental Shelf, Annual Reports 4: 416-730. U.S. Dep. Commer., Natl. Oceanic Atmos. Admin., Environ. Res. Lab., Boulder, Colo.

Feder, H.M. 1979. Distribution, abundance, community structure and trophic relationships of the nearshore benthos of Cook Inlet and NEGOA. In: Environmental Assessment of the Alaskan Continental Shelf, Annual Reports 3:1-83. U.S. Dep. Commer., Natl. Oceanic Atmos. Admin., Environ. Res. Lab., Boulder, Colo.

Feder, H.M. 1981. Distribution, abundance, community structure and trophic relationships of the nearshore benthos of the Kodiak continental shelf. In: Environmental Assessment of the Alaskan Continental Shelf, Final Reports, Biological Studies 9:1-255. U.S. Dep. Commer., Natl. Oceanic Atmos. Admin., Off. Mar. Pollut. Assess., Juneau, Alaska.

Gallagher, A.F., Jr. and N.B. Pola. 1984. The uptake and depuration of petroleum hydrocarbons in marine species: A simulation study of the uptake and depuration of petroleum hydrocarbons and its effect on selected marine species in the Bristol Bay ecosystem. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA, Processed Rep. 84-16, 68 pp.

Gotshall, D.W. 1969. Stomach contents of Pacific hake and arrowtooth flounder from northern California. Calif. Fish and Game 55:75-82.

Haflinger, K.E. and C.P. Roy. 1983. Yellowfin sole predation on three commercial crab species in the southeastern Bering Sea. Unpubl. manuscr. Institute of Marine Science, University of Alaska, Fairbanks, AK 99701. 28 pp.

Hart, J.L. 1973. Pacific fishes of Canada. Fish. Res. Board Can. Bull. 180.

Jewett, S.C. 1978. Summer food of the Pacific cod, Gadus macrocephalus, near Kodiak Island, Alaska. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 76:700-705.

Kanno, Y. and I. Hamai. 1971. Food of salmonid fish in the Bering Sea in summer of 1966. Bull. Fac. Fish., Hokkaido Univ. 22:107-128.

Laevastu, T. and F. Fukuhara. 1984. Quantitative determination of the effects of oil development in the Bristol Bay region on the commercial fisheries in the Bering Sea. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA., Processed Rep. 84-06, 73 pp.

Last, J.M. 1980. The food of twenty species of fish larvae in the west-central North Sea. Gt. Britain Ministry of Agr., Fish. and Food. Fish. Res. Tech. Rep. 60.

Manzer, J.I. 1968. Food of Pacific salmon and steelhead trout in the N.E. Pacific ocean. J. Fish. Res. Board Can. 25:1085-1089.

McLaughlin, P.A. and J.F. Hebard. 1961. Stomach contents of the Bering Sea king crab. Int. N. Pac. Fish. Comm. Bull. 5:5-8.

Mikawa, M. 1963. Karasugarei no setai. (Ecology of the lesser halibut, Reinhardtius hippoglossoides matsuurae, Jordan and Snyder.) Bull. Tohoku. Reg. Fish. Lab. 23:1-41. In Jap. (Transl. by Fish. Res. Board, Canada Transl. Ser. No. 1260.)

Miller, B.S. 1970. Food of flathead sole (Hippoglossoides elassodon) in East Sound, Orcas Island, Washington. J. Fish. Res. Board Canada 27:1661-1665.

Mineva, T.A. 1964. Materialy po biologii nekotorykh vidov Kambal vostochnoi chasti Beringova morya. (On the biology of some flatfishes in the eastern Bering Sea). Tr. Vses. Nauchno-issled. Inst. Morsk. Ryon. Khoz. Okeanogr. 49 (Izv. Tikhookean. Nauchno-Issled. Inst. Tybvn. Khoz. Okeanogr. 51): 215-224. In Russ. (Transl. by Isr. Program Sci. Transl., 1968, pp. 227-235, In: P.A. Moiseev (Editor). Soviet Fisheries Investigations in the northeast Pacific, Part 2, available U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, Va., as TT 67-51204).

Mito, K.I. 1974. Food relationships among benthic fish populations in the Bering Sea. M.S. Thesis, Hokkaido Univ., Hakodate, Jpn., 135 pp.

Musienko, L.N. 1968. Ichthyoplankton of the Bering Sea. In: Soviet Fisheries Investigations in the northeast Pacific, Part II:251-286. Ed: P.A. Moiseev.

Nishiyama, T. 1974. Energy requirement of Bristol Bay sockeye salmon in the central Bering Sea and Bristol Bay, pp 231-343. In: D.W. Hood and E.J. Kelley 1974 (eds.). Oceanography of the Bering Sea with emphasis on renewable resources, Occas. Publ. No. 2 - Inst. Mar. Sci., Univ. Alaska, Fairbanks.

Novikov, N.P. 1964. Osnovnye cherty biologii tikhookeanskogo belokorogo pltusa (Hippoglossus hippoglossus stenolepis Schmidt) y Beringovour more (Basic elements of the biology of the Pacific halibut (Hippoglossus hippoglossus stenolepis Schmidt) in the Bering Sea). Tr. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 49 (Izv. Tikhookean. Nauchno-Issled. Inst. Rybn. Khoz. Okeanogr. 51):167-204. In Russ. (Transl. by Isr. Program. Sci. Transl., 1968, pp 175-219. In: P.A. Moiseev (Ed.), Soviet fisheries investigations in the northeast Pacific, Part 2, available U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, Va., as TT 67-51204.)

Pearson, W.H., D.L. Woodruff, and B.J. Higgins. 1984. Feeding ecology of juvenile king and Tanner crab in the southeastern Bering Sea. (Unpubl. manuscr.) Battelle, Pacific Northwest Lab., Richland, WA 99352. 48 pp.

Pola, N.B., R.K. Miyahara, and A.F. Gallagher, Jr. 1985. Spatial and temporal extent of hydrocarbon contamination in marine species of Bristol Bay. NOAA, NMFS, NWAFC, 7600 Sand Point Way N.E., Seattle, WA. Proc. Rept. 85-08, 40 pp.

Rogers, D.E. et al. 1979. Seasonal composition and food web relationships of marine organisms in the nearshore zone of Kodiak Island. Ann. Rept. Env. Assess. Alaskan Cont. Shelf 4.

Rumyantsev, A.I. and M.A. Darda. 1970. Letniaia sel'd'vostochnoi chasti Beringova moria (Summer herring in the eastern Bering Sea). Tr. Vses Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 70 (Izv. Tikhookean. Nauchno-Issled. Inst. Rybn. Khoz. Okeanogr. 72):402-432. In Russ. (Transl. by Isr. Program Sci. Transl., 1972 pp. 409-441. In: P.A. Moiseev (Ed.), Soviet fisheries investigations in the northeastern Pacific, Part 5, available U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, Va., as TT 71-50127.)

Shimada, A. and J. June. 1982. Eastern Bering Sea Pacific cod food studies. NOAA, NMFS, NWAFC, 7600 Sand Point Wy. N.E., Seattle, Washington 98115, (unpubl.), 41 pp.

Shuntov, V.P. 1970. Sezonnoe raspredelenie chernogo i strelozubykh patusov v Beringovum more (Seasonal distribution of black and arrow-tooth halibuts in the Bering Sea). Tr. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 70 (Izv. Tikhookean, Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 72):391-401. In Russ. (Transl. by Isr. Proram Sci. Transl., 1972, pp. 397-408. In: P.A. Moiseev (Ed.), Soviet Fisheries Investigations in the Northeastern Pacific, Part 5, available U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, Va., as TT 71-50127.)

Simenstad, C.A. 1979. ADF&G-OCS Fish Food Habits Analysis. Ann. Rept. Env. Assess. Alaskan Cont. Shelf 4:411-440.

Skalkin, V.A. 1963. Pitanie kambal v yugo-vostochnoi chasti Beringova morya (Diet of flatfishes in the southeastern Bering Sea). Tr. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 48 OIzv. Tikhookean. Nauchno-Issled. Inst. Rybn. Khoz. Okeanogr. 50):223-237. In Russ. (Transl. by Isr. Program Sci. Trans., 1968, pp. 235-250. In: P.A. Moiseev (Ed.) Soviet Fisheries Investigations in the Northeast Pacific, Part 1, available U.S. Dep. Commer., Natl. Tech. Inf. Serv., Springfield, Va., as TT 67-51203.)

Smith, G.B. 1981. The biology of walleye pollock. In: D.W. Hood and J. Calder (Eds.), The Eastern Bering Sea Shelf: Oceanography and Resources, Volume 1, pp. 527-551. U.S. Gov. Print. Off., Washington, D.C.

Smith, R.L., A.C. Paulson, and J.R. Rose. 1978. Food and feeding relationships in the benthic and demersal fishes of the Gulf of Alaska and Bering Sea. In: Environmental Assessment of the Alaskan Continental Shelf, Final Reports, Biological Studies 1:33-107. U.S. Dep. Commer., Natl. Oceanic Atmos. Admin., Environ. Res. Lab., Boulder, Colo.

Straty, R.R. 1974. Ecology and behavior of juvenile sockeye salmon (Onchorynchus nerka) in Bristol Bay and the eastern Bering Sea, pp. 285-319. In: D.W. Hood and E.J. Kelley (Eds.) Oceanography of the Bering Sea with emphasis on renewable resources, Occas. Publ. No. 2. Inst. Mar. Sci. Univ. Alaska, Fairbanks.

Takahashi, Y. and H. Yamaguchi. 1972. Stock of the Alaskan pollock in the eastern Bering Sea. Bull. Jpn. Soc. Sci. Fish. 38:389-399.

Takeuchi, I. 1960. Rearing experiment of juvenile king crab (Paralithodes camtschatica) in the eastern Bering Sea-observations on molting and growth. 1968 Transl. from: Hokkaido Fish. Exp. Station, Monthly Rept. 17(12)453-460.

Tarverdiyeva, M.I. 1981. O pitanii krabov-strigunov Chionoecetes opilio i C. bairdi v Beringovum more. (On the feeding of snow crabs in the Bering Sea.) Zool. Zh. 60:991-997. (Transl. 1982 Canadian Trans. Fish. Aquat. Sci. No. 4892.)

Wailes, G.H. 1936. Food of Clupea pallasii in southern British Columbia waters. J. Biol. Board Can. 1:477-486.

Wakabayashi, K. 1974. Studies on resources of the yellowfin sole in the eastern Bering Sea. I. Biological characters. Fishery Agency of Japan, Far Seas Fisheries Research Laboratory, Shimuzu, Jpn. 77 pp.

Walters, G.E. and M.J. McPhail. 1982. An atlas of demersal fish and invertebrate community structure in the eastern Bering Sea: Part I, 1978-81. NOAA Tech. Memo. NMFS F/NWC-35.

BIOLOGY AND FISHERY OF
SOUTHEASTERN BERING SEA
RED KING CRAB
(PARALITHODES CAMTSCHATICA, TILESIUS)

by

Francis M. Fukuhara
University of Washington and
Natural Resource Consultants

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

May 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Processed Report 85-11 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

TABLE OF CONTENTS

LIST OF TABLES

Table 33.--Estimated population (in millions) of red king crab by subarea, sex and carapace length groups in the eastern Bering Sea in 1975 and 1979.

Table 34.--Hypothetical oil spill scenarios.

Table 35.--Estimated concentrations and area contaminated by simulated oil spills at Port Heiden, Port Moller and off Cape Newenham.

LIST OF FIGURES

BIOLOGY AND FISHERY OF SOUTHEASTERN BERING SEA RED KING CRAB (PARALITHODES CAMTSCHATICA, TILESIUS)

Francis M. Fukuhara

1. IDENTIFICATION

1.1 Taxonomy

The red king crab, *Paralithodes camtschatica* (Tilesius) is one of 5 species of the genus, three of which inhabit the subarctic North Pacific Ocean and Bering Sea. The taxonomy of the species are as follows:

Kingdom *Animalia*
- Subkingdom *Metazoa*
  - Phylum *Arthropoda*
    - Class *Crustacea*
      - Subclass *Malacostraca*
        - Series *Eumalacostraca*
          - Superorder *Eucarida*
            - Order *Decapoda*
              - Suborder *Reptantia*
                - Section *Anomura*
                  - Family *Lithodidae*
                    - Genus *Paralithodes*
                      - Species *P. camtschatica* (Tilesius)
                        P. platypus (Brandt)
                        P. brevipes (Brandt)
                        P. rathbuni (Benedict)*
                        P. californiensis (Benedict)*
                    - Genus *Lithodes*
                  - Family *Paguridae* (Hermit crabs)

* Taken infrequently in deep water off California

The Lithodids are not true crab such as the Tanner and Dungeness crab but are related to the hermits crabs (Fam. Paguridae). They have lost their habit of living in abandoned snail shells and have taken on the traits of true crabs. Their ancestry is revealed by the asymmetry of the abdomen and first walking legs, the degenerated fifth walking legs, and several other minor structural traits (Marukawa, 1933; Borradaile and Potts, 1961. also see Fig 1). Unlike true crabs which have legs which are jointed in a manner such that they are oriented forward, the legs of king crab are jointed so that the legs are extended backward.

1.2 Morphology

The red king crab has an exoskeleton with a coalesced head and thorax (cephalothorax), abdominal flap, one pair of chelipeds (legs with claws or pincers), three pairs of walking legs and an array of antennae and mouth parts (mandibles, maxillae and maxillipeds). Metamorphosis through five larval stages and growth from the first instar form through adulthood is achieved by molting.

The external morphology of adult king crab has been described in detail by Marukawa (1933). The morphological characteristics of red king crab, *P. camtschatica* are shown in column 2 of Table 1. Characteristics of *P. platypus* and *P. brevipes* are presented for comparison. The red king crab is readily identifiable by the shape and color and number of spines on the posterior and postero-lateral margins and cardiac and branchial regions of the carapace (Fig. 2).

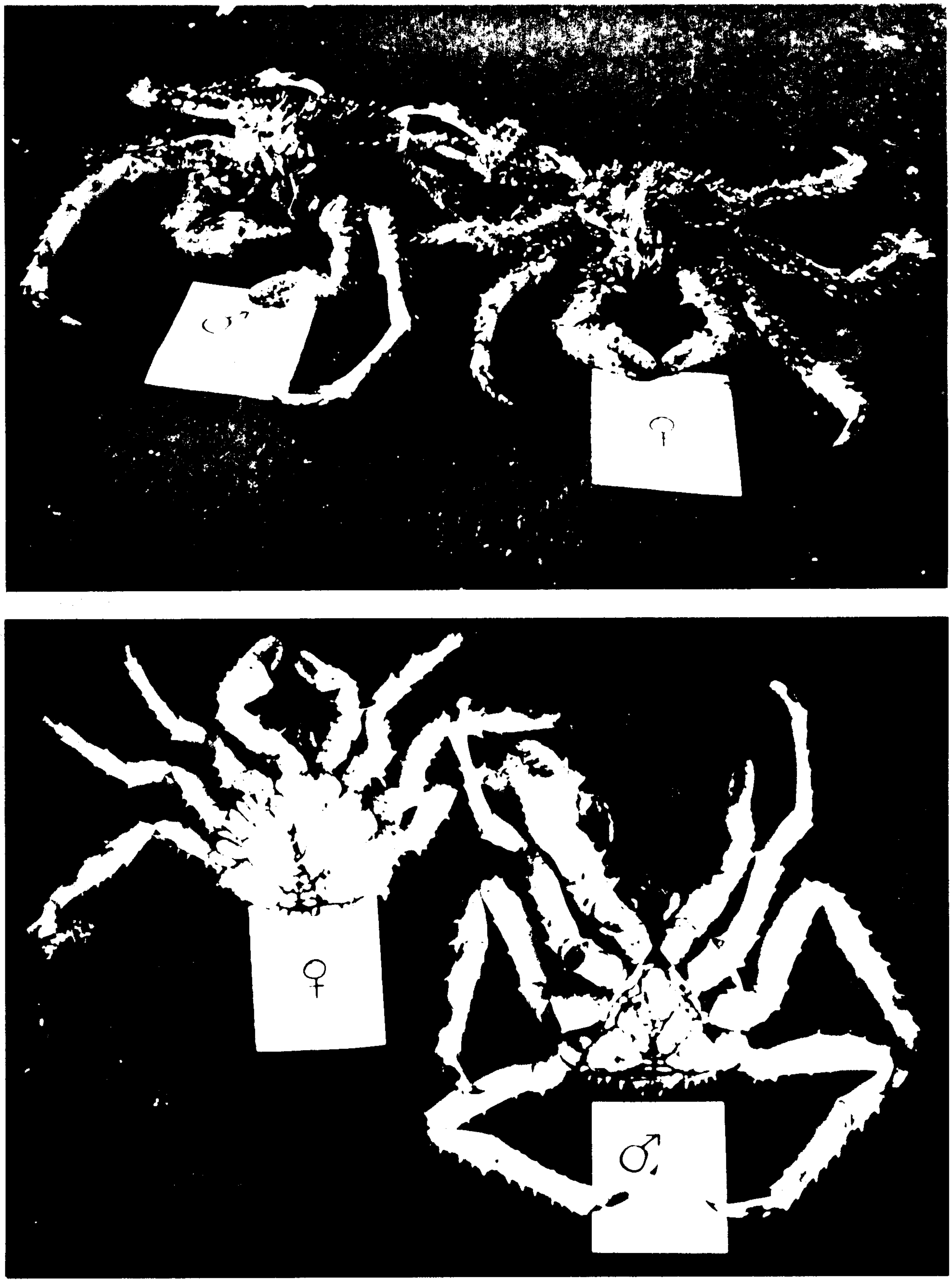


Figure 1. Dorsal and ventral views of adult male and female *P. camtschatica*.

Table 1.--Morphological characters of *P. camtschatica*, *P. platypus* and *P. brevipes*.

	Species		
	P. camtschatica	*P. platypus*	*P. brevipes*
Color of body	Dorsal surface of carapace and legs dark brown, ventral light yellow.	Resembles *P. camtschatica*, but bluish purple on dorsal surface.	Dorsal red, when dried appears blue
Number of spines on carapace			
Posterior margin	8 (4 on each side)	14 (7 on each side)	12 (6 on each side)
Postero-lateral margin	10 (5 on each side)	12 (6 on each side)	12 (6 on each side)
Antero-lateral margin	8 (4 on each side)	8 (4 on each side)	8 (4 on each side)
Anterior margin	4	4	6
Branchial region	18 (9 on each side)	12 (6 on each side)	14 (7 on each side)
Cardiac region	6	4	4
Gastric region	9	9	11
Spines on rostrum			
Central spines	Long, slightly curved for dorsal, terminal portion pointed.	Short, stout, and not curved.	Short, terminal portion slightly rounded.
1st dorsal spine	Well developed.	Wanting	Rudimentary, very small
2nd dorsal spine	One pair, much smaller than 1st dorsal spine	One pair, close to each other	One pair, larger than 1st dorsal spine
3rd dorsal spine	One pair, rarely 3 spines	3 spines arranged in straight line	3 spines, not arranged in straight line
Eye	Slightly protruded, diameter about equal to that of eye-stalk	Resembles that of *P. camtschatica*	Not protruded; diameter is shorter than that of eye-stalk
Antenna	Exopodite transformed to a small spine	Exopodite transformed to 2 branched spines with a very small lateral spine	Exopodite large with complicated spines
Legs	3rd leg long, length of meropodite 70-80% of width of carapace	Longer than that of *P. camtschatica*, length of meropodite of 3rd leg 85-90% of width of carapace	Shorter than that of 2 other species, chelipeds long and developed remarkably
Digit			
Dorsal spine	1	1	1
Ventral spine	1 situated in slightly more frontal position than that of dorsal spine	1 situated in more frontal portion than that of dorsal spine	1 situated in same position compared with that of dorsal spine
Internal spines	In general wanting, rarely retained as trace	5, situated on ventral side	7, sharp, needle-like form

Source: Marukawa (1933).

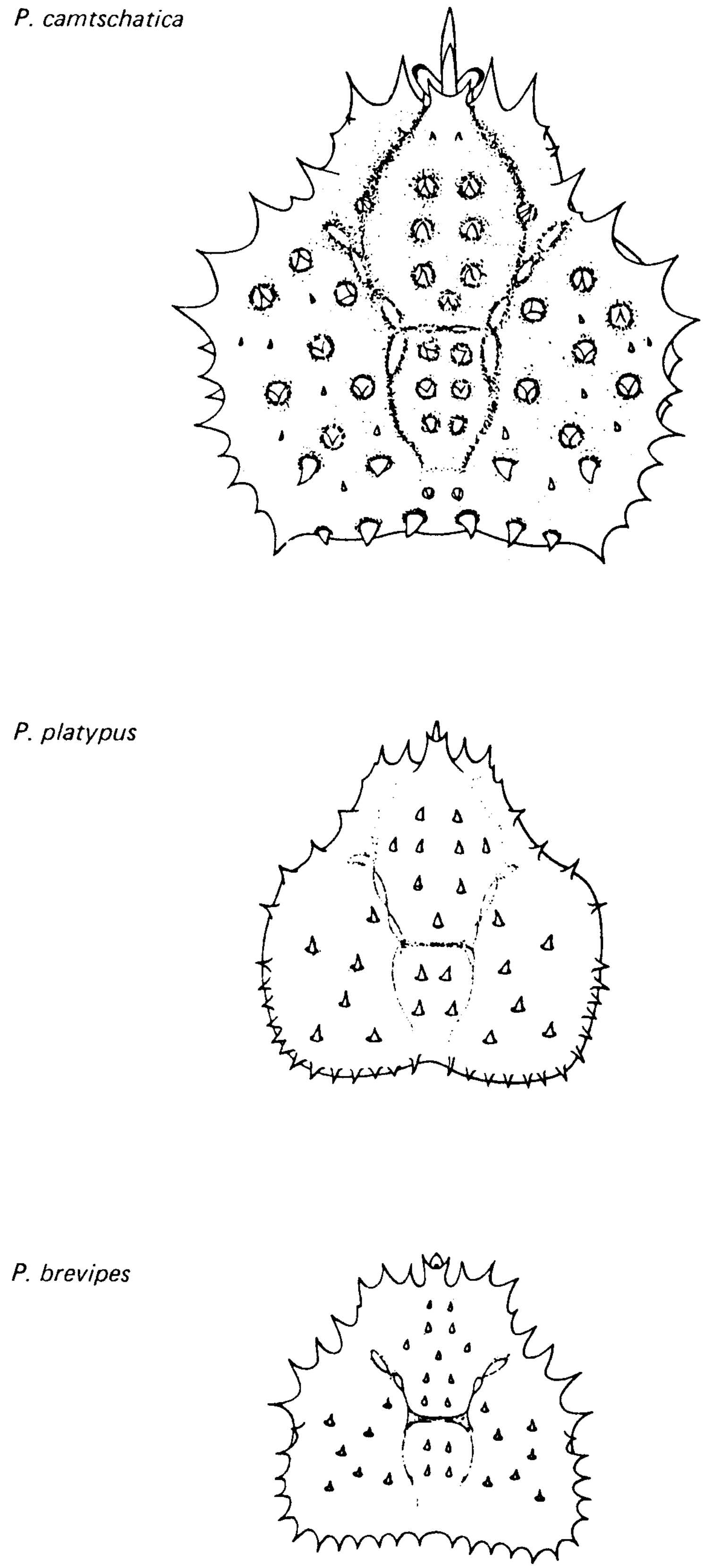


Figure 2. Arrangement of carapace spines on Paralithodes camtschatica, P. platypus and P. brevipes.

Red king crab have four zoea stages (Fig. 3) and one megalops stage. The external morphology of these larval stages for three species of Paralithodes was described by Marukawa (1933) and supplemented and corrected for red king crab larvae by Sato and Tanaka (1949). External morphology of zoea larvae is shown in Table 2.

Marukawa (1933) and Sato and Tanaka (1949) also described the external morphology of the megalops and first adult form of red king crab. These stages are depicted in Fig. 4.

1.3 Internal Morphology

The internal organs and the vascular, nervous, digestive systems of red king crab have been described by Marukawa (1933). Histological studies of the male reproductive system and sperm were also presented by the same author. Based upon microscopic examination of the ductus deferens, Wallace et al. (1949) reported on indications of changes in this structure with the onset of sexual maturity. The nature of these changes or supporting evidence for them were not presented.

1.4 Morphometrics

Data on the size of various body parts such as the claws, certain leg segments and other body parts relative to carapace size has been recorded from mature red king crab from Asian waters by Marukawa (1933). Similar information for southeastern Bering Sea red king crab has been given by Wallace (1949).

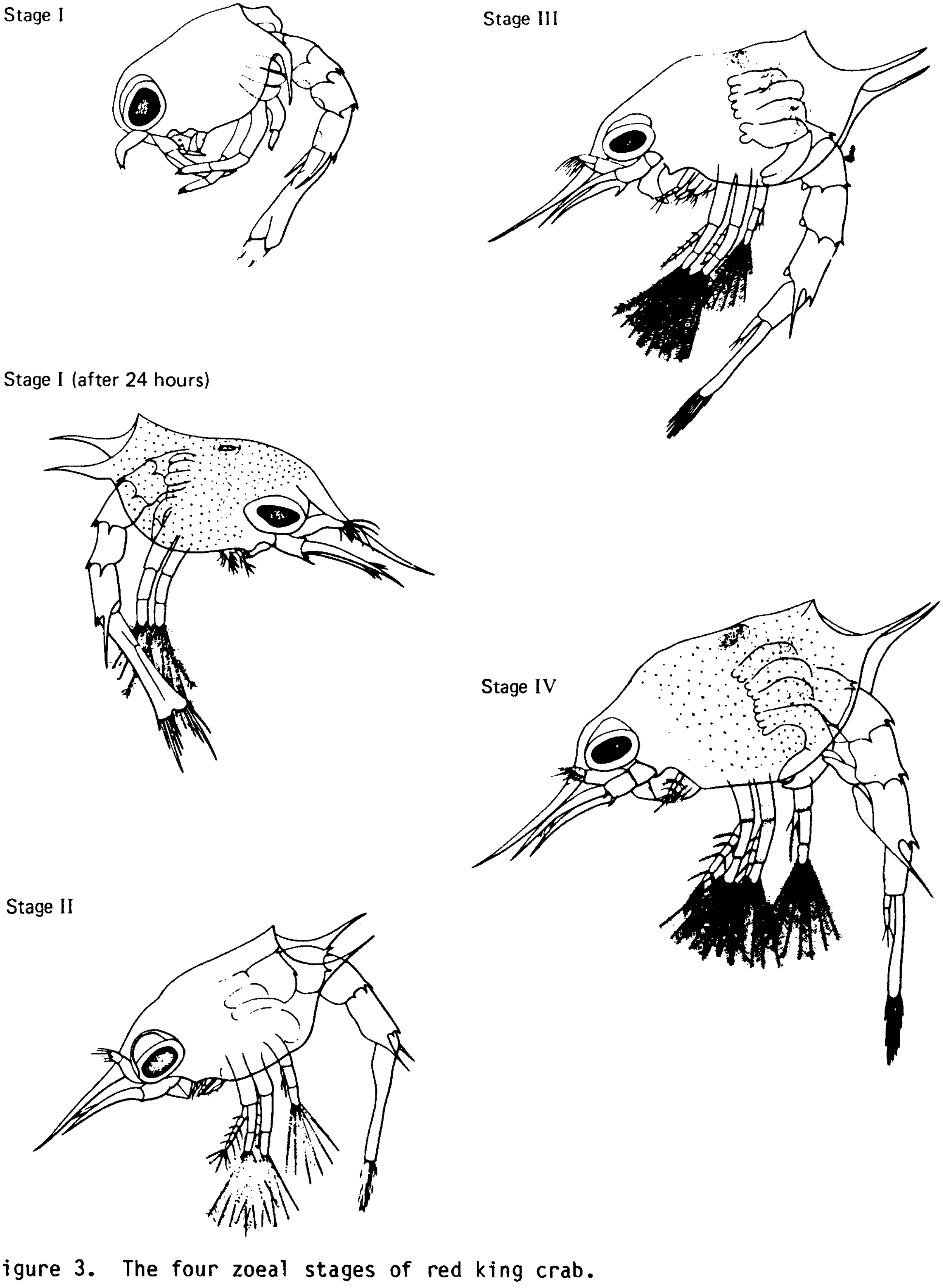


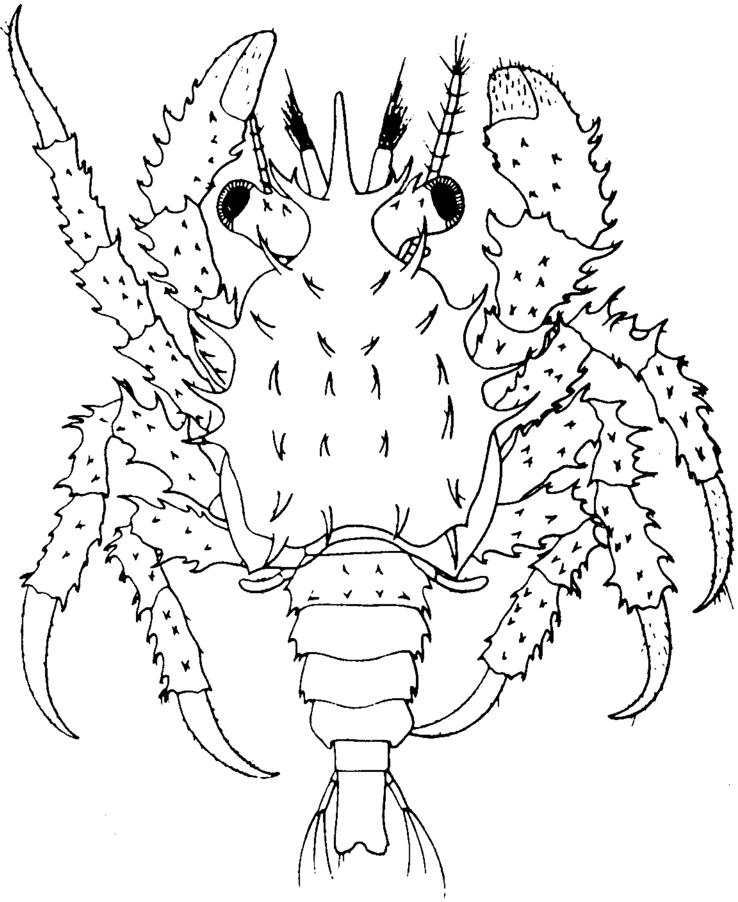
Figure 3. The four zoeal stages of red king crab.

Table 2.--Comparison of zoea larvae of *Paralithodes*.

Parts, compared	P. camtschatica	P. platypus	P. brevipes
Rostral spine	Elongates, beyond the end of antenna	Shorter than that of *P. camtschatica*, its length about equal to that of antenna	Much shorter than that of others, its length about equal to that of antenna
Dorso-lateral spines and dorso-posterial round of carapace	Dorso-lateral spines long and stout, dorsal round of dorso-posterial carapace concaved	Dorso-lateral spines shorter than that of P. camtschatica, dorsal round of dorso-posterial carapace runs nearly straight	Dorso-lateral spines very short, dorsal round of dorso-posterial carapace convexed
Number of spines of telson	7 pairs, through all stages	8 pairs in 1st stage	6 pairs in 1st stage, after 2nd stage 7 pairs
Antenna	Slightly elongated, terminal end of exopodite provided with setae	Slightly shorter than than of P. camtschatica, about the posterior half of inner side of exopodite provided with setae	Distinctly shorter than that of the others, its feature resembled to that of *P. platypus*
Chromatophores	Consisted of red and green, distributed in all stages	Not observed	Resembled *P. camtschatica*, but blue chromatophores distributed on antenna
(1st stage)			
Total length	4.56 m.m.	4.98 m.m.	4.31 m.m.
Width of carapace	1.12	1.16	1.25
Length of carapace	1.45	1.66	1.49
Length of rostral spine	1.08	0.99	0.61
Length of dorso-lateral spines	0.45	0.32	0.12
Length of abdomen	2.14	2.32	2.24
Width of 5th abdominal segment	0.23	0.29	0.27
Width of terminal portion of telson	0.51	0.65	0.50
Length of exopodite of antenna	0.83	0.79	0.53

Source: Marukawa (1933).

Megalops or glaucothoe stage



First instar or adult form

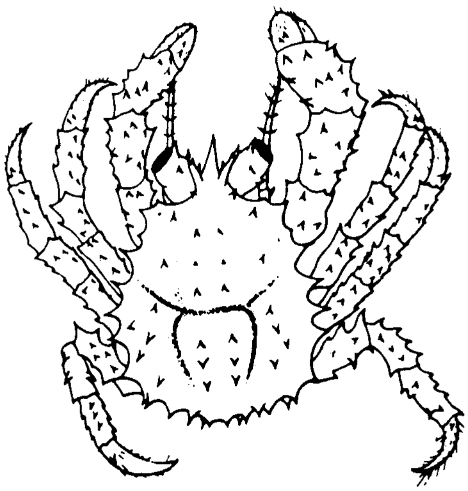


Figure 4. The megalops or glaucothoe stage and first instar or adult form of red king crab.

Although, conventionally, the size of king crab is given in carapace length, some discussions allude to carapace width. Carapace length is longer than carapace width until red king crab attain a width of 20 mm. At 20-25 mm, carapace width is about equal to carapace length and thereafter, width remains longer than length (Marukawa, 1933). The length-width relationship of immature red king crab of eastern Bering Sea is given by Weber (1967) as: Carapace Width = -1.449 + 1.080 X Carapace Length (Fig. 5). Data on length-width relationships for red king crab of mean carapace lengths 60.4-196.9 mm from southeastern Bering Sea were given by Wallace (1949). The slope of the relationship for males was approximately rectilinear (k = 1.10), whereas for females up to 87 mm, k was equal to 1.13. The slope for females larger than 87 mm was slightly deflected (k = 0.96).

The carapace length-body weight relationship of immature eastern Bering Sea king crabs is shown in Fig. 6. The relationship of carapace length to body weight for larger male and female crab (greater than 40 mm) from the Pacific Ocean and Bering Sea is given in Fig. 7.

2. GEOGRAPHIC DISTRIBUTION, HABITAT AND STOCKS

2.1 Geographic Distribution

The red king crab is broadly distributed in the subarctic North Pacific Ocean and contiguous seas on the continental shelf and slope of Asia and North America (Fig. 8). Off the Asian coast, the species occurs northward of Tsushima Strait, through the Sea of Japan to Penzhinskiy Gulf in the northern Okhotsk Sea. In Pacific Asian waters, red king crab occur from Cape

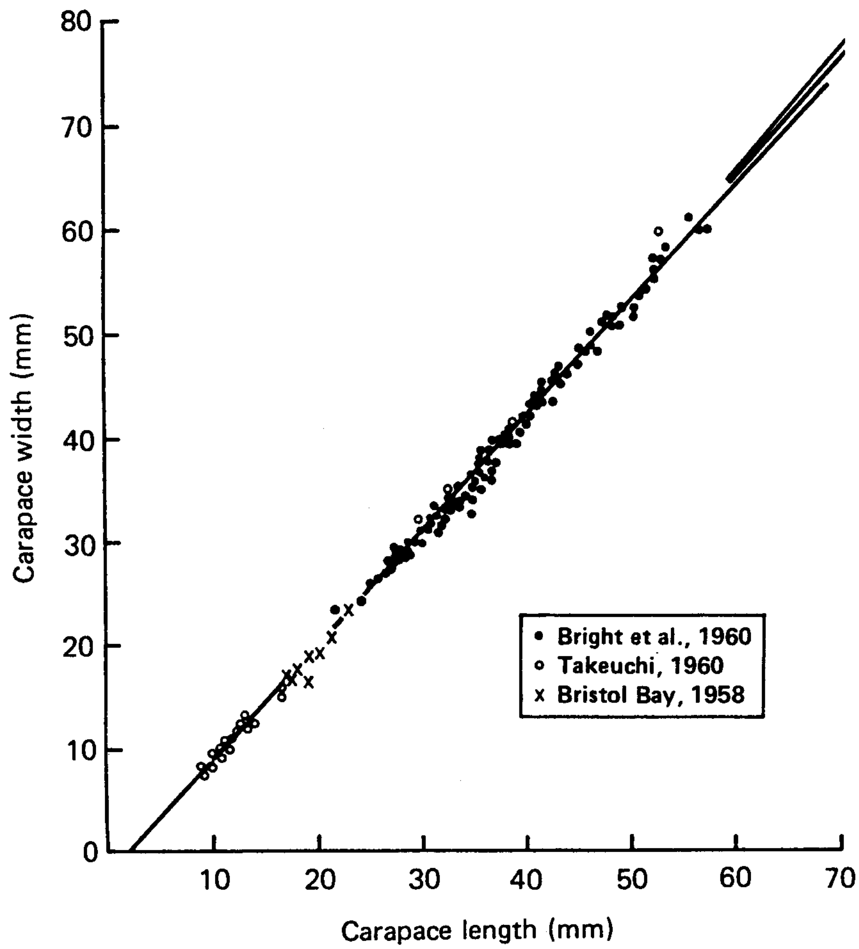


Figure 5. The relationship of carapace width to carapace length in juvenile king crab.

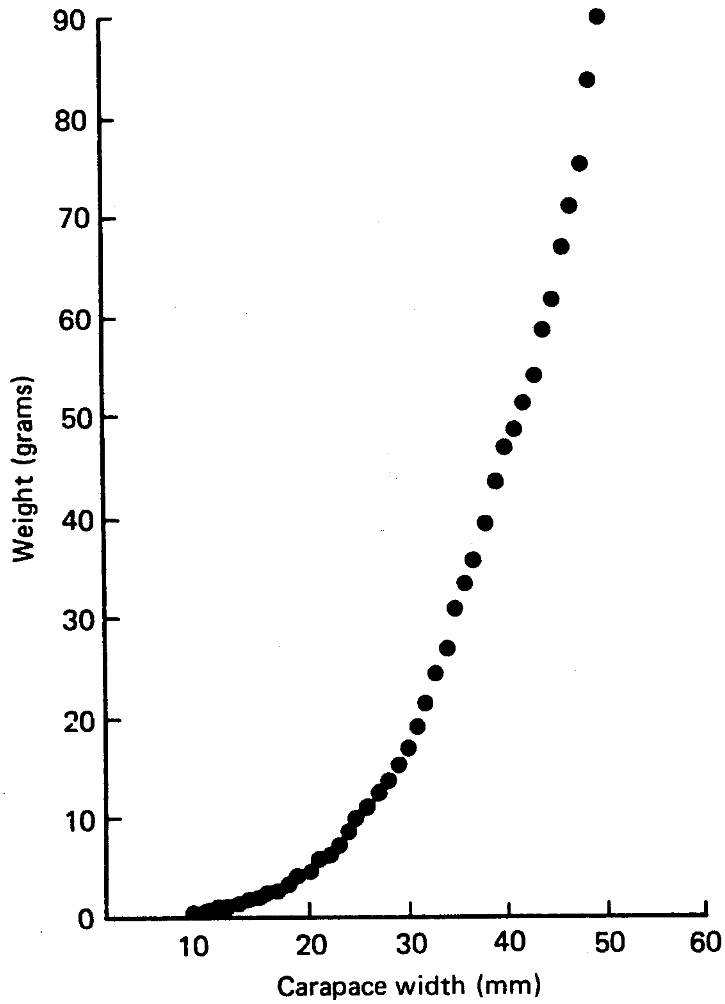


Figure 6. Relationship of carapace length to body weight for immature king crab.

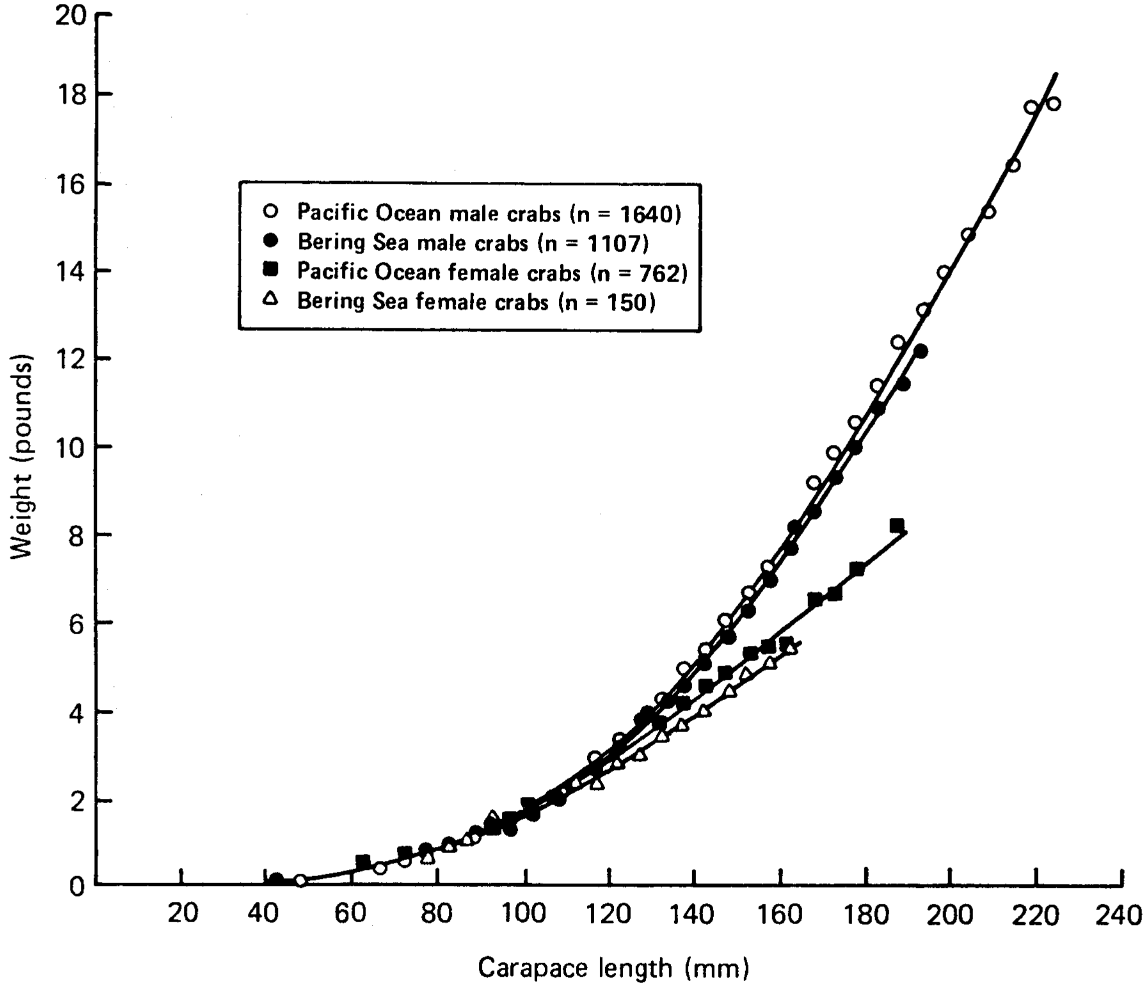


Figure 7. Relation of carapace length to body weight for king crab longer than 40 mm.

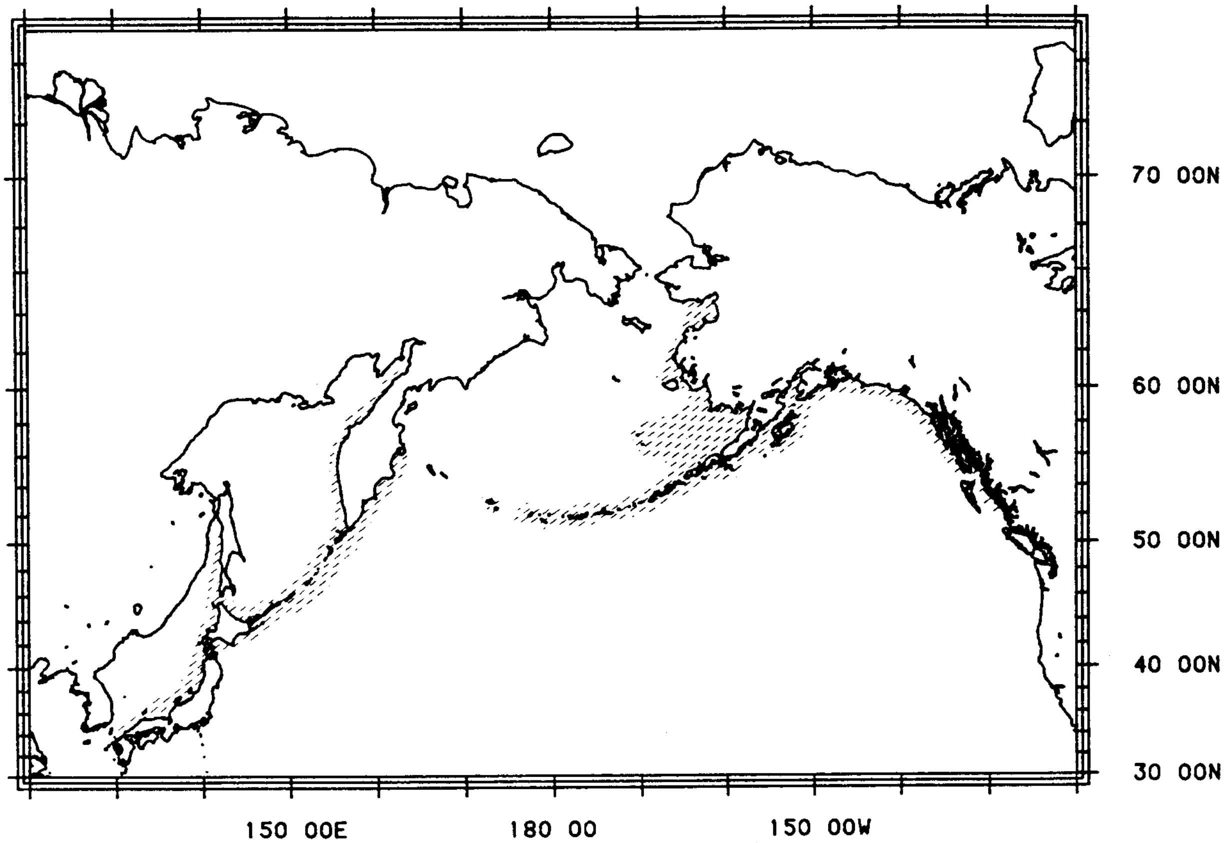


Figure 8. Geographic distribution of red king crab in the North Pacific Ocean and contiguous seas.

Olyutorksi southward to at least Cape Erimo (Vinogradov, 1946). Nakazawa (1912) reported small commercial catches in northern Honshu, Japan.

In the eastern North Pacific Ocean and Bering Sea the northern limit of distribution is Norton Sound. The species occurs in the southeastern Bering Sea (Bristol Bay), along the Aleutian Islands and in the Gulf of Alaska from Unimak Pass eastward and southward to Vancouver Island, British Columbia (North Pacific Fisheries Management Council, King Crab, Draft Fishery Management Plan-1981, hereafter referred to as NPFMC, KC, DFMP-1981).

In Asia, the principal stocks of red king crab occur off West Kamchatka, West Sakhalin, and in the Nemuro and Wakkanai districts of Hokkaido. There is no evidence to indicate that there is intermingling of crabs between these populations. From tagging experiments, Sato (1958) concluded that crabs breed along the entire western Kamchatkan shelf and migrate from south to north. On the the basis of areal variations in sex and size composition and the temporal-spatial distribution of the larval stages of king crab, Vinogradov (1969) concluded that 5 groups constituted the West Kamchatkan red king crab population of which the northernmost group provides the reproduction for virtually the entire West Kamchatkan population.

In North America, red king crab are most abundant in the Bering Sea and Gulf of Alaska. Major fisheries for red king crab are in Prince William Sound, Cook Inlet, Kodiak Island, south Alaskan Peninsula, Aleutian Islands, Norton Sound and southeastern Bering Sea (Fig. 9). There is no direct evidence (such as from tagging) that crab of one stock internmingle with those of another stock (Hayes and Montgomery, 1963; Powell and Reynolds, 1965; Simpson and Shippen, 1968). Due to passive drifting and the rather protracted early life history of king crab, larvae hatched in one locality may settle on

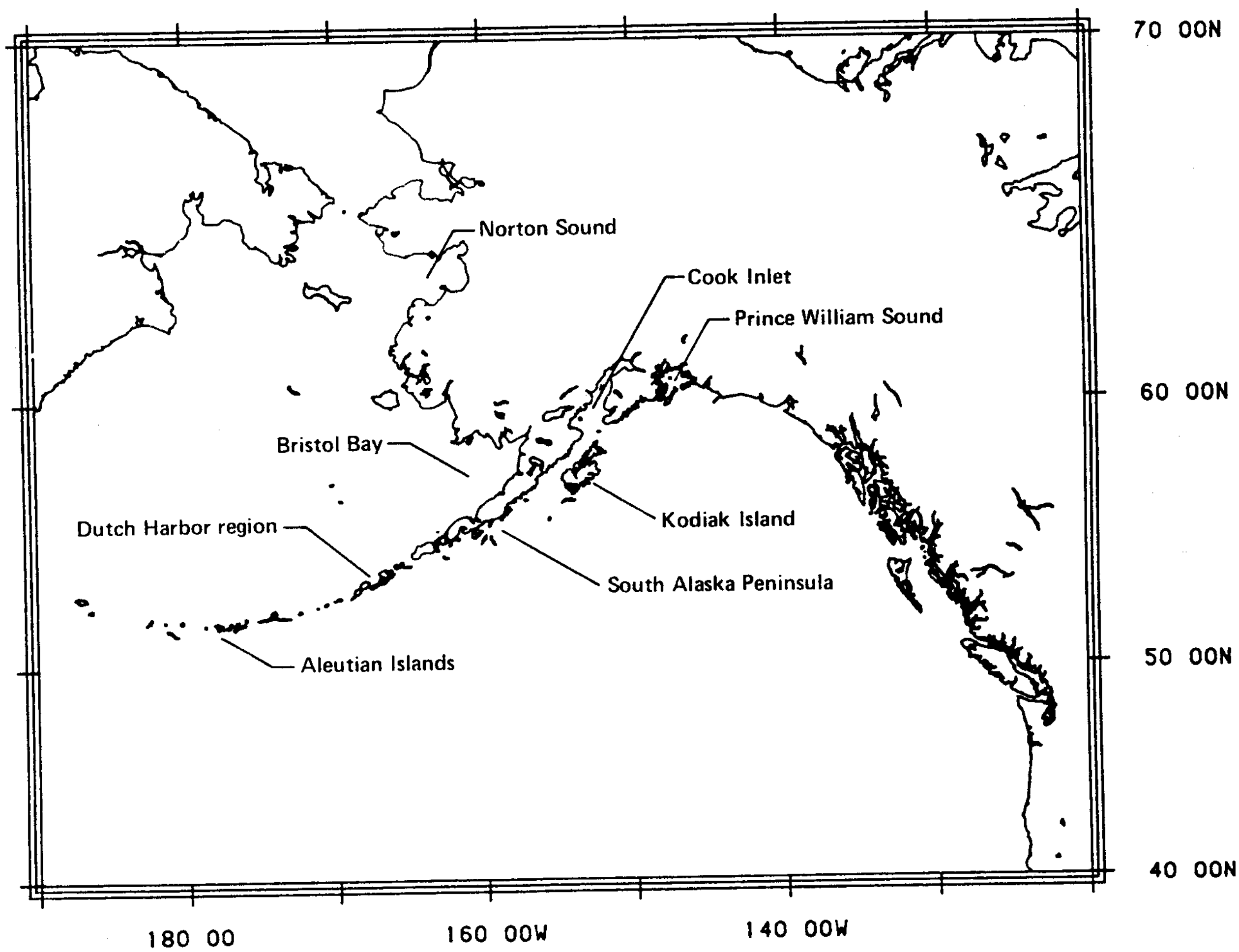


Figure 9. Principal red king crab stocks off North America.

the bottom as megalops or first instars a considerable distance away (Hebard, 1959; Haynes, 1974; Armstrong et al., 1983) and may even contribute to the productivity of another population (Vinogradov, 1969).

2.2 Habitat

2.2.1. Larvae

Zoea are positively phototactic for about 5 days after hatching (Marukawa, 1933). The first zoea stage occupies the upper and middle layers of the water column. Zoeal stages II through IV occupy the middle or lower layers. Zoea occur in water depths of 9-40 fathoms in water temperatures of 0.8° to 4.0°C. Marukawa hypothesized that the zoea must be most numerous in vortices or gyres since the perpetuation of the population must depend upon the ultimate settling of the first instar in environments suitable for survival.

Megalops larvae inhabit the bottom and walk on the 2nd to 4th walking legs and catch prey with their chela. They can, however, swim short distances by moving the pleopods and are frequently attached to sponges, bryozoa and fragments of seaweed. The depth and temperatures of their environment are the same as that for zoea (Marukawa, 1933).

2.2.2 Juveniles

Megalopae and juvenile crab smaller than 30 mm in carapace width inhabit depths of 10-30 fathoms. Relatively little information is available on the distribution and habitat of these early life history groups. Apparently, juvenile king crab less that 2 years old (less than 35 mm carapace length) are mainly solitary, living under rocks and debris (NPFMC DF,-1981). Small crab (carapace length less than or equal to 10 mm) were found in great numbers among sea weed and ascidians (sea squirts) taken in king crab tangle nets off Hokkaido (Nakazawa, 1912). After a thorough search, very young juvenile crabs were found in the region from Ptich'ii Island (57°10'N) to the central area of Penzinskiy Bay. The greatest numbers were taken at depths of 5 to 15 m among stones or boulders (Vinogradov, 1969). Megalopae and juvenile king crab in eastern Bering Sea were also reported to be associated with marine algae, hydroids and sponges (FAJ, 1963a).

According to Weber (1967), juvenile crab inhabit the eulittoral zone until they attain carapace lengths of 40-50 mm. Thereafter, they migrate toward deeper waters but do not occur in quantity on the fishing grounds until after they have grown to sizes of 70-80 mm carapace length. Beginning in their second and third years, crab in the Kodiak area have been observed to congregate in large, tightly packed groups called pods. These pods contain as many as 6000 crab with up to 50 crabs stacked on top of each other (Powell and Nickerson, 1965; Powell, 1974). Weber (1967) also reported that most immatures are gregarious and found in pods although no evidence of such aggregating behavior was presented for Bering Sea red king crab. Weber's search (1967) for immature king crab in the eastern Bering Sea eulittoral zone was not particularly successful. A total of 85 juvenile crab were taken of which 77 were captured in one beam trawl haul. By contrast, a single beach seine haul in Akutan Bay took over 200 immature crab.

2.2.3 Adults

Unlike megalopae and juveniles which on the basis of available evidence appear to inhabit rocky or coarse substrate, adult king crab are known to occur on sand and mud bottoms (Nakazawa, 1912; Marukawa, 1933; Vinogradov, 1946; Wallace et al., 1949; Vinogradov, 1969).

King crab tend to be aggregated by size or life history group or sex (Marukawa, 1933; Vinogradov, 1946; Wallace, et al., 1949; Weber and Miyahara, 1962). Adult crab are not uniformly distributed in area or time but tend to be more concentrated at certain times and places. Very pronounced aggregations of both sexes occur during the spring spawning season. After the mating season, the sexes form separate aggregations throughout the remainder of the year.

In the southeastern Bering Sea where uniform beaches and substrate extend for relatively great distances, crabs tend to be concentrated in particular places (Wallace et al., 1949; Korolev, 1964; Rodin, 1970). Aside from mating, an important determinant of aggregation is the availability of food and perhaps as pointed out by Chebanov (1965), the availability of prey which satisfies some specific, transitory physiological requirement such as the replacement of calcium after molting.

3. LIFE HISTORY

3.1 Embryological Development

After mating in April and May, the eggs are retained on the pleopods under the abdominal flap of the mother crabs for almost a year (Marukawa, 1933; Wallace et al., 1949). The eggs hatch during the inshore spawning migration which begins in late February or March, peaks in April and is completed in May. The time of hatching for southeastern Bering Sea king crab can vary by as much as a month (Weber, 1967; Armstrong, 1983) and may occur from early April to June. Mature females are without eggs for only a brief period. Females molt, mate and ovulate usually within a 1-2 day interval. Studies indicate that a female crab must mate within one week after molting for successful ovulation and fertilization (FAJ, 1963a).

The embryology of king crab has been described in detail by Kajita and Nakagawa (1932) and Marukawa (1933). The following summarization of embryonic development was obtained from Marukawa (1933).

Approx. time after Fertilization	Stage of Development
1- 4 days	Internal Cleavage
5- 20 days	External or superficial cleavage
20- 25 days	Gastrula
35- 38 days	Rudimentary embryo
50- 75 days	Nauplius embryo
100-110 days	Prozoea
150 + days	Postzoea

Seven months after hatching (December) Marukawa noted that the heart was well developed and pulsating at 168-170 times per minute and the embryo was hard to distinguish from the zoea larva which would hatch from the eggs four months hence in April.

3.2 Larval Stages

King crab metamorphose through four zoea stages and one megalops stage. Weber (1967) reports that upon hatching, the prezoeal larvae molt, usually within minutes, into the zoeal form. Although Marukawa (1933) illustrates a newly hatched zoea and a 24 hour old zoea (see Fig. 3) neither Marukawa or any other authors indicate that a molt occurs between these two forms.

From the results of rearing experiments, Marukawa (1933) determined that 5 molts were required to develop from the Zoea I stage, through the Zoea II through Zoea IV and megalops stage to the first adult form. The first molting (Zoea I to Zoea II) occurred 21 days after hatching and the interval between molts for the second through last zoeal stages and from Zoea IV to megalops was 14-16 days. The time required for megalops to metamorphose to the first adult form was also estimated to be about two weeks.

Subsequent experiments and observations have shown that the molting schedule is dependent upon certain environmental variables (Table 3). From the results of temperature controlled rearing experiments, Kurata (1960 & 1961) concluded that first stage zoeal larvae can be reared at temperatures of 2°-15°C with the highest survival within the range of 5°-10°C. Within this range of optimum temperature, larval growth rate increased with higher temperature. The length of time between hatching and molting was estimated to be in excess of 20 days at 2°C, 12 days at 5°C, 7 days at 10°C and about 5 days at 15°C. Kurata calculated that about 465 day-degrees (days X C°) were required to develop from hatching through megalops stage, 291 day degrees of which were required to complete the four zoeal stages.

Table 3.--Days required to finish the molting process.

[Average temperature of the water in parentheses]

Stage	Marukawa's experiment (1933)	Shimizu's experiment (1936)	Sato and Tanaka (1941)
First zoea	21 days (3.8°-6.1°C.)	24 days (2.0°C.)	7 days (9.0°C.)
Second zoea	14 days (6.8°C.)	12 days (5.0°C.)	10 days (8.9°C.)
Third zoea	15 days (7.3°-7.5°C.)	14 days (6.9°C.)	9 days (9.2°C.)
Fourth zoea	14 days (7.8°C.)	14 days (5.5°C.)	9 days (11.3°C.)
Glaucothoe 1/	20 days	--	12 days (14.9°C.)
Total to the glaucothoe 1/	64 days	64 days	35 days
Total to the youngest adult form	84 days	--	47 days

1/ Glaucothoe = megalops

Salinity less than about 21.7/1000 is detrimental to survival of zoea. The growth rate of zoea is not affected by salinities within the range of 21.7-39.7/1000 (Kurata, 1960).

3.3 Juveniles

The first instar or adult form is about 2 mm in carapace length. Growth rate and size at maturity appears to vary somewhat with area (Marukawa, 1933; Powell, 1960). On the evidence of the percentage of ovigerous crabs, Wallace (1949) concluded that female crab in eastern Bering Sea were mature at 86 to 102 mm carapace length. Males were considered to become mature at minimum lengths of 85 to 90 mm. Weber (1967) estimated that both male and female king crab in southeastern Bering Sea matured at about 95 mm. This size is equivalent to five years in age for males and five and a half years for females.

3.4 Adults

Crabs larger than 95 mm constitute the adult population. The sexes are generally segregated except for spawning. After attaining sexual maturity, growth increment per molt remains about the same for males but is drastically reduced in females (Weber, 1967). Sexual dimorphism is also evident in allometric growth which occurs in certain body parts (e.g., size of chela) with the onset maturity (Marukawa, 1933; Wallace et al., 1949).

4. SPAWNING AREAS AND SEASONS

Knowledge relating to the area and season of red king crab spawning in eastern Bering Sea has been obtained from such evidence as the reproductive state of the female or the stage of egg development, the timing and distribution of first stage zoea larvae and the capture of crabs in copulatory embrace.

4.1 Reproduction

Marukawa (1933), Wallace et al. (1949) and Powell & Nickerson (1965) as well as others have described the mating process in king crab. Essential aspects of the reproductive process are as follows:

1. The spring or spawning migration begins in February and March, peaks in April and is completed in May. During this migration, eggs which have been carried for about 11 months hatch into first stage zoea larvae.
2. Upon reaching the spawning grounds the female crab form large aggregations. Through some communication mechanisms, the sexes are attracted to each other. Although experimental evidence is lacking for *Paralithodes*, the attraction is apparently based on a mating pheromone (Rebach and Dunham, 1983).
3. Males select females for their behavior and relative size. In nature, males almost always select females of equal or smaller size (NPFMC, KC, DFMP-1981).

4. Male grasps female by the meropodite of the chelipeds while the female molts.
5. After assisting the female to molt, the male regrasps the female, inverts her beneath his body and spreads spermatophore bands over her gonopores. Only then does the female extrude eggs which are fertilized and attached to the pleopods where they remain protected by the abdominal flap to develop for about 11 months.
6. Male red king crab are polygamous and are capable of fertilizing as many as 7 females (Marukawa, 1933; Wallace, 1949; Powell et al., 1972).

Successful mating requires that fertilization occur within 7 days of molting in the Bering Sea (Weber, 1965; FAJ, 1963a) and 5 days in the Gulf of Alaska according to Powell et al. (1974). Fertilization usually takes place within two hours of molting. In shipboard experiments during the 1961 fishing season scientists of the Fishery Agency of Japan (1963b) observed that when females were placed with males prior to or within 24 hours after molting, mating and ovulation proceeded normally. When females were placed with males 2 to 7 days after molting, mating occurred immediately, however, ovulation was incomplete and unfertilized eggs were dispersed in the water. In all cases where females were separated from males after molting, no ovulation occurred.

There is evidence that it is the old shelled males and not those which have recently molted which participate in mating. Also, small adult males do not participate in mating until 2 years after attaining sexual maturity (NPFMC, KC, DFMP, 1981).

4.2 Spawning Areas

Spawning of Bristol Bay red king crab occurs off the Alaskan Peninsula from near Amak Island and the Black Hill to Port Moller area (Fig. 10).

4.3 Spawning Season

Figure 11 from Weber (1967) shows the percentage occurrence of the stages of egg development with time as observed by several authors during the spring and summer in eastern Bering Sea. The trends in occurrence of females with empty egg cases and new eggs indicates that spawning probably occurred in the first and second deciles of June in 1960 and 1961 and perhaps in the third decile of June and first 10 days of July in 1962. Although the period of spawning may vary according to temperature or other environmental conditions, from these data it appears that it can occur between the beginning of June and the middle of July.

4.4 Fecundity

Fecundity of king crab as estimated by various authors is shown in Table 4.

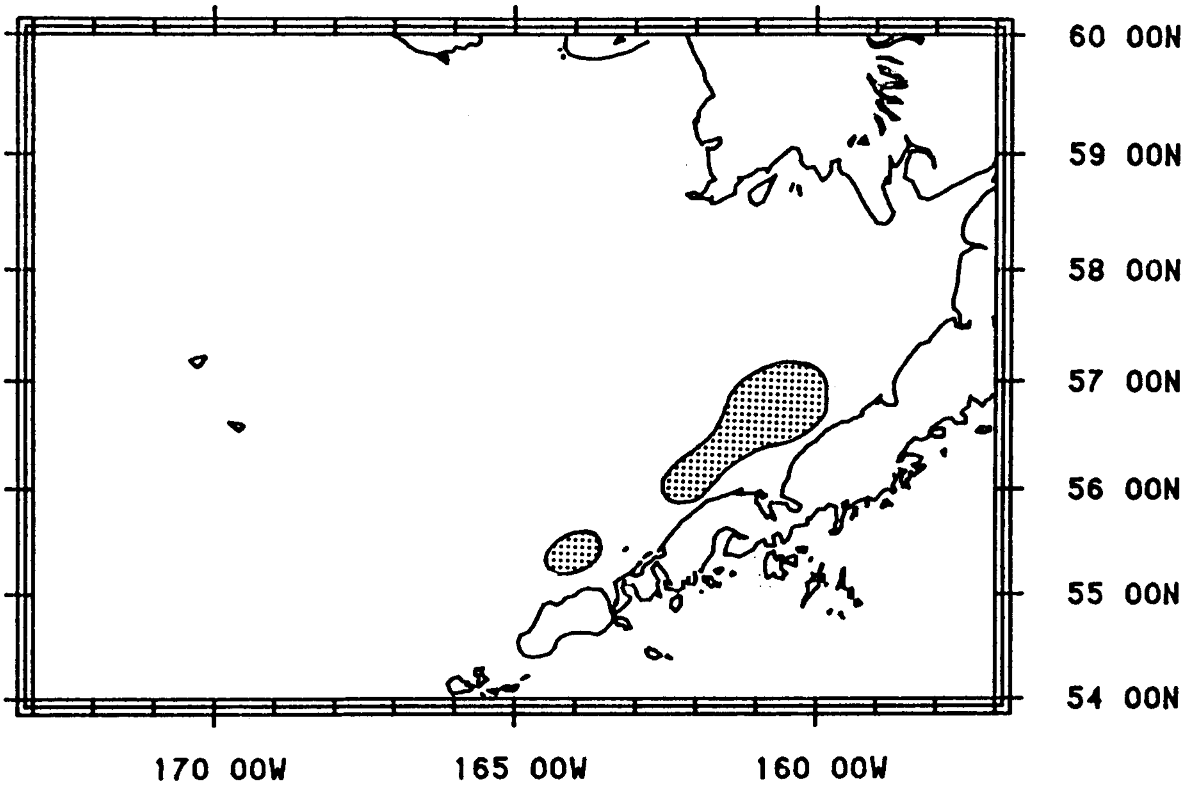


Figure 10. Spawning areas of Bristol Bay red king crab.

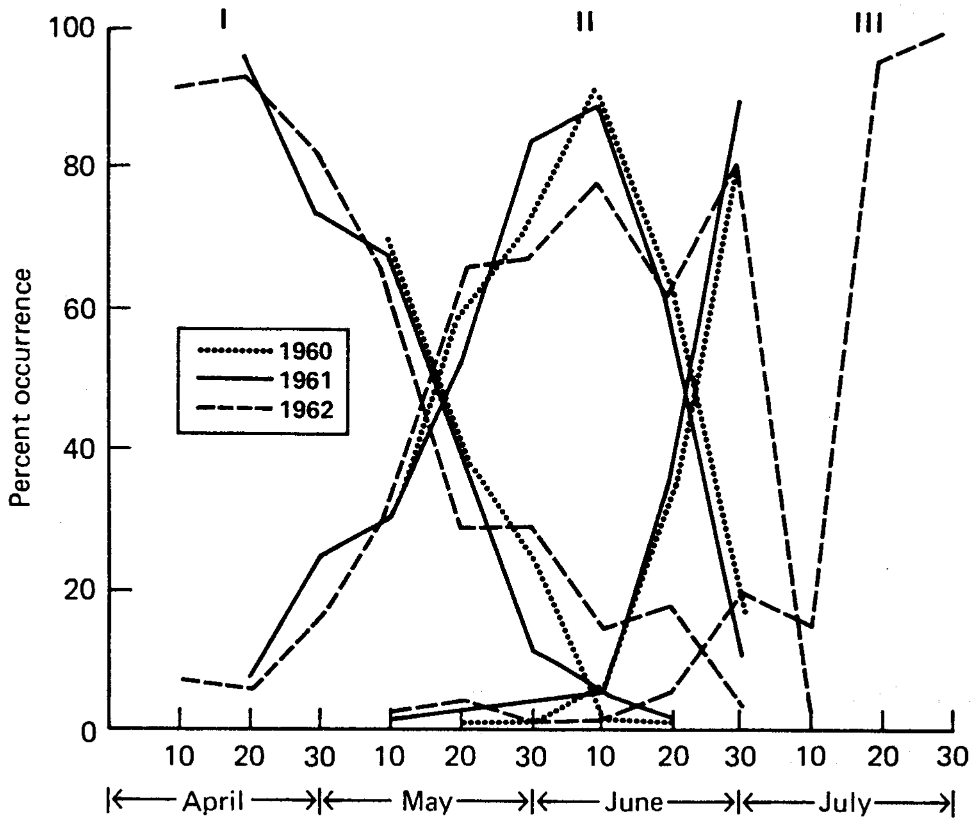


Figure 11. Occurrence of females with eyed eggs, empty egg cases and new eggs.

Table 4. The fecundity of king crab.

Source	Carapace width	No. of eggs	Area
Nakazawa (1912)	127-169 mm	62,550-345,900	Hokkaido
Marukawa (1933)	115-168 mm	69,598-270,204	"
Wallace et al. (1949)	128-145 mm	148,349-446,639	Canoe Bay
Rodin (1970)	94-171 mm	55,408-444,651	Bristol Bay

Nakazwa (1912) and Wallace (1949) held the view that the number of eggs carried by female king crab varies considerably not only between crabs of different size but among females of the same size. Rodin's (1970) studies on the fecundity of eastern Bering Sea king crab, however, indicate comparatively little variation in egg numbers within size groups and a direct relationship between fecundity and size of females (Fig. 12).

In all of these studies the number of crabs examined was very small, therefore, neither the accuracy nor the precision of the estimated fecundity can be evaluated. It is clear, however, that potential egg production in female king crab is very high and each year, all fertilized females characteristically produce a very large number of eggs with larger females tending to have larger egg clutches.

The high fecundity of king crab implies that the species is typically subjected to extremely high natural mortality. Inasmuch as the eggs are protected for almost a year to hatching and natural mortality of older juveniles and adults has been estimated to be relatively low (see later section), most of these very large mortalities occur between hatching and the early juvenile stages. Limited experimental evidence indicates that

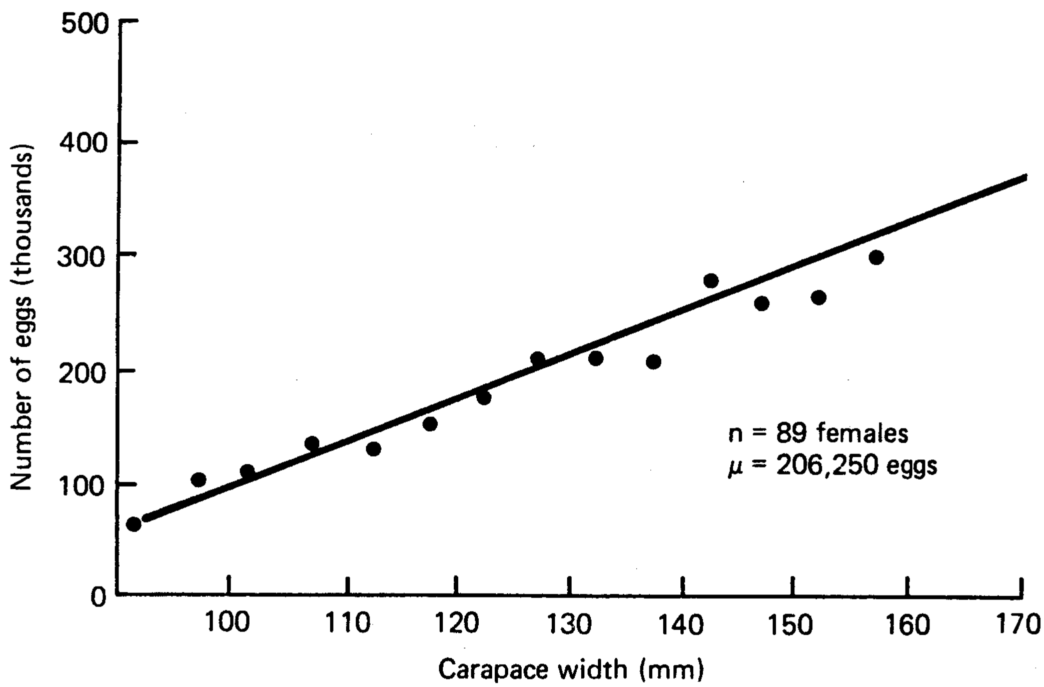


Figure 12. Fecundity of females as a function of size.

vulnerability is greatest at the first zoeal stage and diminishes through successive larval stages (Marukawa, 1933; Kurata, 1960).

5. FOOD AND PREDATORS OF RED KING CRAB

5.1 Food of Larval and Postlarval Crab

The stomach contents of larval and postlarval king crab reported by various authors is given in Table 5.

Marukawa (1933) and Shimizu (1936) considered diatoms to be the important part of the diet of larval king crab. Kurata (1960) in feeding experiments had zero survival of stage I zoea larvae fed exclusively on diatoms. Best survival was achieved with *Artemia nauplii* and Trochophores of *Chone teres*, a polychaete (Kurata, 1959) which indicates that a diet of animal origin must be the principal diet of larval king crab (Kurata, 1960).

5.2 Food of Adult King Crab

Stomach contents of adult king crab as reported by several authors is given in Table 6.

The food of king crab appears to be similar throughout its range. Polychaetes, molluscs, crustaceans and echinoderms have been observed to be the food items of principal importance.

King crab in the eastern Bering Sea must compete for food with a number of other bottom dwelling creatures. These include the Tanner crab (*Chionoecetes bairdi* and *C. opilio*), Pacific cod (*Gadus morhua macrocephalus*),

Table 5.--Stomach contents of king crab larvae and post larvae.

Author	Area	Contents
Marukawa (1933)	Hokkaido, W. Kamchatka	Zoea feed on pelagic diatoms, glaucothoe on bryozoa. Juveniles feed on Navicula, Synedra, Coscinodiscus, Nitzchia, Chaetocerus, Thalassiosira, Biddulphia, Fragilaria, Ceratium, Nereis, Zostera, Detritus
Shimizu (1936)	Hokkaido	Larvae on diatoms
Sato and Tanaka (1949)	Experimental	Zoea fed on Polydora sp., Zoea cannibalize other zoea
Kurata (1959, 1960)	Experimental	Zoea fed trochophores of Polydora, nauplii of Artemia salina and diatoms
Tsalkin (1969)	W. Kamchatka	Hydroids preferred by postlarval king crab
Feder, et. al. (1980)	Cook Inlet	Detritus, diatoms, Bryozoa, Harpacticoid copepods, ostracods

Table 6.--Food of adult king crab.

Author	Area	Contents
Marukawa (1933)	Hokkaido; W. Kamchatka	Cucumaria japonica, Cardium californiens, Astarte borealis, Chrysodomus sp. Spisula sp., Yoldia sp., Schizothaerus sp., Venus sp., Chlamys sp., Fusirius sp., Tellina sp., Pecten yessoensis, Strongylocentrus sp., Cynthia superba, Bryozoa, Zostera, Diatom
Nakazawa (1912)		Clams (Mactra sacchalinensis and Pecten yessoensis), Echinoderm (sea urchins), Sea cucumber (Cucumaria japonica), isopods
Takeuchi (1959)	W. Kamchatka	Clams - Nucula, Acila Yoldia, Musculus, Liocyma Macoma; Snails - Margarites, Pupinaria, Euspira, Tectonatica; Crab - hermit crab and other crab; Amphipods, Barnacles, Echinoidea, Ophiuroidea, Hydroidea, Polychaste worms and fish
Feniuk (1945)	W. Kamchatka	Molluscs, crustaceans and polychaetes
Mikulich (1954) and Kulichkova (1955)	W. Bering Sea	Clams - Yoldia, Serripes, Siliqua, Tellina; Snails - Polinices, Margarites; Crusdacea - amphipods, Cumacea; Echinodermata - Strongylocentrotus, Asterias, Ophiuroidea; sea squirts - Pelonia, Boltenia
McLaughlin and Hebard (1961)	E. Bering Sea	Molluscs, Asteroids, Ophiuroids, Echinoids, Shrimp, Polychaetes, Crustacea
Neiman (1963)	E. Bering Sea	Ophiura sarsi
Chebanov (1965)	S.E. Bering Sea	Ophiura sarsi, Yoldia, spirorbis, polychaetes, isopods, young Chionoecetes. opilia, brown algae, unidentifiable, brown, gelatinous mass
Cunningham (1969)	Bering Sea	Brittlestar (Ophiura sarsi), basketstar (Gorgonocephalus), Sea urchin (strongylocentrus sp.), Sand dollar (Echinarachinius parma) most important by weight. Clams - Nuculana radiata. Clinocardium californiense. Chlamys sp. Snails - Solariella sp. and Buccinidae; crabs - Hyas coarctatus alutacens, Erimacrus isenbeckii, Pagurus sp.; sandfleas - amphipods
Tarverdizva (1976)	E. Bering Sea	Polychaetes, Sand dollars (Echinarachnia parma); gastopods - Trochidas and Nactidae; Clams - Yoldia, Nuculana, Nucula, Cyclocardia
Feder and Jewett (1980)	S. E. Bering Sea	Cockle (Clinocardium ciliatum), Snail (Solariella sp.), Clam (Nucula fossa), Brittlestar (Amphiuridae), Polychaete worm (Cistenides, sp.) and Snow Crab (Chionoecetes spp.)
Feder et. al. (1980)	Cook Inlet, Kamishak Bay, Kachemak Bay	Barnacles, Clams (Spisula polynyma)
Feder & Jewett (1981a)	Izhut Bay, Afognak Island	Fish (probably capelin)
	Kilinda Bay, Kodiak	Clams
	Kodiak and shallow bays of Kodiak	Cockles, crustaceans and fish, Clams (Protothaca staminea and Macoma spp.)
		Cockles (Clinocardium spp.), Acorn barnacles (Balanus crenatus)

yellowfin sole (Limanda aspera), Alaska plaice (Pleuronectes quadrituberculatus), rock sole (Lepidopsetta bilineata), flathead sole (Hippoglossoides elassodon) and rex sole (Glyptocephalus zachirus) (Feder and Jewett, 1981b; Takeuchi, 1959). Most of the fish species are swifter and much more mobile than the king crab. The abundance of these fish species can, therefore, have considerable impact on the growth of the eastern Bering Sea king crab stock.

5.3 Predation on King Crab

Table 7 includes a list of animals which have been reported by several authors to be predators on king crab.

An estimate of the magnitude of predation on larval red king crab has only recently become available (Haflinger and McRoy, 1983). They estimated that 18 billion king crab megalops larvae were consumed in a one month period by yellowfin sole. The authors considered the estimate to be conservative even as a measure of the predation by yellowfin sole alone.

According to Bakkala and Wespestad (1984), the biomass of yellowfin sole in the eastern Bering Sea which was about a million tons in 1975 doubled to about 2 million tons in 1979-1981. In 1982, biomass apparently increased to over 3 million tons and to almost 4 million tons in 1983. Cohort analyses indicate that the eastern Bering Sea yellowfin sole population exceeded 20 billion fish in 1981. The female spawning population of eastern Bering Sea king crab declined rather steadily after 1979 from about 122 million crab to less than 10 million crab in 1983. Although yellowfin sole and king crab compete to some extent for similar food, there are no obvious explanations for

Table 7.--Predators on king crab.

Author	Area	Predators
Gray (1964)		Halibut (Hippoglossus stenolepis) prey on large, recently molted crab.
Powell & Nickerson (1965)	Kodiak	Korean Horsehair crab (Erimacrus isenbeckii) observed to prey on juvenile king crab.
Feder and Jewett (1981a)	Kodiak	Sculpin (Hemilepidotus hemilepidotus) predators on postlarval crab 10 mm in length.
	Bering Sea	Sea otters predators on adult king crab.
Shimada and June (1982)	Bering Sea	Pacific cod.
June (1984)	Bering Sea	Pacific cod.
Haflinger and McRoy (1983)	Bering Sea	Yellowfin sole predation on larval and juvenile king crab. Conservatively estimated that 18 billion king crab larvae are consumed by yellowfin in eastern Bering Sea in a 1 month period.
Pruter (1983)		In areas where king crab are abundant, they composed 2 to 78% of the total weight of stomach contents of Pacific cod in 1981.

the inverse relationship in the abundance of the two groups a seen in Fig. 13. Yellowfin sole cannot possibly prey upon sexually mature red king crab. As mentioned in the previous paragraph, however, zoea and megalops of king crab have been shown to be an important component of the stomach contents of yellowfin sole on the northern Aleutian shelf during the spring and summer seasons. The quantity of larvae can be expected to be directly related to the abundance of fertilized female king crab. It is reasonable to assume then, that the decrease in fertilized female king crab was accompanied by a corresponding decrease in the abundance of crab larvae. The biomass of yellowfin sole has increased substantially in spite of this expected decrease in larval crab abundance. Although larval king were observed by Haflinger and McRoy to constitute an important part of the diet of yellowfin sole at specific times and places, they are obviously a very minor component of the total food intake of eastern Bering Sea yellowfin sole. Although the predation of 18 billion crab larvae seems very substantial, when one considers that the eastern Bering Sea yellowfin sole stock exceeds 20 billion, the consumption rate on the average is slightly more than one king crab larvae per fish.

Even if they constitute only a very minor component of their diet, the predation of 18 billion crab larvae may have some impact on the productivity of the king crab stock. To evaluate whether this potentially large mortality has affected the productivity of the eastern Bering Sea king crab stock, the relationship of the number of king crabs recruited to age 5 and the biomass of yellowfin sole was examined (Fig. 14). Although the predation by yellowfin sole may have been one of many forces of mortality which may have contributed to the suppression of recruitment, there is no obvious evidence of a negative

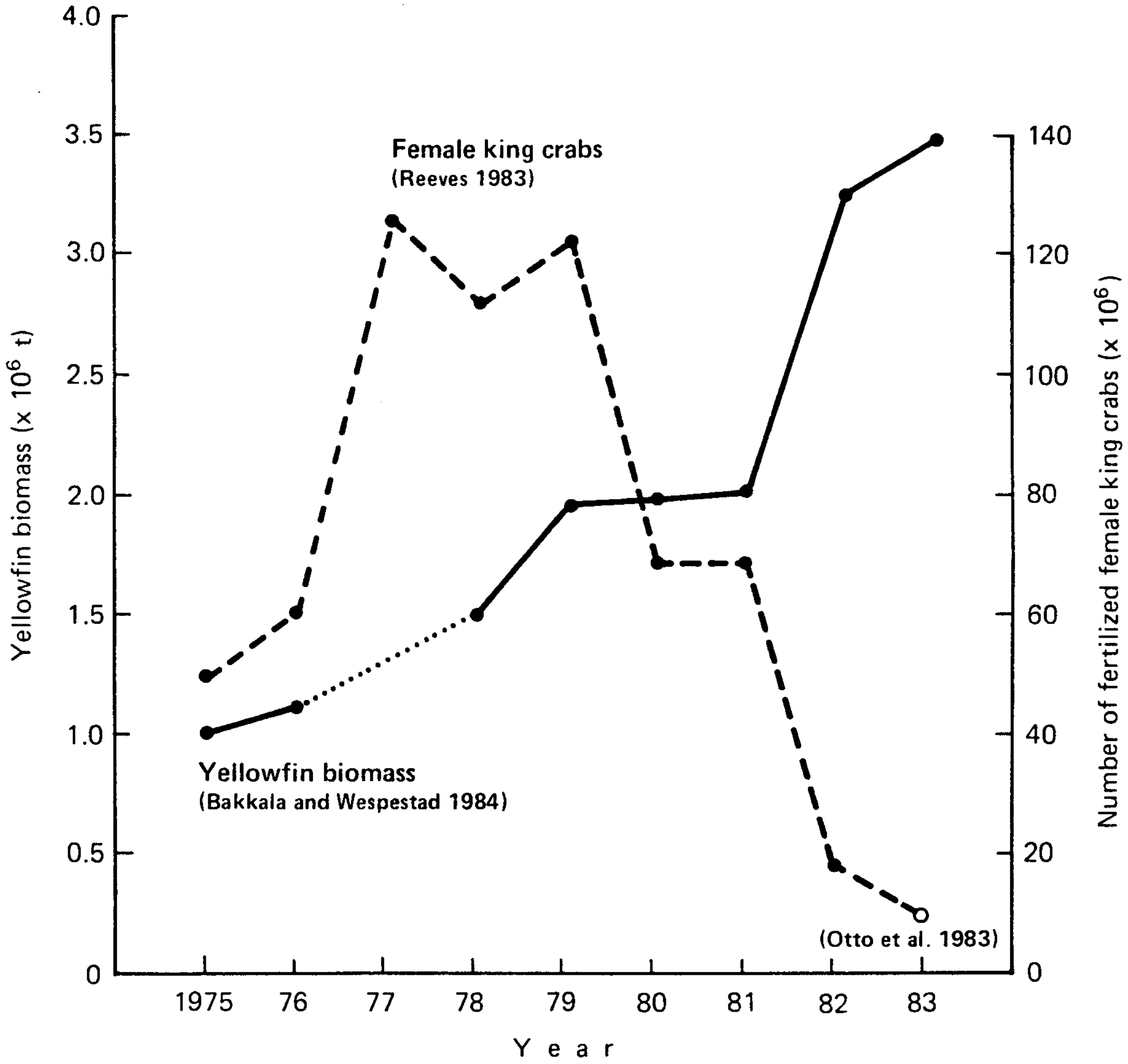


Figure 13. Yellowfin sole biomass and number of fertilized female king crab.

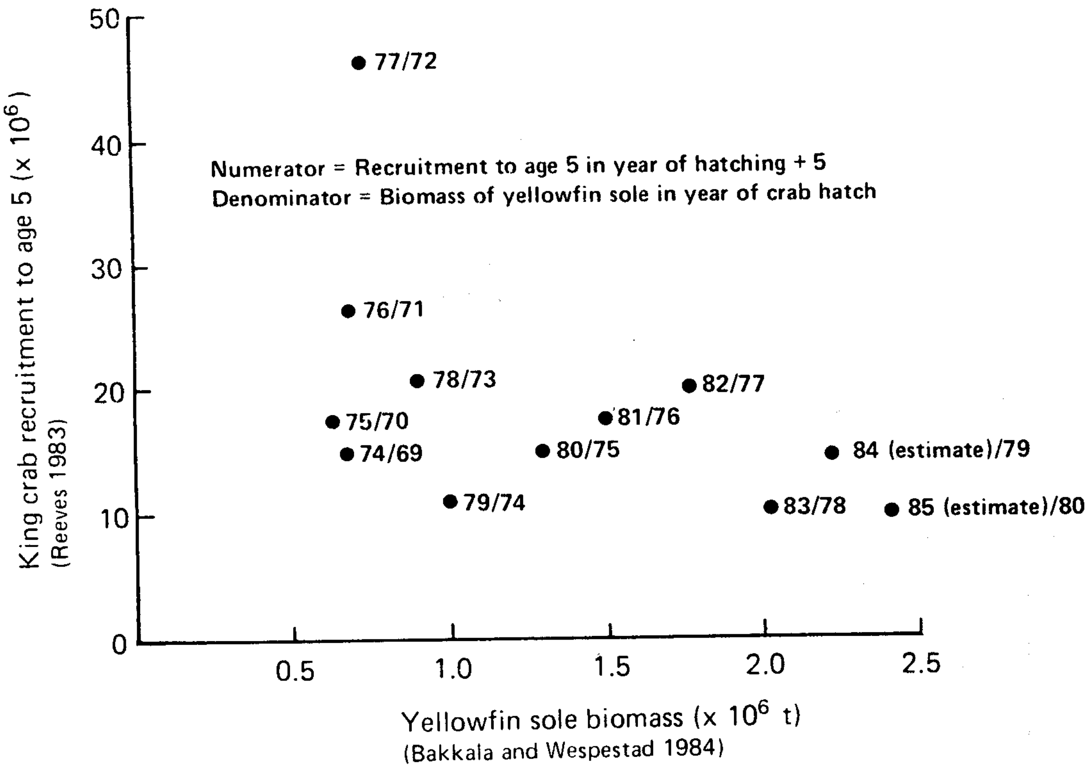


Figure 14. Relationship between yellowfin sole biomass and king crab recruitment to age 5.

trend in the recruitment of crab which might be attributable to the increasing biomass of yellowfin sole. The foregoing discussions have assumed an increasing trend in the biomass of the eastern Bering Sea yellowfin sole population as indicated by the NMFS trawl surveys. An increase of this magnitude in the biomass of yellowfin sole in a single year could not have occurred through recruitment, survival and growth of the exploitable stock. Bakkala and Wespestad (1983 & 1984) attribute some of the increase in biomass to an increase in the area surveyed and to the better bottom tending qualities of the trawl gear used in the 1982 survey (and thereafter).

Other flatfish (e.g., rock sole and flathead sole, which may have a combined biomass of about a million mt) sculpins (*Myoxocephalus* spp.) and elasmobranchs (*Rajidae*) which are resident to the area and transient species such as several species of Pacific salmon migrating through the northern Aleutian shelf waters may also prey upon larval and juvenile king crab. The food habits of the Walleye pollock (*Theragra chalcogramma*) are not very well known. It is conceivable that pollock also consume pelagic larvae of red king crab. If crab larvae constitute even a minor part of their diet, because of the substantial biomass of pollock (more than 6 million mt in 1983) the total consumption of larvae may be substantial.

Pacific halibut (*Hippoglossus stenolepis*) and Pacific cod (*Gadus morhua macrocephalus*) are the only fish species which have been reported to consume adult king crab. The deep water flounders such as the Greenland turbot (*Reinhardtius hippoglossoides*) and arrowtooth flounder (*Atheresthes evermanni* and *A. stomias*) and also the skates (*Rajidae*) appear to have the capability to prey upon adult crab.

June (pers. com.) examined the red king crab content in the stomachs of Pacific cod collected in eastern Bering Sea trawl surveys between May 5 and July 20, 1981. The remains of red king crab were in 10% of the total cod stomachs examined and 14% of the stomachs of cod 410-780 mm in length. The stomachs contained whole crabs as well as legs only. All of the crab in the stomachs of cod had new shells which were soft and flexible, indicating they were recently molted crabs. Determination of the sex of crabs was difficult due to partial digestion and the softshelled condition of the crabs. All crabs for which sex could be determined were females, which seems reasonable, considering the area and period of sampling. For the same reasons, measurements could be obtained from only 7 of the 34 whole crabs extracted from cod stomachs. These crabs were from 53.4 to 160.3 mm in carapace width. It was estimated that 58% of the crabs consumed were less than 100 mm carapace width, therefore, almost half the crab consumed were sexually mature females.

The biomass of Pacific cod in the area inhabited by king crab was estimated by the trawl survey to be about 240 thousand t. Assuming a minimum consumption of red king crab of 0.051% of cod body weight per day, Pacific cod were estimated to have eaten about 123 mt or about 110,000 king crab, daily. Using the maximum estimated ration of 0.551% of body weight per day, 1,300 mt or 1,163,500 king crab would be consumed each day. Applying these minimum and maximum daily consumption rates to the 30 days or so during which females might be expected to be in softshelled condition, the potential mortality to female crab from cod predation during the spawning and postspawning period may range from 3.3 million to 34.9 million crabs (June, pers. com.).

Evidence supporting June's observations concerning cod predation upon female king crab is shown in Fig. 15. The biomass of Pacific cod of eastern

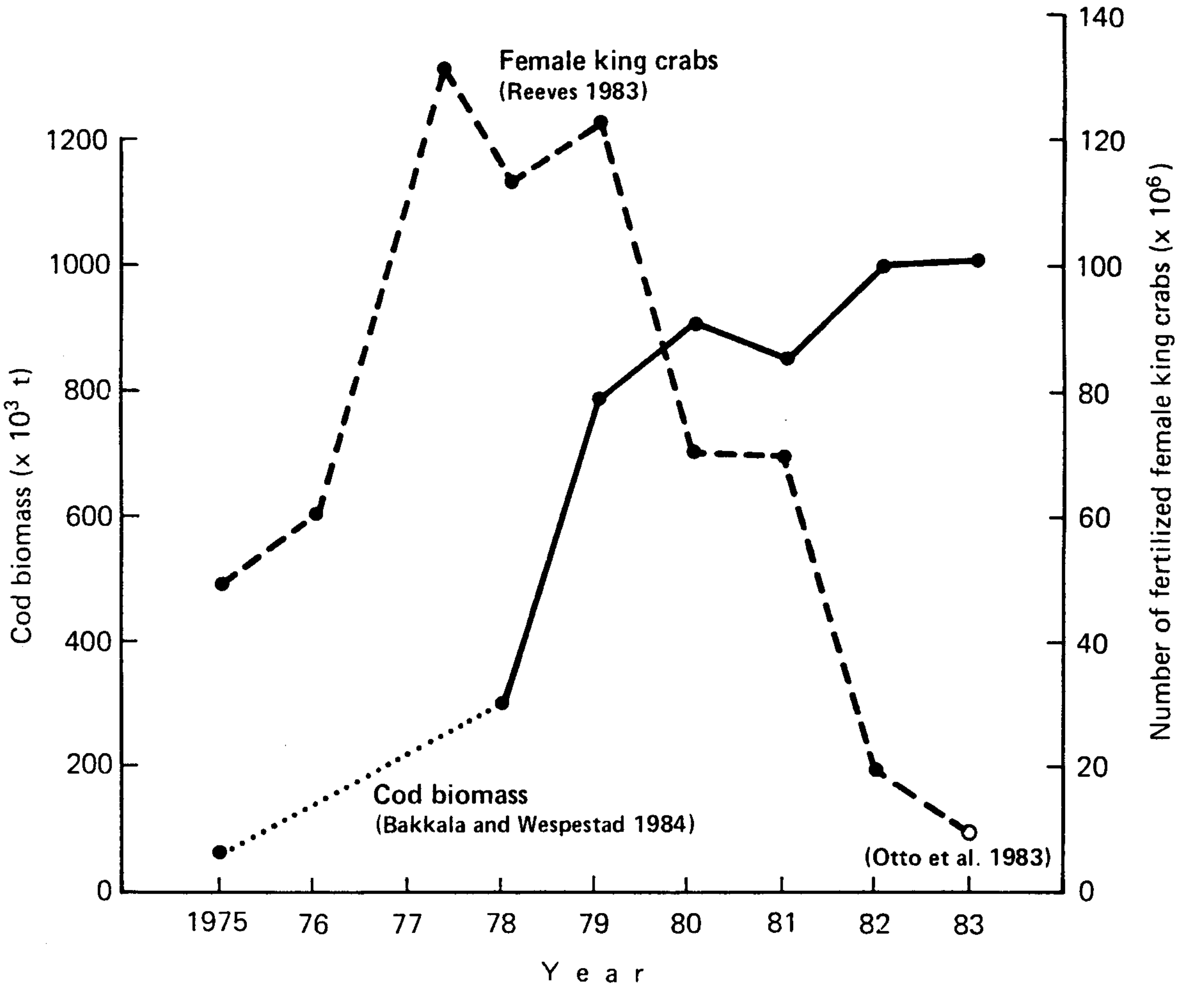


Figure 15. Number of fertilized female king crab and biomass of Pacific cod in eastern Bering Sea.

Bering Sea as estimated by the NMFS trawl surveys increased from about 300,000 tons in 1978 to almost 800,000 tons in 1979 and over 1 million tons in 1983 (Bakkala and Low, 1984). Although the increasing catch per unit effort (CPUE) from the Japanese longline fishery indicates some increase in the abundance of cod (2X from 1979 to 1981), the indication of increase was considerably less than the 4 to 5 fold increase in CPUE from 1976 to 1983 in the trawl surveys (Bakkala & Wespestad, 1984). The rapid increases in biomass indicated from the trawl surveys cannot reasonably be attributed to biological, population growth and is more likely a reflection of the underestimation of the eastern Bering Sea Pacific cod resource in years prior to 1982 when less efficient trawls were utilized.

Although the rate of increase remains a question, there is no doubt that the biomass of Pacific cod has increased in recent years. As the biomass of Pacific cod increased, there was a corresponding decrease in the number of fertilized female king crab from over 120 million in 1979 to less than 10 million in 1983 (Fig. 15).

From the evidence at hand, predation by Pacific cod can reasonably account for a substantial portion of the observed decline in the adult female king crab of eastern Bering Sea. In combination perhaps with mortalities which might occur in discarding female crabs in the king crab fishery, predation by Pacific cod appears to be the most reasonable explanation for the decline of the female spawning stock. One can only speculate on the mortality from cod predation (and other fish predators) which might accrue to other components of the eastern Bering Sea stock during their respective molting periods.

The sea otter (Enhydra lutris) is the only mammal which has been reported to consume adult king crab. Although there is no substantiating evidence, the harbor seal (Phoca vitulina) and the deeper diving ice seals (ringed seal, Phoca hispida; ribbon seal, P. fasciata; and bearded seal, Erignathus barbatus) may also include adult king crab in their diets.

6. GROWTH, AGE AND NATURAL MORTALITY

6.1 Growth

King crab grow by shedding their exoskeleton in a process called molting. The growth rate of crabs then is determined by the frequency of molting and the amount of growth added with each molt.

6.1.1 Molting Process

The molting process in king crab has been described by Marukawa (1933), Weber (1967), Sakuda (1958) and others. One or two weeks prior to molting, coloration of the shell changes and spaces between the abdominal plates begin to widen slightly. About three days before molting the crab becomes very inactive and ceases to feed (Marukawa, 1933) and the abdomen begins to swell. Within a day of molting (12-18 hours according to Weber, 1967 and 1-6 hours before according to Takeuchi, 1960; Powell, 1960 and JFA, 1963) the abdomen swells very rapidly, rupturing the abdominal covering and subsequent sloughing off of the abdominal plates. Simultaneously, pressure is exerted under the carapace leading to breaks in the sides and posterior margins of the old shell. The muscles become flabby and shrink sufficiently to be withdrawn past the strictures of the leg joints. A colorless mucuslike substance is deposited between the old and newly developing shells. Ultimately, the crab backs out through an opening between the hind margin of the carapace and the upper abdominal plates. In molting, all structures of ectodermal origin are discarded. These include not only the carapace and integument of the legs but also the mouth parts, esophagus, stomach, chitinous plates around the stomach, the hindgut, tendons and certain gill tissues (Marukawa, 1933).

The observed time required for molting ranges from 4 minutes (Sakuda, 1958) to 40 minutes (Takeuchi, 1960). Marukawa (1933), the Japan Fishery Agency (1963) and Weber (1967) generally agree that the actual molting requires ten minutes or less. Mihara (1932) estimated that adult females require 13 minutes to molt and that adult crabs in general required 13-15 minutes. He estimated that juvenile crab required about 9 minutes.

Although the actual process of molting is relatively brief, there is a period of three or four days after molting when the crab remains relatively inactive and not feeding and an additional week or so (about ten days after molting) before the new carapace is as hard as the old (Marukawa, 1933). Crabs are particularly vulnerable to mortality during molting. Results of larval rearing experiments show that large mortalities of Zoea I larvae (which was sometimes 100% in experiments) occur with the onset of molting. Marukawa (1933) observed that such mortalities occurred at about the time of the transition from yolk absorption to the feeding stage. Sato and Tanaka (1949) and Kurata (1960) observed large mortality to Zoea I larvae at the time of molting indicating that some extraordinary stress may be associated with ecdysis, at least, in the first zoeal stage. Similar physiological stress, although perhaps to a lesser degree, may also contribute to debilitation and mortality in later moltings as well. In all postlarval size groups, premolting lethargy and the temporary loss of the hard, spiny, protective exoskeleton for as long as ten days, increases greatly the susceptibility of crabs to predation.

6.1.2 Molting Frequency

Molting does not occur with uniform frequency but varies with age and sex of crab.

The initial molts although resulting in growth are essentially for metamorphic transitions through the four zoeal stages and the single megalops stage to the first adult form. Table 8 from Kurata (1961) records the molting history of a single crab which was reared under experimental conditions through 13 molts. Kurata as well as Marukawa (1933) identify five molts from hatching to the first instar or adult form. Weber (1967) describes an additional molt which occurs usually within minutes of hatching between the prezoeal form and the Zoea I larvae. Although Marukawa (1933) illustrates a newly hatched larva it was not described as a prezoea nor was there mention of a molt from this form to the first zoeal stage. The intermolt intervals of the single crab described in Table 8 are considerably shorter than those estimated by other authors, particularly for the duration of each of the five larval stages. Marukawa (1933) calculated the first molt to occur about 21 days after hatching. Subsequent molts from Zoea II to Zoea III, Zoea III to Zoea IV were estimated to occur at about two week intervals. He presumed molting from Zoea IV to the megalops stage required an additional two weeks.

Table 8.--The hatching and molting history of a single king crab reared in captivity.

Hatched:	14 April	Zoea I
1st molting:	22 April	Zoea II
2nd molting:	30 April	Zoea III
3rd molting:	9 May	Zoea IV
4th molting:	19 May	Glaucothoe
5th molting:	1 June	Small crab 1st instar
6th molting:	22 June	Small crab 2nd instar
7th molting:	14 July	Small crab 3rd instar
8th molting:	2 August	Small crab 4th instar
9th molting:	19 August	Small crab 5th instar
10th molting:	2 September	Small crab 6th instar
11th molting:	19 September	Small crab 7th instar
12th molting:	9 October	Small crab 8th instar
13th molting:	9 November	Small crab 9th instar

This schedule of larval development can, however, be modified by environmental circumstances. Kurata (1960) has shown that temperature is the most important factor governing rate of development of larval crab, assuming the availability of sufficient food. Within the limit of temperatures in which zoea larvae can survive (2° to 15°C), Kurata (1960 & 1961) found a linear relationship (i.e., development proceeded more rapidly at higher temperatures) which was expressed in terms of degree-days (Temperature in Degrees Centigrade X No. of Days). He calculated that 460 degree days were required for development from hatching to the first adult form. Considering this heat budget requirement, in eastern Bering Sea surface and subsurface temperatures, Weber (1967) estimated that a prezoea hatched in May would attain the first adult stage by mid-August. Empirical verfication of this calculated schedule was obtained in studies of larvae distribution in eastern Bering Sea by Takeuchi (1962), Rodin (1970), Haynes, (1974) and Armstrong et al. (1983).

In summary: After hatching in April and May, larval king crab undergo 5 molts, metamorphosing through 4 zoeal stages and a megalops stage before attaining the first adult form. This process requires slightly less than three months, with the first adult forms which are about 2mm in carapace length settling on the bottom in July and August.

From hatching to the end of the first year, king crab molt a total of from 11-13 times, including the 5 larval molts (Marukawa, 1933; Kurata, 1961; Weber, 1967). The size of crab at the end of the first year was given by Marukawa as 6.5 mm carapace length. For crab at Unalaska, Weber (1967) found crab of this age to range from 9-14 mm with an average carapace length of 11 mm.

Between the ages of 1 and 3, juvenile king crab undergo eight molts. At the end of the third year, the carapace lengths range from 50-67 mm with an average of 60 mm (Weber, 1967).

From the ages of 3 to 7 years, both male and female king crab molt once a year. For the female the annual molt is a necessary precursor to ovulation although females can molt without necessarily ovulating. For males the annual molt appears to occur in late fall or winter in Bering Sea (Wallace, 1949) and is unrelated to spawning.

After 7 years of age, females continue to molt annually, however, there is an increasing frequency of males which skip molting for one or two years (very few molt less frequently than biennially).

6.1.3 Age and Growth

The maximum size of crab reported from Asian waters is 226 mm carapace width or 181 mm carapace length (Kajita & Nakagawa, 1932). The largest crab of record which I was able to find in the literature was a male crab measuring 224 mm in carapace length taken in the Pacific Ocean (Wallace et al., 1949). The largest female taken in the Pacific was 189 mm. The largest male taken in 1941 in the Bering Sea was 197 mm in carapace length and the largest female, 170 mm (Wallace et al, 1949).

The maximum age of king crab is difficult to accurately ascertain. An approximation of the longevity of king crab has been obtained through tagging experiments by Powell (1965) and Hoopes and Karinen (1972). From the estimated age at tagging and the years intervening before recovery, Hoopes and Karinen estimated the age of one male and one female to be 17 (carapace length

= 170 mm and 157 mm, respectively) and one female with carapace length of 162 mm to be 18 years of age. Based upon the size-age relationship of these tagged crabs, it is conceivable that the 197 mm carapace length crab captured by Wallace et al. (1949) may have been almost 20 years old, the maximum age of Bering Sea king crab conjectured by Kurata (1961).

6.1.3.1 Larval Growth

Table 9 shows the size of the body and various body parts of the four zoeal stages. Total body length increases by about 10% in the first two molts and by 22% in the last molt from Zoea III to Zoea IV. Armstrong et al. (1983) calculated the dry weight of king crab from the mature egg through the megalops stage (Fig. 16).

6.1.3.2 Juvenile Growth

The growth of immature king crab has been described by a number of authors (Nakazawa, 1912; Kajita & Nakagawa, 1932; Wang, 1936; Kurata, 1961a & 1961b; Powell, 1960; Bright et al., 1960; Weber, 1967; Takeuchi, 1960). As mentioned by Weber (1967) the various sources present an array of growth curves which differ far more than can be simply explained by racial and environmental variability. Weber's (1967) study of the growth of juvenile king crab in eastern Bering Sea is not only directly relevant to our specific geographic area of concern but was the most thorough. Information relevant to the age and growth of juvenile king crab are summarized in Figs. 17 & 18. Among other things, Weber concluded the following:

Table 9.--Rate of growth of zoea larvae in each stage after molting.

Parts, measured	Size of 1st stage	(2nd stage) Size	(2nd stage) Rate of growth by 1st. moulting	(3rd stage) Size	(3rd stage) Rate of growth by 2nd moulting	(Last stage) Size	(Last stage) Rate of growth by 3rd moulting
Total length	4.56 mm.	5.02 mm.	10%	5.58 mm.	16.5%	6.85 mm.	17%
Length of rostral spine	1.08	1.25	16	1.58	26	1.62	2.5
Length of carapace	1.45	1.70	17	2.08	22	2.41	21
Width of carapace	1.12	1.29	15	1.41	15	1.78	26
Length of abdomen	2.14	2.16	1	2.24	4	2.78	24
Width of 2nd abdominal segment	0.30	0.37	23	0.45	22	0.51	12
Width of 5th abdominal segment	0.23	0.27	17	0.32	15	0.43	34
Length of the longest spine of telson	0.51	0.57	12	0.60	5	0.66	10
Length of dorso-lateral spine of carapace	0.45	0.56	25	0.91	62	1.00	10
Length of exopodite of 1st maxilliped	0.49	0.51	4	0.59	14	0.60	2
Length of exopodite of 2nd maxilliped	0.51	0.53	4	0.60	13	0.64	7
Length of exopodite of 3rd maxilliped	0.34	0.37	9	0.49	32	0.49	-
Length of exopodite of antenna	0.83	0.87	5	1.03	18	1.11	8
Longest diameter of eye	0.48	0.49	2	0.50	2	0.51	2
Shortest diameter of eye	0.28	0.28	-	0.28	-	0.30	8
Length of abdominal appendages	-	-	-	0.06	-	0.60	900
Length of uropods	-	-	-	0.26	-	0.37	50

Source: Marukawa (1933)

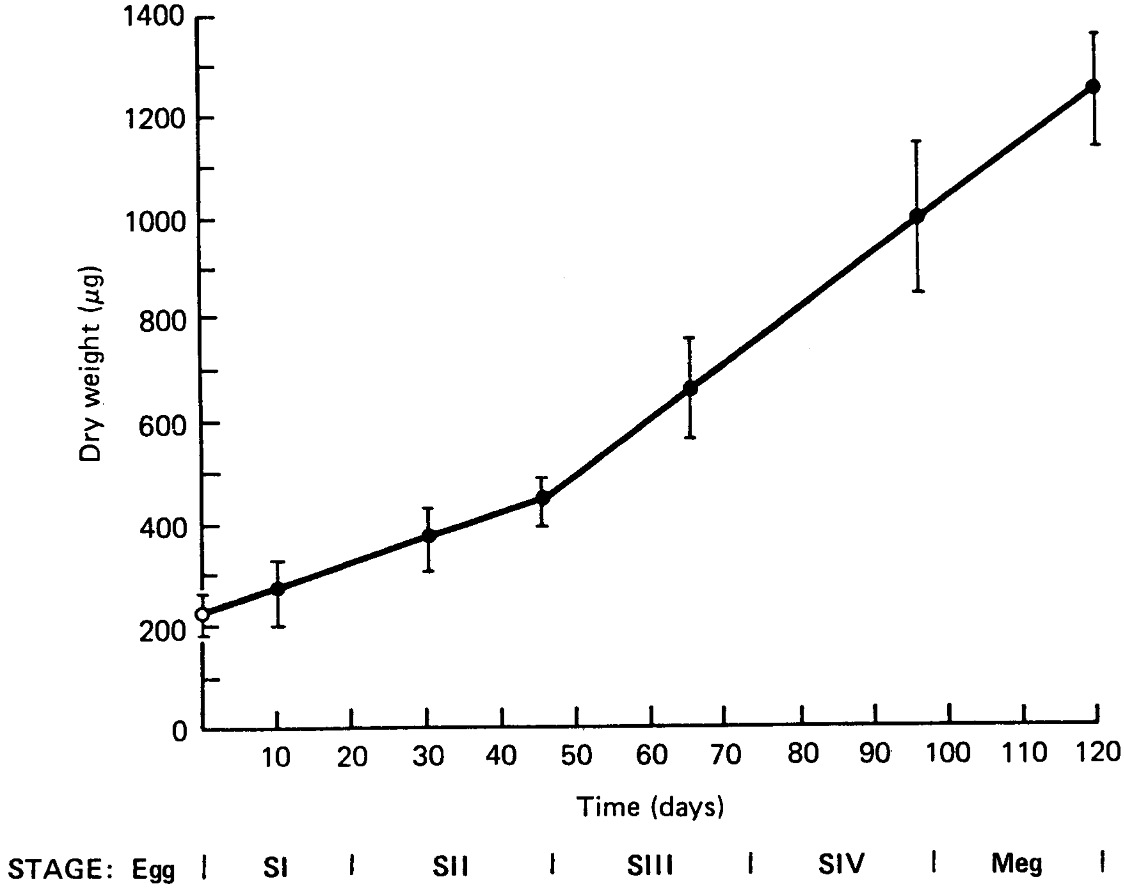


Figure 16. Increase of dry weight of king crab larvae from egg through megalops stage.

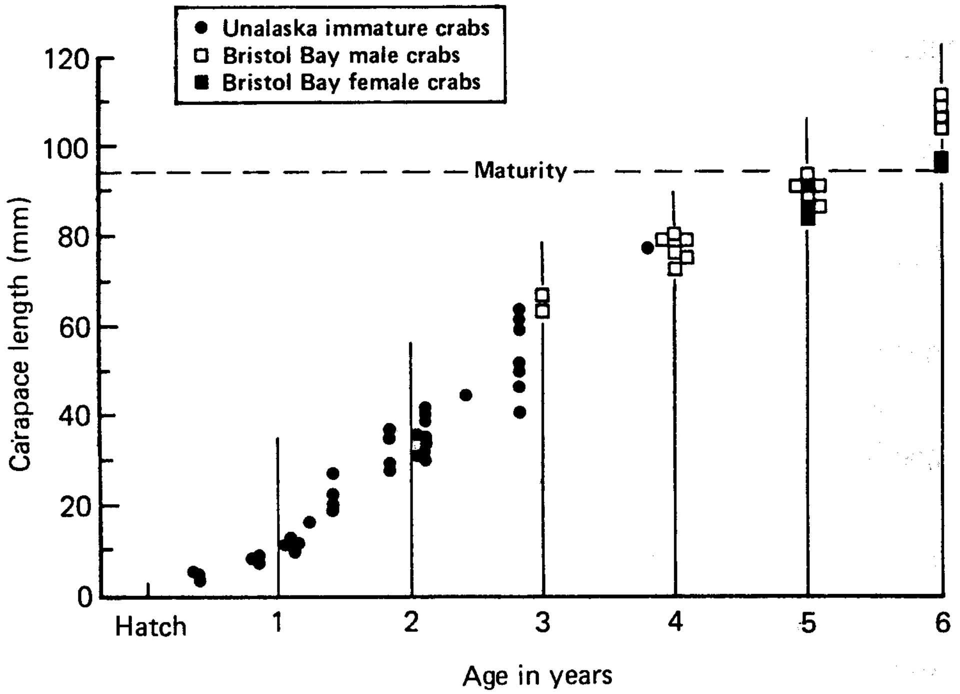


Figure 17. Modal carapace length relative to age for immature king crab.

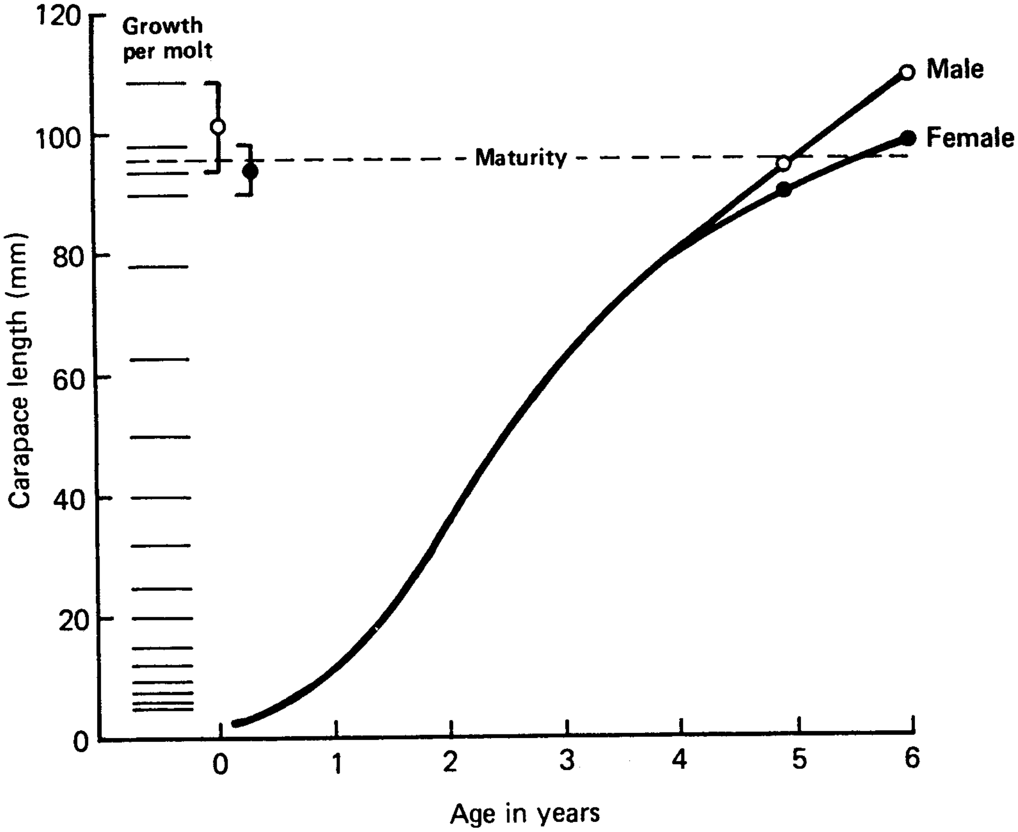


Figure 18. Growth curves of immature king crab of southeastern Bering Sea.

1. Both male and female king crab in eastern Bering Sea mature at about 95 mm carapace length (about 5 years for males and 5 1/2 years for females).
2. Growth per molt for confined crabs 4 mm to 60 mm in carapace length ranged from 23% at 10 mm to 27% at 50 mm. Growth rate of unconfined crabs 9-27 mm was one percent greater.
3. From an analysis of the progression of length modes indicates that the average lengths attained by juveniles at ages 1 through 6 are as shown in Table 10.
4. Immature crabs longer than 65 mm molt annually.

6.1.3.3 Growth of Mature Crabs

The growth of adult king crab of various geographic regions has been described by a number of authors. Age and growth of crabs around Hokkaido was studied by Nakazawa (1912), Kajita and Nakagawa (1932), Marukawa (1933), Mihara (1936), Wang (1937) and Kurata (1961). The pre-World War II studies which were based upon size frequency analyses produced irreconcilable differences in estimates of longevity, size at age and growth rate. A critique of these studies is given by Weber and Miyahara (1962) in which they concluded that due to differences in interpretation of modal values in length frequency analyses, the earlier studies tended to rather severely underestimate or overestimate growth rates and longevity of king crab.

The growth of king crab in the Gulf of Alaska has been discussed by Powell (1967), Eldridge (1975) and McCaughran and Powell (1977).

More recent studies on the age and growth of adult king crab have obtained more direct estimations of growth increments based upon tagged crab

Table 10.--Average length by age of immature king crabs of southeastern Bering Sea.

Age (years)	Average carapace length (mm)	
	Male	Female
1	11	11
2	35	35
3	60	60
4	78	78
5	94	90
6	109	98

Source: Weber (1967)

as well as consideration of shell condition relative to the frequency and probability of molting. Studies of Gulf of Alaska king crab include those by Powell (1967), Eldridge (1975) and McCaughran and Powell (1977). Growth rate of mature king crab of the Kodiak area (or any area other than eastern Bering Sea) will not be discussed in any detail in this report. It is sufficient to note that king crab south of the Alaska Peninsula are larger and have a faster growth rate than king crab of eastern Bering Sea (Wallace et al., 1949; Powell, 1967).

Growth of Bering Sea king crab has been studied by Weber and Miyahara (1962), Weber (1965), Kurata (1961), Hoopes and Greenough (1970). Results of these studies were critically evaluated and incorporated into a growth model which took into account molting history and probabilities as well as size specific natural mortality (Balsiger, 1974).

Wallace et al. (1949) observed that female king crab taken in the eastern Bering Sea in 1941 were oviferous at 86-102 mm in carapace length. Weber (1967) examined the same relationship with the addition of data from the three years, 1956-1958 and concluded that the majority of females in eastern Bering Sea became mature at 90-100 mm carapace length. On the basis of changes occurring in the size of the merus and chela relative to carapace size and histological changes in the ductus deferens, Wallace et al. (1949) tentatively concluded that male king crab of eastern Bering Sea attained sexual maturity at approximately 100 mm carapace length. For eastern Bering Sea crab, the size at maturity for both sexes of king crab has been accepted as being about 95 mm carapace length. For males, this length corresponds to an age of about 5 years and for females 5 1/2 years.

An analysis of the progression of mean length frequency modes in successive years by Weber and Miyahara (1967) showed a rather consistent annual growth increment of 15 mm for adult male king crabs. The mean expected growth increment resulting from regression analysis (Expected Growth Increment $= Y = 13.14 + 0.018X$) varied from 15.1 mm for carapace length of 110 mm to 16.0 mm for carapace length 160 mm, a difference of less than 1 mm. On the strength of these analyses, growth increment per molt was considered by Weber and Miyahara to be 16 mm for male Bering Sea king crab 110 mm and larger.

Curves for the growth in length of mature (ages 5-14) male and female king crabs which have been used in most recent evaluations of the condition of the eastern Bering Sea king crab stock are given in Fig. 19. Comparable curves for the growth in weight are shown in Fig. 20.

6.2 Natural Mortality

6.2.1 Eggs

As previously mentioned, king crab eggs are retained by the female for about 11 months and develop entirely within the protected environment of the abdominal flap. Marukawa (1933) observed that very few eggs remain on the abdomen of the female as dead eggs after the completion of hatching. He, therefore, concluded that the percentage of eggs hatching or survival of eggs to hatching was extremely high.

Otto et al. (1982) and Reeves (1983) reported a high incidence of crab with incomplete egg clutches in the 1982 Bering Sea king crab surveys. Fertilized females in 1982 were dominated by larger and old shelled

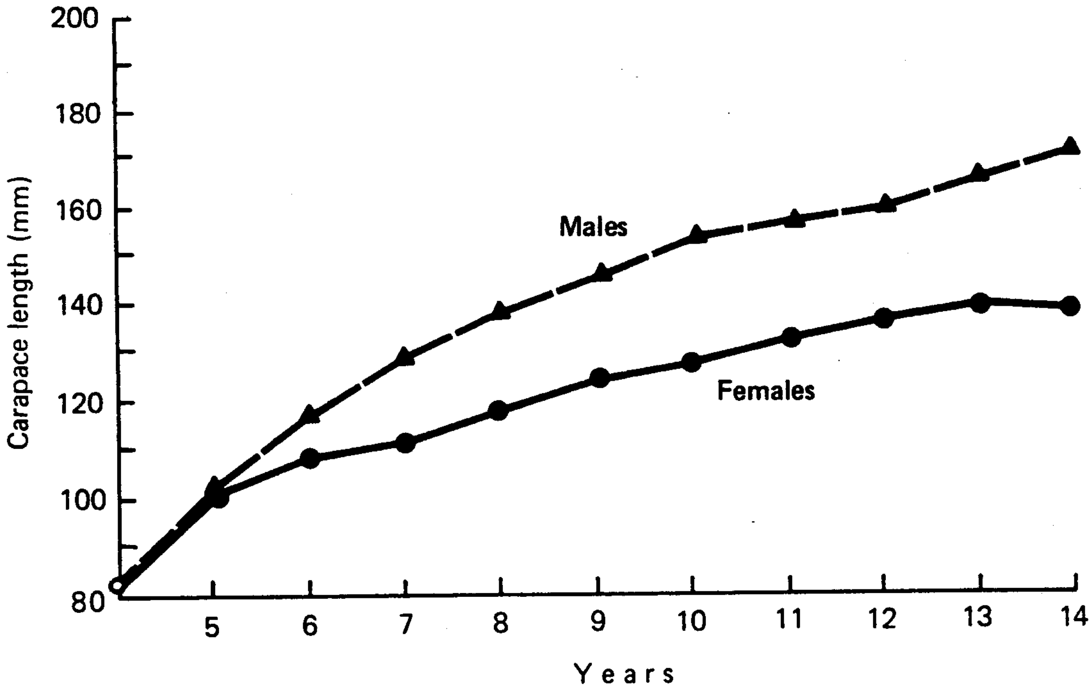


Figure 19. Average lengths of mature king crab at ages 5-14.

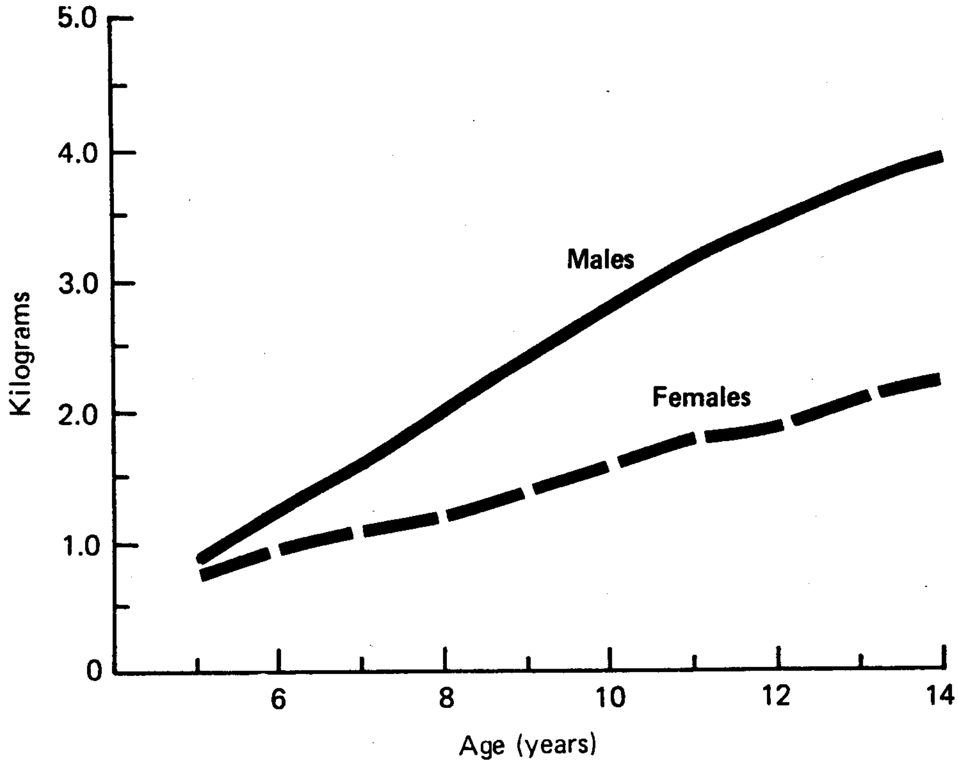


Figure 20. Growth in weight of male and female king crab.

individuals which were almost totally replaced by smaller, new shelled females having smaller but full egg clutches in 1983. One possible explanation for the prevalence of incomplete egg clutches may be that the older females in the 1982 survey did not undergo the annual molt as is typical for female crab (Reeves, pers. comm.).

6.2.2 Larval Mortality

Very little reliable information is available regarding mortality in larval king crab. If we compare the potential increment to any king crab stock which might result from a single year's larval releases (say, 200,000/mature female) against the actual numbers of parturient crab in the spawning stocks, it is obvious that natural mortality from egg hatching to maturity is very large. Marukawa (1933) estimated the density of newly hatched zoea larvae and applied it to the 458 square mile area of the Sea of Nemuro. From this procedure he calculated the total Stage I zoeal population to be about $2{,}248 \times 10^9$. He estimated that these 2.2 trillion larvae were released by a population of about 11.2 million females and 20 million males. Although Marukawa's estimate is based upon a number of unverified assumptions, it serves to illustrate that the total mortality to a cohort of king crab is very substantial. It is reasonable to assume that the most of this very large mortality occurs in the earlier life history stages.

From observations of larvae reared in laboratory experiments and from zoea collected periodically from the natural environment, Marukawa (1933) concluded that larval mortality was extremely high. Zoea I were found to have poorest survival (6.5%). Eighty percent of the surviving Zoea II lived to be

Zoea III and 86% of these survived to the last zoea stage. Survival from the last zoea to the megalops stage was also about 86%. From these observations, about 3.58% of the eggs hatched survive to become megalopae. This is a mortality of 96.4% up to the megalops stage all but about 3% of which occurs during the first zoeal stage. Marukawa attributed the large mortality during the first zoeal stage to the transition between yolk sac and free feeding. This implies either an inadequate quantity of appropriate food items at this critical transitional stage or perhaps developmental inadequacies and abnormalities which may prevent zoea from feeding in the presence of adequate food (Vladimirov, 1975).

On the basis of estimates of the quantity of zoea larvae, fecundity, observed larval mortality and intuitively reasonable survival rates of postmegalops crab, Marukawa estimated that only 14 crab out of 1,000,000 hatches survive to the desired commercial size of 160 mm carapace width.

6.2.3 Adult Mortality

Natural mortality in adult king crab occurs from spawning senescence, predation, fishery encounters (discards in target or nontarget fisheries), parasitism, and diseases.

The average annual natural mortality for male king crab in eastern Bering Sea for three year periods between 1968 and 1979 was estimated by Reeves and Marasco (1980) to be M = 0.26. Age specific (5-14 yrs) natural mortalities for males and females is given in Table 11 (Reeves, 1980). The estimated average annual instantaneous natural mortality for male (1968-79) and female

Table 11.--Age-specific population parameters used in king crab simulations.

	NATURAL MORTALITY (annual M)		AVERAGE LENGTH (mm)	
Age	Male	Female	Male	Female
5	.13	.58	105	100
6	.12	.58	117	107
7	.08	.58	128	112
8	.08	.58	137	117
9	.11	.58	145	122
10	.23	.58	152	127
11	.50	.58	157	132
12	.57	.58	162	136
13	.61	.58	166	139
14	.76	.58	170	142

*Ages 5-7 estimated by back-calculation using the natural mortality schedule

Source: Reeves 1980 (unpublished data)

(1970-79) king crab are shown in Tables 12 and 13, respectively. The adjusted natural mortality schedule for the exploitable males is given in Table 14.

7. DISTRIBUTION AND ABUNDANCE IN E. BERING SEA

7.1 Larval Distribution and Abundance

Information concerning the distribution of larval king crab in eastern Bering Sea can be found in Takeuchi (1962), Korolev (1964), Rodin (1970), Haynes (1974) and Armstrong et al., (1983). There is very little information concerning the distribution of megalopae and 1st year juveniles. Data on the zoeal stages is quantitative to the extent of ascertaining areas and timing of hatching from differences in relative abundance of the larval stages. There have been no estimates of the quantitative magnitude of the successive stages of larvae from which one can estimate the extent of natural mortality from the Zoea I stage through the first instar stage.

Time of hatching, the reference point from which age is calculated, for eastern Bering Sea king crab extends from mid-April to mid-June (Takeuchi, 1962; Niwa, 1962; Fishery Agency of Japan, 1963; Korolev, 1964). According to Weber (1967) 50% hatching falls in mid-May although this timing can vary by as much as a month (Fishery Agency of Japan, 1956 & 1963; Weber, 1967).

Figure 21 shows the distribution and abundance of male crabs during the inshore migration periods of 1960 through 1963 in southeastern Bering Sea. The migratory distribution of females was basically similar with concentrations observed off Amak Island, Black Hill and Port Moller areas (Fishery Agency of Japan, 1964). The Port Moller area was the most important with respect to

Table 12.--Estimate of average annual instantaneous natural mortality for exploited male red king crabs.

	MILLIONS OF MALE CRABS												
Age	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	Mean
9	2.7	3.1	2.5	--	2.3	4.7	8.5	9.5	13.4	14.2	20.2	17.7	
10	1.2	1.0	0.6	--	1.0	1.3	2.1	2.5	4.5	4.7	6.2	7.1	
11	0.9	0.5	0.3	--	0.3	0.9	3.5	2.0	2.9	3.3	4.6	4.5	
12	0.6	0.3	0.1	--	0.3	0.5	0.7	1.3	1.5	2.0	2.1	3.5	
13	0.3	0.2	0.0	--	0.1	0.2	0.2	0.5	0.7	0.7	1.4	2.3	
14	0.5	0.3	0.1	--	0.2	0.1	0.1	0.3	0.3	1.5	0.5	1.3	
$\hat{Z}_p$	.37	.49	.65	--	.55	.73	.88	.64	.72	.50	.68	.48	
Period p	66-68	67-69	68-70	69-71	70-72	71-73	72-74	73-75	74-76	75-77	76-78	77-79	
$\bar{f}_p$	20,279	52,181	80,860	104,655	140,075	173,950	205,414	205,431	246,347	328,351	395,950	433,410	
$\hat{q}_p$ ($\times 10^{-5}$)	--	--	.326	,326	.331	.247	.239	.193	.155	.122	.084	.076	
$\hat{M}_p$			.39	--	.09	.25	.39	.24	.34	.10	.35	.15	.26

Source: Reeves & Marasco (1980)

Table 13.--Estimate of average annual instantaneous natural mortality for female red king crabs.

	MILLIONS OF FEMALE CRABS										
Age	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	MEAN
8	1.0	--	0.7	5.6	4.1	4.1	8.2	16.1	6.7	13.9	6.7
9	0.7	--	0.3	5.3	4.7	3.6	6.8	12.3	5.2	7.5	5.2
10	0.8	--	0.3	3.4	2.3	2.7	3.2	5.9	3.6	6.3	3.2
11	0.5	--	0.2	2.5	1.7	1.0	1.6	3.8	2.4	2.5	1.8
12	0.3	--	0.1	1.0	0.7	0.4	0.3	0.7	0.4	0.6	0.5
13	0.2	--	0.1	0.9	0.6	0.3	0.2	0.6	0.3	0.6	0.4
14	0.2	--	0.1	0.4	0.4	0.1	0.3	0.6	0.5	0.4	0.3
$\hat{Z}$											.58

Source: Reeves & Marasco (1980)

Table 14.--Adjusted natural mortality schedule for exploited male red king crabs 9-14 years.

AGE	BALSIGER M ESTIMATES	1970-1979 AVERAGE STOCK	ADJUSTED M ESTIMATES
9	.15	10.0	.11
10	.30	3.3	.23
11	.66	2.5	.50
12	.75	1.3	.57
13	.80	.7	.61
14	1.00	.5	.76
Weighted Average	.34		

Source: Reeves & Marasco (1980)

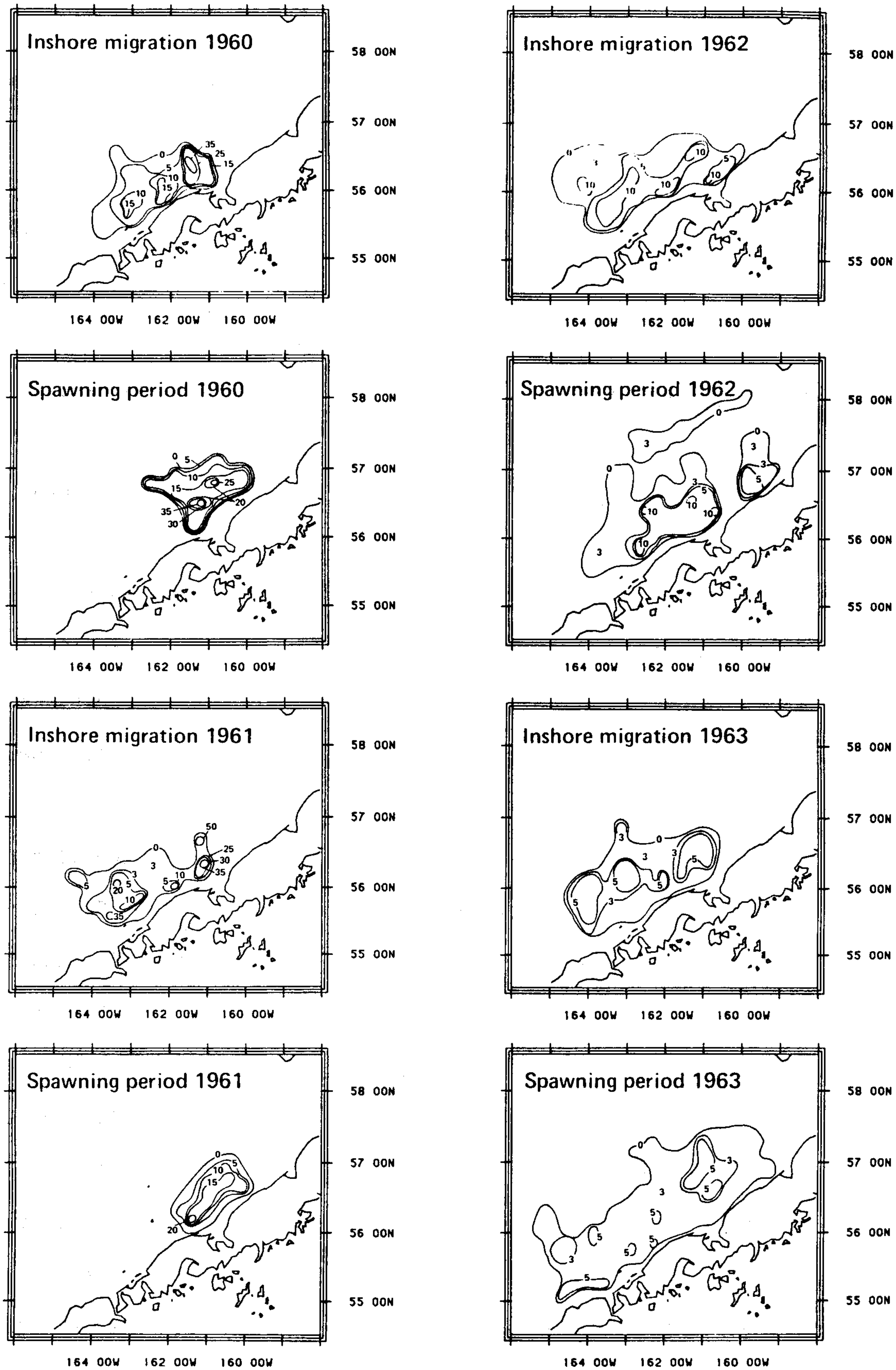


Figure 21. Distribution of male crab during inshore migrations and spawning period, 1960-63.

total area occupied and relative abundance and in these waters, females were even more abundant than males (Fishery Agency of Japan, 1964). Since hatching occurs during the inshore migration, at least the first zoeal stages should also be most abundant in these areas. Takeuchi (1962 & 1968), Rodin (1970), and Haynes (1974) have shown that the greatest abundance of first stage zoea also occurs from Unimak Pass to Port Moller, particularly in the latter area. In nature, predation is an additional and substantial source of mortality.

On the basis of the counter clockwise direction and speed of prevailing currents in the southeastern Bering Sea, Hebard (1959) speculated that larvae hatched at Amak Island could be transported northeastwardly along the North Aleutian Shelf to metamorphose in the Port Moller area. Takeuchi (1962) and Haynes (1974) recognized oceanic transportation of larvae as one explanation for the northeastward shifts in the relative abundance of successive zoeal stages collected in their surveys.

Sampling in June-July, 1965, Rodin (1970) observed Zoea Stage II through IV larvae distributed from Unimak Island to waters north of Cape Seniavin with the greatest abundance in the latter area (Fig. 22). Haynes (1974) observed a progression in the abundance of king crab larvae in southeastern Bering Sea from the Black Hill-Port Moller area in May, northeastwardly, to the area off Ugashik Bay at the head of Bristol Bay in mid-July when no more larvae were taken (Fig. 23). This eastward shift in areas of abundance was accompanied by a progression in larval stages. First stage zoea decreased in abundance and conversely, last stage zoea increased in abundance as the season progressed (Fig. 24). Larvae were most abundant (more than 1000/square meter of sea surface) near Unimak Pass and Port Moller and least abundant (less than

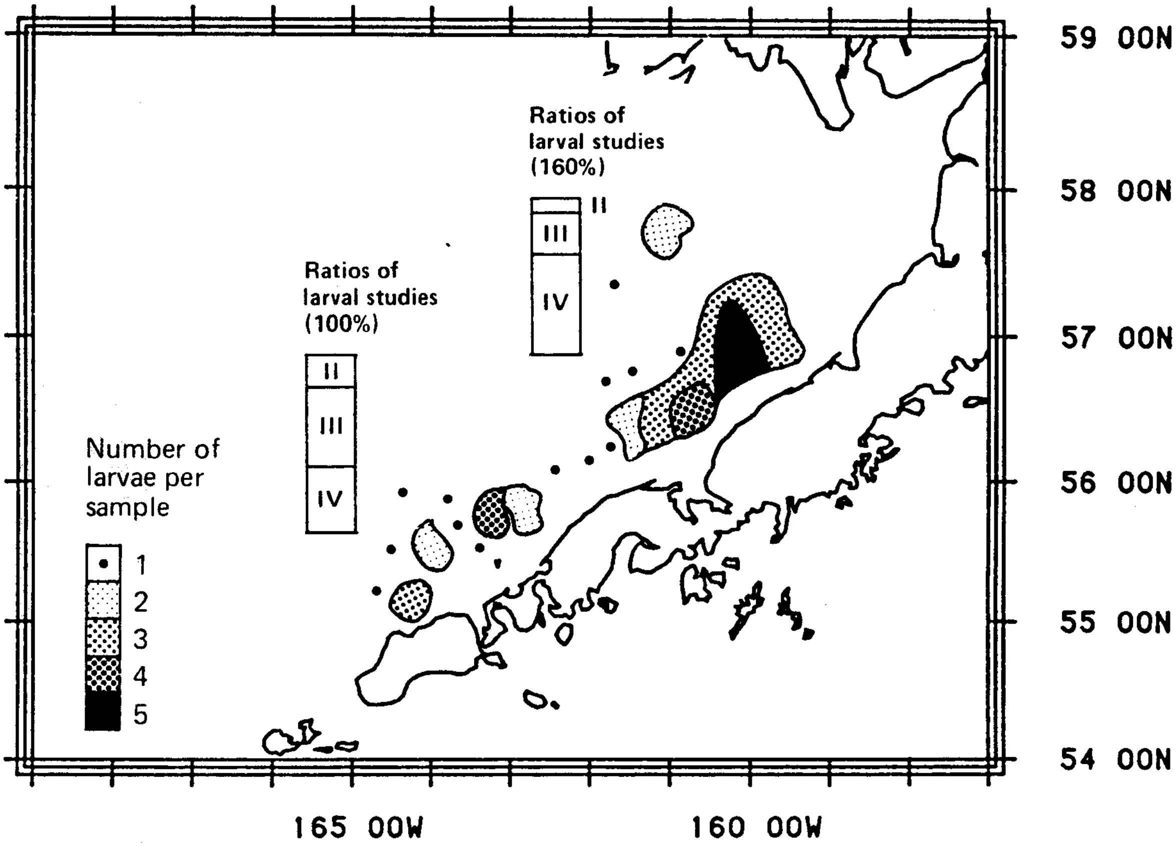


Figure 22. Distribution of king crab larvae (June-July 1965).

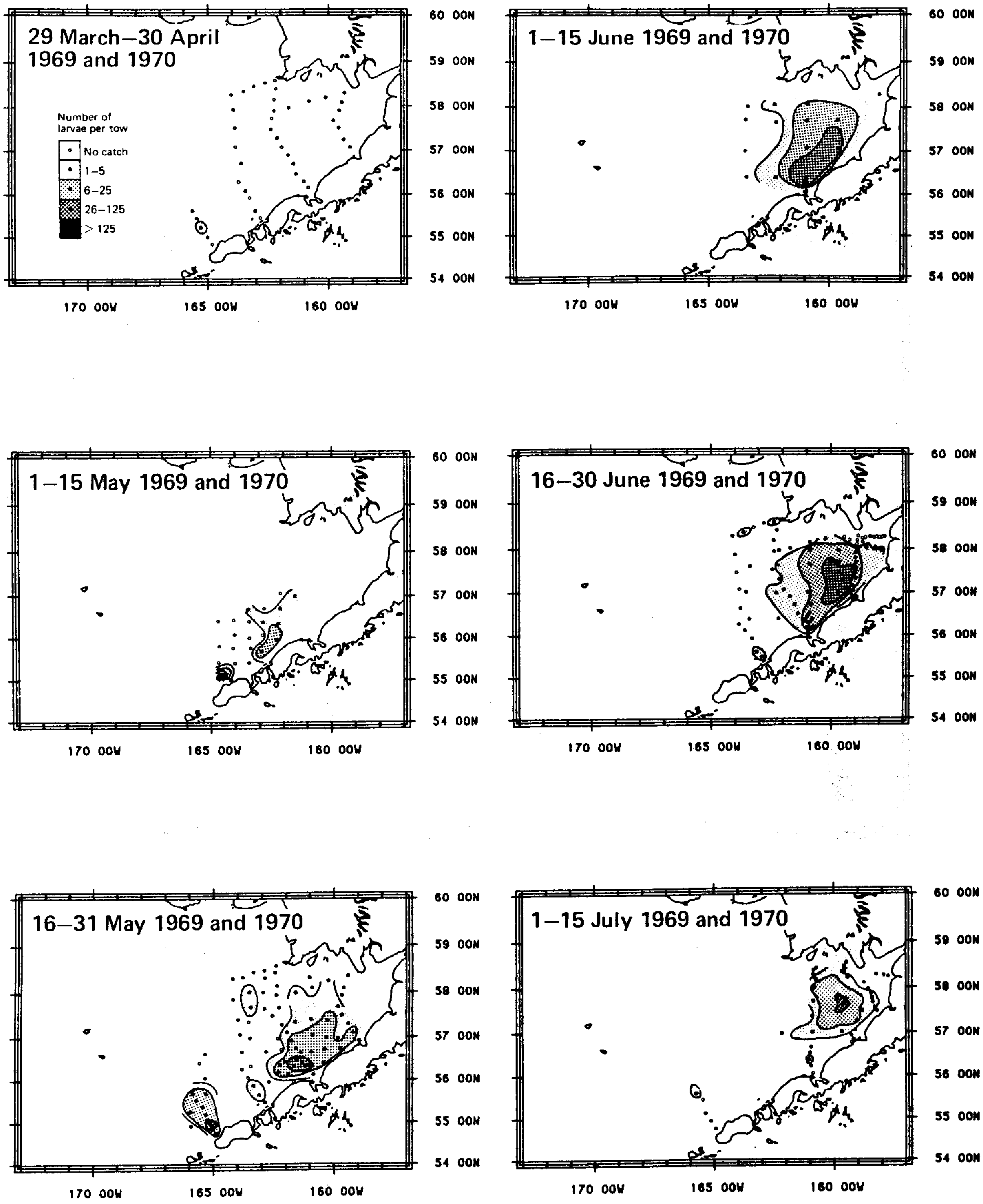


Figure 23. Distribution of king crab larvae in southeastern Bering Sea, May-July 1969-70.

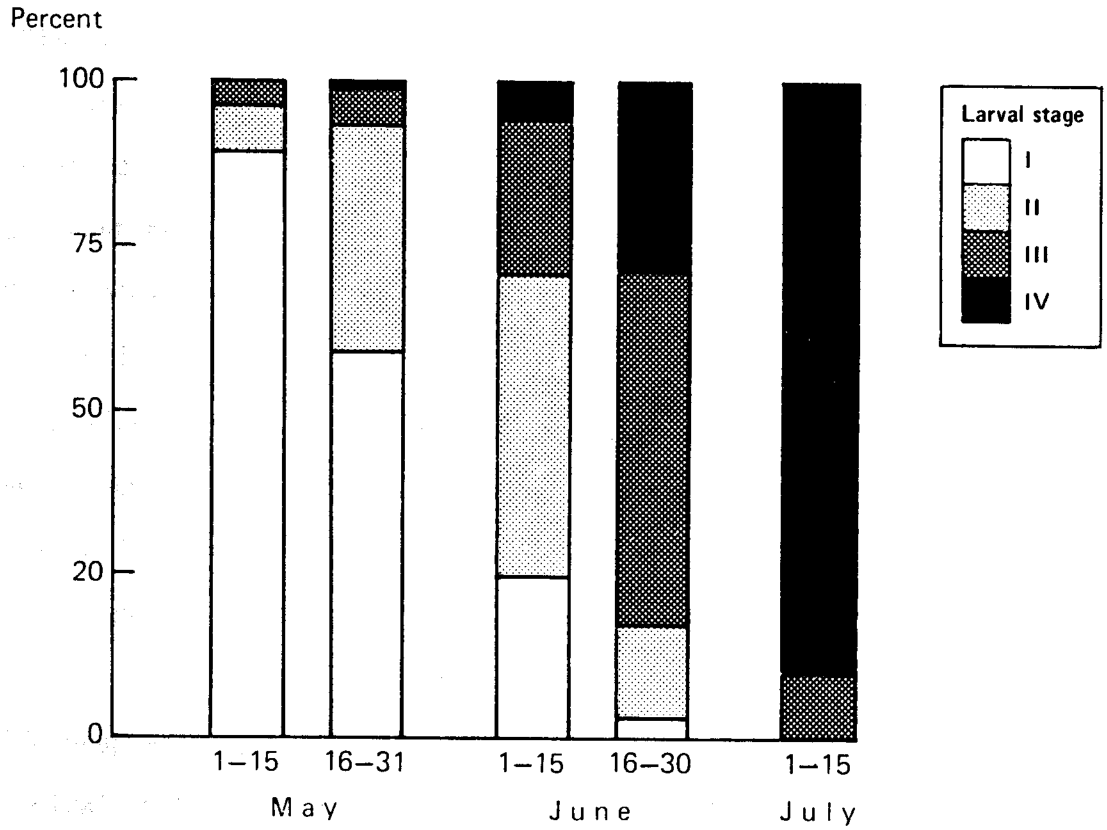


Figure 24. Percentages of 4 king crab zoeal stages in eastern Bering Sea, May-July 1969-70.

10/square meter of sea surface) in the more central and western sampling stations.

Armstrong et al. (1983) analysed over 1000 zooplankton samples taken in southeastern Bering Sea in 1976 through 1981. Red king crab larvae were absent over most of St. George Basin and occurred from off western Unimak Island eastward to about Port Heiden (Fig. 25). The highest densities of larval red king crab occurred from western Unimak Island to Port Moller where concentrations were typically 5,000-50,000 larvae/100 m^2. Maximum densities were 67,000 larvae/100 m^2 off Otter Pt., Unimak Island in one sample in 1977 and 114,000 larvae/100 m^2 in one sample taken in 1980 off Port Moller. Average abundance was highest from Black Hill to Cape Seniavin (Table 15). Although larvae were captured in waters between Unimak Pass and Amak Island by Haynes (1974) in 1970-71 and by NOAA (Armstrong et al., 1983) in 1976-77, they occurred there in very small numbers in the 1978 collections and were virtually absent in 1982 (Fig. 26 and Table 16).

The 1982 survey data indicated that densities of larvae were generally lower closest to the shore (20-40 m) and higher in depths 41-80 m (Table 16).

In the 1982 surveys, larvae were broadly distributed along the northern Aleutian Shelf in June from False Pass north eastward to C. Seniavin, whereas in August, their presence was limited to the easternmost stations off Port Heiden (Fig. 26).

Some indications of annual variation in the distribution and abundance of larval, eastern Bering Sea king crab are obtainable from Armstrong et al. (1983). Annual variation in levels of abundance are suggested but are difficult to quantify due to the small number of samples relative to the time-space dimensions of larval distribution. Their data also suggest that larval

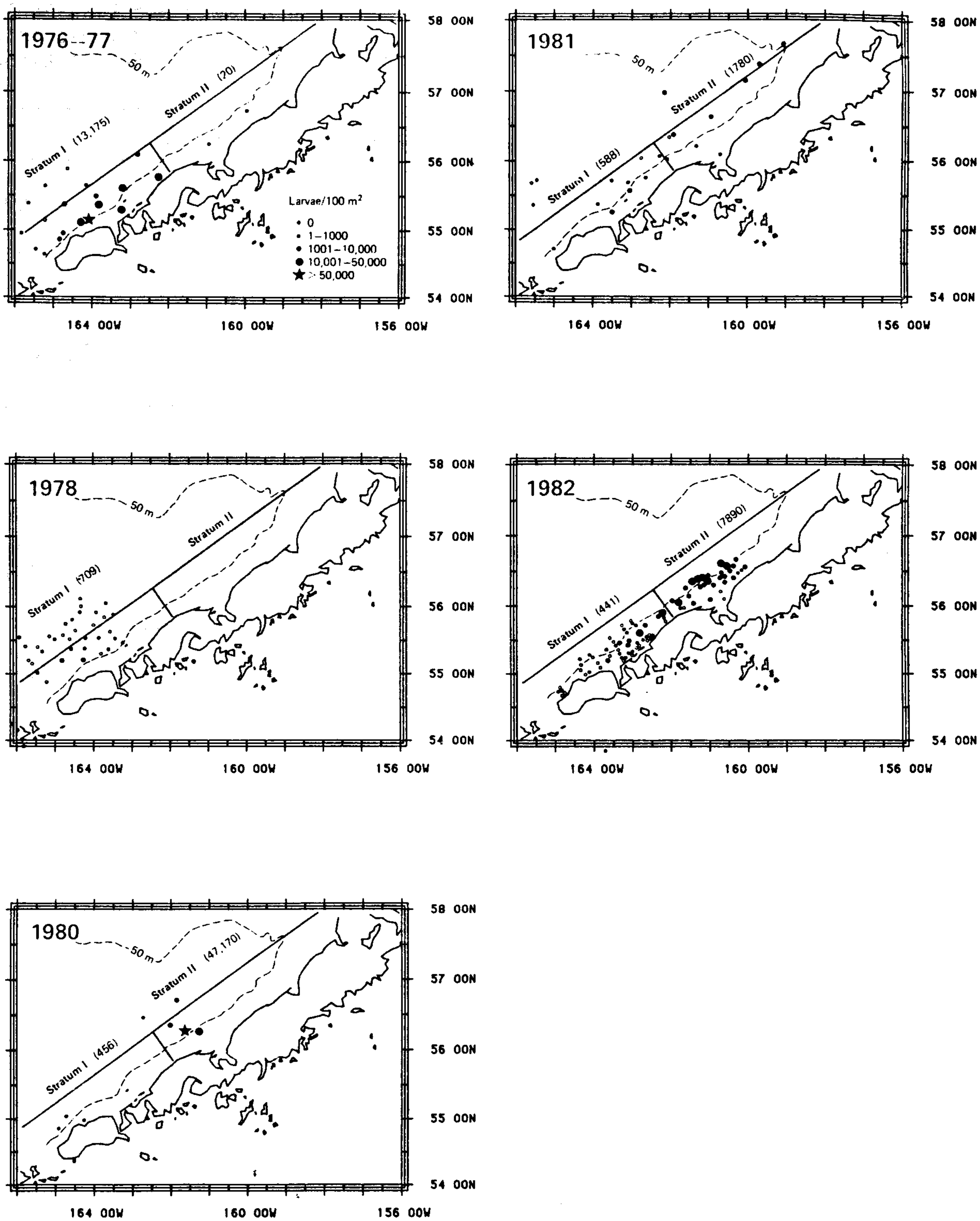


Figure 25. Annual differences in distribution and abundance of red king crab larvae along the northern Aleutian Shelf.

Table 15.--Mean abundance of larval red king crab along the North Aleutian Shelf during May and June in 1976 through 1982. The region is divided into two strata that separate distributions east and west of 162°W latitude near Black Hills. Values are larvae/100 m^2.

	Stratum I				Stratum II			
Year*	n**	$\bar{X}$	±1 SD	Range	n	$\bar{X}$	±1 SD	Range
1976-77	15	13,175	17,200	650-67,000	2	20		0-39
1978	12	709	537	170-1,760			none	
1980	5	456	421	0-850	3	47,170	58,300	7,500-114,000
1981	8	488	943	0-2,570	9	1,780	1,512	0-4,500
1982	48	441	1,181	0-6,620	30	7,893	1,584	0-36,240

* Larval densities in 1976-77 were very similar in Stratum I so they were combined for a larger sample size. No samples were collected in either Stratum in 1979.

**n = the total number of stations collected, including zero stations.

Source: Armstrong et al. (1983)

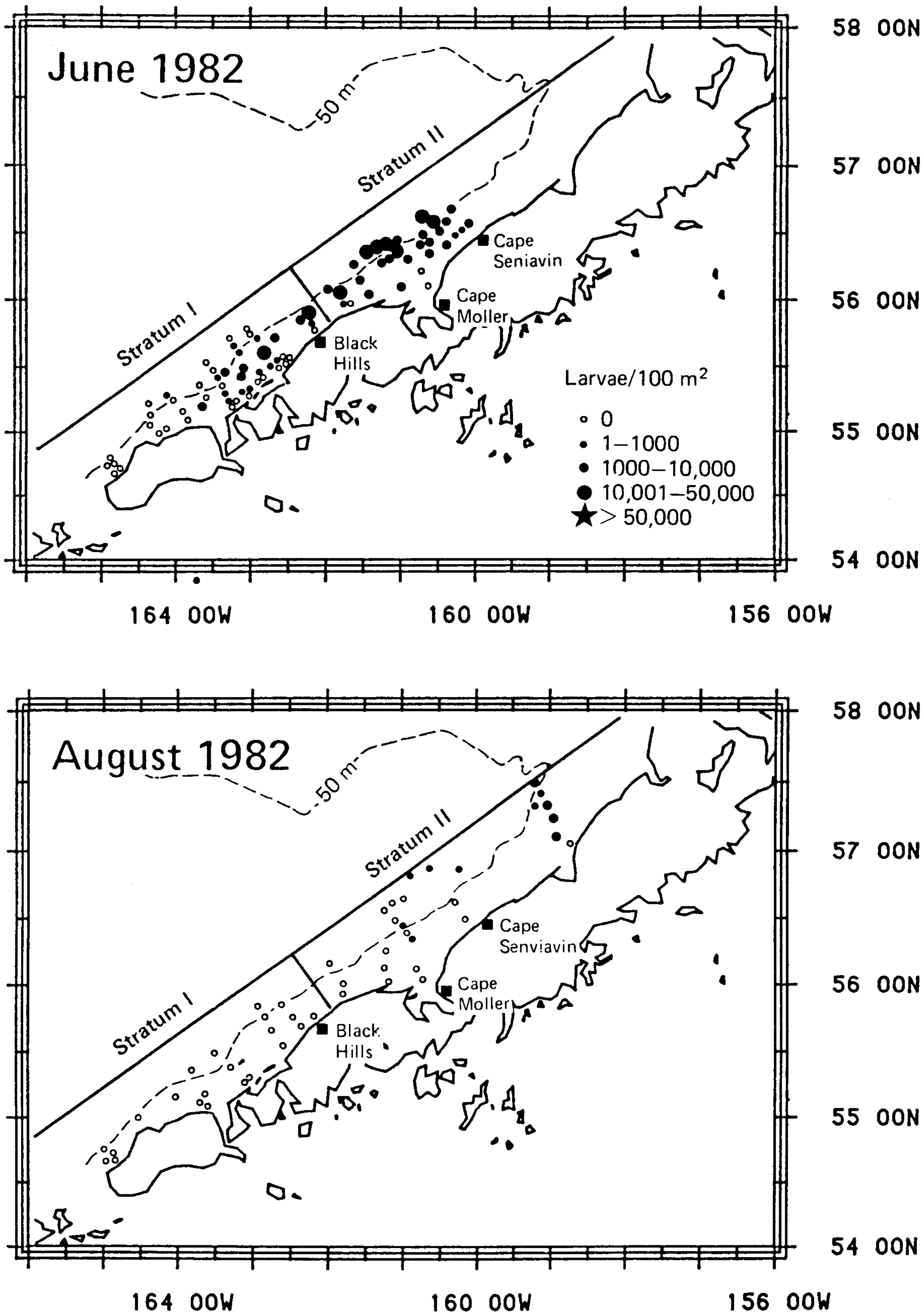


Figure 26. Distribution and relative abundance of red king crab larvae in June and early August 1982.

Table 16.--A summary of larval red king crab densities in June 1982, along the North Aleutian Shelf. Stations were grouped into three depth intervals along six transect lines to contrast nearshore and longshore distribution.

Transect line	Depth* interval	n**	$\bar{X}$ (no. larvae/100 m^2)	Range
A	1	3	0	--
	2	3	0	--
	3	2	0	--
B	1	2	202	0-405
	2	3	350	120-590
	3	2	0	--
C	1	3	26	0-78
	2	1	6,624	--
	3	3	80	0-126
D	1	2	125	0-250
	2	1	12,231	--
	3	1	1,120	--
E	1	2	2,000	0-4,000
	2	2	6,930	4,300-9,550
	3	5	15,350	8,800-24,700
F	1	3	780	50-1,300
	2	5	17,300	6,400-36,240
	3	0	--	--

* 1 = 20-40 m, 2 = 41-60 m, 3 = 61-80 m.

**n = number of stations on the transect lines within each depth interval.

Source: Armstrong et al. (1983)

abundance is greater eastward of Black Hill (Table 15). Excepting 1982, however, the number of stations and samples upon which such a conclusion is based is small. The evidence is, however, consistent with the views of Takeuchi (1962), Rodin (1970) and Haynes (1974) who concluded on the basis of their studies that the Port Moller area was the more important of the egg hatching sites for eastern Bering Sea red king crab.

Additional information on the relative abundance of the larval stages of king crab in eastern Bering Sea and the timing of development is presented by Armstrong et al. (1983). Stage I zoea occur from before April 18 into the first three weeks of June. Stage II larvae begin to occur in April, maximize in abundance in May-June and disappear after early July. Stage III zoea were encountered from about May 11 through August 10. Last stage zoea larvae occurred in samples collected from the June 1-21 period through August 10. Similarly, megalops larvae were first taken in the first three weeks of June and their abundance increased through the August 1-10 sampling period (Fig. 27). Armstrong et al. (1983) indicate that megalopae are common from early July to early August but there was no mention of their distribution or habitat. From Fig. 28 it appears that all megalopae encountered by Armstrong et al. (1983) were taken offshore of Izembek Lagoon. Examination of the proportion of earlier and later zoeal stages at scattered longitudinal intervals along the northern Aleutian Shelf indicates a tendency toward earlier hatching or more rapid development of larvae in the westward areas (Fig. 28).

Armstrong et al. considered that 1980 and 1982 were probably years of good larval production along the northern Aleutian Shelf. Collections of

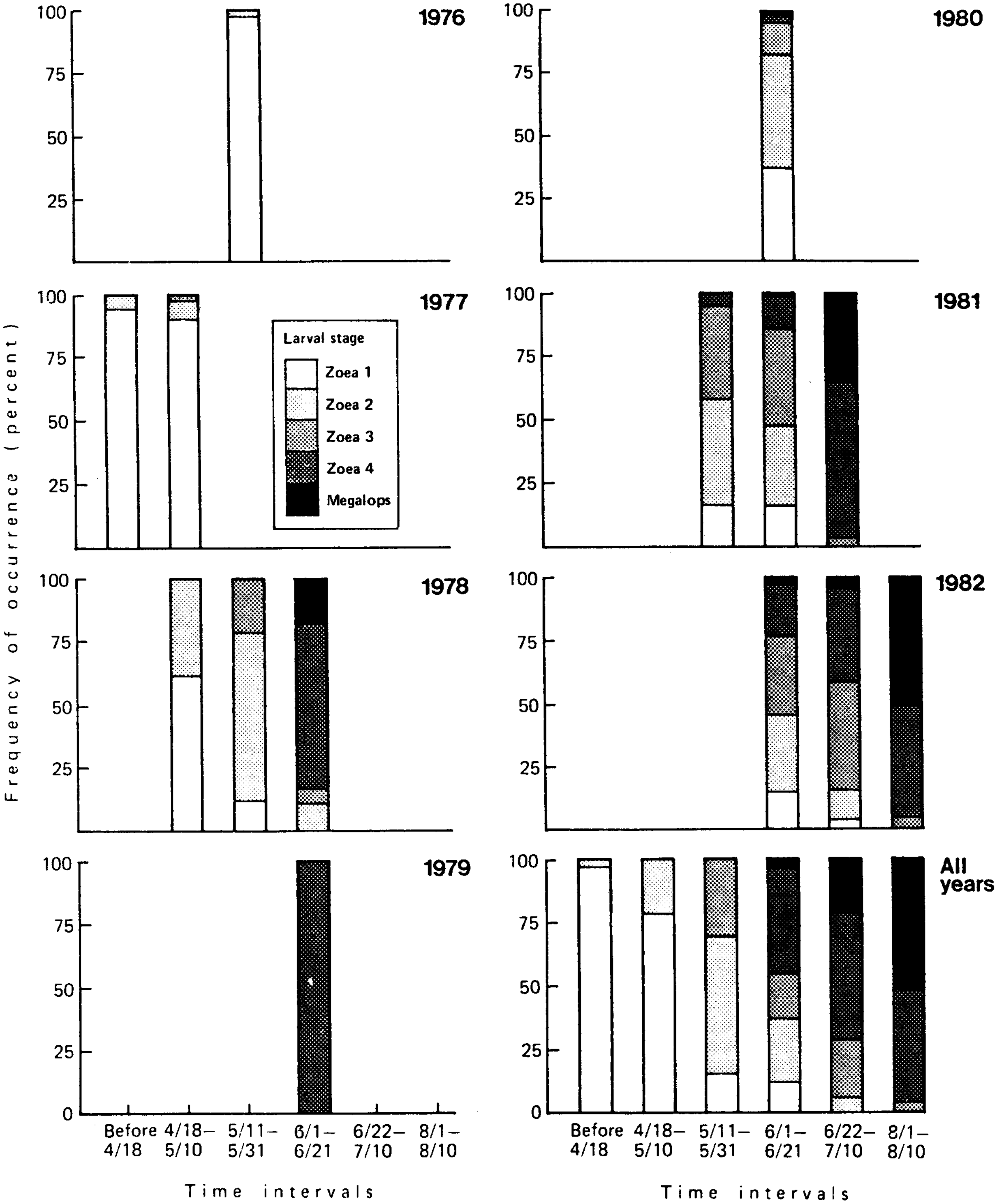


Figure 27. Frequency of occurrence of larval stages, April to August 1976-82.

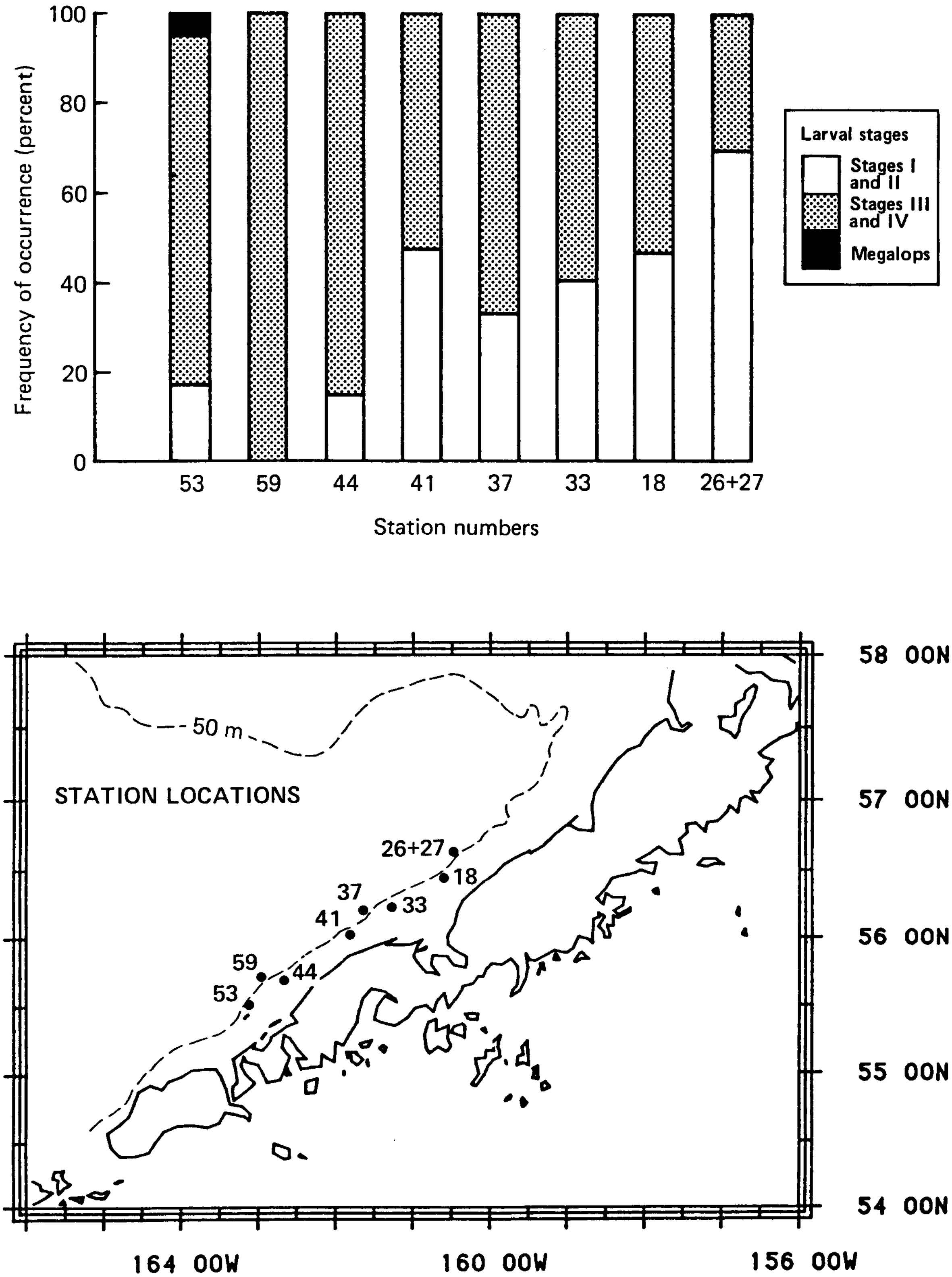


Figure 28. Differences in apparent hatch time.

larvae in April and June of 1983 indicate a drastic reduction from 1982 levels.

7.2 Juvenile Distribution and Abundance

As mentioned in Sec. 2.2.2, juvenile crabs less than 50 mm tend to inhabit the eulittoral zone where little if any survey effort has been expended. Juvenile king crab do not inhabit the area of the survey and fishing grounds until they attain a size of from 70-80 mm. The mesh sizes of the trawls used in the surveys are probably not small enough to efficiently capture the smaller juvenile king crab. Juvenile king crab, therefore, are not representatively sampled in the trawl surveys and their distribution and relative abundance is not very well known. Although not as complete as for the older age groups, there is some information relating to the distribution of juvenile king crab in the eastern Bering Sea. Juvenile crab 2-33 mm in carapace length were adventitiously captured in waters off Port Moller-Cape Seniavin in tanglenets in one of the fishing grounds of the Japanese tanglenet crab fishery (Fig. 29). Because of the regularity of occurrence, this area was the site of Japanese research on juvenile king crab from 1956 through 1960. Most of the crab taken in these studies were discovered attached to the netting or on marine algae or Hydrozoa. Although incomplete, a summary of observations relative to these immature crab which are of a size equivalent to age 3 and less is contained in the following table.

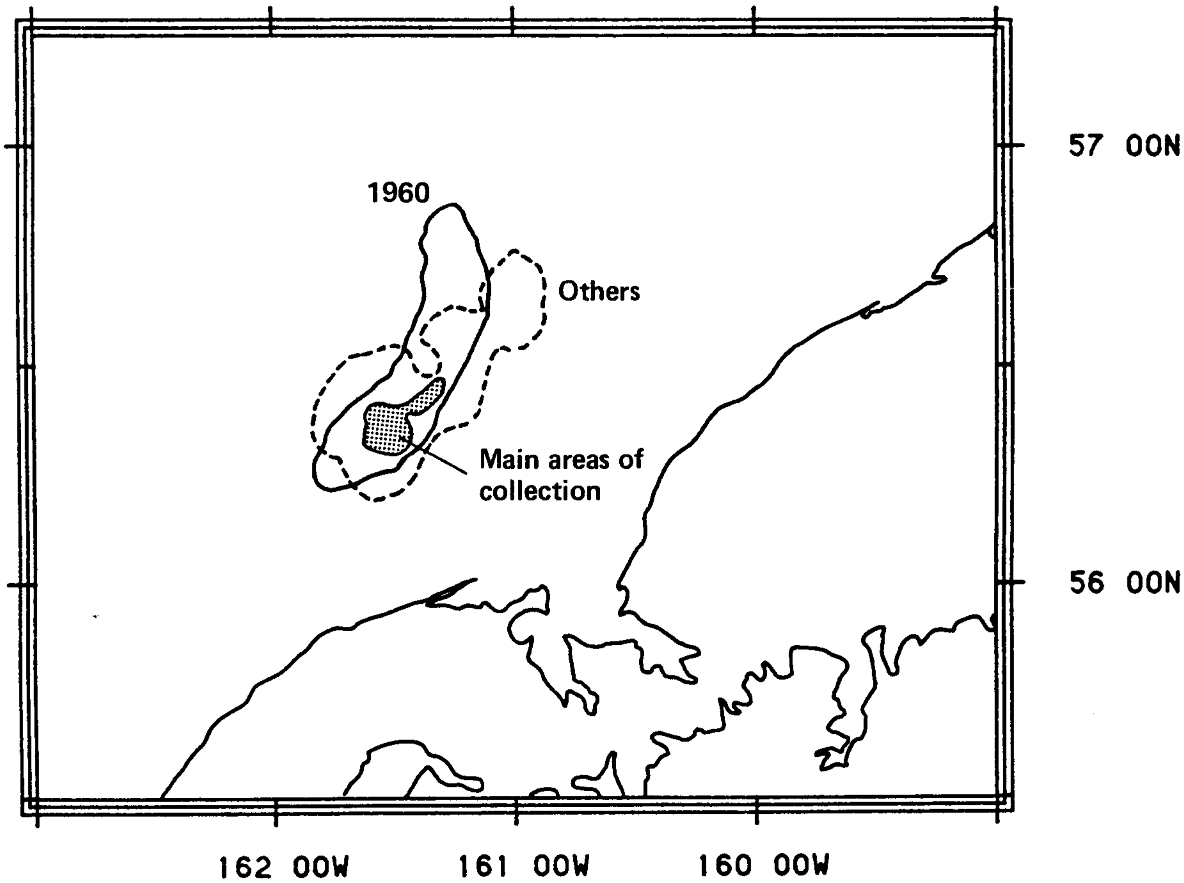


Figure 29. Areas in which juvenile crab were collected.

Table 17. The number and size of juvenile red king crab (2-33 mm carapace length) captured off Port Moller (1956-60).

Year	Dates	No.	Size Range	Bottom Temp. C°
1956	6/13-20	208	5 mm to 32.8 mm	1.57 - 1.86
1957	5/29-6/15	3,084	less than 20 mm	3.47
1958	5/29-6/18	2,172	----	3.75
1959	6/27-7/1	36	----	----
1960	6/1-7/6	506	9 mm to 16.6 mm	----

Data source: Fishery Agency of Japan (1963).

Korolev (1964) reported on the capture of eastern Bering Sea juvenile crabs 0.5-1.0 mm carapace diameter in sponges. These sizes are less than the minimum size of the first instar (2 mm) reported by other investigators. Trawl catches of crab 2.5-7 cm were also reported by Kosolev to be associated with sponges and hydroids. Because of the apparent need of megalopae and small juveniles to associate with these organisms, he concluded that the main region for crab reproduction must be eastward of a longitude which is slightly west of 161°25'W. This is apparently an area where large concentrations of sponges and hydroids occur, the northern limits of which run 60 to 70 miles from the coast of the Alaska Peninsula (Korolev, 1964).

Juvenile king crab are widely distributed over a large area of the northern Aleutian Shelf during the spring migration and spawning periods (Fig. 30). Adult males and females had similar distributions and formed areas of high density. The distribution of juveniles showed only one or two areas of relatively high abundance and their distribution seemed unrelated to that of the adults.

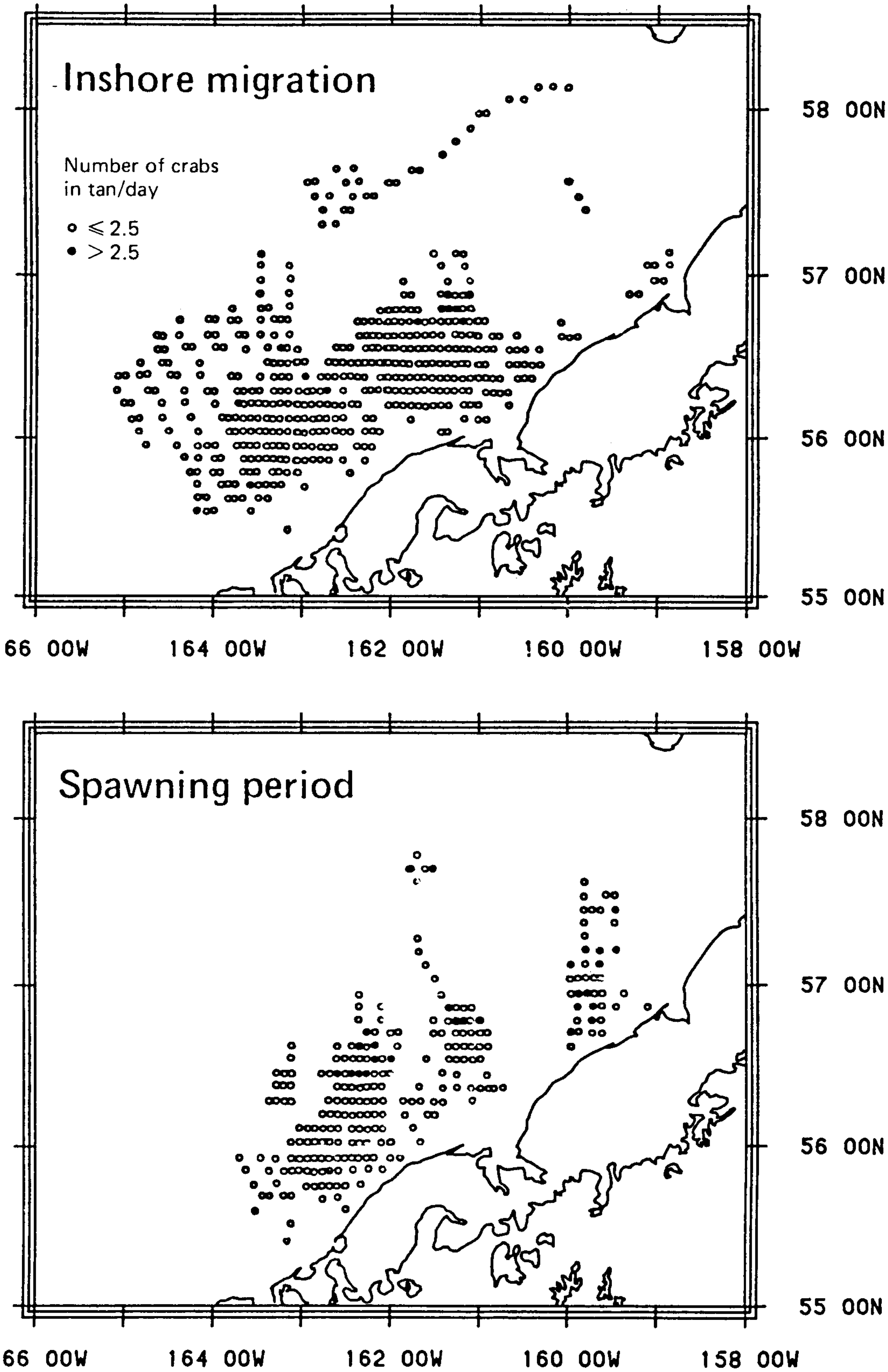


Figure 30. Distribution of juvenile crab during the spring migration and spawning seasons.

The winter distribution of smaller male crab (presumably immature) in eastern Bering Sea was described by Chebanov (1965). In a trawl survey from 15 December 1963 to 4 January 1964, smaller males dominated the hauls eastward of eastern Unimak Island to Port Moller (Fig. 31).

7.3 Distribution and Abundance of Adults

Knowledge concerning the distribution and abundance of adult king crab in southeastern Bering Sea was been obtained from Japanese, Soviet and United States research and survey cruises as well as from records of the commercial fishing operations. The latter provides information mostly on the distribution of the exploited stock which in the case of king crab are males over a certain minumum size. This minimum retention size has been smaller in the past, however, since 1974 after which the resource was exploited exclusively by the United States fleet, minimum size has been 165 mm carapace width or 135 mm carapace length.

Research and survey vessel cruises have provided information on the distribution of both sexes and on males smaller (as well as larger) than the legal, minimum retention size. The resource surveys of the National Marine Fisheries Service (NMFS), NOAA have been done most regularly since the early 1970's and have been the most comprehensive in terms of coverage of the eastern Bering Sea although generally limited in time to the spring and summer.

Important purposes of the MNFS surveys were to assess and forecast stock condition as inputs to management of the Bristol Bay king crab stock. As such, information on the distribution of king crab has been obtained for the

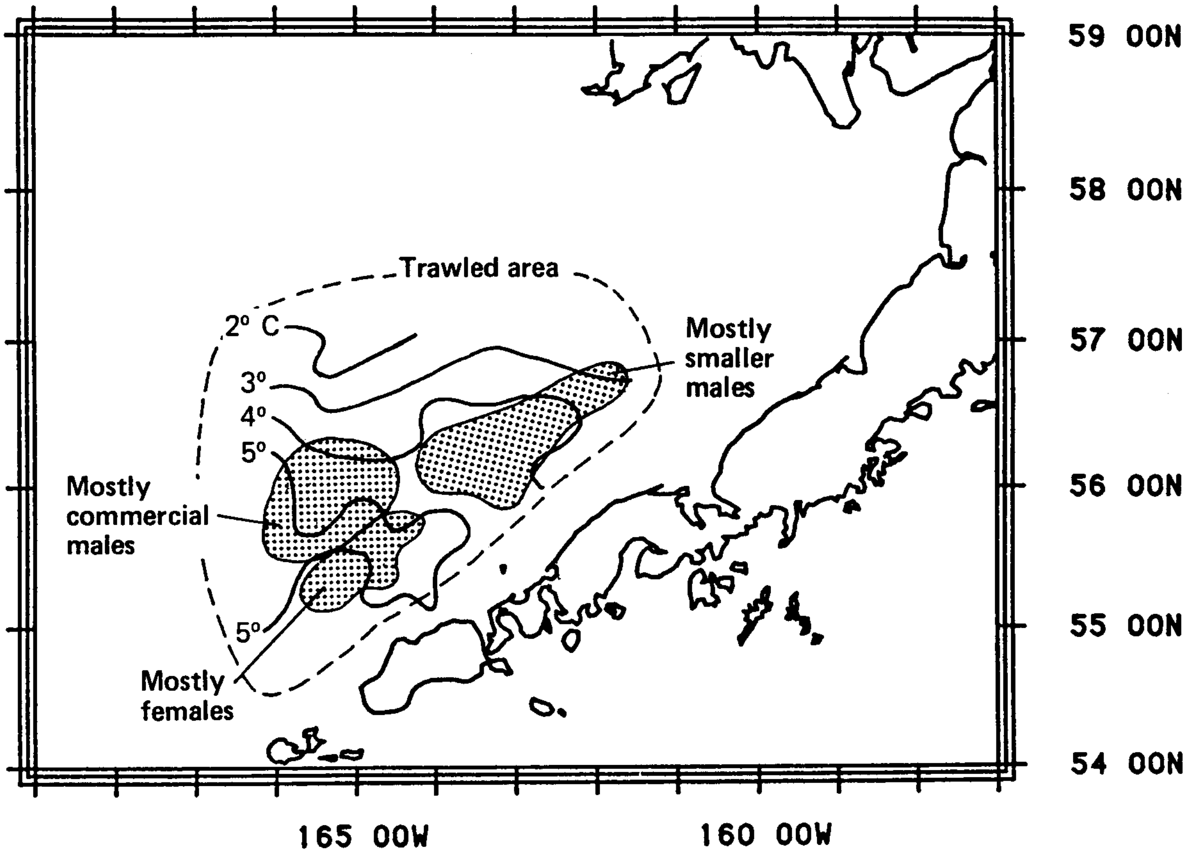


Figure 31. Winter distribution of king crab.

following five size and sex categories which are of relevance to the current management rationale for the eastern Bering Sea stock.

7.3.1 Distribution and Abundance of Legal-size Males over 134 mm (Carapace Length).

This category of king crab constitutes the exploited portion of the stock. Typically, this size category has molted twice since attaining sexual maturity. The annual distribution and abundance of this group from 1973 through 1983 as estimated from trawling surveys is shown in Fig. 32. Crabs of this size group are distributed very widely over the southeastern Bering Sea shelf, generally between the 50 and 100 m isobaths. With very few exceptions, however, they are not very abundant in the nearshore areas. Over all years, legal sized crabs were most frequently abundant in those offshore waters off Unimak Pass to Port Moller (Fig. 33).

The areal distribution of commercial catches of red king crab are shown in Fig. 34.

7.3.2 Distribution and Abundance of Males 110-135 mm (Carapace Length).

Crabs in this size category are sexually mature but below the minimum size for retention by the fishery. Their overall distribution and areas of highest density are quite similar to those for the legal sized male crab (Fig. 35). Areas of greatest abundance occur in the more offshore waters north of Unimak Island and Isembeck Lagoon to Port Moller (Fig. 36).

KING CRAB
1973–78
Males > 134 mm
Catch in number/mi^2

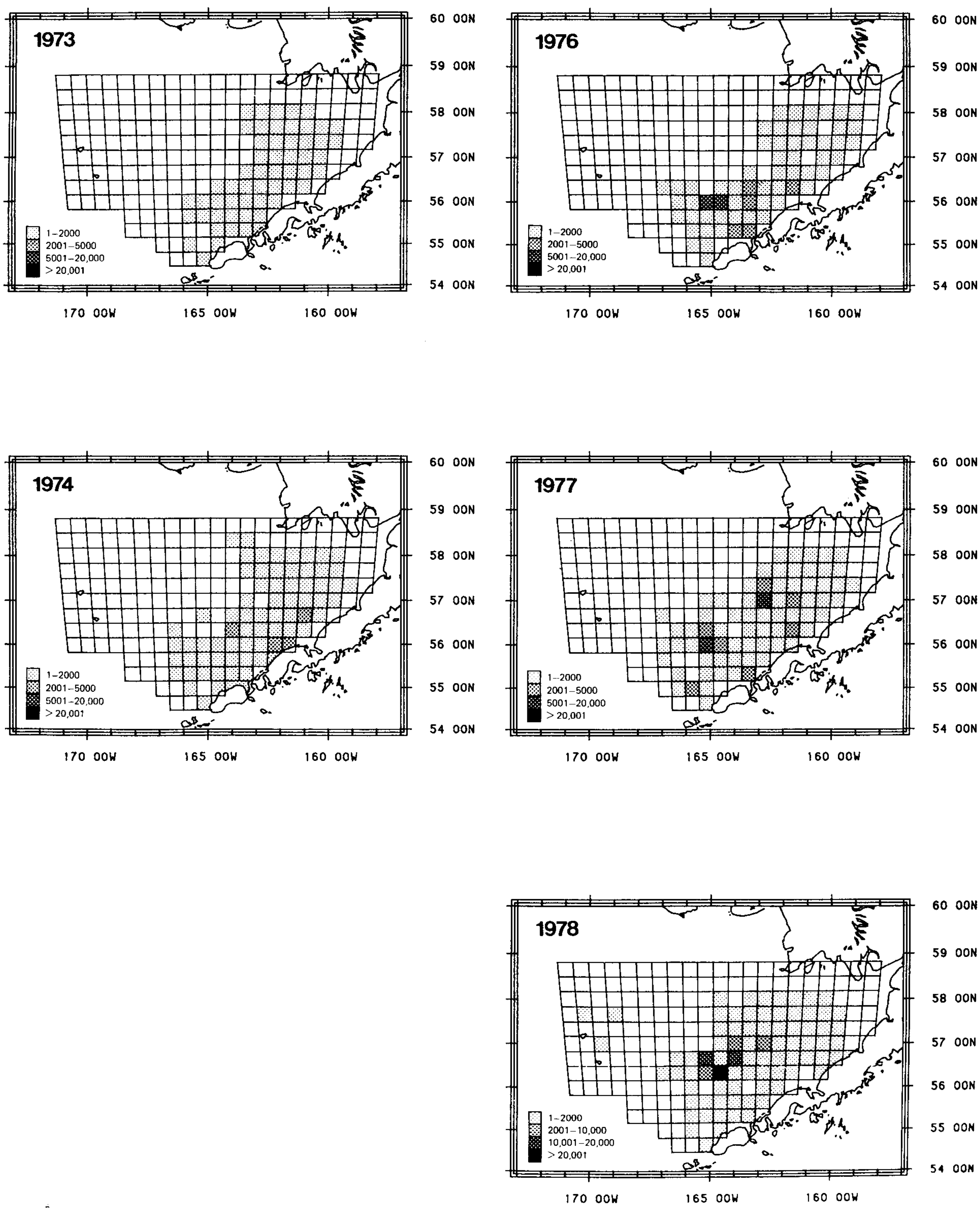


Figure 32. Annual distribution of legal males (>134 mm carapace length), 1973-1983.

KING CRAB
1979–83
Males > 134 mm
Catch in number/mi²

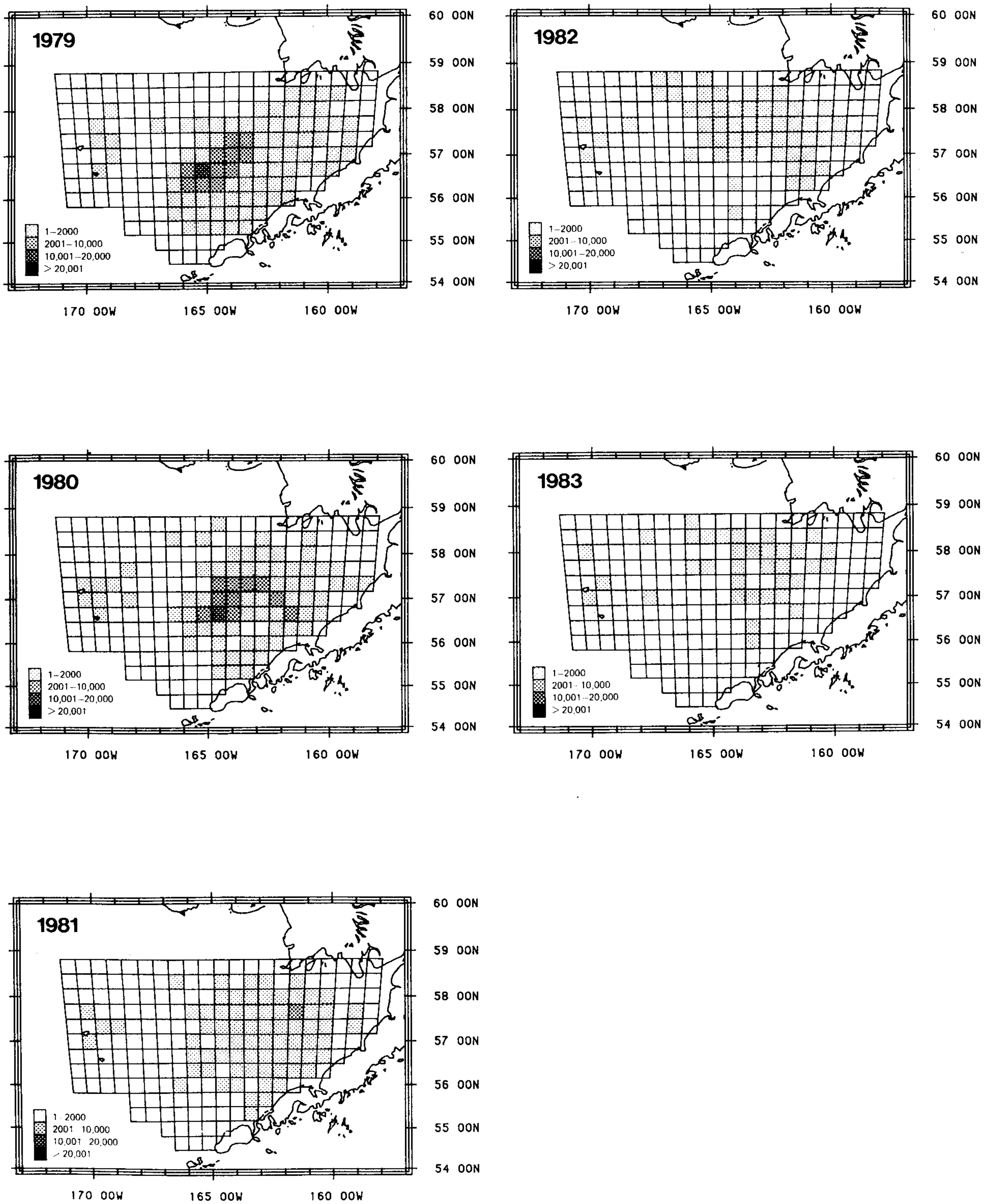


Figure 32. Continued.

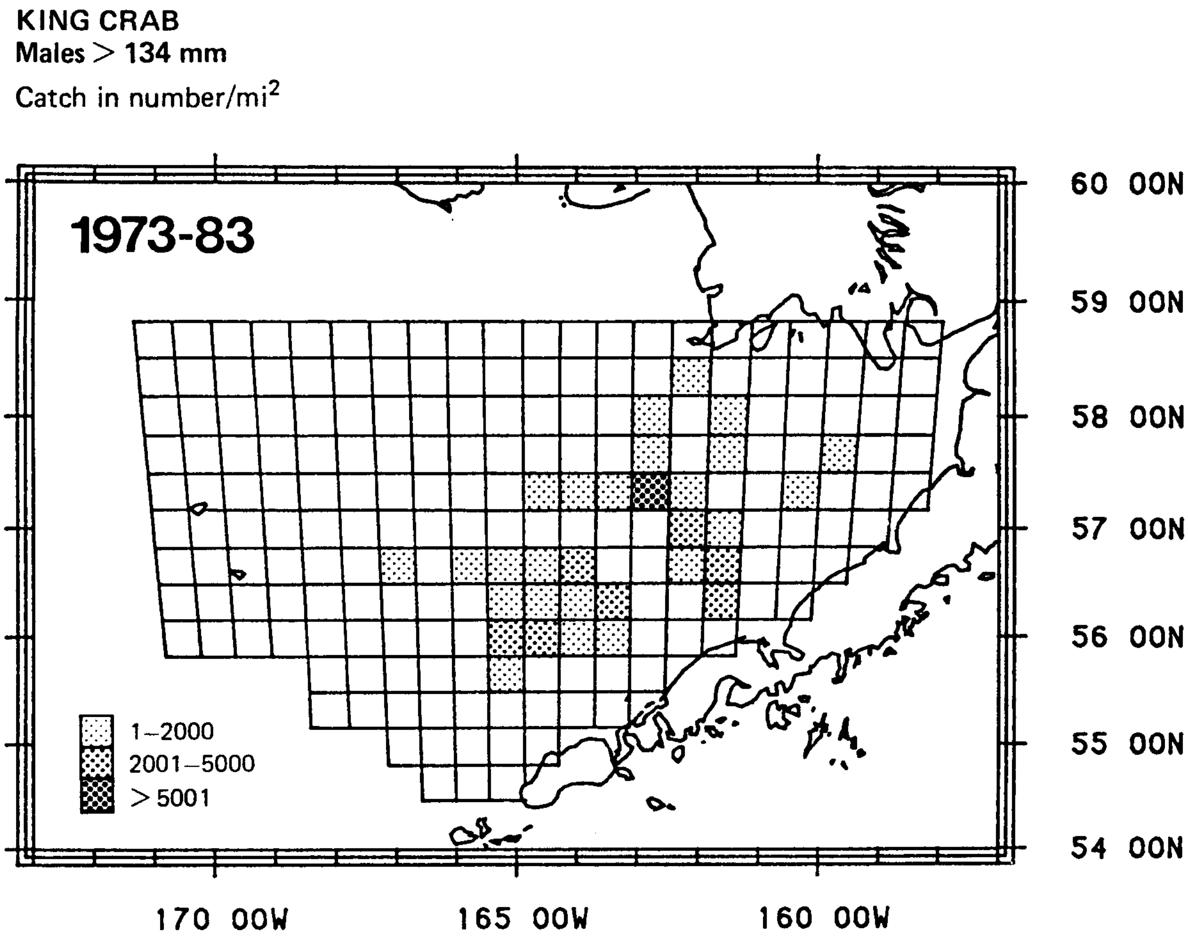


Figure 33. Areas of greatest abundance of legal males, 1973-83.

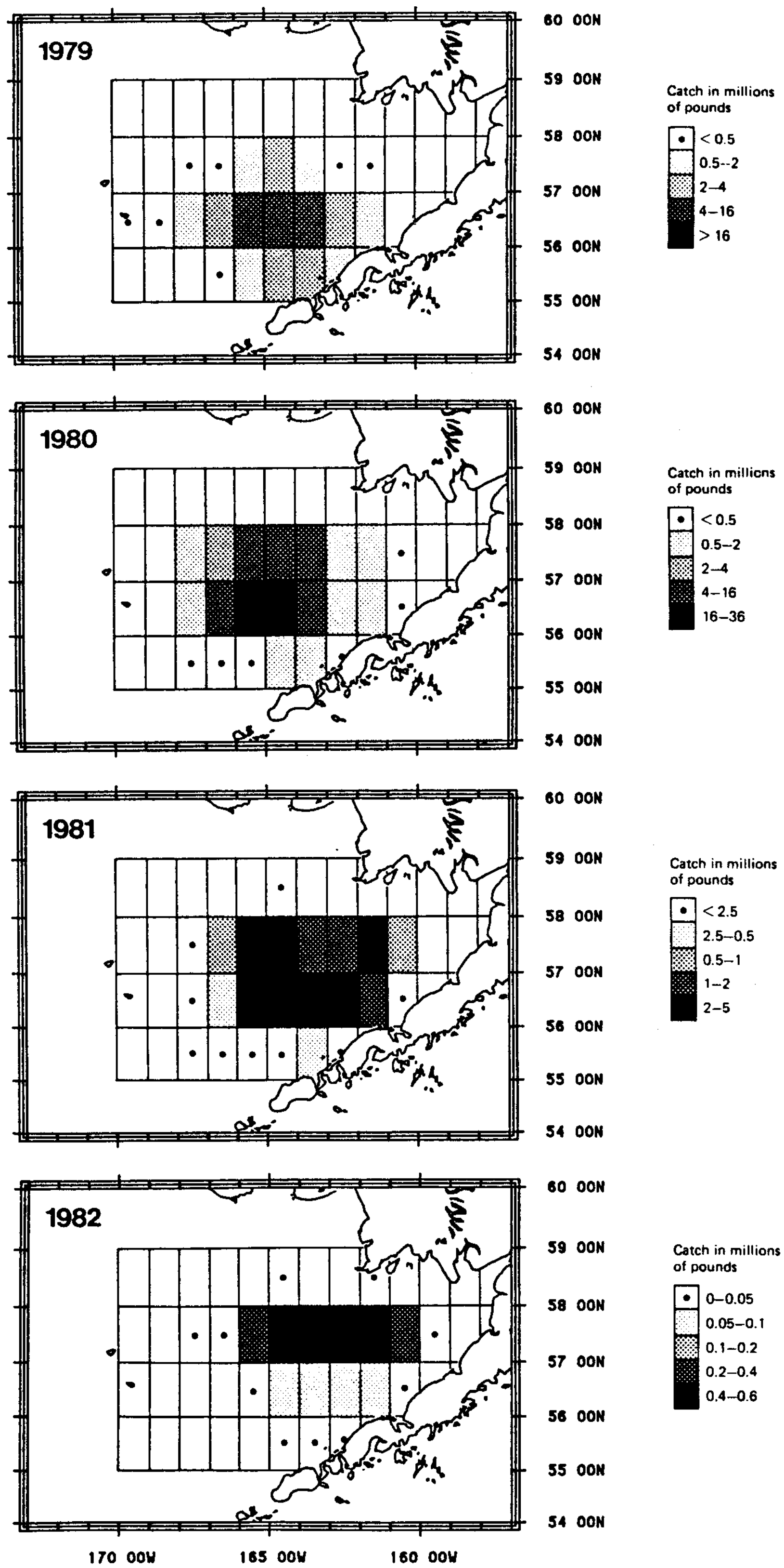


Figure 34. Areas of commercial catch of red king crab in eastern Bering Sea, 1979-82.

KING CRAB
1979–83
Males 110–135 mm
Catch in number/mi^2

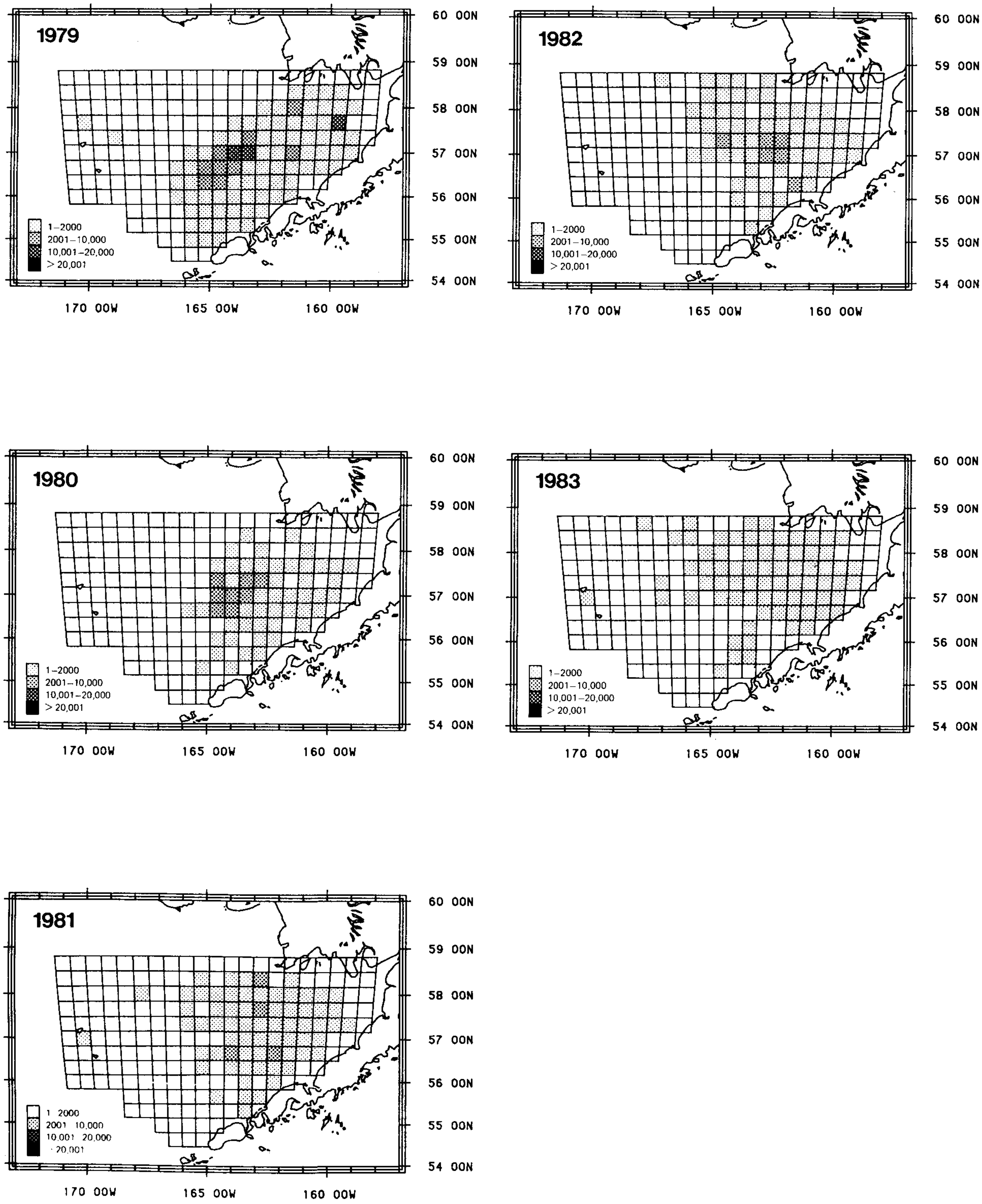


Figure 35. Distribution of male king crab 110 mm to 135 mm carapace length, 1973-83.

KING CRAB
1973–78
Males 110–135 mm
Catch in number/mi^2

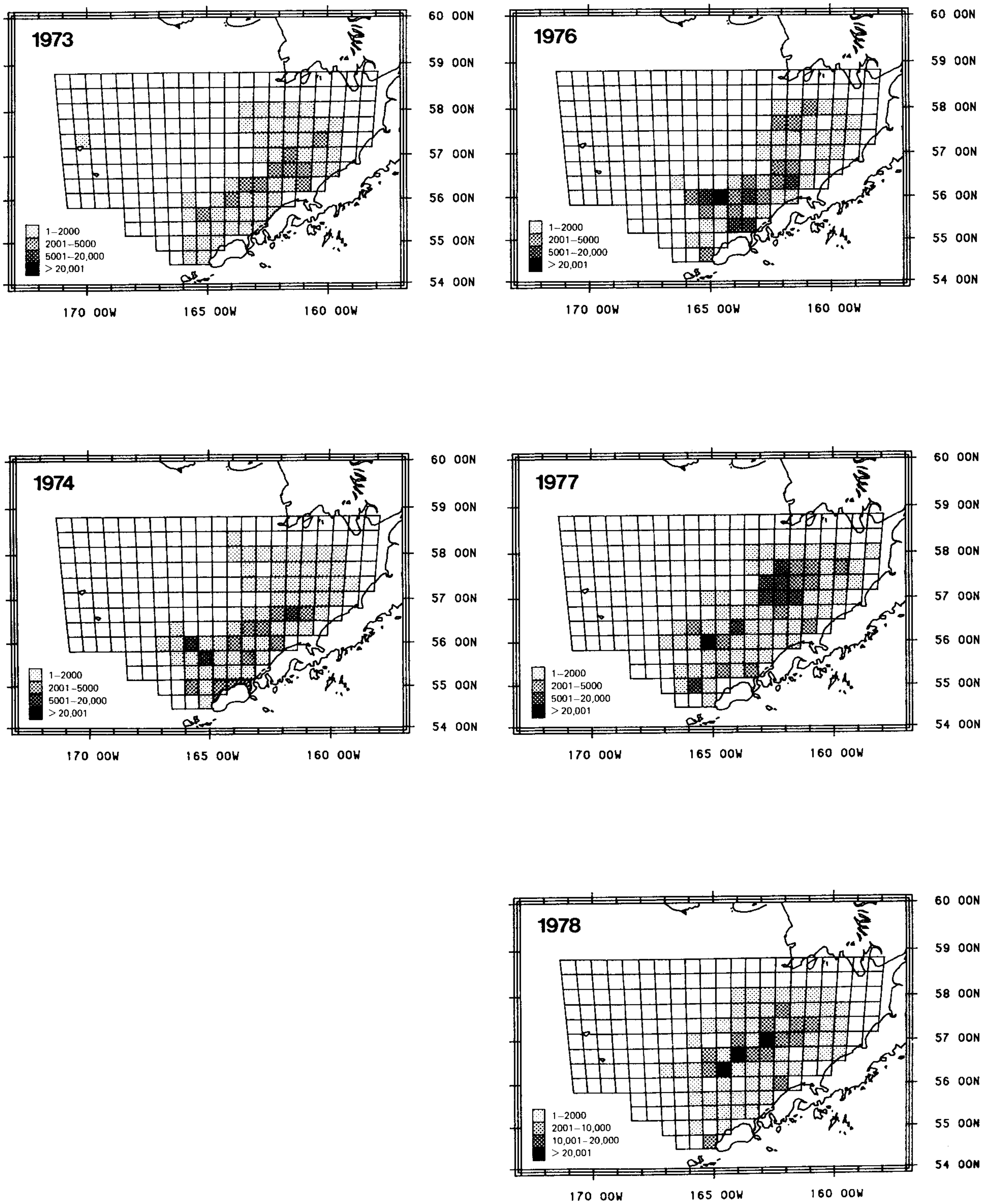


Figure 35. Continued.

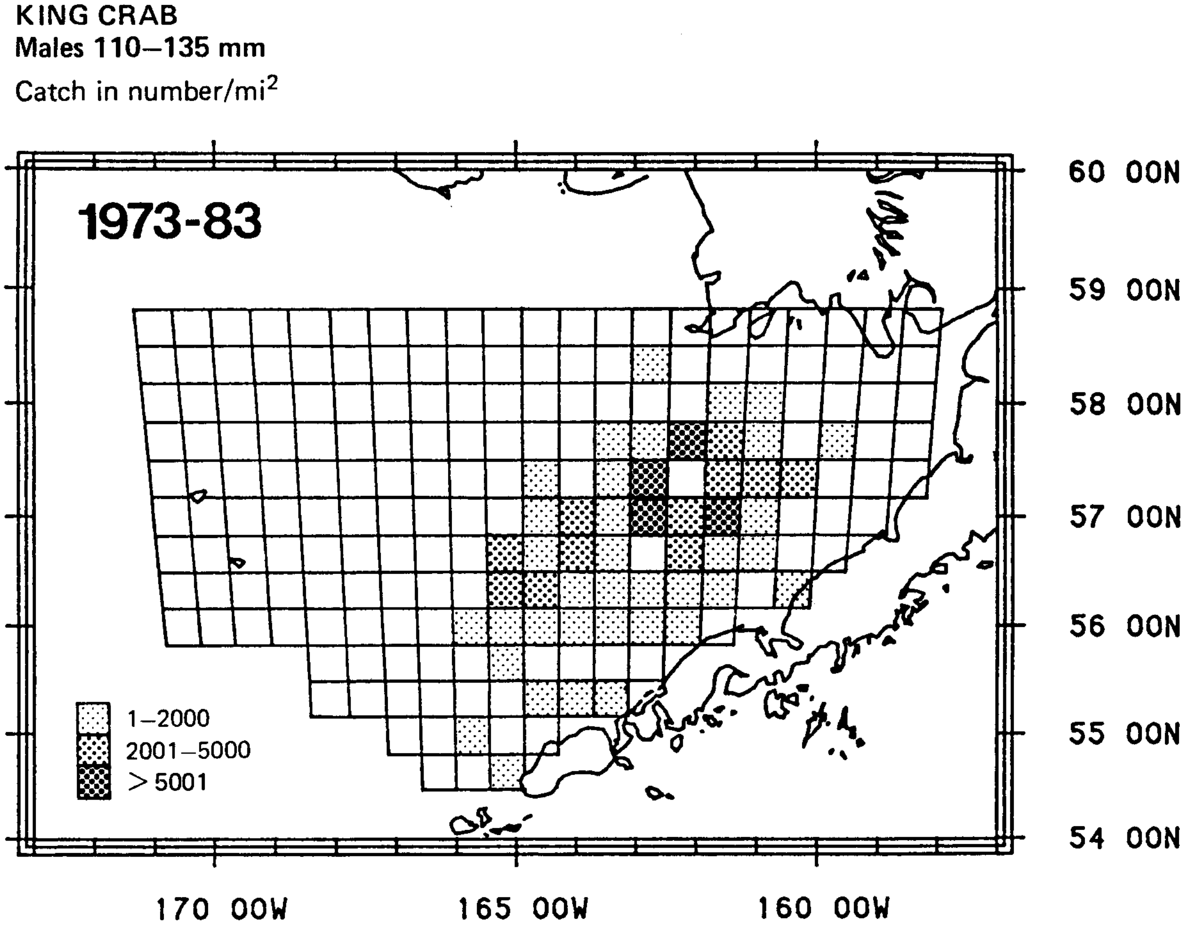


Figure 36. Areas of greatest abundance of males 110 mm to 135 mm carapace length, 1973-83.

7.3.3 Distribution and Abundance of Males less than 110 mm (Carapace Length).

Sexually immature male crab (less than 110 mm carapace length) were broadly encountered in the southeastern Bering Sea surveys from waters west of Unimak Pass to the easternmost stations sampled (Fig. 37). Unlike the larger males which tended to be less abundant in the more inshore survey areas, crabs of this size category were abundant in the nearshore stations between Unimak Island and Port Moller as well as in off shore waters where high densities of larger crab occurred (Fig. 38).

7.3.4 Distribution and Abundance of Mature Females (greater than 89 mm carapace length).

Mature females tended to be most abundant along the more inshore waters from from Unimak Island eastward almost to Port Heiden (Fig. 39). Maximum densities occurred off western Unimak Island and over a rather large area seaward of the Alaska Peninsula between Black Hill and Cape Seniavin (Fig. 40).

7.3.5 Distribution and Abundance of Immature Females (less than 90 mm carapace length).

Immature female king crab were broadly distributed from Unimak Pass to inner Bristol Bay (Fig. 41). They were most abundant in the nearshore areas westward of Cape Seniavin as well as in offshore waters north of Black Hill-Port Moller (Fig. 42).

KING CRAB
1973–78
Males < 110 mm
Catch in number/mi^2

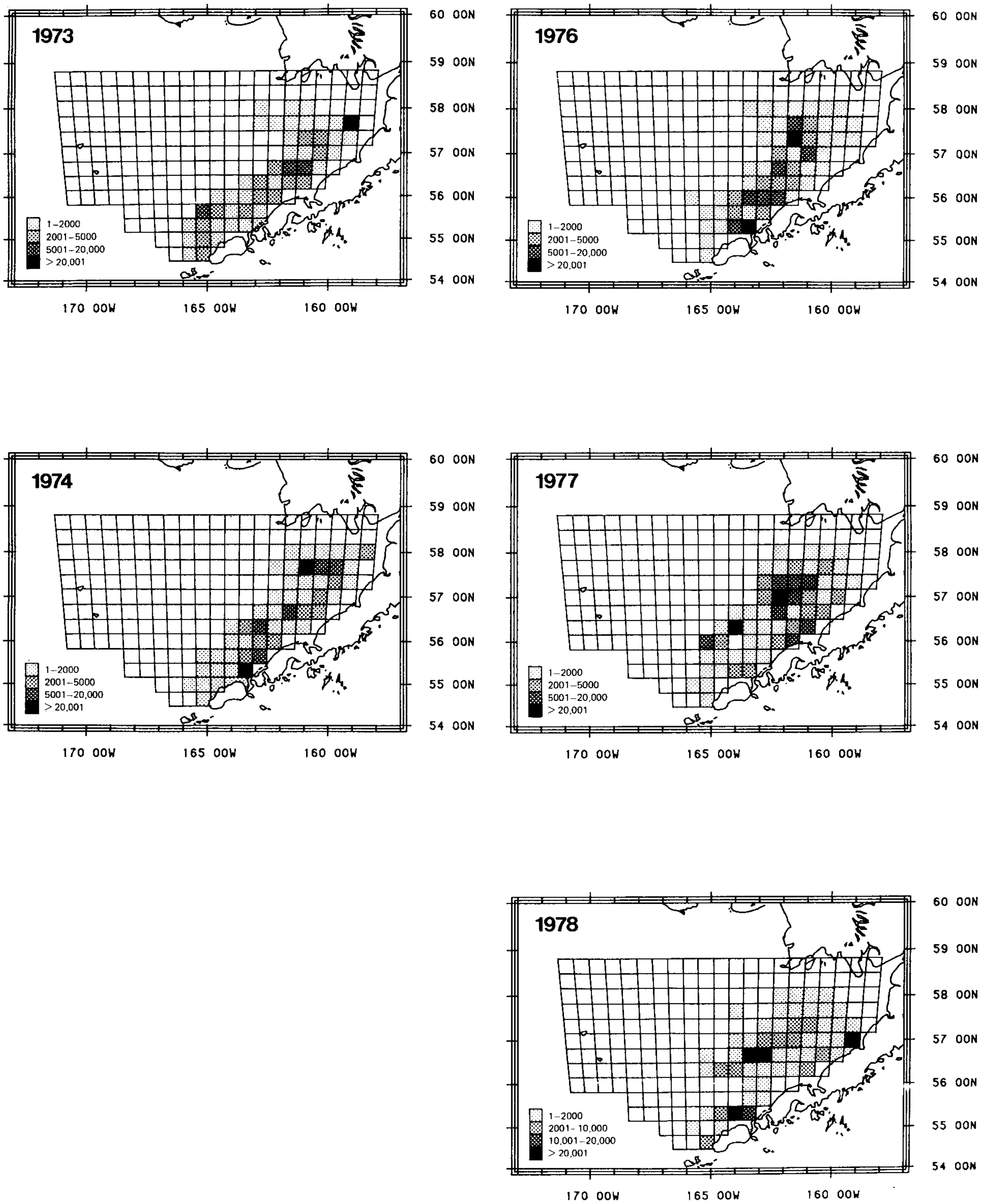


Figure 37. Distribution of male king crab >110 mm carapace length, 1973-83.

KING CRAB
1979–83
Males < 110 mm
Catch in number/mi²

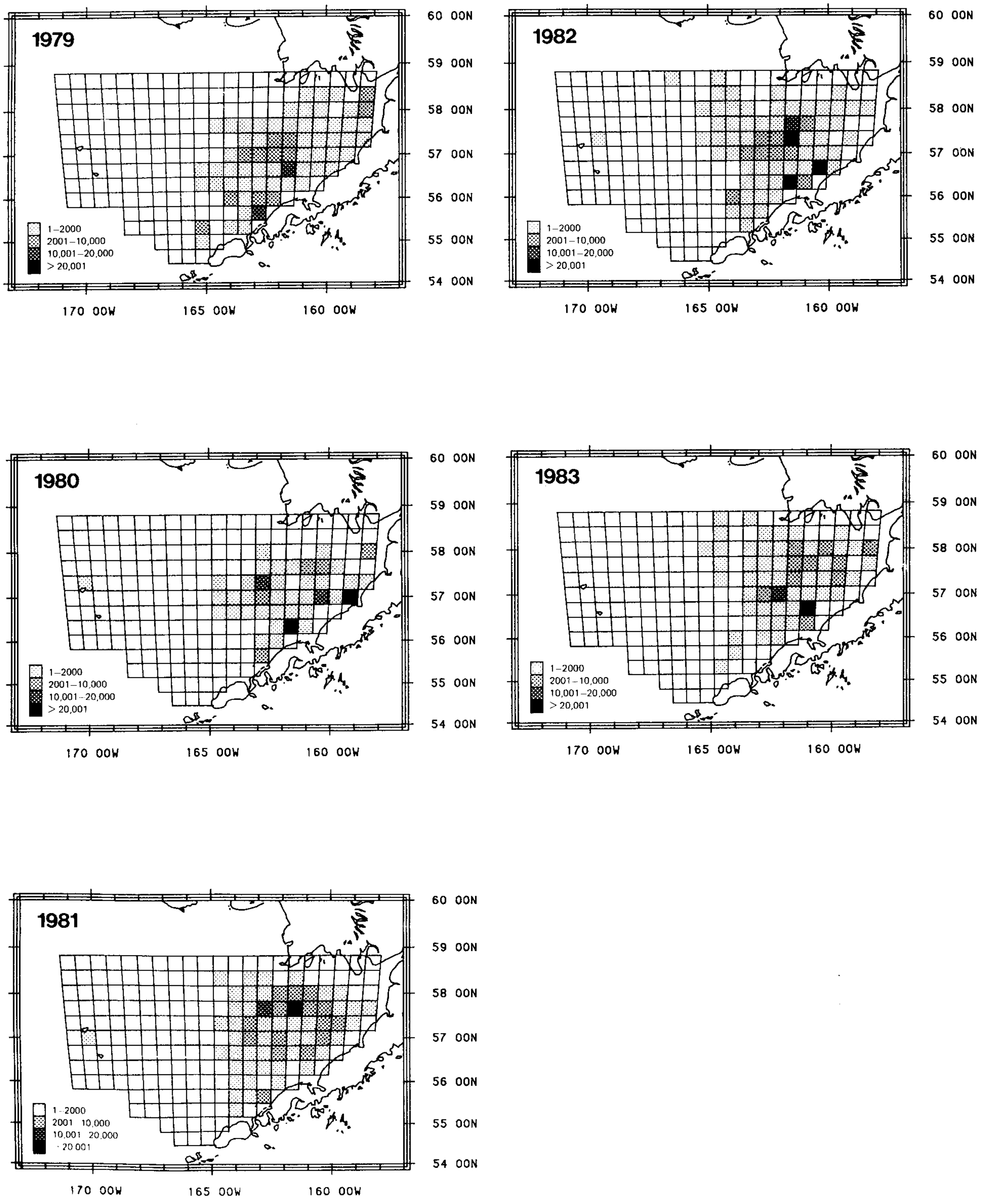


Figure 37. Continued.

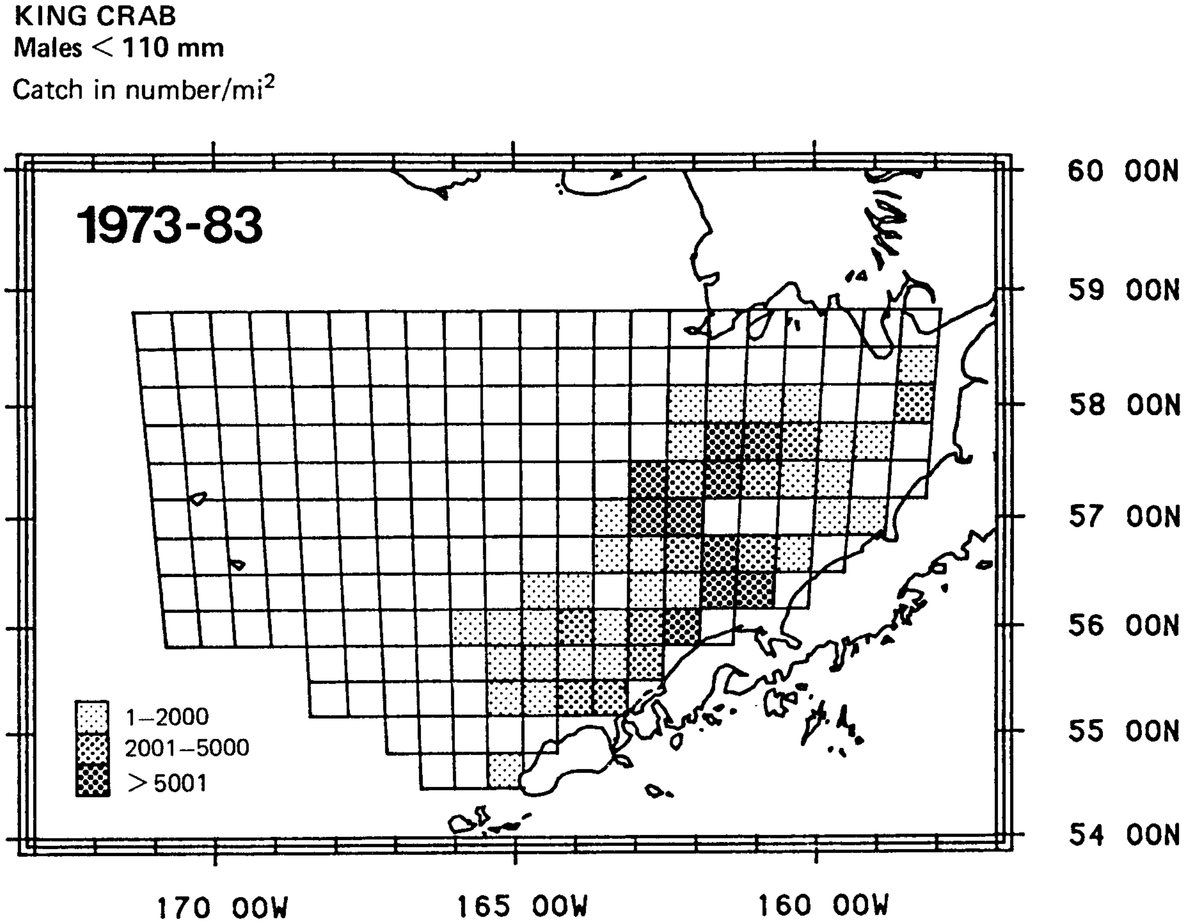


Figure 38. Areas of greatest abundance of males <110 mm carapace length, 1973-83.

KING CRAB
1973–78
Females > 89 mm (> 99 mm for 1973 and 1974)
Catch in number/mi^2

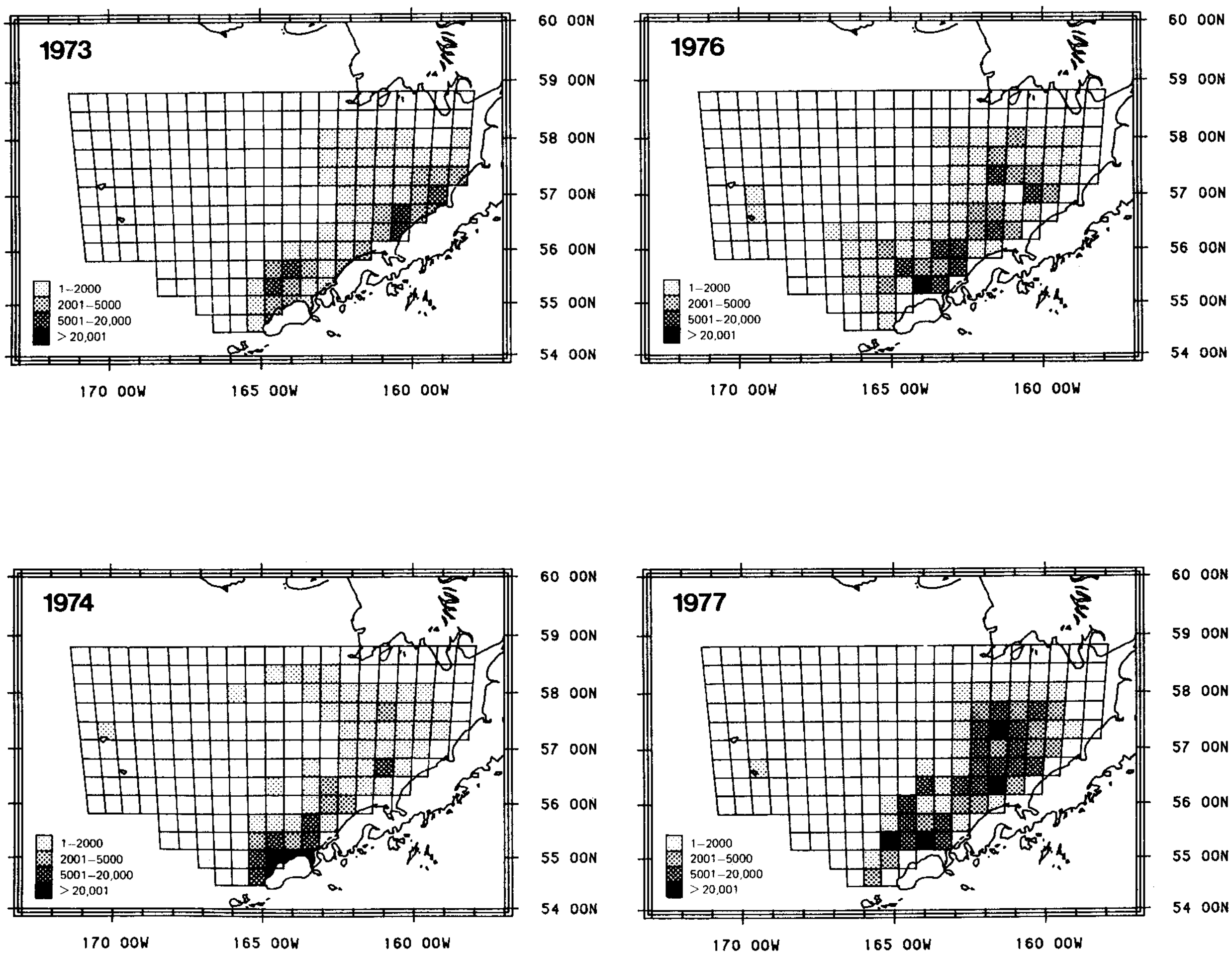


Figure 39. Distribution of female king crab >89 mm carapace length, 1973-83.

KING CRAB
1979–83
Females > 89 mm (> 99 mm for 1973 and 1974)
Catch in number/mi²

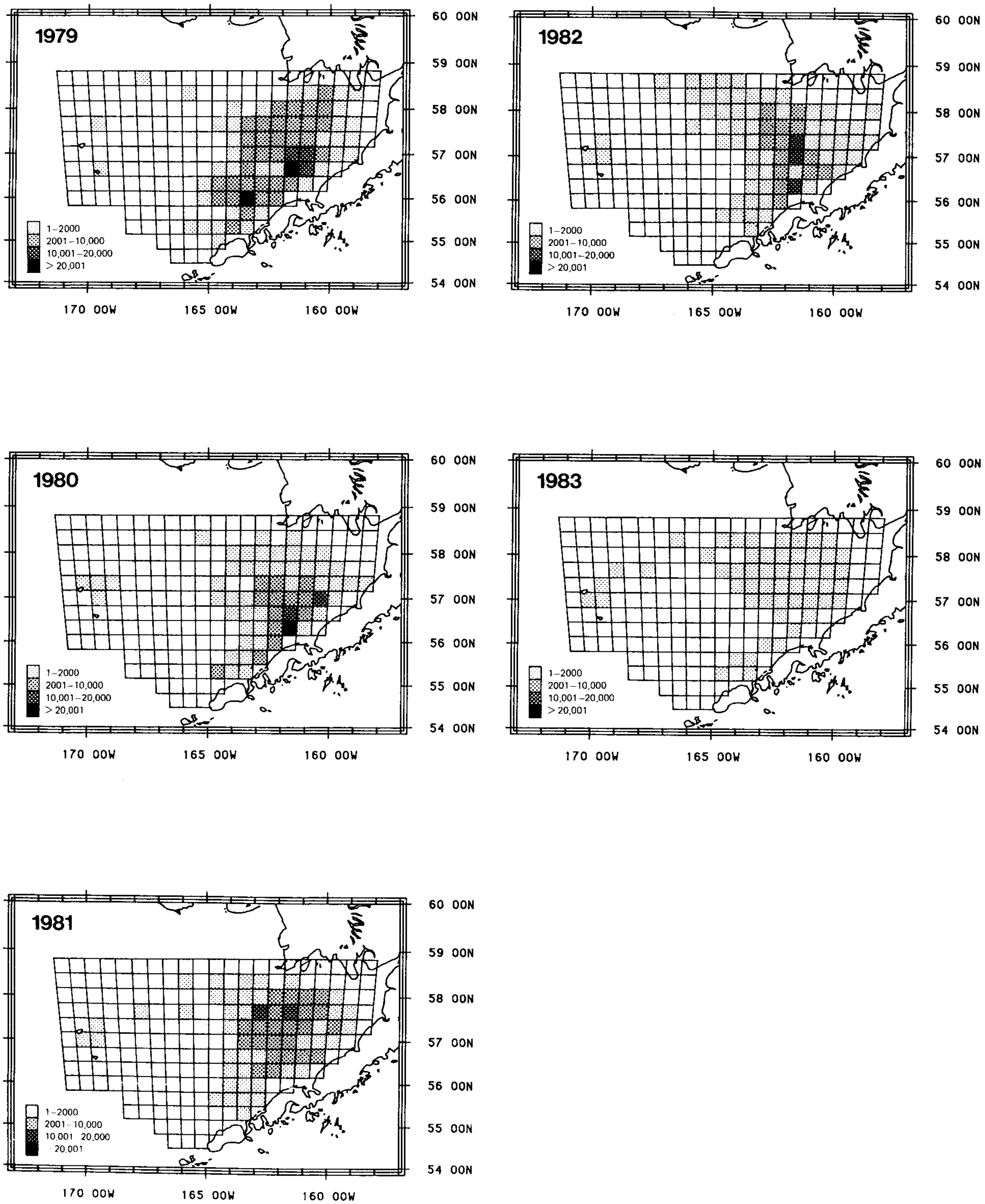


Figure 39. Continued.

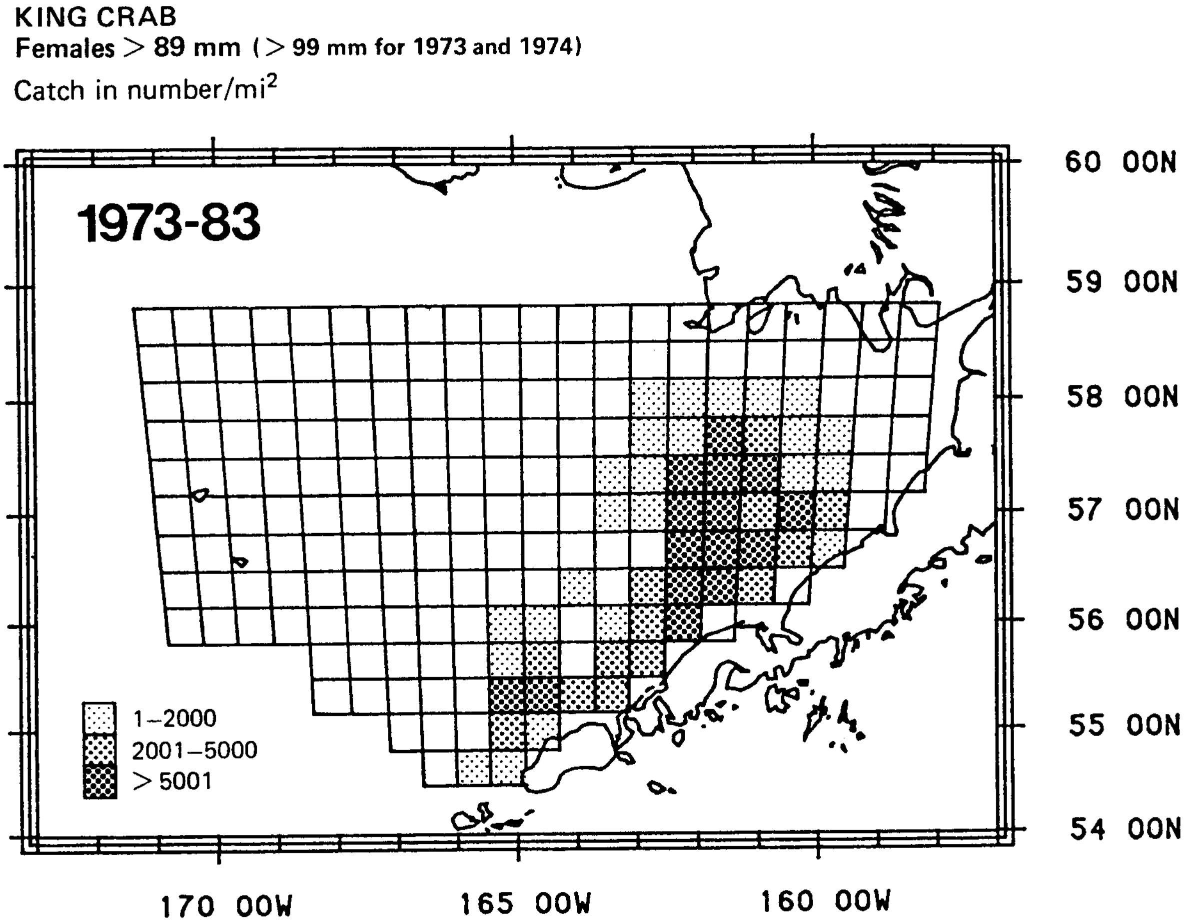


Figure 40. Areas of greatest abundance of females >89 mm carapace length, 1973-83.

KING CRAB
1973–78
Females < 90 mm (< 89 mm for 1973 and 1974)
Catch in number/mi^2

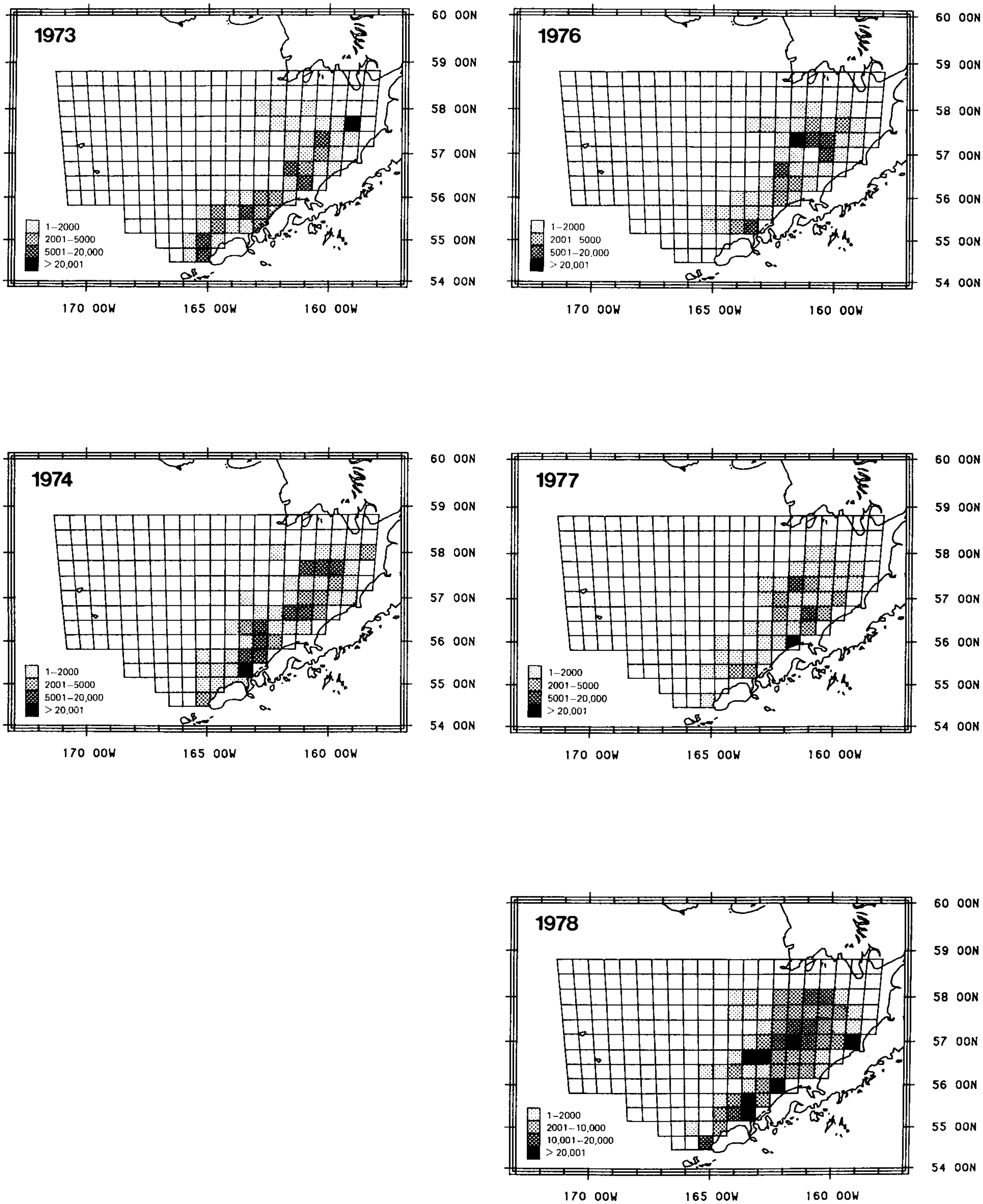


Figure 41. Distribution of immature females (>90 mm carapace length), 1973-83.

KING CRAB
1979–83
Females < 90 mm (< 89 mm for 1973 and 1974)
Catch in number/mi^2

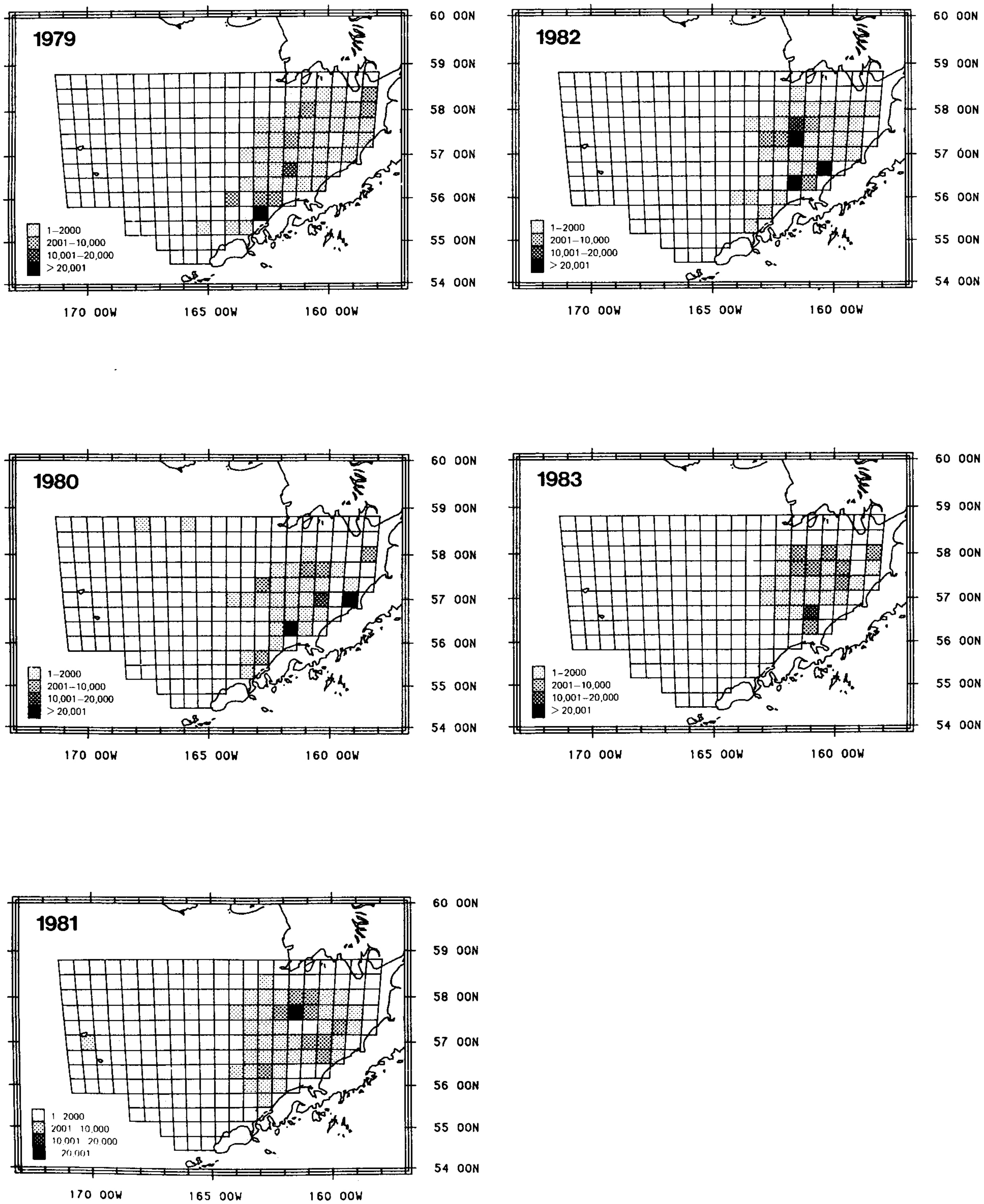


Figure 41. Continued.

KING CRAB
Females < 90 mm (< 100 mm for 1973 and 1974)
Catch in number/mi²

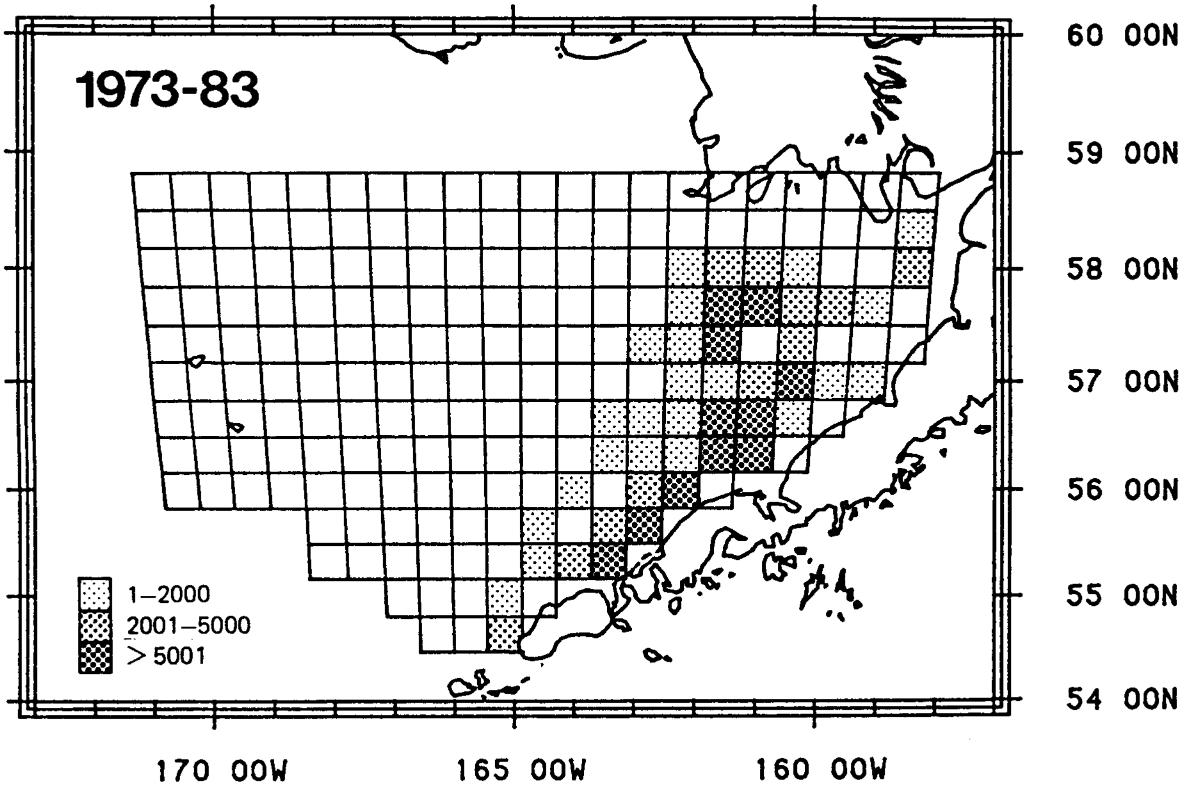


Figure 42. Areas of greatest abundance of immature females (<90 mm carapace length), 1973-83.

The NMFS studies survey many species of commercial importance other than king crab, therefore, the area surveyed is far larger than the habitat of that species. Also, the surveys have mostly been done in the spring and summer months but they have not commenced earlier than May and terminated no later than August. This schedule may suffice to enumerate the stock and its essential components for the purposes of obtaining population parameters and characteristics for monitoring and assessment of annual changes. Information contained in the foregoing figures are, however, annual summarizations over total survey area and time. As such seasonal variations in the areal distribution of the 5 size-sex categories of crab are obscured.

Little information is available regarding the winter distribution of king crab in eastern Bering Sea. In a 1963-64 winter trawl survey of eastern Bering Sea, Chebanov (1965) obtained information on crab distribution (Fig. 31). Larger legal size males (16.5 cm in width) were dominant in Zone I (depths 95-118 m). Females carrying brown and violet eggs were predominant in Zone II although some smaller males (14 cm width) were also present. Zone III was dominated by small males (90-95 m depth). The few females taken in Zone III carried brown and violet eggs. The first and third zones followed closely the 4° and 5°C isotherms while the predominant temperature in Zone II was 5°C.

Chebanov (1965) hypothesized that newly molted crab require calcium which is available from Ophiura sarsi (a brittlestar). He, therefore, reasoned that the distribution of king crab in the eastern Bering Sea would be associated with this species during or immediately after molting. After calcium deficits were met, crabs switch to a diet of molluscs.

8. THE SOUTHEASTERN BERING SEA RED KING CRAB FISHERY

8.1 History of the Fishery

The history of the eastern Bering Sea crab fishery has been described by Miyahara, 1954; Hoopes, 1970; Balsiger, 1974. The most recent and comprehensive review was given by Otto (1981).

Commercial exploitation of king crab in the eastern Bering Sea was initiated by Japanese interests in 1930. There was no operation in 1931 but the fishery recommenced in 1932 and continued through 1939. This fishery consisted of 1 or 2 factoryships which caught and processed a maximum of 2.1 million crab in 1933 to a minimum of 242 thousand crab in 1939 (Table 18). After a hiatus of 13 years, exploitation of eastern Bering Sea red king crab resumed in 1953 with a United States fishery consisting of a small trawler/processor and a Japanese expedition consisting of one large factoryship, 6 small tanglenet boats and 6 small trawlers (Miyahara, 1954). The United States fishery in eastern Bering Sea diminished to zero in 1959 and remained at low levels until after 1970. The Japanese fishery dominated catches until 1970, declined thereafter and stopped catching king crab after 1974. Soviet fisheries operated for 13 years from 1959 through 1971.

Post World War II landings of king crab from the eastern Bering Sea are summarized in Fig. 43. The total landings are characterized by modal catch of 26.8 thousand mt in 1964, a decline to 8.6 thousand mt in 1971, a steady and sharp increase to a maximum of 58.9 thousand mt in 1980, followed by a precipitous decline to 15.2, 1.4 mt and to zero mt in 1981, 1982 and 1983, respectively. The total catch through 1970 reflects the landings of the

Table 18.--Catch and pack of Japanese floating factoryships in the Bering Sea, 1930-39.

Year	Ships Operated	Ship Days Operated	Crabs Caught	Cases Packed 1/
	....	...(Number)...	....	....
1939	1	37	241,791	6,206
1938	1	67	461,040	13,385
1937	1	74	485,900	13,148
1936	1	51	290,900	7,849
1935	1	139	746,450	15,504
1934	2	242	1,347,025	30,364
1933	2	289	2,088,998	49,396
1932	1	125	1,178,280	34,365
1931	0	0	0	0
1930	1	95	1,001,600	24,572

1/ One case is equal to 96 1/2 lb. cans or 48 1-lb. cans.

Note: Information obtained from Japanese Fisheries Agency.

Source: Miyahara (1954)

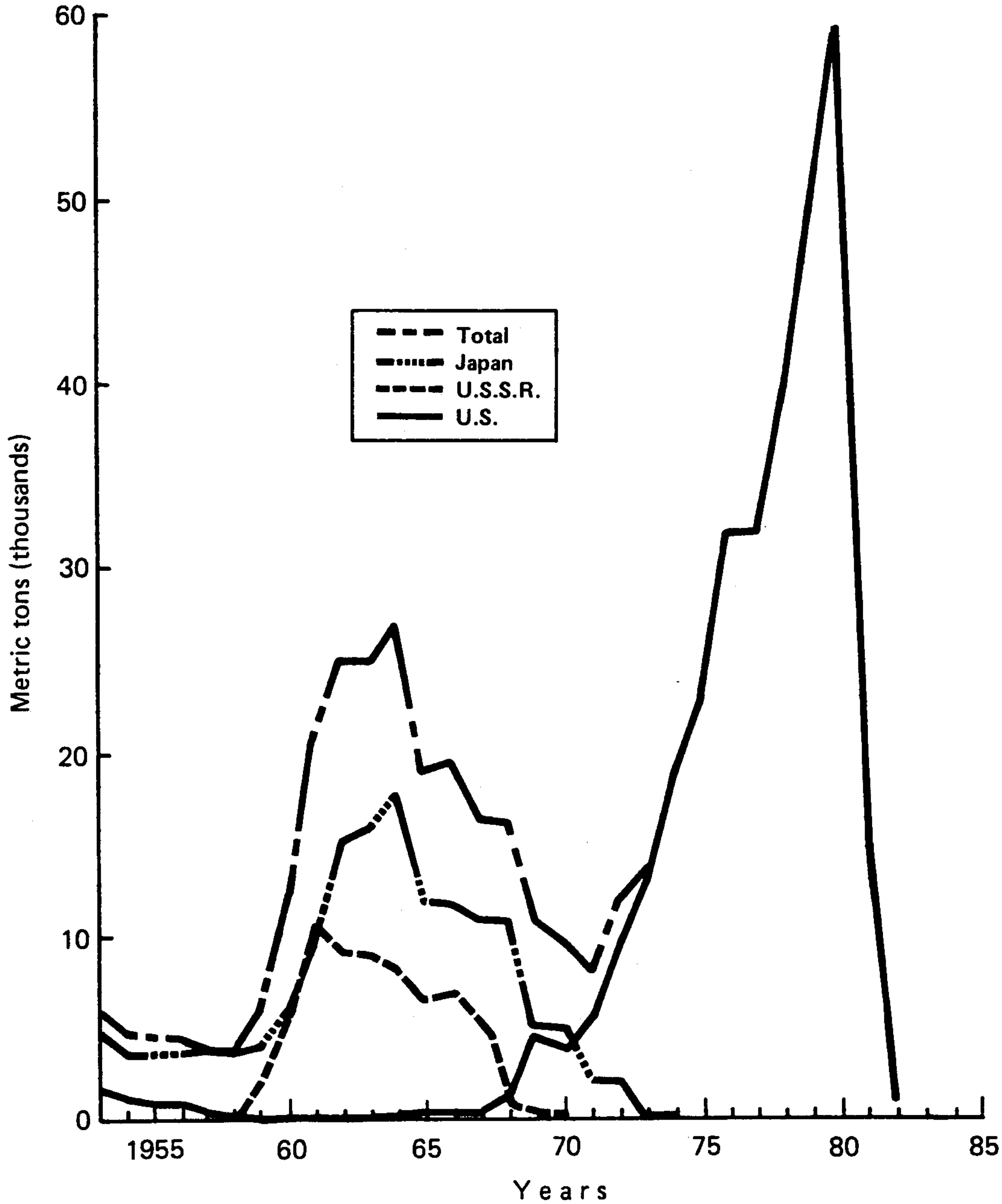


Figure 43. Annual all-nation red king crab catch in eastern Bering Sea, 1958-82.

foreign fisheries (particularly Japan). The total catch after 1974 was, of course, exclusively that of the United States fishery. The decline after 1964 reflects the imposition of quotas on the foreign fisheries by the United States government.

8.2 Regulations

The objectives of fisheries management are to regulate the quantity and quality of the catch in a manner which maximizes the productivity and yield from the resource. Determining the quality and quantity of catch to achieve this objective requires considerable knowledge concerning the biology of the species and must in many instances be modified in accordance with certain economic and operational realities.

For most of the period during which the foreign effort dominated the eastern Bering Sea king crab fisheries there was insufficient biological information upon which rational biological management measures could be based. During this period, the foreign fisheries were essentially unregulated except for self imposed limitations on seasonal catch and minimum size limits which probably accommodated operational convenience more than resource condition and productivity. Assessment of stock condition was based upon trends in catch per unit effort (CPUE), trends in average size of crab, and relative proportions of legal to sublegal sizes of crab (Rodin, 1970; Korolev, 1964; various INPFC Proceedings 1955 through 1974).

In 1964, the United States ratified the International Convention of the Continental Shelf (April 29, 1958) and declared king and Tanner crab as creatures of the United States continental shelf. As a consequence, quotas and other regulations were imposed in the eastern Bering Sea crab fishery through bilateral, executive agreements between the Government of the United States and the Governments of Japan and the Union of Soviet Socialist Republics, respectively.

Since 1974, the fishing has been exclusively by the United States fleet and subject to regulation by the Alaska Department of Fish and Game and the since 1976 by the North Pacific Fisheries Management Council (NPFMC) established by the Fisheries Conservation and Management Act of 1976 (FCMA-1976) under the authority of which the United States extended authority for management of fisheries stocks seaward to 200 miles. As required under this law, a fisheries management plan (FMP earlier referred to as NPFMC KC DFMP-1981) for eastern Bering Sea king crab was drafted in November 1981 which specified all considerations relevant to the rational management of stocks and orderly conduct of fisheries. Although statutory authority for management under FCMA was vested in the Secretary of Commerce, the NPFMC suggested that the State of Alaska develop the regulatory and management process subject to Council and Secretarial (Dept. of Commerce) review. It was also suggested that the implementation of the provisions of the FMP be delegated to the State of Alaska to avoid unnecessary and expensive duplication of effort and to utilize the established expertise of State biological, management and enforcement personnel.

The objectives and rationale for the management of eastern Bering Sea king crab, regulatory measures necessary to achieve these ends are discussed in detail in the NPFMC KC DFMP-1981. The DFMP also discusses in detail some reporting and inspection requirements which are necessary to assure compliance to regulations. Other considerations to minimize vessel, gear, and interfishery conflicts are also discussed.

Essential regulations for the king crab fishery in The Bristol Bay District (Statistical Area T) as cited in Article 12 of the 1982/83 edition of the Regulations of the Alaska Board of Fisheries for Commercial Fishing in Alaska is shown in Table 19.

8.3 Fishing Methods and Effort

Eastern Bering Sea king crab have been exploited by distant water fisheries utilizing factoryships and catcher boats and by the United States fleet which is an aggregation of independently operated vessels which typically deliver and sell catches to shorebased processing plants. Most crab were taken either in tanglenets or pots (traps) although some trawling was also utilized.

8.3.1 The Japanese Fishery

The Japanese fisheries in eastern Bering Sea were described by Miyahara (1954). The fleet composition, effort and catch for the Japanese fishery from 1953 through 1974, the last year of operation is given in the following table.

Table 19

ARTICLE 12
STATISTICAL AREA T (BRISTOL BAY AREA)
REGULATIONS FOR REGISTRATION AREA

5 AAC 34.800. DESCRIPTION OF STATISTICAL AREA. Statistical area T has as its northern boundary the latitude of Cape Newenham (58°39'N lat), as its southern boundary the latitude of Cape Sarichef (54°36'N lat), as its western boundary 168° W long and includes all waters of Bristol Bay.

Authority: AS 16 05 251(a)(2)

5 AAC 34.810. FISHING SEASONS. (a) After an opening time and date for taking king crab set forth in (b) of this section, no person may possess or transport aboard any registered king crab vessel or any tender, any species of king crab until that vessel has complied with the inspection provisions of sec. 30(b) of this chapter.

(b) Red, blue and brown king crab 6 1/2 inches (165 mm) or larger in width of shell may be taken or possessed from 12:00 noon September 10 through April 15 unless closed earlier by emergency order, except that red, blue and brown king crab seven inches (178 mm) or greater in width of shell may be taken or possessed during periods opened and closed by emergency order.

Authority: AS 16 05 060
AS 16 05 251(a)(2),(3)

5 AAC 34.815. HARVEST STRATEGY. This department shall manage the king crab fishery for a harvest of approximately 60 percent of the estimated population of legal size male red and blue king crab.

Authority: AS 16.05.251(a)(2),(3)

5 AAC 34.820. SIZE LIMITS (a) Male red, blue and brown king crab 6 1/2 inches (165 mm) or greater in width of shell may be taken or possessed.

(b) Male red, blue and brown king crab seven inches (178 mm) or greater in width of shell may be taken or possessed as provided in 5 AAC 34.810(b).

Authority: AS 16.05.251(a) (2),(3),(7)and(10)

5 AAC 34.825. LAWFUL GEAR (a) King crab may be taken by pots only. King crab taken by means other than pots must be immediately returned unharmed to the sea.

(b) Otter trawls with a ground line or head line exceeding 60 feet (18 m) in length may not be aboard any vessel engaged in taking or transporting king crab.

(c) In addition to the pot storage provisions of 5 AAC 34.050(c), king crab pots may be stored during the closed season in waters enclosed by a line from 55°53'N lat. 164°20'W long. to 56°20'N lat., 163°W long. to 56°20'N lat., 162°10' W long. to 56°03'N lat., 162°10'W long. to 55°18'N lat., 164°20'W long. to the starting point.

Authority: AS 16.05.251(a)(2),(4),(7),(10)

5 AAC 34.840. INSPECTION POINTS. Initial inspection points are located at Unalaska, Akutan and other points specified by the department Reinspection points are located at Unalaska, Akutan, King Cove and other points specified by the department.

Authority: AS 16.05.251(a)(2),(4),(7)

Table 20. Fleet composition, effort and catch of the Japanese crab fishery, 1953-74.

Year	Ships	Ind. boats 1/	DL Boats 2/	Tans 3/	Pots 3/	Crabs 3/
1953	1	6	6	106.3		1,276
1954	1	6	6	60.5		1,061
1955	1	12	6	99.1		1,129
1956	1	2	8	147.1		1,079
1957	1	3	8	83.6		1,171
1958	1	2	8	98.7		1,130
1959	1	2	8	78.4		1,292
1960	1	3	9	93.1		1,611
1961 spr	2	4	11	166.4		1,946
1961 aut	3	16	0	90.3		1,082
1962 spr	3	12	19	300.7		3,236
1962 aut	2	12	4	136.2		1,715
1963	2	9	17	642.4		5,476
1964	2	12	17	638.9		5,895
1965	2	10	17	452.2		4,216
1966	2	10	19	447.3		4,202
1967	2	?	?	440.5		3,764
1968	2	16	17	484.7	151.6	3,853
1969	2	30	10	271.9	615.1	2,073
1970	2	40	5	252.3	797.1	2,080
1971	2	36	4	27.5	1,111.0	886
1972	2	36	4	12.1	1,104.0	874
1973	2	36	2	0	1,023.0	228
1974	2	30		0	852.2	476

1/ Independent boats.
2/ Deck loaded boats.
3/ 1000s of tans
1000s of potlifts
1000s of crabs

8.3.2 The Soviet Fishery

The Soviet eastern Bering Sea king crab fishery consisted of one factoryship and eight catcher boats in 1959. The principle gear used was tanglenets. Soviet effort utilized in the fishery from 1959 through 1971 is given in Table 21.

Table 21. Soviet effort in the eastern Bering Sea king crab fishery, 1959-71.

Year	Nets lift
1959	64.0
1960	191.6
1961	388.0
1962	419.7
1963	536.1
1964	607.5
1965	618.7
1966	617.2
1967	657.0
1968	241.0
1969	248.1
1970	228.9
1971	190.0

8.3.3 The United States Fishery

Fishing methods, vessels and gear are described in detail by Browning (1980).

The pots (traps) utililized by this fishery are steel frames enclosed in heavy nylon webbing and fitted with entry tunnels on opposing sides of the gear. These pots are built in several sizes--6 feet by 6 feet (1.8 X 1.8 m), 6.5 by 6.5 feet (2 X 2 m), 6.5 by 7 feet (2 X 2.1 m) and 8 by 8 feet (2.4 X 2.4 m). The pots are 31-36 inches in depth (.8-.9 m) and they may weigh from 300-800 pounds (136.1-362.8 kg.).

For fishing, the pots are baited and set in strings of from a couple of dozen to 100 or more pots. Each vessel fishes several strings which may be set parallel or in any direction desired by the skipper. Gear is soaked for 12 hours to a couple of days but may be retrieved earlier or later depending upon weather condition or forecasts.

Since 1966 the United States fishery has utilized pots exclusively. The effort expended annually in terms of vessels and potlifts and the catch in both numbers and weight from the United States eastern Bering Sea king crab fishery is given in Table 22. There was a rapid increase in the numbers of vessels participating in this fishery from 9 in 1966 to 236 in 1979 and 1980. The fleet increased not only in number but the older vessels were replaced by newer, larger (Table 23) and more efficient vessels. Increased efficiency is apparent in the annual average potlifts per vessel which increased from 302 in 1966 to over 3000 in 1972, 1977 and 1981.

9. CURRENT EASTERN BERING SEA CRAB FISHERY AND CONDITION OF THE STOCK

9.1 Management Philosophy and Goals

Management of the eastern Bering Sea king crab fishery considers not only matters relating to yield from the stock but also the safety of the fleet, facilitation of regulation, and minimization of conflict within the fishery and with the schedule and operation of other fisheries.

9.1.1 Management of Spawning Stock

The goal of eastern Bering Sea king crab management is to ensure a spawning stock of fertilized females which will maximize recruitment to the fishery. This requires the maintenance of some optimum number of mature females as well as a harvesting strategy which assures the retention in the

Table 22.--Historic U.S. red king crab catch in the Bristol Bay registration area of the Bering Sea, 1966 to 1982.

Year	Vessels	No. of Lndgs.	No. Crab	No. Pounds	Pots Lifted	Avg. Wt.	CPUE
1966	9	15	140,554	997,321	2,720	7.1	52
1967	20	61	397,307	3,102,443	10,621	7.8	38
1968	59	261	1,278,592	8,686,546	47,496	6.8	27
1969	65	377	1,749,022	10,403,283	98,426	5.9	18
1970	51	309	1,682,591	8,559,178	96,658	5.1	17
1971	52	394	2,404,681	12,945,776	118,522	5.4	20
1972	64	611	3,994,356	21,744,045	205,045	5.4	20
1973	67	454	5,000,383	28,190,214	200,909	5.6	25
1974	108	599	7,653,944	41,945,768	211,918	5.5	36
1975	102	592	8,745,294	51,326,259	205,096	5.9	43
1976	141	984	10,603,367	63,919,728	321,010	6.0	33
1977	130	1,020	11,733,101	69,967,868	451,273	5.9	26
1978	162	926	14,745,709	87,618,320	406,165	5.9	36
1979	236	889	16,808,605	107,828,057	315,226	6.4	53
1980	236	1,250	20,845,350	129,948,436	567,292	6.2	37
1981	178	1,026	5,307,947	33,591,368	542,250	6.3	10
1982	91	255	541,009	3,001,210	141,656	5.6	4

Source: Eaton (1983)

Table 23.--Number and size of U.S. vessels engaged in eastern Bering Sea crab fishery, 1966-77.

Year	Total Number	Size: Average keel length (feet)	Size: Average net weight (tons)
1966	9	85.9	75.0
1967	20	95.8	114.1
1968	59	91.9	112.5
1969	65	93.0	116.3
1970	51	86.0	116.0
1971	52	85.0	117.1
1972	64	91.1	133.2
1973	67	92.4	141.0
1974	104	94.6	144.1
1975	104	90.5	131.0
1976	142	90.8	136.3
1977	144	93.3	138.4

Source: Eaton (1979)

spawning stock of a certain quantity and size group of males, which can effectively fertilize the females.

9.1.1.1. Female Brood Stock and Recruitment

The relationship between the number of fertilized females and the number of 5 year old recruits produced is shown in Fig. 44 from Reeves (1984). A fit of the data through 1981 to the Ricker (1954) model indicated that a maximum in recruitment occurs at an abundance of about 20 million fertilized females (Reeves, 1982). The comparatively short historical data base for this analysis was recognized by Reeves (1982) who anticipated that the acquisition of information from additional years might change the form of the spawner/recruit curve. In subsequent analyses which included data through 1983, the minimum spawning female population required to maximize recruitment was indicated to be in the range of 31-36 million (Reeves, 1984). At the current stage of knowledge, the spawner/recruit relationship was considered by Reeves (1982) to be a precautionary model delineating the spawning stock threshhold rather than a prognostic model for recruitment.

Regarding recruitment, from the data in Fig. 44, maximum recruitment of age 5 crabs (46 million) was produced by the smallest stock of fertilized female crab (11 million). Also, the very numerous fertilized females of 1973 (1974 hatching) produced a near record low recruitment of 5 year old recruits. With the exception of the 1971 brood stock, fertilized female spawning stocks ranging from 11 million (1970) to 126 million (1977) have produced recruitment of age 5 male crabs ranging from 11 million to 27 million. From these data it is apparent that a very wide range (about 120

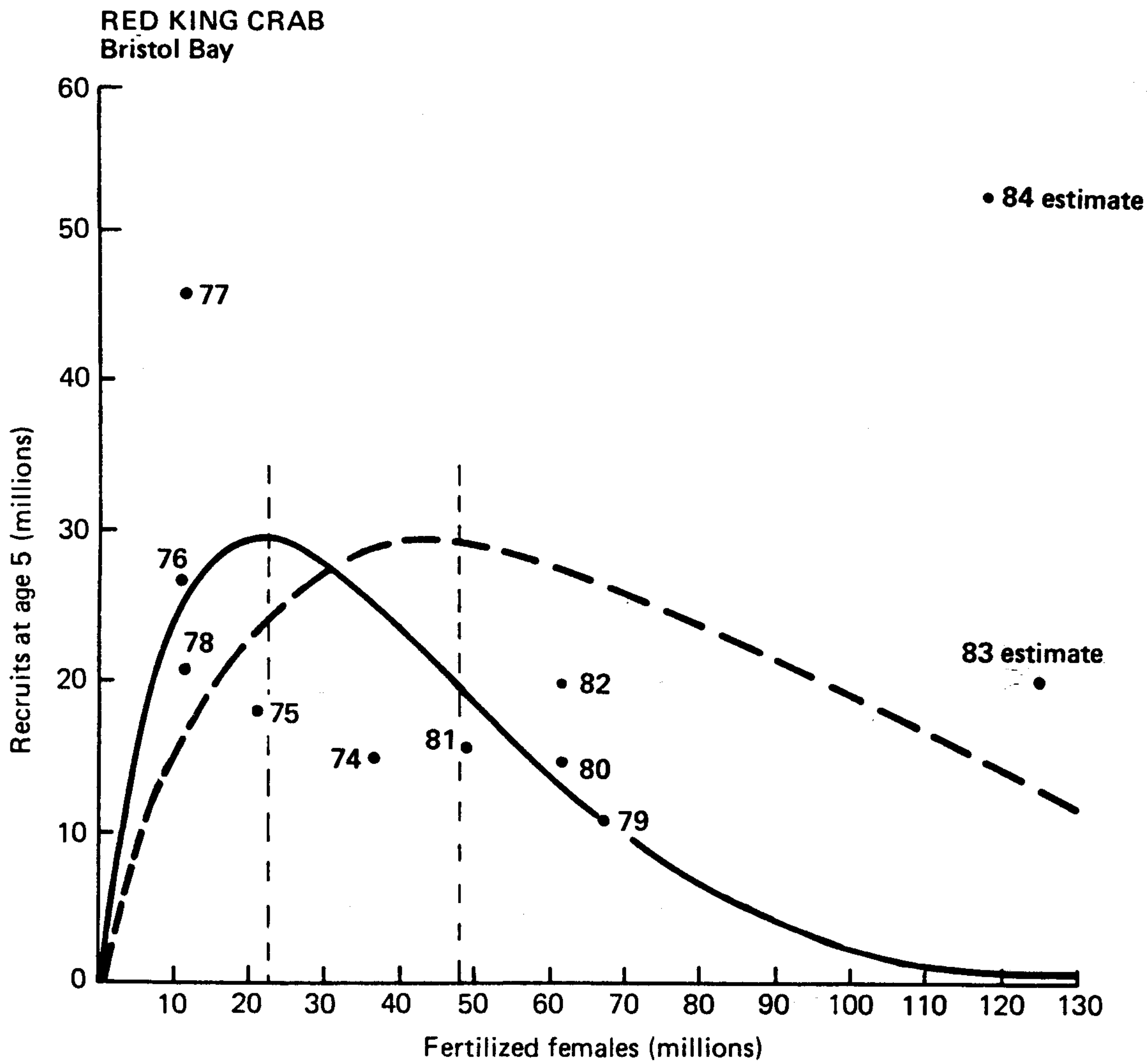


Figure 44. Spawner-recruit relationship for Bristol Bay red king crab.

million) of female spawning stock has produced a much more limited range (excepting 1977, 16 million) of 5 year old recruits. Therefore, although we may statistically specify a range of spawning stock sizes which will maximize recruitment, extreme variability in the spawner/recruit relationship precludes any reliable forecast of the recruitment from any level of female spawning stock size.

On the basis of trends indicated in Fig. 44, Reeves (1982) ascertained that recruitment of 5 year olds would be maximized by fertilized female spawning stock sizes of from 20 million to 40 million.

9.1.1.2. Minimum Retention Size

The allowable catch is the maximum harvest of males which does not result in a decline in the female spawning stock below optimum levels. To assure that males have the opportunity to spawn at least once before being subjected to harvesting, the minimum retention size is set at the size attained 3 years after 50% of the male population becomes sexually mature. This minimum size is 6 1/2 inches (165 mm) in carapace width or 135 mm in carapace length. Therefore, although male king crabs are essentially fully recruited to the survey trawl gear at age 5 which served as the reference age for the previous discussions concerning stock/recruitment, male crabs are actually recruited to the fishery at age 8 or 9.

An annual exploitation rate of 0.4 was estimated as satisfactory to achieve management goals. Due, however, to severe declines in population abundance since 1981, this rate has been adjusted downward to 0.2 in 1982 and to zero in 1983.

9.1.1.3. Fishing Season

Since the management of the fishery under the FCMA, the fishing season has been from September (Sept. 10 in 1982 regulations) to April. The allowable catch is generally taken in about a month, therefore, the season is always terminated within the calendar year.

Various factors have been considered in setting the fishing season. The season is set to protect molting and spawning crab or crabs in certain growth stages, to discourage small vessels from operating in bad weather, to maximize the quality and quantity of crab meat content and to minimize dead loss (mortalities in transporting crab to processors). Consideration is given to coordination with other fisheries which use the same vessels or facilities or for proper timing to better distribute fishing effort.

9.1.1.4. Storage of Gear Which is Not Fishing

From previous descriptions of gear it is clear that king crab pots are large, numerous and present considerable difficulties in transportation and storage. To mimimize these problems, provisions have been made to store unbaited pots in designated pot storage areas. The pot storage areas in easter Bering Sea are designated in the fishery regulations (Table 19).

9.2 Catch and Abundance

The commercial catch of red king crab from the eastern Bering Sea from 1953 through 1982 is shown in Table 24 and was discussed earlier (Fig. 43).

Table 24.--Annual red king crab catches in the Bristol Bay registration area of Bering Sea by United States, Japan and U.S.S.R., 1953-82.*

Year	United States	Japan	U.S.S.R.	Total
1953	2,935	10,374	0	13,309
1954	2,535	8,202	0	10,737
1955	2,269	8,185	0	10,454
1956	2,146	7,877	0	10,023
1957	749	8,197	0	8,946
1958	7	7,808	0	7,815
1959	0	9,031	4,334	13,365
1960	600	13,292	13,606	27,498
1961	427	20,884	23,708	45,019
1962	68	33,716	20,559	54,343
1963	653	35,430	19,533	55,616
1964	823	39,438	18,732	58,993
1965	1,429	27,025	14,269	42,723
1966	997	26,330	16,026	43,353
1967	3,102	23,638	9,998	36,738
1968	8,686	24,043	3,426	36,155
1969	10,403	12,210	2,173	24,786
1970	8,559	11,253	1,731	21,543
1971	12,946	4,722	1,412	19,080
1972	21,745	4,720	0	26,465
1973	28,190	228	0	28,418
1974	41,946	476	0	42,423
1975	51,326	0	0	51,326
1976	63,919	0	0	63,919
1977	69,968	0	0	69,968
1978	87,618	0	0	87,618
1979	107,828	0	0	106,828
1980	129,948	0	0	129,948
1981	33,591	0	0	33,591
1982	3,001	0	0	3,001
TOTAL	698,414	337,079	149,507	1,185,000
AVERAGE	23,280	15,321	11,500	39,500

* - All catches shown in thousands of pounds.

Source: Eaton (1983)

Table 25.--Population estimates for eastern Bering Sea king crabs from NMFS surveys (millions of crabs).

Bristol Bay and Pribilof Red King Crabs		
Year	Pre-recruits[1/]	Legals[1/]
1969	19.5	9.8
1970[2/]	8.4	5.3
1972	8.3	5.4
1973	25.9	10.9
1974	31.2	20.8
1975	29.6	21.2
1976	49.3	32.7
1977	63.9	37.6
1978	52.5	46.6
1979	38.8	45.5
1980	23.9	36.1
1981	18.9	11.3
1982	17.1	4.4
1983[3/]	10.5	1.5

1/ 5.2" - 6.4" = pre-recruits
>6.5" = legals

2/ 1971 excluded from population estimates

3/ Includes crabs from northern district

Source: Reeves (1983)

Table 26.--Annual abundance estimates (millions of crabs) for P. camtschatica in the Pribilof and Bristol Bay Districts from NMFS surveys.

	Males					Females			
Size: 1/	<110	110-134	>134	120-134	Total	<90	>89	Total	Grand Total
1969	41.0	20.3	9.8	9.6	71.1	18.3	28.5	46.8	117.9
1970	9.5	8.4	5.3	5.2	23.2	4.9	13.0	17.9	41.1
1972 2/	14.1	8.0	5.4	4.7	27.5	7.0	12.1	19.1	46.6
1973	50.0	25.9	10.8	14.2	86.7	24.8	76.8	101.6	188.3
1974	59.0	31.2	20.9	20.0	111.1	37.7	72.0	109.7	220.8
1975	84.9	31.7	21.0	18.6	137.6	70.8	58.9	129.7	267.3
1976	70.2	49.3	32.7	30.7	152.2	35.9	71.8	107.7	259.9
1977	80.2	63.9	37.6	35.3	181.7	33.5	150.1	183.6	365.3
1978	62.9	47.9	46.6	30.9	157.4	38.2	128.4	166.6	324.0
1979	48.1	37.2	43.9	27.4	129.2	45.1	110.9	156.0	285.2
1980	56.8	23.9	36.1	15.3	116.8	44.8	67.6	112.5	229.3
1981	56.6	18.4	11.3	8.9	86.3	36.3	67.3	103.6	189.9
1982	107.2	17.4	4.7	8.5	129.3	77.2	54.8	132.0	261.3
1983 3/	43.3	10.4	1.5	4.9	55.2	24.3	9.7	34.0	89.2
	(51.5)	(12.6)	(1.9)	(6.0)	(66.1)	(30.2)	(12.5)	(42.7)	(108.8)
Limits 4/									
Lower	34.0	8.8	1.1	4.1	45.8	17.4	7.6	26.8	77.3
Upper	52.6	12.0	1.9	5.8	64.7	31.2	11.8	41.2	101.4
±%	21	15	27	17	17	28	22	21	13

1/ Carapace length (mm).

2/ Limited survey in 1971, not used for population estimate.

3/ 1983 data includes small numbers of crab from the Northern District; numbers in parens were computed by multiplying catches of the R/V Alaska by 1.56.

4/ With 95% confidence; precision for numbers in parens differs by less than 1% from the percentage given.

Source: Otto et al. (1983)

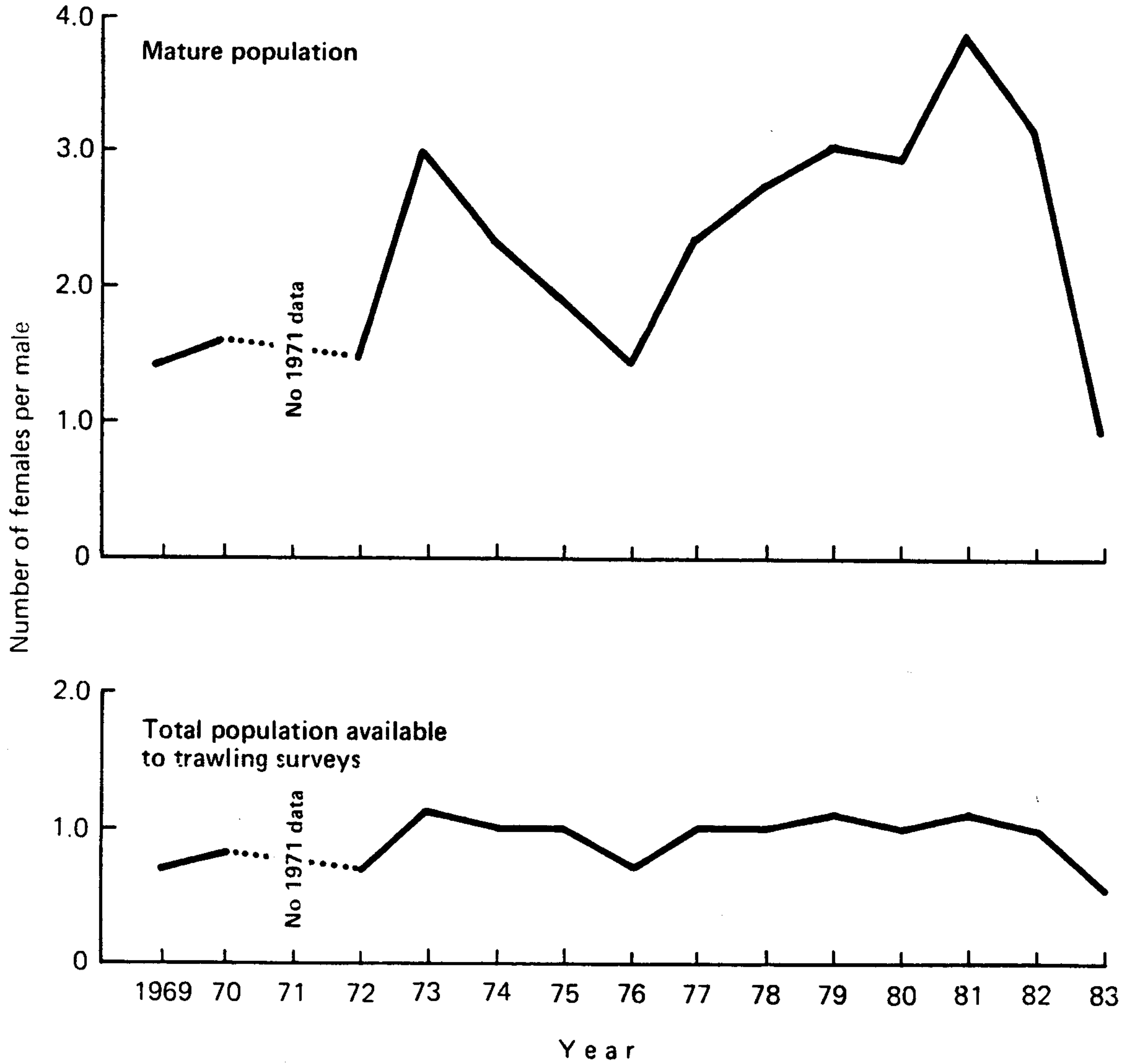


Figure 45. Sex ratios for Bristol Bay red king crab population.

Population estimates for males in the eastern Bering Sea king crab stock have been obtained annually in surveys by MNFS research vessels. The population of legal sized crab increased from about 5 million in 1970 to about 46 million in 1978 and 1979. Since 1980, the number of legal size males has dwindled to 1.5 million crab in 1983 (Table 25).

Pre-recruits were at a maximum in 1977 (64 million) but their numbers have gradually declined to about 10.5 million crab in 1983 (Table 25). In the 1982 survey, it appeared that a large year class had been recruited to the trawl survey (Table 26). There was, however, no sustained indications of the presence of such a year class in the 1983 survey in which the estimate of the number of immature males was the lowest since 1972.

The estimate of the mature female population has decreased from a high of 150 million in 1977 to 9.7 million in 1983 (Table 25). This is about one half the lower limit of the range of 20 million to 40 million fertilized females which present management rationale considers necessary to maintain optimum productivity. There are no signs of improvement in the female spawning stock in the immediate future, inasmuch as the abundance of immature females is also at the lowest levels since 1973.

9.3 Sex Ratio

In a polygamous species such as the king crab it seems intuitively reasonable to maintain more females than males in the spawning population. The ratio of females to males was calculated for the adult and total populations for the years 1969 through 1983 in Fig. 45 from data in Table 25. Whereas, the number of adult females has outnumbered adult males by

2 and 3 times since 1977, the 1983 survey indicates that there are as many if not slightly more males than females both of which are at very low levels of abundance.

9.4 Area of Fishing

The areas of fishing and the distribution of fishing effort for the years 1979 through 1982 was previously discussed in Section 7.3.1 of this report and Fig. 34.

9.5 Condition of the Stocks

From the foregoing discussion, it is quite clear that several principal components of the Bristol Bay red king crab stock have catastrophically declined. Abundance of legal males (greater than 134 mm) is the lowest on record--so low that no fishery on Bristol Bay red king crab was permitted in 1983. The abundances of pre-recruit and males less than 110 mm are also at very low levels. Under normal conditions of molting, growth and natural mortality, recruitment would be expected to be about 4 million crab for each of the next two years. Under abnormally high mortalities, survival to recruitment may be reduced by one-half. In either event, for the next two years, the abundance of legal crab can be expected to be low (Otto, et al., 1983).

The record low population of only 9.7 million mature females in the Bristol Bay red king crab stock is of particular concern. This is about half the lower limit of the range of 20-40 million fertilized females which was suggested by Reeves (1981) as the reasonable number necessary to maximize recruitment. To add to the concern, the estimated numbers of immature females is the lowest in the past decade.

There have been conjectures but no satisfactory explanation for these catastrophic declines in the eastern Bering Sea red king crab stock. Otto etal (1983) have discussed possible causes. Unusually high predation of crab as a result of the increasing abundance of cod and halibut has been identified as a likely source of reduced survival of king crab. A protozoan parasite and one or several viruses may also be involved.

9.6 Size Frequency Distribution

The size frequency distribution of female and male king crabs captured in the annual trawl surveys 1975 through 1983 is given in Fig. 46 and for the exploited population from 1977 through 1982 in Fig. 47.

9.7 Fisheries Imposed Mortality

The trawl and longline fisheries for groundfish and the king and Tanner crab fisheries have been considered as likely sources of mortality to eastern Bering Sea king crab.

9.7.1 Discards in King and Tanner Crab Fisheries

Observations were made of 746 potlifts during the red king crab fishery in September and October 1982 (Griffin et al., 1983). In these potlifts, for

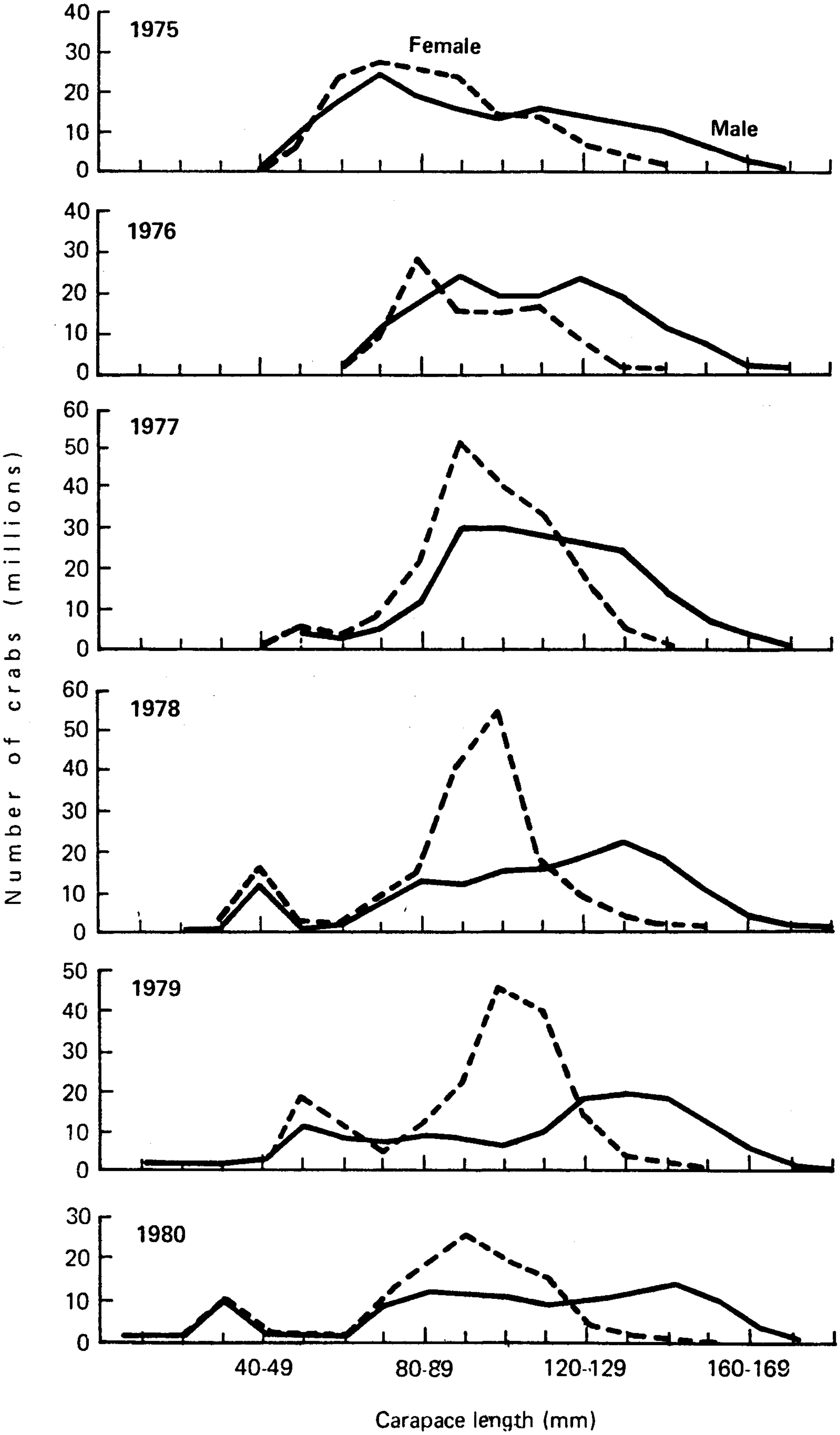


Figure 46. Size frequency distribution of Bristol Bay red king crab taken in trawl surveys.

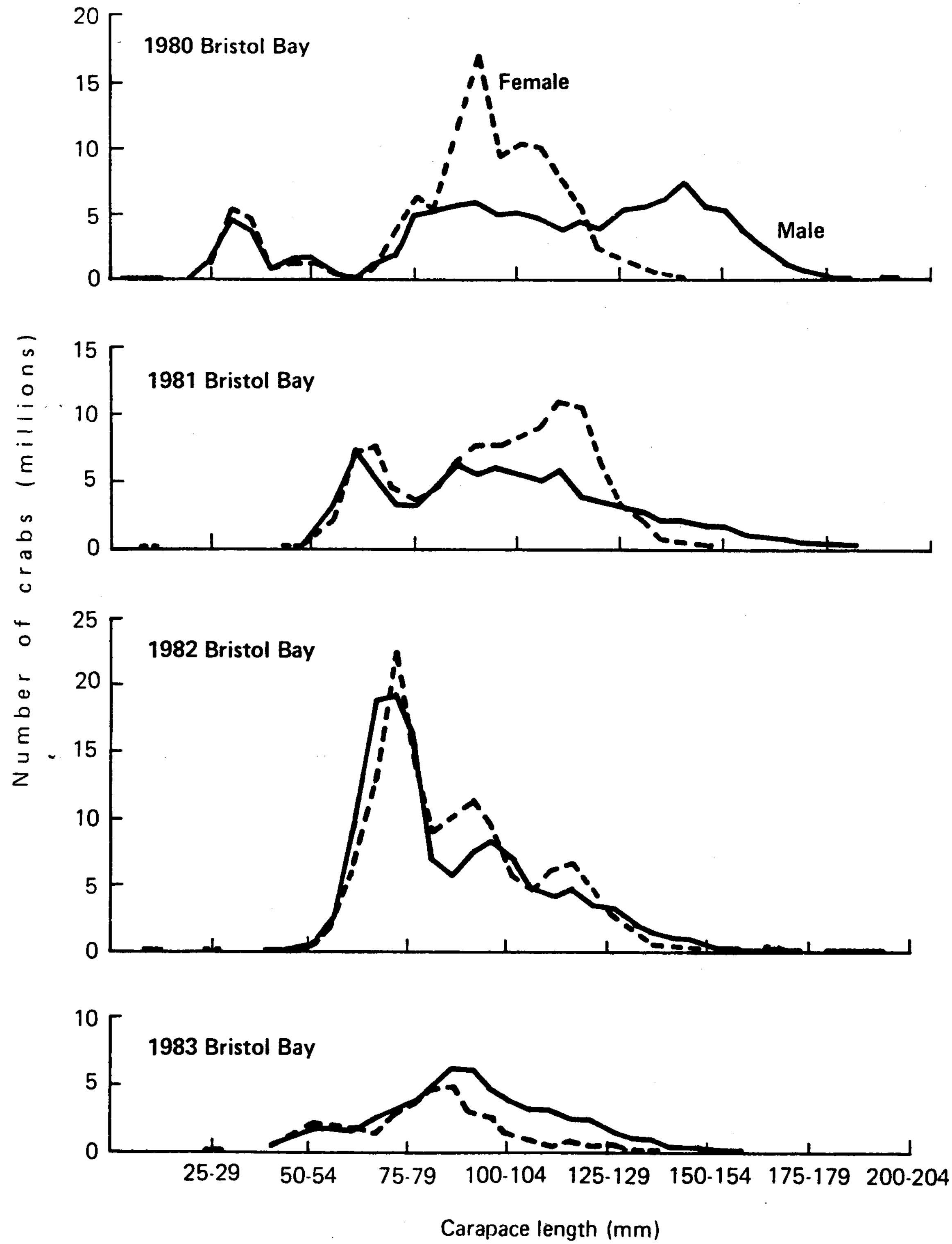


Figure 46. Continued.

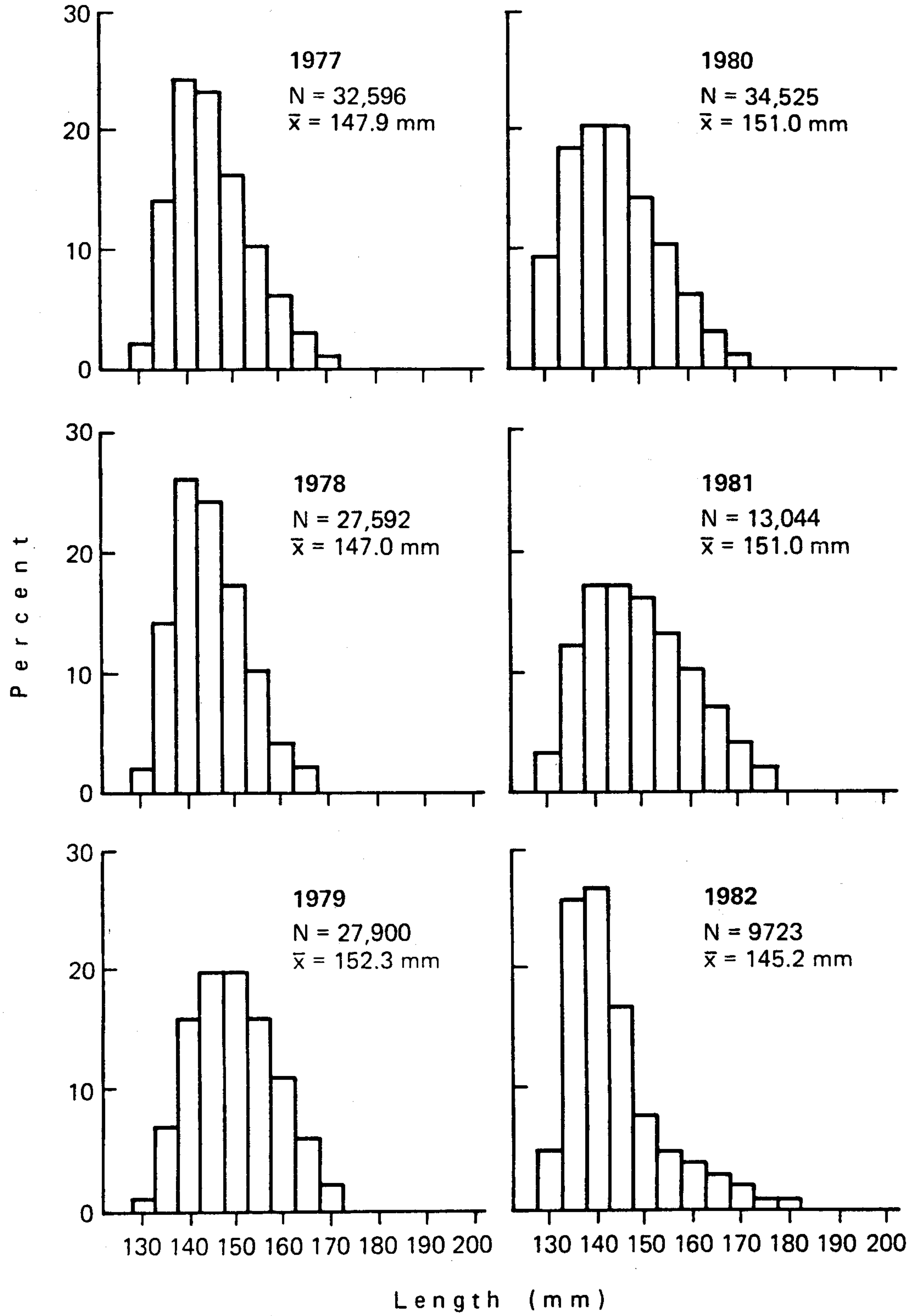


Figure 47. Size frequency distribution of Bristol Bay red king crab taken in the fishery.

each legal male caught, one female and 7.3 sublegal males were caught and discarded.

If the ratios of 7.8:1 (sublegal males:legals) and 1:1 (females:legals) are applied to some recent years catches, as many as 152 million sublegals and 20.8 million females may have been caught and returned to the sea in the 1980 eastern Bering Sea king crab fishery (Table 27).

Table 27. Discard of crabs 1977-82 assuming ratio of discards to legal crab in 1983 observations.

Year	Est. No. of Sublegals (million)	Est. No. of Females (millions)
1977	85.4	11.7
1978	107.3	14.7
1979	122.6	16.8
1980	151.8	20.8
1981	41.3	5.3
1982	3.7	0.5
Total	512.1	69.8

King crab are also taken incidentally in the Tanner crab pot fishery and the trawl fisheries. In observations made during the Tanner crab fishery in March and April of 1983, 1.6 king crab were discarded for every legal Tanner crab caught (Griffin et al., 1983).

No reliable estimates are available on the survival of crab discarded and returned to the sea from the king or Tanner crab fisheries. Otto et al., (1983) express the view that the incidental catch by directed and non-directed fisheries have had some influence but do not account for the declines in the abundance of king crab (Table 26).

9.7.2 Incidental Catch of King Crab in Trawls and Longlines.

The annual incidental catch of king crab by the trawl and longline fisheries operating east of 170°E in the eastern Bering Sea is given in Table 28.

Table 28. Incidental catch of red king crab by trawl and longline fisheries east of 170° in eastern Bering Sea.

	1980		1981		1982	
	(Nos)	(mt)	(Nos)	(mt)	(Nos)	(mt)
Trawl						
Foreign	157,954	208	115,751	143	129,530	150
Joint-Venture	289,540	241	1,082,163	642	193,896	90
Total Trawl	447,494	449	1,197,914	785	323,426	240
Longline	11,034	7	6,935	5	6,898	5.6
Grand Total	458,528	456	1,204,849	790	330,324	245.6

1 Nelson et al (1980).
2 Nelson et al (1981).
3 Nelson et al (1982).

The incidental catch of king crab by trawlers and longliners in eastern Bering Sea may exceed 1 million animals, however, this quantity is small by comparison to the potential number of crabs which might be caught and dicarded by the king crab fishery per se. The mortality resulting from handling of crab in their capture, handling and return to the sea has not been determined.

Concern has also been expressed regarding the possible mortalities caused by crab pots which are stored without bait in the southeastern Bering Sea. Crabs may also be crushed by the setting of crab pots or by the action of the ground lines on trawls. Trawling may also disturb the substrate or habitat of juvenile crab. Evaluation of these possible sources of mortality has not been documented.

10. EFFECTS OF OIL ON KING CRAB

The impact of an oil spill on eastern Bering Sea king crab stock will depend upon the chemical composition and physical properties of the petroleum or petroleum derivative, the concentrations and duration of hydrocarbons in the water column and near or on the benthos, the time and area of the spill and the developmental stage of the oiled crab. Meteorological conditions will, of course, influence the transport and weathering of the spill and hydrographic variables will also be involved in the distribution of hydrocarbons beneath the sea surface. Water temperature is important in that it can be expected to affect the rates of hydrocarbon uptake and metabolization as well as the decomposition and weathering of hydrocarbons in the environment.

An oil spill accident in the eastern Bering Sea can affect the king crab resource and the fishery in several ways. Certain hydrocarbons in sufficient concentration may cause acute or chronic lethal effects to adults, juveniles, larvae or eggs of king crab. Sublethal effects such reduced fecundity, feeding or growth rates, modifications of behavior or interference with chemical communications systems may also occur. Crabs may become unacceptable for human consumption because of visible fouling or offensive odor and taste due to accumulation of hydrocarbons in the flesh. This may lead to consumer wariness and avoidance of crab from and even outside the oil impacted sites, irrespective of demonstrable adulteration of the products. Fouling of fishing vessels and gear and the pre-emption of fishing areas and times are also possible consequences of oil spills.

Available evidence indicates that the sensitivity of crab to hydrocarbons is dependent upon the life history stage of the animal as well as the concentration and chemical composition of the petroleum or derivitive.

10.1 Sensitivity of Eggs and Larvae to Petroleum Hydrocarbons

10.1.1 Eggs

Information on the effects of petroleum hydrocarbons on the development of red king crab eggs could not be found. In his discussion of the impacts of the AMOCO CADIZ accident, Laubier (1980) noted no significant difference in the fishery statistics for lobsters in 1978 (year of the accident) and 1979. However, the number of egg-bearing females was extremely low in both years (Leglise & Raguenes, 1979; Laublier, 1980). This caused concern for the productivity of the population 4 and 5 years after the spill. It was suspected that the spider crab, Maria squinado, was similarly impacted.

Although there is no information on the effect of oil on the development of king crab eggs. If analogous to fish and eggs are relatively more senstive, then oil concentrations less than those which have lethal effect on king crab larvae (0.8-0.9 ppm for 72 hrs) might be acutely toxic to certain embryonic stages. Latent mortality to larvae caused by developmental aberrations attributable to hydrocarbon exposure might also be expected.

It should be reiterated that king crab eggs are carried by the female for more than 11 months of the year. This provides the embryos protection from predation and extreme fluctuations in the external environment. The fate of the embryo is, however, inextricably tied to the well being of the mother. The distribution of egg-bearing females and their sensitivity and exposure to oil is, therefore, very relevant to assessing the impact of oil on the embryonic development of king crab.

10.1.2. Larvae

Mecklenburg and Rice (1976) conducted experiments on the sensitivity of king crab and coonstripe shrimp (Pandalus hypsinotus) to water soluble fractions (WSF) of Cook Inlet crude oil. The 96 hour mean tolerance limits (96TLm = concentration at which 50% of the animals died after 96 hours) for stage I larvae of both king crab and coonstripe shrimp were 4.2 to 8.6 ppm. It was found, however, that concentrations 20 to 70 percent less than the 96 TLm caused a cessation in swimming and ultimate death. Molting of stage I larvae was inhibited. Molting success was affected by duration of exposure and concentration of oil. Molting was permanentlyinhibited in larvae exposed to concentrations of 0.8 to 0.9 ppm for 72 hours. Although experimental evidence is lacking, similar effects may occur with much lower concentrations if duration of exposure were increased from 72 or 96 hours to the 2 to 3 week intermolt interval of each of 4 zoeal crab stages.

King crab larvae were also found to be more susceptible to toxicity during molting than during the intermolt stage. Stage I larvae were unsuccessful in molting at WSF of 0.69 ppm while the 96 TLm for the intermolt stage I larvae was 8.0 ppm.

Crustacean larvae may be less resistant to hydrocarbon toxicity than adults because the former undergo 5 molts at 2 to 3 week intervals. Earlier stages of crustacean larvae are generally more sensitive to petroleum hydrocarbons than later larval stages (e.g., for Lobster; Wells, 1972: for crab; Katz, 1973).

10.1.3 Juveniles

The 96 hour TLm for juvenile king crab was 4.21 ppm with Cook Inlet crude oil (202 ppb UV naphthalene equivalents) and 5.10 ppm (408 ppb UV naphthalene equiv.) with No. 2 fuel oil (Rice et al., 1976). Juvenile crab were able to cleanse themselves shortly after removal to clear sea water. Methylnaphthalene concentrations were below 1 microgram /gram (wet weight) after 96 hours (Rice et al., 1976).

Oxygen consumption rate in juvenile crab was depressed by 50% after 1 hour exposure to oil concentrations of 7.45 ppm and was depressed further with time. After 4 hours, 3 of the 6 crabs were dead. WSF of 6.58 resulted in 30% reduction in oxygen uptake, however, after three hours these crabs began to recover. At concentrations of 1.48 ppm, oxygen uptake of crabs exposed to oil did not differ from that of the controls (Rice et al., 1976). Smith (1976) reported on histological and structural alterations in the gill epithelial cells in juveniles held in sea water containing WSF of crude oil for 6 days. Epithelial cells in the gills are necessary for respiration and excretion.

The extent to which these changes affect the viability of king crab was not discussed.

10.1.4. Adults

Acute toxicity to adult king crab was studied by Rice et al., (1976) in bioassays using WSF and oil-water dispersions (OWD) of Cook Inlet treated and Prudhoe Bay crude oils. Their results using Prudhoe Bay crude are summarized in the following table.

Table 29. TLm (median tolerance limit) at 24, 48 and 96 hour exposure to Prudhoe Bay crude for adult king crab (in ppm).

Exp.	Temp.	WSF	OWD
24TLm 50	3.8-7.8 C.	2.53 (2.30-2.79)	18.07 (12.93-25.24)
48TLm 50	"	2.47 (2.26-2.70)	12.60 (10.00-15.71)
96TLm 50	"	2.35 (2.16-2.55)	5.30 (0.93-30.11)

WSF of Cook Inlet oil, benzene and naphthalene depressed the heart rate of adult king crab. Heart rate returns to normal as crude oil or aromatics concentration in sea water decline. There was a tendency for the heart rate to decrease further during each depression/recovery cycle. Benzene produced quicker response and more severe and longer lasting heart rate depression than naphthalene or crude oil (Mecklenburg et al., 1976).

Oxygen consumption rate parelled the decrease in heart rate. The depression of oxygen consumption under oil exposure depended on the size of crab. Larger crab were thought to have greater ability to degrade oil (Mecklenburg et al., 1976).

10.2 Tainting of King Crab from Exposure to Oil

Tainting is defined as any alteration to the appearance (including color), texture, odor or flavor of king crab caused by exposure to oil. If severe enough, any one of these oil spill abberations will not only destroy the marketability of the tainted crab but may also trigger consumer suspicion and avoidance of untainted king crab from non-oiled waters.

Tainting is generally associated with the odor or taste of food products. Generally, the human olfactory system has comparatively high sensitivity to phenols, and sulphur compounds. Major tainting components of petroleum are phenols, dibenzothiophenes, naphthenic acids, mercaptans, tetradecanes and methylated naphhthalenes (Connell & Miller, 1981).

Kerhoff (1974), Paradis & Ackman (1975) and Hardy et al. (1976) found tainting of fish and shellfish to be caused at levels of crude or refined petroleum products in the range of 4 to 300 ppm.

The concentrations of hydrocarbons in the environment per se may not necessarily be indicative of the level of tainting achieved in the tissues of marine animals. Some animals may have enzyme systems which very efficiently degrade and metabolize petroleum hydrocarbons. On the other hand, other animals are known to accumulate certain petroleum components and biomagnify them in various body tissues.

Biomagnification factors (concentration of a component in a tissue divided by the concentration of that component in the water) of 4 naphthalenic hydrocarbons in gill, viscera and muscle tissue were calculated by Rice, et al. (1976). Data from Rice et al. (1976) are summarized and given in Table 30.

Table 30. Biomagnification of naphthalenic hydrocarbons in king crab. Ratios of tissue concentrations to exposure water concentrations for gill, viscera and muscle tissues.

Tissue	Naphth.	Methyl-Naphth.	Dimethyl Naphth.	Trimethyl Naphth.
Gill	N.A.	---	---	---
Viscera	250	1,260	1,260	800
Muscle	20	60	60	---

The bioaccumulation of hydrocarbons by king crab was very high, particularly in the viscera and for methylnaphthalenes, dimethylnaphthalenes, and trimethylnaphthalenes. The accumulation of several hydrocarbons with exposure time and schedules of depuration are given in Table 31.

Connell and Miller (1981) cited experiments done by Wilder (1970) with Bunker C oil and oil plus detergents. He found that external contamination did not necessarily lead to tainting in the muscles of lobster (*Homarus americanus*). The consumption of oil and its presence in the gut did not lead to tainting of the muscle tissues. Lobsters which were fed herring coated with oil showed no indication of tainting whatsoever (Anon., 1970).

Table 31.--Aromatic hydrocarbons in king crab tissues.

[c indicates <0.05 μg/g, d <0.2 μg/g]

Exposure/ depuration time (hours)	Amount of given component[a] (μg/g)					Total aromatic hydrocarbons (μg/g)
	X	N	MN	DMN	TMN	
			GILL TISSUE			
Control	0.3	d	d	d	d	<10
Exposure						
3	0.5	d	d	d	d	<10
10	0.2	d	d	d	d	<10
20	0.2	d	d	d	d	<10
48	0.2	d	d	d	d	<10
96	0.3	d	d	d	d	<10
Depuration						
3	0.2	d	d	d	d	<10
10	0.6	d	d	d	d	<10
20	0.4	d	d	d	d	<10
48	0.2	d	d	d	d	<10
96	0.2	d	d	d	d	<10
			VISCERAL TISSUE			
Control	2.0	c	3.2	0.2	c	40
Exposure						
3	1.9	2.0	2.7	0.5	c	35
10	3.0	c	1.9	1.6	0.1	55
20	4.0	2.5	9.4	4.8	0.2	60
48	1.0	1.8	15.8	6.5	0.4	40
96	1.2	1.8	13.9	6.0	0.2	40
Depuration						
3	3.0	2.5	14.4	2.7	0.1	35
10	4.0	0.2	5.4	1.4	c	35
20	1.8	0.9	6.9	1.2	c	40
48	1.5	0.7	4.3	0.5	c	30
96	1.8	c	0.5	0.1	c	20

Table 31.--Continued

[c indicates <0.05 μg/g, d <0.2 μg/g]

Exposure/ depuration time (hours)	Amount of given component[a] (μg/g)					Total aromatic hydrocarbons (μg/g)
	X	N	MN	DMN	TMN	
			MUSCLE TISSUE			
Control	0.1	c	c	c	c	<1
Exposure						
3	c	0.05	0.05	0.05	c	1
10	0.2	0.1	0.2	0.2	c	4
20	0.7	0.2	0.6	0.3	c	5
48	0.1	0.1	0.3	0.1	c	2
96	0.1	0.1	0.4	0.1	c	2
Depuration						
3	0.1	c	0.1	c	c	2
10	0.5	c	0.1	c	c	3
20	0.2	c	c	c	c	2
48	0.1	c	0.1	c	c	1
96	0.1	c	c	c	c	1

[a] X = A biogenic polyene with a retention time similar to that of a C_{28} n-paraffin; N = naphthalenes; MN = methylnaphthalenes; DMN = dimethylnaphthalenes; TMN = trimethylnaphthalenes, methylethylnaphthalenes, and propylnaphthalenes.

Table from Rice, et al., 1976

Other investigators have reported the tainting of lobster by petroleum hydrocarbons. Lobster taken after the Torrey Canyon spill reportedly tasted of paraffin. The crab, Cancer pagurus, was also reported to be tainted (Simpson, 1968). Chemical analyses of crustaceans after the AMOCO CADIZ spill showed preferential hydrocarbon accumulation in the hepatopancreas (290 ppm) rather than in the flesh, although the concentrations in the latter were in the range of 40-60 ppm (Leglise, 1979).

Although Laubier (1980) made no mention of tainting in lobsters or other crustaceans, the tainting of oysters by petroleum hydrocarbons was discussed. Oysters showing total hydrocarbon concentrations of 20 to 30 ppm were considered to be slightly polluted by fossil fuels. On a practical basis, an average value of 60 plus or minus 20 ppm, wet weight was considered as the upper limit for human consumption.

11. PROVISIONAL APPRAISAL OF THE EFFECTS OF OIL SPILLS AT PORT MILLER, PORT HEIDEN AND OFF CAPE NEWENHAM ON RED KING CRAB

This report has summarized knowledge concerning the distribution, reproduction, age and growth, commercial harvest and current condition of the eastern Bering Sea red king crab stock. Available information on the sensitivity of larvae, juvenile and adult king crab to some hydrocarbons was also presented. From this information it is possible to make some preliminary appraisals of how oil spills at various sites in the eastern Bering Sea might be expected to impact the king crab resource.

From the available information, it is possible to approximate the vulnerability of different life history stages and physiological states of king crab to petroleum hydrocarbons. The effect of the timing of a spill can be evaluated, at least by season. For reasons which will be discussed later, however, oil impact appraisals in this report will stop short of quantitatively estimating the petroldeum-imposed mortality to king crab or the consequencies of this mortality to the productivity of the stock--only the possibilities of such effects would be discussed.

11.1 Potential Impacts of Spills in the Spring and Summer

From the foregoing discussion, it is apparent that oil spills in the eastern Bering Sea might have some lethal or sublethal effects on the red king crab population or cause operational disruptions to the fishery. The impacts will depend upon a number of factors. The most obvious of these are, the type and amount of petroleum product involved, the timing and location of the spill, the distribution and persistence of the hydrocarbons in the water column and on (or in) the bottom, and the number, age, sex and physiological or life history stage of the king crab inhabiting the oiled area. Operational disruptions would include the pre-emption of fishing grounds by the spill or cleanup activity, and the possible tainting of crab.

There is adequate evidence that the earlier life history stages and certain physiological stages of marine animals are particularly sensitive to petroleum hydrocarbons. It is therefore, useful to review the seasonal events and distribution of eastern Bering Sea red king crab relative to the hypothetical oil spill sites off Port Moller, Port Heiden and Cape Newenham.

As is the case with temperate and subarctic marine organisms, the biology and distribution of red king crab in the eastern Bering Sea is a chronological sequence of seasonal events. The seasonal occurrence of life history events such as the spring spawning migration, egg release and hatching, mating, molting, and feeding migrations have been determined. Although past observations indicate some annual variations, there is sufficient consistency to permit some reasonable approximations of the timing and areal dimensions of these seasonal sequence of events.

Events critical to the perpetuation and productivity of the eastern Bering Sea red king crab stock occur during the spring and summer. It is during the spring that both male and female adult king crab form separate aggregations during the spawning migration on the northern Aleutian Shelf. During this spawning migration, females release eggs which they have carried for almost a year. The emerging larvae molt five times through 4 zoeal and 1 megalops stage before attaining the first adult form during the summer.

Mating of king crab also occurs in the late spring and early summer. This entails chemical communications of the female with the male by the release of pheromones. Also during mating, the female molts - a necessary prerequisite of ovulation.

Available evidence indicates that juvenile red king crab less than three years old (40-50 mm carapace length) are year round residents of the eulittoral zone. Therefore, they too would inhabit the nearshore waters of the NAS during the spring and summer.

There are no reliable estimates of the number of larvae in the eastern Bering Sea for any past year and no method for predicting larval abundance in any future year. The available information has been primarily useful for identifying the areas and timing of egg hatching, spawning migrations and mating. Although some of the available information may be useful as indices for comparing time/area variations in relative abundance within a year, their utility as indices of annual variation have not been demonstrated. With regard to enumerating the larvae of king crab (eggs and ichthyoplankton in general) the fundamental problems of developing adequate sampling gear, strategies and designs for quantitative assessments need yet to be resolved.

No reliable estimates are available for larval mortality of red king crab in eastern Bering Sea. Considering the relatively high fecundity of the species (55,000 to 445,000 eggs/female), the mortality rate of larval king crab can be surmised to be very high. For king crab in the Sea of Nemuro, mortality from the Zoea I stage to the megalops stage was calculated to be about 96% of which 93% (about 2 trillion larvae) was estimated to occur before the second zoeal stage. Marukawa (see Sec. 6.2.2) estimated that only 14 out of 1 million larvae hatched survived to attain the commercially desired size of 160 mm carapace width. Haflinger and McRoy (1983) calculated that 18 billion larvae were consumed by predators in the northern Aleutian shelf in a one month period. Total mortality could be expected to be considerably greater since the authors considered their calculations to be a very conservative estimate of the mortality attributable only to predation.

The accuracy of these estimates are not amenable to simple verification nor are they directly applicable to estimating larval mortality in eastern Bering Sea king crab in any past or future year. They do, however, illustrate that larval mortality is normally very high. Even if the mortality attributable to oil could be estimated with reasonable accuracy, such mortality would be expected to be but a small part of total larval mortality. Whether the effects of such mortality could be accurately assessed against the background of very large and no doubt, highly variable natural mortality is problematical.

The assessment of the effects of larval mortality (natural or oil-imposed), is frustrated because quantitative association between larval population size and stock productivity does not exist. No data are available on the relationship of larval survival or numbers and subsequent recruitment to the exploitable population. We have, however, discussed in Sec. 9.1.1.1, the relationship of the number of fertilized females and resulting recruitment. A broad range of females (11 million to 67 million) has produced recruitment ranging from 11 million to 46 million with the largest recruitment resulting from the least abundant female spawning stock.

Assuming no large annual variations in the average number of eggs per female, there should be a direct relationship between the number of fertilized females and the number of larvae hatched. The relationship between larval abundance and recruitment then can be expected to be extremely variable and difficult to predict. Even if the component of total mortality which is attributable to an oil spill can be calculated, the assessment of its impact on population productivity will be extremely difficult considering the extremely variable and unpredictable recruitment which has resulted from the large range of natural fluctuations in spawners and larvae. The dynamics of the red king crab population abundance observed to date, one could not reliably and quantatively predict the impact of oil spill mortality or whether the change will be manifest as an increase or decrease in population productivty.

Available data indicate that juvenile red king crab of less than 50 mm carapace length inhabit the eulittoral zone throughout the year. In the spring and summer months this size group of crab have consistently occurred in waters offshore of the Port Moller-Cape Seniavin area. From the available data, oil spills at either the Port Moller or Port Heiden sites which persist for 96 hours at concentrations of about 4 ppm crude oil of 5 ppm No. 2 fuel oil can be expected to kill half the juvenile king crab which are impacted. Contamination at these levels have been shown (see later discussion) to be a relatively small area in relation to the plausible distribution area of juveniles.

The estimated proportions of the eastern Bering Sea king crab population in each of the subareas (Fig. 48) of eastern Bering Sea as estimated from results of the Northwest and Alaska Fisheries Center trawl surveys in 1975 and 1979 are given in Tables 32 and 33. The proportions of the red king crab population in area 1 within which are located two of the hypothetical spill sites were 70% and 81%, for 1975 and 1979, respectively. Two percent(1975) and 11% (1979) of the population were estimated to inhabit subarea 4 (containing the site of the third hypothetical spill site) during the period of the surveys. Nine percent (1979) and 28% of the population were estimated to be outside the areas contaminated by the hypothetical spills (Table 32).

Immature male and female crab are relatively abundant from False Pass eastward to Port Moller. They are most extensively distributed in highest abundance in waters between 161° and 163°W and south of 58°N. In 1975, 94% of the immature females and 86% of the immature males occurred in subarea 1. In the 1979 survey virtually all the immature males and females were taken in subarea 1 (94% and 99%, respectively). Considering information from all

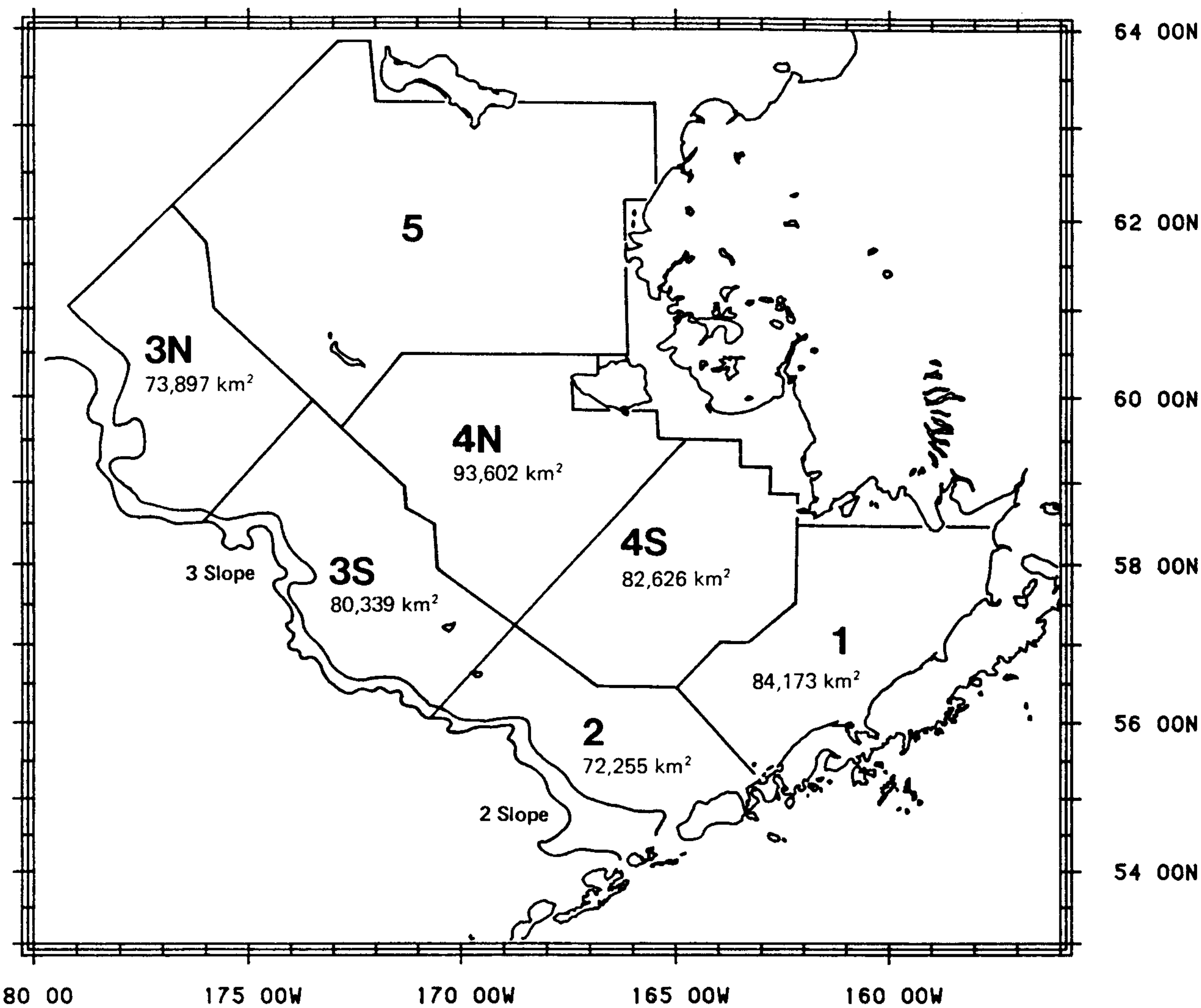


Figure 48. Subareas of the trawl survey area.

Table 32.--Estimated population of red king crab (males and females) during the 1975 and 1979 eastern Bering Sea trawling surveys.

Subarea	Estimated population (millions of crab)		Proportion of total estimated population	
	1975 1/	1979 2/	1975 1/	1979 2/
Inner Shelf				
4	2.3	25.8	0.02	0.11
1	85.1	196.1	0.70	0.81
Outer Shelf				
3	0.1	0.3	<0.01	<0.01
2	34.1	20.0	0.28	0.08
TOTAL	121.9 3/	242.3		
95% Conf. Int.	(91-153)	(181-303)		

1/ Pereyra, et al. (1976).

2/ From Pers. Comm. T. Sample.

3/ This estimate is less than half the population estimate for the same population and year as given in Table 26.

Table 33. Estimated population (in millions) of red king crab by subarea, sex and carapace length groups in the eastern Bering Sea in 1975 and 1979.

Subarea	Males				Females			
	<110	110-134	>134	Total	<90	>89	Total	TOTAL
1975 1/								
Inner Shelf								
4	0.4	0.8	0.6	1.8	0.2	0.3	0.5	2.3
1	20.5	15.1	12.8	48.4	13.2	23.5	36.7	85.1
Outer Shelf								
3	0	0	0	0	0	0.1	0.1	0.1
2	2.8	5.3	5.0	13.1	0.6	20.7	21.3	34.4
TOTAL	23.7	21.2	18.4	63.3	14.0	44.6	58.6	121.9
1979 2/								
InnerShelf								
4	0.4	5.7	13.3	19.4	0.1	6.2	6.3	25.7
1	32.3	25.4	19.0	76.7	22.5	96.8	119.3	196.0
Outer Shelf								
3	0	0.1	0.2	0.3	0	t	t	0.4
2	1.5	3.8	6.7	12.0	0.2	7.8	8.0	20.0
TOTAL	34.2	35.0	39.2	108.4	22.8	110.8	133.6	242.1

1/ Pereyra, et al. (1976)

2/ T. Samples (Pers. Comm.)

3/ This estimate is less than half the population estimate for the same population and year as given in Table 26.

years, this category of immature crab can be expected to be impacted by spills at the Port Moller and Cape Newenham sites.

Adult female king crab appear to be distributed in the northern Aleutian Shelf and inner Bristol Bay areas in the spring, summer and autumn. In the 1975 survey, 53% of the mature females were indicated to occur in subarea 1 and 97% in 1979. Very limited observations indicate they may be further to the westward (north of Unimak Island) in the winter (Fig. 31). During the spring migration, spawning period and postspawning feeding migrations, females occur along Unimak Island and the Alaskan Peninsula with heaviest concentrations off the Black Hill to Cape Seniavin areas.

Mature male red king crab of prerecruitment size (110-134 mm carapace length) appear to be most abundant south of 58°W between 161° and 163°W. In 1975 and 1979, about 70% of this size group were taken in subarea 1. In 1975 and 1979, 75% and 89% of these prerecruits were taken in subareas 1 and 4 combined.

Data from the 1975 survey indicates that during the spring and summer months, most of the legal size males occur in subarea 1 (70%) with very few in subarea 4 (3%). Indications from the 1979 survey are that legal size males are more evenly distributed between subareas 1 and 4 (48% and 34%, respectively).

11.2 King Crab Distribution in Fall and Winter.

Information on the distribution of legal size crab in autumn is very good because in recent years the fishery has been permitted only in September or later. During the fishing seasons of 1979 through 1982, the areas from which most king crab landings were taken have been west of 161°W. This longitude is west of both the Port Heiden and Port Moller and beyond the expected eastward flowing trajectory from oil spills at these sites. The latitude of the Cape Newenham spill site, however, is on the northern border of some very productive fishing areas. The impact of spill scenarios at the Cape Newenham site in terms of effects on the resource, tainting of the catch, pre-emption of fishing areas will depend upon wind conditions prevailing at the time of the spill. The king crab pot storage area appears to be east of the spill trajectory of a spill at Port Moller and well south of the expected trajectory of a spill at Cape Newenham. Unless very strong easterly winds accompany the former or very strong northerly winds are associated with the latter, the special crab pot storage area designated in the Alaska Fishery Regulations should not be impacted by any of the proposed hypothetical oil spill scenarios. The regulations do, however, permit pot storage during the closed season in waters shallower than 30 fathoms (55 m) in depth. Any pots stored in the Port Miller or Port Heiden areas under these regulations may become foiled for shorter periods of time.

As previously mentioned, given the uncertainties concerning the trajectory and fate of oil in the hypothetical spill scenarios and the absence or inadequacies in critical information regarding the toxicology, distribution and population dynamics of the eastern Bering Sea king crab, it is not possible to forecast with reliability, the impact of an oil accident on population productivity.

11.3 Impact Estimates from Hypothetical Oil Spill Scenarios

Hypothetical oil spills of Prudhoe Bay crude oil and automotive diesel fuel are given in Table 34. The areas contaminated by various concentrations of water soluble fractions (WSF) from these oil spill scenarios was provided by the Rand Corporation. Contamination, uptake and depuration of hydrocarbons by various commercially valuable species in eastern Bering Sea were simulated by Gallagher and Pola (1985) and Pola, Miyahara and Gallagher (1985). Estimated concentrations and areas contaminated in the hypothetical spills as given by Gallagher and Pola (1985) are summarized in Table 35.

The effect of petroleum hydrocarbons on red king crab was discussed in the previous section. Information relating to the toxicity of WSF on the life history stages of king crab is summarized below.

No information was available regarding the effect of petroleum hydrocarbons on eggs.

Stage 1 zoea were unsuccessful in molting at WSF concentrations of 0.69 ppm while the 96TLm for stage 1 larvae during the intermolt stage was 8.0 ppm. Molting was, however, permanently inhibited at 0.8-0.9 ppm with exposure time of 72 hrs. For purposes of this discussion we will assume WSF >1.0 ppm are lethal to larvae.

Juveniles survived 96 hours of exposure to concentrations of 5.1 ppm and cleansed themselves shortly after removal to clear water. Three of 6 juvenile crab died after four hours of exposure to 7.45 ppm.

The 96TLm50 for adults was reported as 2.35 ppm (WSF) and 5.3 ppm (OWD). It does not seem reasonable, however, that the threshhold concentration for mortality in adults should be lower than for juveniles. It

Table 34.--Hypothetical oil spill scenarios.

Scenario	Oil type	Volume	Duration	Temperature	Simulation grid	Locations in Bristol Bay
Well blowout	Prudhoe Bay crude	20,000 bbl/day	15 days	9.3°C	(50 x 50)	Port Moller Port Heiden Cape Newenham
Tanker accident	Automotive diesel	200,000 bbl (instantaneous)	10 days	9.3°C	(32 x 34)	Port Moller Port Heiden Cape Newenham

Source: Gallagher & Pola (1985)

Table 35.--Estimated concentrations and area contaminated by simulated oil spills at Port Heiden, Port Moller and off Cape Newenham.

	Conc./days	Area contaminated %	Area contaminated Km^2
Blowout Scenario			
WSF 1/	0.1-1.0 ppm/17	3	300
TARS	0.1-1.0 ppm/8	3	300
Accident Scenario			
WSF	max >5 ppm/4	2	50
	1-5 ppm/12	10	450
	0.1-1 ppm/15	22	1000
TARS	5 ppm/15	5	225
	1-5 ppm/28	19	825
	0.1-1 ppm/30	28	1200

1/ Less than 0.5 ppm in all areas.

Source: Summarized from Gallagher & Pola (1985).

is assumed, therefore, that concentrations necessary to affect mortality in adults is at least as great as that which is lethal to larvae (max. = 8.0 ppm) and juveniles (7.45 ppm). For purposes of the following discussions, 96TLm50 for both juvenile and adult crab will be a 5.0 ppm.

These data indicate that first stage larvae, particularly during molting are most sensitive to hydrocarbon toxicity with a lower threshhold of about 0.7 ppm (WSF).

11.3.1 Well Blowout

In the well blowout scenarios, maximum subsurface WSF concentrations never exceed 0.34 ppm (Pola, Miyahara, and Gallagher, 1985). This concentration is well below the minimum concentration which has been experimentally shown to affect larvae. We can, therefore, expect that the well blowout scenario will have no effect on eastern Bering Sea crab stocks.

11.3.2 Tanker Spill

The tanker spill of 200,000 bbl of automotive diesel fuel results in contamination levels which are assumed to be toxic to adult king crab (i.e., >5 ppm). These concentration are estimated to occur in about 2% of the contaminated area (50 km^2). This area of comtamination is indeed very small considering that the eastern Bering Sea king crab stock is distributed over about 200,000 km^2 (trawl survey subareas 1, 2 and part of 4, see Fig. 48).

During the months of the survey (1975 & 1979), about 90% of the red king crab population was estimated to be in subareas 1 & 4 (Fig. 48 & Table 32). A spill at the Port Moller or Port Heiden sites might be expected to contaminate 0.06% of subarea 1 at concentrations >5 ppm. Assuming the number of adult crab exposed to such comtamination is proportional to the area, one-half of 0.06% (assuming LD_{50} = 5ppm) or 0.03% of the adult population of king crab in subarea 1 and less thn 0.03% of the total eastern Bering Sea adult stock may suffer mortality from the simulated spill.

Since we are assuming the same toxicity level (5.0 ppm) for juveniles, the proportion of mortalities to the juvenile king crab population can be expected to be similar to that of the adults. Although not reflected in either the 1975 or 1979 surveys (Table 33), juveniles would be expected to be more numerous than adults (juveniles may not be as available to the trawl gear and they are not as efficiently retained by the gear). Most of the juveniles in the 1975 and 1979 surveys were taken in subarea 1 (Table 33). The trawl surveys, however, may not sample in areas inhabited by most juveniles and crab younger than 5 years are not efficiently retained by the sampling gear. There are, therefore, no reliable quantitative estimates of the numbers or areal distribution of juvenile king crab upon which to base an estimate of oil-imposed mortality.

Within the area impacted by the hypothetical oil spill scenarios, king crab larvae are mostly confined to the Port Moller-Port Heiden areas (Subarea 1) and during the months of May-August. The available evidence indicates that Port Moller is the most important egg-hatching area and larval abundance the greatest in the Port Moller to Cape Seniavin area (Sect. 7.1). An instantaneous spill of 200,000 bbls of automotive diesel fuel may result in WSF concentrations which are potentially lethal to larvae (>0.8 ppm) over 10 to 20% (1000 km^2) of the contaminated area. The actual impact of this contamination in mortality to larvae and on the productivity of the eastern Bering Sea crab stock is difficult to estimate. There are no reliable quantitative estimates of the temporal-spatial distribution of king crab larvae. Natural mortality sustained by the successive larval stages of king crab is not known. Although not quantitatively estimated, natural mortality in the larval stages is extremely large and variable. The detection and evaluation of oil-imposed mortality against a background of large and highly variable on-going natural mortality problematic. Even if oil-imposed mortality could be successfully isolated from natural mortality, we have no knowledge as to whether such mortalities are simply additive or whether and to what extent density related compensatory mechanisms may come into play.

The eastern Bering Sea king crab stock is presently in extremely poor condition. The level of abundance of the exploitable stock is so low that no fishery was permitted in 1983. The abundance of pre-recruits is at a near record low level, indicating that the moratorium (or low level of fishing) may continue in the foreseeable future. Of most concern, however, from the standpoint of stock productivity is the evidence that the abundance of adult females is the lowest on record and less than half the lower range of the number of females required to maximize the yield from this stock. The abundance of immature females is also near the record minimum level (Table 25 and Sect. 9). There has been no good explanation for this decline in females for a resource in which the fishery targets exclusively on larger males. Increased predation, diseases and mortalities imposed by the king and Tanner crab and trawl fisheries have been advanced as possible causes. Regardless of the causes, the fact remains that the eastern Bering Sea king crab stock has suffered a catastrophic decline. Although the records have indicated that the highest stock recruitments have been produced from the lowest recorded female, spawning populations, we are not assured that such the relationship was not attributable to sampling errors or variations or to unusually favorable survival conditions. Given the many uncertainties regarding our knowledge of eastern Bering Sea king crab stock dynamics there are no indications which suggest any substantial improvement in the condition of the eastern Bering Sea king crab stock in the foreseeable future.

12. LITERATURE CITED

Anonymous
1970. Lobsters unharmed by oil pollution. Fish. of Canada, Vol. 22(10): p. 20

Armstrong, David A., Lewis S. Incze, Deborah Wencker and Janet L. Armstrong.
1983. Distribution and abundance of decapod crustacean larvae in the southeastern Bering Sea with emphasis on commercial species. Fin. Rept. to: OCSEAP - Office of Mar. Poll. Asses., Contr. No. NA81-RAC-0059, Res. Unit: RU-609: 386 pp.

Bakkala, R. G. and V. G. Wespestad.
1983. Yellowfin Sole. In NOAA Tech. Memo. NMFS F/NWC-42. Condition of Groundfish Resources of the Eastern Bering Sea and Aleutian Islands Region in 1982. Edit. by R. G. Bakkala and L. L. Low, March 1983: pp. 51-79.

1984. Pacific Cod. In: NOAA Tech. Memo NMFS F/NWC-53. Condition of Groundfish Resources of the Eastern Bering Sea and Aleutian Islands Region in 1983. Ed. R. G. Bakkala and L. L. Low; March 1984: pp. 21-36.

1984. Yellowfin Sole. In: NOAA Tech. Memo NMFS F/NWC-53. Condition of Groundfish Resources of the Eastern Bering Sea and Aleutian Islands Region in 1983. Ed. R. G. Bakkala and L. L. Low, March 1984: pp. 37-60.

Balsiger, J. W.
1974. A computer simulation model for the Bering Sea king crab population. Ph.D. Thesis, University of Washington. 198 pp.

Borradaile, L. A., L. E. S. Eastham, F. A. Potts and J. T. Saunders.
1951. The Invertebrata, A Manual for the Use of Students Cambridge at the University Press, 1951. 725 pp.

Bright, Donald B., Floyd E. Durham and Jens W. Knudsen.
1960. King crab investigations of Cook Inlet, Alaska Dept. Biol., Allan Hancock Foundation, Univ. South. Calif., 180 pp. (processed).

Chebanov, S. M.
1965. Biology of the king crab, Paralithodes camtschatica (Tilesius), in Bristol Bay. Sov. Fish. Inv. in the Northeast pacific. Pacific Sci. Res. Inst. Mar. Fish. and Ocean (TINRO). Izvestiya, Vol. 53: pp. 82-84.

Connell, D. W. and G. J. Miller.
1981. Petroleum hydrocarbons in aquatic ecosystems - behavior and effects of sublethal concentrations: Part II. Ibid. Vol. 11(2): pp. 105-162.

Cunningham, D.
1968. A study of the food and feeding relationships of the Alaskan king crab, Paralithodes camtschatica. Master's Thesis, San Diego State College.

Eaton, M. F.
1979. Status of the United States tanner and King crab fishery in the eastern Bering Sea, 1979. Report prepared for the 1979 Annual Meeting of the Int. North Pac. Fish. Comm., Tokyo, Japan, 1979.

1980. United States king and tanner crab fishery in the eastern Bering Sea (Document submitted to the annual meeting of the International North Pacific Fisheries Commission, Anchorage, AK, October, 1980). 47 p. Westward Reg. Off., Div. Comm. Fish, Alaska Dept. Fish & Game, P.O. Box 686, Kodiak, AK 99615.

1981. United States king, tanner, and Korean hair crab in the eastern Bering Sea 1980. (Document submitted to the annual meeting of the International North Pacific Fisheries Commission, Vancouver, Canada, October 1981.) Westward Reg. Office, Div. Comm. Fish., Alaska Dept. Fish & Game, P.O. Box 686, Kodiak, AK 99615.

1982. United States king, tanner, and Korean hair crab in the eastern Bering Sea 1981. (Document submitted to the annual meeting of the International North Pacific Fisheries Commission, Tokyo, Japan, October 1982.) Alaska Dept. of Fish & Game, Comm. Fish., Westward Region, P.O. Box 686, Kodiak, AK 99615.

1982. United States king, tanner, and Korean hair crab in the eastern Bering Sea, 1982. (Document submitted to the annual meeting of the International North Pacific Fisheries Commission, Anchorage, AK, October 1983). Alaska Dept. Fish and Game, Comm. Fish., Westward Reg. Office, P.O. Box 686, Kodiak, AK 99615.

1983. United States king, tanner, and Korean hair crab in the eastern Bering Sea, 1982. Report prepared for the 1983 Annual Meeting of the International North Pacific Fisheries Commission, Anchorage, AK, October, 1983. Alaska Dept. of Fish & Game, Comm. Fish., Westward Reg. Office, P.O. Box 686, Kodiak, AK 99615.

Eldridge, P. J.
1975. An analysis of the Kodiak stocks of Alaska king crab, Paralithodes camtschatica. Ph.D. Dissertation, Univ. of Washington, Seattle, WA.

Feder, H. M. and S. C. Jewett.
1980. A survey of the epifaunal invertebrates of the southeastern Bering Sea with notes on the feeding biology of selected species. Rep. R78-5, Inst. Mar. Sci., Univ. of Alaska, Fairbanks.

1981a. Distribution, abundance, community structure and trophic relationships of the nearshore benthos of the Kodiak shelf. Rep. 81-1, Inst. Mar. Sci., Univ. of Alaska, Fairbanks.

1981b. Feeding interactions in the eastern Bering Sea with emphasis on the benthos. The Eastern Bering Sea Shelf: Oceanography and Resources, Ed. Hood and Calder. Vol. II, pp. 1229-1261.

Feder, H. M., A. J. Paul, M. K. Hoberg, S. C. Jewett, G. M. Matheke, K. McCumby, J. McDonald, R. Rice and P. Shoemaker.
1980. Distribution, abundance, community structure and trophic relationships of the nearshore benthos of Cook Inlet. NOAA/OCSEAP, Final Rep.

Feniuk, V. E.
1945. Analysis of stomach contents of king crab. Pacific Sci. Res. Inst. of Fish. and Ocean. (TINRO)-Izvestiya, 19:21-42.

Fishery Agency of Japan
1956. A summary of king crab research conducted by Japan in the eastern Bering Sea in 1955 under the I.N.P.F.C. program. Ann. Rept. for 1956, Intl. North Pac. Fish. Comm.

1961a. Progress Report on King Crab Research in the eastern Bering Sea. Int. North Pacific Fish. Comm. Ann. Rept. for 1960. pp. 70-75.

1961b. Preliminary analysis of king crab stocks in the eastern Bering Sea. Unpubl. mansc. dated Oct. 1963, 19 pp.

1963a. Report on king crab research in the eastern Bering Sea. Int. North Pacific Fish. Comm. Ann. Rept. 1961. pp. 74-82.

1963b. Preliminary analysis of king crab stocks in the eastern Bering Sea. Unpubl. Mansc. dated Oct. 1963, 19 pp.

1964. King crab investigations in the eastern Bering Sea. Int. North Pacific Fish. Comm. Ann. Rept. for 1963. pp. 88-101.

Gallagher, Arthur F., Jr. and Nancy B. Pola.
1984. The Uptake and Depuration of Petroleum Hydrocarbon in Marine Species - A simulation study of the uptake and depuration of petroleum hydrocarbons and its effect on selected marine species in the Bristol Bay ecosystem. Resource Ecology and Fisheries Management Division, Northwest and Alaska Fisheries Center, NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Griffin, Kenneth L., Martin F. Eaton and Robert Otto.
1983. An observer program to gather in-season and post-season on-the-grounds red king crab catch data in the southeastern Bering Sea. Final Rep. Contr. No. 82-2, North Pacific Fishery Management Council, December 1983.

Haflinger, K. E. and C. P. McRoy.
1983. Yellowfin sole (Limanda aspera) predation on three commercial crab species (Chionoecetes opilio, C. bairdi and Paralithodes camtschatica) in the southeastern Bering Sea. Inst. Mar. Sci., Univ. of Alaska. Final Rep. to Natl. Mar. Fish. Serv., Contr. No. 82-ABC-00202, Nov. 1982. 28 pp.

Hardy, R., Mackie, P. R., K. J. Writtle, Howgate and Eleftheriou
1976. Unpublished data as cited by Corner, E. D. S., R. P. Harris, K. J. Whittle, and P. R. Mackie in Effects of pollutants on aquatic organisms, Lockwood, A.R.M., Ed., Cmabridge Univ., Cambridge, 1976.

Hayes, M. L.
1973. King and tanner crab research in the eastern Bering Sea, 1973. Report prepared for 1973 annual meeting of Intern. North Pacific Fish. Comm., Tokyo, Japan. Oct. 1973.

Hayes, M. L. and D. T. Montgomery.
1963. Movements of king crabs tagged and released in Shumagin Islands area, 1957-62. U.S. Fish & Wildl. Serv., Spec. Sci. Rept. - Fish. 458: 7 pp.

Haynes, Evan B.
1974. Distribution and relative abundance of larvae of king crab, Paralithodes camtschatica, in the southeastern Bering Sea. Fish. Bull. 72(3):804-812.

Hebard, James F.
1959. Currents in southeastern Bering Sea and possible effects upon king crab larvae. U.S. Fish & Wildl. Serv., Spec. Sci. Rept. - Fish., No. 293, 11 pp.

Hoopes, D. T.
1970. Trends in the eastern Bering Sea king crab fishery (1953-1969). Nat. Mar. Fish. Serv., Auke Bay Lab. 11 pp. Processed Report.

Hoopes, D. T. and J. F. Karinen.
1972. Longevity and growth of tagged king crabs in the eastern Bering Sea. Natl. Mar. Fish. Serv., Bull. Vol. 70(1):225-226.

Kajita, Tomonosuke and Kazuichi Nakagawa.
1932. Research on king crabs. Rept. Fish. Inv., Hokkaido Pref. Fish. Exp. Sta. No. 27: 163 pp.

Katz, L. M.
1973. The effects of water soluble fraction of crude oil on larvae of the decapod crustacean, Neopanope texana (Sayi). Envir. Pollut. 5:199-204.

Kerhoff, M.
1974. Oil pollution of the shellfish areas in the Oosterschelde estuary. Intern. Counc. Explor. Sea, Fish. Improv. Comm. CM 1974/E:13.

Korolev, N. G.
1964. The biology and commercial exploitation of king crab, Paralithodes camtschatica (Tilesius), in the southeastern Bering Sea. Sov. Fish. Inv. in the Northeast Pacific Part II. All-Union Sci. Res. Inst. of Mar. Fish. and Ocean (VNIRO). Trudy, Vol. pp. 102-108.

Kulichkova, V. A.
1956. Feeding of Kamchatka crabs during the spring-summer period on the shores of Kamchatka and Sakhalin. Pacific Sci. Res. Inst. of Fish. and Ocean. (TINRO)-Izvestiya, 43:21-42.

Kurata, Hiroshi.
1959. Studies on the larva and post-larva of Paralithodes camtschatica, I. Rearing of the larvae with special reference to the food of the zoea. Bull. Hokkaido Reg. Fish. Res. Lab., No. 20, pp. 76-83.

1960a. Studies on the larva and postlarva of Paralithodes camtschatica, II. Feeding habits of the zoea. Ibid. No. 21, pp. 1-8.

1960b. Studies on the larva and postlarva of Paralithodes camtschatica, III. The influence of temperature and salinity on the survival and growth of larva. Ibid. No. 21, pp. 9-14.

1961a. Studies on the larva and post-larva of Paralithodes camtschatica, IV. Growth of the post-larva. Hokkaido Pref. Fish. Exp. Sta. Monthly Rept., 18(1):1-9.

1961b. On the age and growth of king crab Paralithodes camtschatica. Ibid. 18(1):10-22.

Laubier, Lucien.
1980. The Amoco Cadiz oil spill: An ecological impact study. Ambio Vol. 9(6):268-276.

Leglise, M. and G. Raguenes.
1979. Suivi des effects du naufrage de L'Amoco Cadiz sur lez crustaces commerciallisables dans la zone polluee. Amoco Cadiz. Fates and effects of the oil spill. Proc. Int. Symp. Centre Oceanologique de Bretagne Brest (France) November 19-22, 1979. pp. 775-787.

Marukawa, Hisatoshi.
1933. Biological and fishery research on Japanese king crab, Paralithodes camtschatica (Tilesius). J. Imp. Fish. Exp. Sta., Tokyo, Pap. 37, No. 4, 152 pp.

McCaughran, D. A. and G. C. Powell.
1977. Growth model for Alaskan king crab (Paralithodes camtschatica). J. Fish. Res. Bd. Canada. 34:989-995.

McLaughlin, P. A. and J. Hebard.
1961. Stomach contents of the Bering Sea king crab. Int. North Pacific Fish. Comm. Bull. 5:5-8.

Mecklenburg, T. A. and Rice, S. D.
1976. Effects of Cook Inlet crude oil, benzene, and naphthalene on heart rates of the Alaskan king crab (Paralithodes camtschatica). Science in Alaska, Proc. 27th Alaska Sci. Conf., Fairbanks. p.184.

Mihara, Takeo.
1936. An observation on the time required for molting and growth of king crab. Hokkaido Pref. Fish. Exp. Sta., Monthly Rep. No. 325, pp. 12-13.

Miyahara, Takashi.
1954. The 1953 Japanese king crab factoryship expedition. U.S. Fish & Widl. SErv. Comm. Fish. Rev. Vol. 16(12).

Nakazawa, Kiichi.
1912. A study of the Hokkaido crab. Zoological Magazine (Dobutsugaku Zasshi), 24(279):1-12.

Neiman, A. A.
1963. Quantitative distribution of benthos on the shelf and upper continental slope in the eastern part of the Bering Sea. In: Sov. Fish. Inv. in the Northeastern Pacific. Pacific Sci. Res. Inst. Fish & Ocean (TINRO). Vol. 50(1):143-217.

Nelson, Russell, Jr., Robert French, and Janet Wall.
1981. Summary of U.S. observer sampling on foreign fishing vessels in the Bering Sea/Aleutian Islands region, 1980. (Documents submitted to the annual meeting of the International North Pacific Fisheries Commission, Anchorage, Alaska, September 1981.) Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Niwa, Kazumi.
1962. King crab investigations in the eastern Bering Sea, 1962. Unpubl. mansc., Fish. Agency of Japan, October 1962, 25 pp.

North Pacific Fisheries Management Council.
1981. Fishery Management plan for Western Alaska King Crab. North Pac. Fish. Manag. Council. November 1981. 93 pp. and two appendices.

Otto, Robert S.
1981. Eastern Bering Sea crab fisheries. From: The Eastern Bering Sea Shelf: Oceanography and Resources. Vol. II, pp. 1037-1066.

1983. Results of the 1982 eastern Bering Sea crab survey with notes on current population trends. Report to the North Pacific Fishery Management Council and Alaska Board of Fisheries, Anchorage, AK. March 1983. 16 pp.

Otto, R. S., A. K. Fukuyama and T. M. Armetta.
1978. King and tanner crab research in the eastern Bering Sea, 1978. Report prepared for the 1978 annual meeting of the iNt. North Pac. Fish. Comm., Vancouver, Canada, Oct. 1978.

Otto, R. S., A. K. Fukuyama, T. M. Armetta, R. A. McIntosh and R. N. McBride.
1979. King and tanner crab research in the eastern Bering Sea, 1979. Report prepared for the 1979 annual meeting of the Int. North Pac. Fish. Comm., Tokyo, Japan, Oct. 1979.

Otto, R. S., R. A. MacIntosh, K. L. Stahl-Johnson, and S. J. Wilson.
1983. United States crab research in the eastern Bering Sea during 1983. (Document submitted to the annual meeting of the International North Pacific Fisheries Commission, Anchorage, Alaska, October 1983) 57 pp. Northwest and Alaska Fisheries Center, Natl. Mar. Fish. SErv., NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112.

Otto, R. S., J. E. Reeves, and J. Burns.
1977. King and tanner crab research in the eastern Bering Sea, 1977. Report prepared for the 1977 annual meeting of the Int. North Pac. Fish. Comm., Anchorage, AK, Oct. 1977.

Otto, R. S., R. A. MacIntosh, T. M. Armetta and S. Wilson.
1980. King and tanner crab research in the eastern Bering Sea, 1980. Report prepared for the 1980 annual meeting of the Int. North Pac. Fish. Comm., Anchorage, AK, Oct. 1980.

Otto, R. S., R. A. MacIntosh, T. M. Armetta and W. S. Meyers.
1982. United States crab research in the eastern Bering Sea during 1982. Report prepared for the 1982 Annual Meeting of the Int. North Pac. Fish. Comm., Tokyo, Japan, Oct. 1982.

Otto, R. S., R. A. MacIntosh, T. M. Armetta, W. S. Meyers and K. L. Stahl.
1981. United States crab research in the eastern Bering Sea during 1981. Report prepared for the 1981 Annual Meeting of the Int. North Pac. Fish. Comm., Vancouver, Canada, Oct. 1981.

Otto, R. S., R. A. MacIntosh, K. L. Stahl-Johnson and S. J. Wilson.
1983. United States crab research in the eastern Bering Sea during 1983. Report prepared for the 1983 Annual Meeting of the Int. North Pac. Fish. Comm., Anchorage, AK, Oct. 1983.

Paradis, M. and R. G. Ackman.
1975. Differentiation between natural hydrocarbons and low level diesel oil contamination in cooked lobster meat. J. Fish. Res. Bd. Canada. 32(2):316-320.

Pola, Nancy B. and R. K. Miyahara.
1984. Spatial and Temporal Extent of Hydrocarbon Contamination in Marine Species of Bristol Bay. Resource Ecology and Ecosystem Simulation Task, Resource Ecology and Fisheries Management Division, Northwest and Alaska Fisheries Center, 7600 Sand Point Way NE, Seattle, WA 98115.

Powell, G. C.
1960. Growth of king crabs in the vicinity of Kodiak Island, Alaska. Unpubl. mansc., Alaska Dept. Fish & Game, 42 pp.

1967. Growth of king crab in the vicinity of Kodiak Island, Alaska. Alaska Dept. Fish and Game Inform. Leaf. 92, Juneau.

1974. Gregarious king crabs. Sea Frontiers, Vol. 20(4):206-211.

Powell, G. C. and R. B. Nickerson.
1965. Reproduction of king crab (*Paralithodes camtschatica* Tilesuis). J. Fish. Res. Bd. Canada 22:101-111.

Powell, G. C. and R. E. Reynolds.
1965. Movements of tagged king crabs, *Paralithodes camtschatica* (Tilesuis), in the Kodiak Island-Lower Cook Inlet region of Alaska, 1954-1963. Alaska Dept. Fish and Game Info. Leaf. 55, Juneau, AK.

Powell, G. C., K. E. James and C. L. Hurd.
1974. Ability of male king crab, *Paralithodes camtschatica*, to mate repeatedly, Kodiak, Alaska, 1973. Fish. Bull. 72(1):171-179.

Reeves, J. E.
1975. King and tanner crab research in the eastern Bering Sea, 1975. Report prepared for the 1975 annual meeting of the Int. North Pac. Fish. Comm., Vancouver, Canada, Oct. 1975.

1983. Projected catches for Bristol Bay red king crab. Northwest and Alaska Fish. Cent., (NMFS/NOAA). Unpubl. Rep. dated March 1983. 10 pp.

Reeves, J. E., R. A. MacIntosh and R. N. McBride.
1974. King and tanner crab research in the eastern Bering Sea, 1974. Report prepared for the 1974 annual meeting of the Int. North Pac. Fish. Comm., Seattle, WA Oct. 1974.

Reeves, J. E. and R. Marasco.
1980. An Evaluation of Alternate Management Options for the Southeastern Bering Sea King Crab Fishery. NWAFC Processed Report 80-6. Northwest and Alaska Fisheries Center, Nat. Mar. Fish. Serv., NOAA. March 1980: 85 pp.

Reeves, J. E., R. N. McBride and N. Newcome.
1976. King and tanner crab research in the eastern Bering Sea, 1976. Report prepared for the 1976 annual meeting of the Int. North Pac. Fish. Comm., Tokyo, Japan. Oct. 1976.

Rice, S., D. Short, and J. F. Karinen.
1977. Comparative oil toxicity and comparative animal sensitivity, in Fates and Effects of Petroleum Hydrocarbons in Marine Organisms and Ecosystems, Wolfe, D. A. Ed., Pergamon Press, New York, 1977, 78 pp.

Rice, S. D., J. W. Short, C. C. Broderson, T. A. Mecklenburg, D. A. Moles, C. J. Misch, D. L. Cheatham, and J. F. Karinen.
1976. Acute toxicity and uptake-depuration studies with Cook Inlet crude oil and several subarctic marine organsims. Northwest Fish. Cent., Auke Bay Lab. Processed Report, May 1976. 90 pp.

Rodin, V. E.
1970. Some data on the distribution of king crab (Paralithodes camtschatica Tilesius) in the southeastern Bering Sea. Soviet Fisheries Investigation in the Northeastern Pacific part V. Pacific Sci. Res. Inst. of Fish & Ocean (TINRO). Vol. 72:143-148.

Sakuda, Henry
1958. Observations of molting female king crabs, Paralithodes camtschatica, U.S. Fish & Wildl. Serv., Spec. Sci. Rept. Fish. No. 274, 5 pp.

Sato, Sakae.
1958. Studies on the larval development and fishery biology of king crab, Paralithodes camtschatica (Tilesius). Bull. Hokkaido Reg. Fish. Lab., No. 17, pp. 1-102.

Sato, Sakae and Shogo Tanaka.
1949a. Study on the larval stage of Paralithodes camtschatica (Tilesius), I. Morphological Research Hokkaido Fish. Exp. Sta., Sci. Pap., No. 1, pp. 7-24.

1949b. Study on the larval stage of Paralithodes camtschatica (Tilesuis), II. On the rearing. Ibid., No. 3, pp. 18-30.

Shimada, A. and J. June.
1982. Interim progress report on eastern Bering Sea Pacific cod food habits. Unpublished Report, RACE Div., NWAFC, NOAA.

Shimizu, Jiro
1936. Outline of the rearing experiment on king crab zoea. Hokkaido Reg. Fish. Res. Lab. 10 day report (Hokusuishi Junpo), 327: pp. 4-8.

Simpson, A. C.
1968. The Torrey Canyon disaster and fisheries. Lab. Leaf., Maff U.K., 18, 1.

Simpson, R. R. and H. H. Shippen.
1968. Movement and recovery of tagged king crabs in the eastern Bering Sea, 1955-63. Bull. Int. North Pac. Fish. Comm. 24:11-123.

Smith, M. A.
1976. Chronic effects of oil exposure on the ultrastructure of king crab gills and other tissue. Science in Alaska. Proc. 27th Alaska Sci. Conf., Fairbanks, p. 184.

Tarverdieva, M. I.
1976. Feeding of the Kamchatka king crab, Paralithodes camtschatica, and Tanner crabs, Chionoecetes bairdi and Chionoecetes opilio in the southeastern part of the Bering Sea. Biologiya Morya 2:41.

Takeuchi, Isamu.
1959. Food of king crab (Paralithodes camtschatica) off the west coast of Kamchatka in 1958. Bull. Hokkaido Reg. Fish. Res. Lab. 20:67-75.

Takeuchi, Isamu.
1960. On the rearing experiment of young king crabs, Paralithodes camtschatica, in the eastern Bering Sea. Observations on molting and growth. Hokkaido Pref. Fish. Exp. Sta., Monthly Rept., 17(2):453-460.

1962. On the distribution of zoea larvae of king crab, Paralithodes camtschatica, in the southeastern Bering Sea in 1960. Bull. Hokkaido Reg. Fish. Res. Lab., No. 24, pp. 163-170.

1967. Food of the king crab, Paralithodes camtschatica, off the west coast of the Kamchatka Peninsula, 1958-1964. Ibid. 28:32-44.

Tsalkina, A. V.
1969. Characteristics of the epifauna of the West Kamchatka shelf (from problems of commercial hydrobiology). Fish. Res. Bd. Canada Transl. Ser. No. 1568.

Vinogradov, L. G.
1941. Kamchatskii krab (king crab). (In Russian) TINRO, Vladivostok, U.S.S.R.

1946. On the geological distribution of king crabs. (Vladivostok, Izvestia Tikhookeanskii Nauchno-issledovatelskii Institut Rubnogo Khoziaistva Okeanografii). Rept. Pacific Res. Instl. Fish. and Ocean., Vol. 22, pp. 195-232.

1949. On the reproduction mechanism in the stock of Kamchatka crab (Paralithodes camtschatica) in the Okhotsk Sea off Western Kamchatka. Proc. All Union Sci. Res. Instl. Mar. Fish. and Ocean. Publ. by Pishchevaua Promushlennost, Moscow, 65:337-344, 1969.

1969. On reproduction mechanism in the stock of Kamchatka crab (Paralithodes camtschatica) in the Okhotsk Sea off western Kamchatka. From: Problems of commercial hydrobiology. VNIRO 65:337-344, 1969 (F.R.B. Can. Trans. Ser. 1540).

Vladimirov, V. I.
1975. Critical periods in the development of fishes. J. Ichthyology, 15:851-868.

Wallace, W. Marvin, Camile J. Pertuit and Arthur R. Hvatum.
1949. Contribution to the biology of the king crab (Paralithodes camtschatica Tilesius). U.S. Fish & Wildl. Serv., Fish. Leaf., No. 340, 50 pp.

Wang, Yi-Kuan.
1937. On the stock of king crab, Paralithodes camtschatica (Tilesius), in the seas of Hokkaido and Sakhalin. bull. Jap. Soc. Sci. Fish., 5(5):291-294.

Weber, D. G.
1965. Growth of the immature king crab, Paralithodes camtschatica (Tilesius). Unpubl. Master's Thesis, University of Washington, 100 pp.

1967. Growth of the immature king crab, Paralithodes camtschatica (Tilesius). Int. N. Pac. Fish. Comm., Bull. 21, pp. 21-53.

Weber, Douglas D. and Takashi Miyahara.
1962. Growth of the adult male king crab, Paralithodes camtschatica (Tilesius). U.S. Fish & Wildl. Serv., Fish. Bull., Vol. 62, pp. 53-75.

Wells, P. G.
1972. Influence of Venezuelan crude oil on lobster larvae. Marine Pollution Bull. 3:105-106.

MODELING THE BIOLOGICAL IMPACT OF AN OIL SPILL; BIOS MODEL

by

Nancy B. Pola

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

June 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Program Documentation No. 24 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

INTRODUCTION

The BIOS (Biological Impact of an Oil Spill) ecosystem simulation model has been documented in several recent publications (Swan 1984, Gallagher 1984, Gallagher and Pola 1984, Pola et al. 1985). The model was developed at the request of the Outer Continental Shelf Environment Assessment Program (OCSEAP) as part of their eastern Bering Sea environmental impact study. Two hypothetical oil spill scenarios (well blowout and tanker diesel spill) were simulated at each of three locations in the eastern Bering Sea: Offshore of Port Moller, Port Heiden and Cape Newenham.

During the course of the study, the BIOS model was modified to address particular questions. For example, species-specific uptake and depuration rates and their relative sensitivities were determined using a version of the model with no spatial resolution (Gallagher and Pola 1984), while the spatial and temporal extents of "tainting" of fish were examined using a gridded version of the model with fewer species, but including fish migrations (Pola et al. 1985).

This document describes the BIOS model concept and presents three versions of the model developed for particular applications. It is intended to be used by the prospective modeller as a general guide for application of a BIOS-type model to any location. In addition, it serves a library maintenance function by presenting the present physical locations (tape, disk, etc.) and file names of model computer source code, input data and output programs.

BIOS MODEL

Conceptualization

Effective computer simulation of the impact of an oil spill on an ecosystem is dependent upon the accuracy of field and empirical data. Ecosystem interactions are complex and poorly understood; the added stress imposed on the ecosystem by an oil spill further complicates the situation. The eastern Bering Sea ecosystem has been effectively simulated by such models as PROBUB (Prognostic Bulk Biomass Model) and DYNUMES (Dynamical Numerical Marine Ecosystem Simulation), both developed by Dr. Taivo Laevastu of the Northwest and Alaska Fisheries Center (NWAFC; Laevastu et al. 1982, Laevastu and Larkins 1981). General ecosystem simulation concepts used in these models were adapted to the BIOS model. Available information on oil toxicity and the effects of pollution on fish were then incorporated into the BIOS model.

Many of the processes included in DYNUMES and PROBUB were not applicable to the simulation of the oil-spill scenarios. For example, the simulation of growth was unnecessary, due to the short time step (daily) and duration of the BIOS model run ($\leq$50 days). The DYNUMES species composition was adjusted to include only those species known to occupy the Bristol Bay region in summer. However, several species groups were divided into juvenile and adult stages, to allow for differences in susceptibility to oil toxins. The effect of oil on the biota was modeled as a single-compartment uptake-depuration process. No attempt was made to partition the effect of oil among various compartments (gut, liver, etc.) due to insufficient quantitative data on oil uptake processes. As a general rule, the BIOS model was kept as simple and generic as possible, to avoid unnecessary assumptions.

Simulation

Gridded daily subsurface oil concentrations for each scenario and location were provided by Rand Corporation. Sedimentation of the oil was simulated with a model developed by Laevastu and Fukuhara (1985). The subsurface oil concentrations (oil dissolved or in suspension in the water column, referred to as WSF) and the sedimented oil concentrations (oil in or upon the sediments, migration velocity components, and G_x and G_y are contamination gradients:

$$G_x = [C(t)_{n,m+j} - C(t)_{n,m}] \tag{7}$$

$$G_y = [C(t)_{n+i,m} - C(t)_{n,m}] \tag{8}$$

The subscripts i and j are defined as:

$$i = \begin{cases} 1 & , \quad V < 0 \\ 0 & , \quad V = 0 \\ -1 & , \quad V > 0 \end{cases}$$

$$j = \begin{cases} -1 & , \quad U < 0 \\ 0 & , \quad U = 0 \\ 1 & , \quad U > 0 \end{cases}$$

such that the gradients G_x and G_y are taken in the "upstream" direction. The contamination is then redistributed over the grid:

$$C(t+1)_{n,m} = C(t)_{n,m} - R_{x,n,m} - R_{y,n,m} \tag{9}$$

$$C(t+1)_{n,m+j} = C(t)_{n,m+j} + R_{x,n,m} \tag{10}$$

$$C(t+1)_{n+i,m} = C(t)_{n+i,m} + R_{y,n,m} \tag{11}$$

The migration time step, t, is restricted by the stability criterion:

$$t|U^*| < L \tag{12}$$

where U^* is the maximum migration speed in km/day. That is, for a migration speed of 15 km/day and grid spacing of 2 km, $t < .13$ days.

COMPUTER PROGRAMS AND DATA FILES

File Names and Locations

Computer FORTRAN source codes for all three model versions reside on disk and tape files on the Northwest and Alaska Fisheries Center (NWAFC) Burroughs B7800 computer. All BIOS files are stored under user code REFM0250. Disk files are located on the TYVO pack and tape files are located on tape number 4857. The following are the program and data file names:

Program Files

PROG/BIOS/NOGRID	:Nongridded version of the BIOS model used to estimate model parameters.
PROG/BIOS/GRID	:Gridded version of the model; uses subsurface oil concentrations (WSF) as input.
PROG/BIOS/MIGR	:Gridded version of the model with fish migrations and only two fish species.
SUBROUTINE/PLOTR	:Generalized subroutine to draw line plots of up to four variables.

Input Data Files

OCSEAP/OILCON/LOC1	:Gridded WSF for accident scenario, Port Möller.
OCSEAP/OILCON/LOC2	:Gridded WSF for accident scenario, Port Heiden.
OCSEAP/OILCON/LOC3	:Gridded WSF for accident scenario, Cape Newenham.
OCSEAP/OILCON/BLOW/LOC1	:Gridded WSF for blowout scenario, Port Moller.
OCSEAP/OILCON/BLOW/LOC2	:Gridded WSF for blowout scenario, Port Heiden.
OCSEAP/OILCON/BLOW/LOC3	:Gridded WSF for blowout scenario, Cape Newenham.

Program Listings

Annotated FORTRAN source codes for the three BIOS model versions and for the plotting subroutine are listed in the following pages. An example of a plot generated by the plotting subroutine is given in Figure 1.

referred to as TARS) were used as input to the BIOS model. Model calculations were performed with a daily time step at each grid point. A 32 x 34 grid was used at each location for the accident scenario and a 50 x 50 grid was used for the blowout scenario; in each case, 2 km grid spacings were used.

Wind and water temperatures used by Rand Corp. in the calculations of the oil trajectories were chosen so as to maximize the oil concentrations in the water. The selected conditions corresponded to those typical of August. The fish species which would be expected in August at each location were then determined (Fukuhara (1985), and fish biomasses over each grid were estimated (Gallagher and Pola 1984). Biomass was assumed to be equally distributed over all grid points, due to insufficient spatial resolution of the data (Pola et al. 1985), and was kept constant over the short duration (≤50 days) of the simulations.

Fish contamination was simulated by a single-compartment uptake-depuration model (Wilson 1975). The species-specific uptake and depuration rates were determined from field and empirical studies (Gallagher and Pola 1984) and were kept constant for each species group throughout each simulation. Contamination was computed in parts per million (ppm; mg hydrocarbons per kg biomass). Contamination of 5 ppm was taken as the threshold level for "tainting" (detectable aroma or taste of petroleum) of fish, based on available empirical data (Pola et al. 1985). In a recent study, Teal (1977) found that uptake of contaminants from the water column (through respiration or swallowing) was approximately equal to uptake of contaminants from feeding. In the absence of studies to the contrary, this result was incorporated into BIOS; that is, uptake through feeding was computed and the resulting contamination was multiplied by two. It was assumed that adequate food was available for all modelled fish species, therefore starvation was not included in BIOS. The fraction of pelagic or demersal food in each species' diet was estimated; contamination of the food was assumed to be directly proportional to the concentration of the napthalene fraction of the WSF (for pelagic food) or the TARS (for demersal food).

Three versions of the BIOS model were eventually developed. The first, BIOS/NOGRID, was used to determine species-specific uptake and depuration rates and their sensitivities. It contains no spatial resolution and the external oil concentration is preset as a constant, or as a linear or exponential function of time. Sixteen species groups (Table 1) were used in BIOS/NOGRID, as well as in the second version of the model, BIOS/GRID. This second version includes spatial resolution and uses the gridded WSF values provided by Rand Corp. and TARS concentrations computed by the Laevastu and Fukuhara (1985) model. The final model version, BIOS/MIGR, includes fish migrations. A larger computational grid (e.g., 64 x 68 for the accident scenario) is used in this version; however, only two fish species groups are included. Migration speeds and directions are input to BIOS/MIGR.

Computation

The amount of contamination in a fish species (C_f) at any time step (t_d) is computed in all versions of BIOS as:

$$C_f(t_d) = \frac{k_1 C_o(t_d)}{k_2} \ (1-\exp(-k_2)) + C_f(t_d-1)\exp(-k_2) \tag{1}$$

where C_o is the external oil concentration, k_1 is the uptake rate, and k_2 is the depuration rate. Equation 1 is a finite-difference approximation to the single compartment model discussed by Wilson (1975) and Moriarty (1975).

Equation 1 can be rewritten as:

$$C_f(t_d) = C_U + C_D \tag{2}$$

where C_U is the amount of contamination taken up by a fish species at simulation time step t_d and C_D is the amount accumulated over previous time steps, after depuration. The uptake of contamination is computed in the model as:

$$C_U = (F_p B_p C_{WSF} + F_d B_d C_{TARS})\ (1-\exp(-k_2)) \tag{3}$$

where F_p and F_d are the fractions of pelagic and demersal food, respectively, in a species' diet, B_p and B_d are the pelagic and demersal bioconcentration factors, and C_{WSF} and C_{TARS} are the napthalene fractions of the oil concentrations in the water column and in the sediments, respectively.

All versions of the model were run for up to 50 days. The oil concentrations provided by Rand Corporation were computed for 10 days in the accident scenario and for 15 days in the blowout scenario. At time steps greater than those limits, the oil concentrations in the water column for the gridded model versions (BIOS/GRID and BIOS/MIGR) were decayed at a constant rate:

$$WSF(t_d)_{n,m} = WSF(t_d-1)_{n,m}e^{-k} \tag{4}$$

where a decay rate (k) of 0.3 was estimated from the Rand data.

Migrations are simulated in BIOS/MIGR by the advection of contamination through the enlarged grid, keeping biomass constant. The amount of contamination leaving gridpoint (n,m) in the x-direction is:

$$R_{x,n,m} = (G_x t|U|)/L \tag{5}$$

and in the y-direction is:

$$R_{y,n,m} = (G_y t|V|)/L \tag{6}$$

where t is the migration time step, L is the grid spacing, U and V are the

Table 1.--Species groups in the BIOS model.

No.	Species
1	Herring juveniles
2	Herring adults
3	Pollock juveniles
4	Pollock adults
5	Pacific cod juveniles
6	Halibut juveniles
7	Yellowfin sole juveniles
8	Other flatfish juveniles
9	Yellowfin sole adults
10	Other flatfish adults
11	Pacific cod adults
12	King and Bairdi crab juveniles
13	King and Bairdi crab adults
14	Mobile epifauna
15	Sessile epifauna
16	Infauna

```
$RESET FREE
$SET LIST LINEINFO STACK
FILE  6(KIND=PRINTER)
FILE  7(KIND=DISK,NEWFILE=.TRUE.)
      DIMENSION TABLE(16),TABLE1(30,12),TJ(16),TCH(16),CONVAL(4),
     &KOMAX(4),FOODCMP(16),KK2(16),SAVDEC(50,16),PWSF(50),
     &PTARS(50),SFDCMP(16)
      REAL KK2,K2,KOMAX,NEWOIL
      DATA CONVAL/.005,.10,1.0,10.0/
      DATA J1,J2,J3,IFPLOT/1,6,16,0/
      DATA TJ/.016,.010,.012,.007,.015,.012,.012,.012,.006,.006,
     *.007,.012,.006,.019,.006,.006/
      DATA FOODCMP/1.00,.95,.95,.72,.81,.43,.20,.20,.15,.25,.30,
     *.30,.10,0.0,0.0,0.0/
      DATA KK2/.198040,.132027,.198040,.132027,.198040,.1664,.1664,.1664
     &,.1109,.1109,.132027,.334234,.222823,.198042,.03460,.06930/
C
C*************************************************************************
C
C       THIS VERSION IS USED FOR SENSITIVITY ANALYSIS
C
C       THIS PROGRAM USES THE OIL UPTAKE AND DEPURATION EQUATION FROM
C       FEDOIL. THE CONC IS DECREASED AFTER DAY 1 BY: CONC=CONC*EXP(-0.3)
C       THIS PROGRAM FOLLOWS THE DURATION OF THE CONTAMINATION; I.E.
C       FOR 24, 48, OR 96 HOURS.
C
C-------------------------------------------------------------------------
C
C       KK2(J) IS THE DEPURATION RATE CONSTANT FOR SPECIES J
C
C       K2 IS THE KK2 VALUE AFTER ADJUSTING FOR + OR - SOME X PERCENT FOR
C       SENSITIVITY ANALYSIS.
C
C       BCFPEL IS THE BIOCONCENTRATION FACTOR OF EACH PELAGIC SPECIES J
C
C       SBCFP IS THE BCFPEL VALUE AFTER ADJUSTING FOR + OR - SOME X
C       PERCENT FOR SENSITIVITY ANALYSIS.
C
C       BCFDEM IS THE BIOCONCENTRATION FACTOR OF EACH DEMERSAL SPECIES J
C
C       SBCFD IS THE BCFDEM VALUE AFTER ADJUSTING FOR + OR - SOME X
C       PERCENT FOR SENSITIVITY ANALYSIS.
C
C       FRCNAF IS THE FRACTION OF WSF THAT IS NAPHTHALENES.
C
C       FRCNAC IS THE FRACTION OF TARS THAT IS NAPHTHALENES.
C
C       FOODCMP IS THE FOOD COMPOSITION AS FRACTION OF PELAGIC FOOD IN
C       A PREDATORS DIET.
C
C       SFDCMP IS THE FOOD COMPOSITION VALUE, FOODCMP, AFTER ADJUSTING FOR
C       + OR - SOME X PERCENT FOR SENSITIVITY ANALYSIS.
C
C-------------------------------------------------------------------------
C
C       IPRINT=1 MEANS CONC=CONC*RATEX2 FOR LL GT 1; IPRINT=0 MEANS CONC
C       IS CONSTANT UP TO LL EQ LLVAL AND THEN EQ 0 THEREAFTER; IPRINT=2
```

```
C       MEANS CONC IS CONSTANT UP TO LL EQ LLVAL AND THEN C THEREAFTER,
C       BUT THE EQUATION USED IS NOT "THE FEDOIL EQUATION" BUT THE BASIC
C       EQUATION FROM THE LITERATURE. IPRINT=3 MEANS CONC=CONC*RATEX2 FOR
C       LL GT 1; THE EQUATION USED IS NOT THE "FEDOIL EQUATION" BUT
C       THE EQUATION FROM THE LITERATURE. (IF THE EQUATION FROM THE
C       LITERATURE IS USED, SIMPLE DEPURATION STARTS AT LL GT LLVAL.)
C
C       IBCF=1 MEANS THE SENSITIVITY ANALYSIS IS DONE ON BCFPEL AND/OR
C       BCFDEM. IPEL=1 MEANS SENSITIVITY ANALYSIS ON BCFPEL AND IDEM=1
C       MEANS SENSITIVITY ANALYSIS ON BCFDEM.
C
C       ISEN=0 MEANS -X% AND ISEN=1 MEANS +X%.
C       SENANL IS THE % CHANGE FOR THE SENSITIVITY ANALYSIS.
C
C       IFDCMP=1 MEANS THE SENSITIVITY ANALYSIS IS DONE ON THE FOOD
C       COMPOSITION TABLE, FODCMP.
C
C***********************************************************************
C       SET CONSTANTS
C
      K=8
      LLVAL=10
      LLMAX=30
      RAD=0.01745329
      ALP=30.*RAD
      GKAP=175.*RAD
      VALCA=COS(ALP*K-GKAP)
      R2=0.6
      RATEX2=EXP(-R2)
      FRCNAP=.50
      FRCNAD=.10
      BCFPEL=170.
      BCFDEM=170.
      IPRINT=1
      SENPRT=.10
      ISEN=1
      IFDCMP=1
      IPEL=0
      IDEM=0
      IBCF=0
C-----------------------------------------------------------------------
C
C
      DO 999 IISEN=1,10
      SENANL=SENANL+.10
      SEN=SENANL*100.
C
C
      IF(IFPLOT.NE.1)GO TO 7777
      WRITE(7,609)
      WRITE(7,/)J1,J2,J3
  609 FORMAT(" CONTAMINATION IN SPECIES FROM ART/FEDOL13"
     &", TEST RUN #6")
C
C
 7777 DO 99 J=1,16
      K2=KK2(J)
      RATEXP=EXP(-K2)
      SBCFP=BCFPEL
      SBCFD=BCFDEM
```

```
      SFDCMP(J)=FDDCMF(J)
      IF(IFDCMP.EQ.1) GO TO 760
      IF(IBCF.EQ.1) GO TO 720
      GO TO 860
  720 IF(ISEN.EQ.0) GO TO 740
      IF(IPEL.EQ.0) GO TO 730
      SBCFP=BCFPEL+(BCFPEL*SENANL)
  730 IF(IDEM.EQ.0) GO TO 860
      SBCFD=BCFDEM+(BCFDEM*SENANL)
      GO TO 860
  740 IF(IPEL.EQ.0) GO TO 750
      SBCFP=BCFPEL-(BCFPEL*SENANL)
  750 IF(IDEM.EQ.0) GO TO 860
      SBCFD=BCFDEM-(BCFDEM*SENANL)
      GO TO 860
C
  760 IF(ISEN.EQ.0) GO TO 830
      SFDCMP(J)=FDDCMF(J)+(FDDCMF(J)*SENANL)
      IF(SFDCMF(J).GT.1.0) SFDCMF(J)=1.0
      GO TO 860
  830 SFDCMP(J)=FDDCMF(J)-(FDDCMF(J)*SENANL)
      IF(SFDCMF(J).LT.0.) SFDCMP(J)=0.0
C
  860 IF(IPRINT.EQ.1) GO TO 97
      PRINT 71,J,IPRINT,K2
   71 FORMAT(1H1,"TABLE OF CONTAMINATION FOR DIFFERENT LEVELS OF CONSTAN
     &T EXTERNAL CONCENTRATIONS FOR SPECIES ",I3/,1X,"AFTER DAY 15, CONV
     &AL=0.0, NEWOIL IS ALWAYS SET TO OILCON"/,1X,"THE "FEDOIL EQUATION"
     & IS USED IN THIS RUN. IPRINT =",I3,", K2 = ",F7.6)
      PRINT 69,SBCFP,SBCFD,FRCNAP,FRCNAD
   69 FORMAT(1X," BCFPEL = ",F8.3,", BCFDEM = ",F8.3,", FRCNAP = ",F5.3,"
     &, FRCNAD = ",F5.3)
      IF(IFDCMF.EQ.1) GO TO 1200
      IF(IBCF.EQ.0) GO TO 98
      IF(ISEN.EQ.0) GO TO 610
      IF(IPEL.EQ.0) GO TO 607
      PRINT 605,SEN
  605 FORMAT(1X," SENSITIVITY ANALYSIS: BCFPEL = BCFPEL + ",F6.2,"% FOR A
     &LL SPECIES")
  607 IF(IDEM.EQ.0) GO TO 98
      PRINT 615,SEN
  615 FORMAT(1X," SENSITIVITY ANALYSIS: BCFDEM = BCFDEM + ",F6.2,"% FOR A
     &LL SPECIES")
      GO TO 98
  610 IF(IPEL.EQ.0) GO TO 617
      PRINT 620,SEN
  620 FORMAT(1X," SENSITIVITY ANALYSIS: BCFPEL = BCFPEL - ",F6.2,"% FOR A
     &LL SPECIES")
  617 IF(IDEM.EQ.0) GO TO 98
      PRINT 625,SEN
  625 FORMAT(1X," SENSITIVITY ANALYSIS: BCFDEM = BCFDEM - ",F6.2,"% FOR A
     &LL SPECIES")
      GO TO 98
C
 1200 IF(ISEN.EQ.0) GO TO 1210
      PRINT 1205,SEN
 1205 FORMAT(1X," SENSITIVITY ANALYSIS: FDDCMP =FDDCMP + ",F6.2,"% FOR A
     &LL SPECIES")
      GO TO 98
 1210 PRINT 1215,SEN
```

```
 1215 FORMAT(1X,"SENSITIVITY ANALYSIS: FOCCMP =FOCCMP - ",F6.2,"% FOR A
     &LL SPECIES")
      GO TO 98
C
   97 CONTINUE
      PRINT 70,J,R2,IPRINT,K2
   70 FORMAT(1H1,"TABLE OF CONTAMINATION FOR DIFFERENT LEVELS OF CONSTAN
     &T EXTERNAL CONCENTRATIONS FOR SPECIES ",I3/,1X,"AFTER DAY  1, CONV
     &AL=CONVAL*EXP(-",F3.1,"); THE "FEDOIL EQUATION" IS USED IN THIS RU
     &N. IPRINT =",I3,", K2 = ",F7.6)
      PRINT 69,SBCFP,SBCFD,FRCNAP,FRCNAD
      IF(IFDCMP.EQ.1) GO TO 1400
      IF(IBCF.EQ.0) GO TO 98
      IF(ISEN.EQ.0) GO TO 640
      IF(IPEL.EQ.0) GO TO 647
      PRINT 605,SEN
  647 IF(IDEM.EQ.0) GO TO 98
      PRINT 615,SEN
      GO TO 98
  640 IF(IPEL.EQ.0) GO TO 667
      PRINT 620,SEN
  667 IF(IDEM.EQ.0) GO TO 98
      PRINT 625,SEN
      GO TO 98
C
 1400 IF(ISEN.EQ.0) GO TO 1410
      PRINT 1205,SEN
      GO TO 98
 1410 PRINT 1215,SEN
C
C
   98 CONTINUE
C     TOH(J)=TJ(J)+(0.35*TJ(J)*VALCA)
C
      NEWOIL=0.0
      OILVAL=0.0
      DO 80 ICON=1,4
      CONC=CONVAL(ICON)
C
C
      ICON1=ICON+2*(ICON-1)
      ICON2=ICON1+1
      ICON3=ICON2+1
C
      DO 50 LL=1,LLMAX
      OILCON=0.0
      VALUE=0.0
      IF(LL.GT.30) GO TO 52
      TABLE1(LL,ICON1)=0.0
      TABLE1(LL,ICON2)=0.0
      TABLE1(LL,ICON3)=0.0
   52 CONTINUE
      IF(IPRINT.NE.1.AND.IPRINT.NE.3) GO TO 55
      IF(LL.GT.1) CONC=CONC*FATE)2
C     IF(LL.EQ.10.OR.LL.EQ.20) CONC=CONVAL(ICON)/2.0
      GO TO 56
   55 IF(LL.LE.LLVAL) GO TO 56
      CONC=0.0
   56 WSF=CONC
      TARS=CONC
```

```
      IF(ICON.NE.3) GO TO 15
      PWSF(LL)=WSF
      PTARS(LL)=TARS
   15 IF(LL.GT.30) GO TO 57
      TABLE1(LL,ICON1)=WSF
      TABLE1(LL,ICON2)=TARS
   57 CONTINUE
C
      IF(SFDCMP(J).GT.0..AND.SFDCMP(J).LT.1.0) GO TO 20
      IF(SFDCMP(J).EQ.1.0) GO TO 30
      CO=TARS*FRCNAD
      VALUE=CO*SBCFD*2.0
      IF(J.EQ.16) VALUE=CO*SECFD
      IF(LL.EQ.1) KCMAX(ICON)=VALUE
      GO TO 130
   20 PEL=SFDCMP(J)
      DEM=1.0-PEL
      CO1=WSF*FRCNAP
      CO2=TARS*FRCNAD
      VALUE1=(CO1*SECFP)
      VALUE2=(CO2*SECFD)
      VALUE=(PEL*VALUE1+DEM*VALUE2)
      IF(LL.EQ.1) KCMAX(ICON)=VALUE
      GO TO 130
   30 CO=WSF*FRCNAP
      VALUE=(CO*SECFP)
      IF(LL.EQ.1) KCMAX(ICON)=VALUE
  130 CONTINUE
      IF(IPRINT.EQ.2.OR.IPRINT.EQ.3) GO TO 1130
      OILCON=VALUE*(1.0-RATEXP)+NEWOIL*(RATEXP)
      NEWOIL=OILCON
      GO TO 1140
 1130 IF(LL.GT.LLVAL) GO TO 1135
      RATEX3=EXP(-K2*LL)
      OILCON=VALUE*(1.0-RATEX3)
      IF(LL.EQ.LLVAL) OILVAL=OILCON
      GO TO 1140
 1135 RATEX3=EXP(-K2*(LL-LLVAL))
      OILCON=OILVAL*RATEX3
 1140 CONTINUE
      IF(LL.GT.30) GO TO 54
      TABLE1(LL,ICON3)=OILCON
   54 CONTINUE
      IF(ICON.NE.3) GO TO 50
      SAVDEC(LL,J)=OILCON
C
   50 CONTINUE
C
      NEWOIL=0.0
      OILVAL=0.0
C
      PRINT 60,CONVAL(ICON),WSF,TARS
   60 FORMAT(1X,"FOR CONVAL = ",F9.3," THE FINAL WSF CONC = ",F9.3," AND
     & THE FINAL TARS CONC = ",F9.3)
      PRINT 65,CONVAL(ICON),KCMAX(ICON)
   65 FORMAT(1X,"FOR CONVAL = ",F9.3," THE MAX CONC = ",F9.3)
C
   80 CONTINUE
C
C
```

```
      PRINT 73
   73 FORMAT(//4X,"TIME",50X,"CONSTANT"/,4X,"STEP",47X,"CONCENTRATIONS"/
     &)
      PRINT 74,(CONVAL(M),M=1,4)
   74 FORMAT(19X, 4(F8.4,19X)/)
      PRINT 174
  174 FORMAT(15X, 4("WSF",5X,"TARS",6X,"INT",6X)/)
C
C
      DO 888 N=1, 30
      PRINT 75,(N,(TABLE1(N,M),M=1,12))
   75 FORMAT(4X,I3,2X,12F9.3)
  888 CONTINUE
C
      PRINT 775,(N,N=1,16)
  775 FORMAT(//5X,"FOOD COMPOSITION TABLE (FRACTION PELAGIC) FOR SPECIES
     &:",/1X,16(1X,I3,1X))
      PRINT 777,(SFDCMP(N),N=1,16)
  777 FORMAT(1X,16F5.2)
C
C
   99 CONTINUE
C
C
      IF(IFPL(1.NE.1)GO TO 999
      IF(SENAML.NE.SENPRT) GO TO 999
      DO 600 LL=1,LLMAX
      WRITE(7,608)PWSF(LL),PTARS(LL),SAVDEC(LL,J1),SAVDEC(LL,J2),
     &SAVDEC(LL,J3)
  608 FORMAT(5F10.3)
  600 CONTINUE
C
  999 CONTINUE
C
C
 9998 IF(IFPL(1.NE.1) GO TO 9999
      CLOSE(7,DISP=KEEP)
C
C
 9999 STOP
      END
```

```
$RESET FREE
$SET OWN OWNARRAYS
FILE  1(KIND=DISK,TITLE="OCSEAP/OILCON/LOC1",FILETYPE=7)
FILE  2(KIND=DISK,TITLE="OCSEAP/OILCON/LOC2",FILETYPE=7)
FILE  3(KIND=DISK,TITLE="OCSEAP/OILCON/LOC3",FILETYPE=7)
FILE  6(KIND=PRINTER)
FILE  7(KIND=DISK,FILETYPE=7)
FILE  9(KIND=DISK,NEWFILE=.TRUE.)
      COMMON/ELK1/NE,ME,K,LL,ISL
      COMMON/ELKBIC/LOC,ACTBIO(16)
      COMMON/TAPBIO/BIOLC(3,16)
      COMMON/ELKOIL/OILCON(16,32,34)
      COMMON/ELKNEW/NEWOIL(16,32,34)
      COMMON/OIL/WSF(32,34),TARS(32,34)
      DIMENSION ITAB1(10,4),ITAB2(5,4),TI1(5,2),TI2(5,2),IT(5)
      DIMENSION ISL(32,34),D(32,34),TB(4),S7(32,34),S8(32,34),
     &IS(32,34)
C
C
C   DATA STATEMENT FOR SUBROUTINE FEDOIL. IFEDOL=0 FOR NO PRINTING OF
C   OUTPUT; IFEDOL=1 FOR PRINTING OF SUMMARY TABLE ONLY; IFEDOL=2 FOR
C   PRINTING OF CONCENTRATIONS AT EACH GRID POINT ONLY; IFEDOL=3 FOR
C   PRINTING OF BOTH.
C
      DATA IFEDOL/0/
C
      REAL NEWOIL
      NE=32;ME=34;K=8;LL=1;LLMAX=50;LOC=2
C
      DO 25 J=1,16
      ACTBIO(J)=BIOLC(LOC,J)
   25 CONTINUE
C
   30 IF(LL.GT.10) GO TO 35
      READ(LOC,/)NHRS
      READ(LOC,/)((WSF(N,M),M=1,ME),N=1,NE)
      GO TO 40
C
   35 DO 38 N=1,NE
      DO 38 M=1,ME
      WSF(N,M)=WSF(N,M)*EXP(-0.3)
      S7(N,M)=WSF(N,M)
   38 CONTINUE
      GO TO 42
C
C
C  CHANGE OIL CONCENTRATIONS FROM PPB TO PPM
C
C
   40 CONTINUE
      DO 32 N=1,NE
      DO 32 M=1,ME
      WSF(N,M)=WSF(N,M)/1000.
   32 S7(N,M)=WSF(N,M)
C
C  COMPUTE OIL ON THE BOTTOM
```

```
   42 CONTINUE
      BLC=1.
C     BLC=2 CONTINUOUS SOURCE, BLO=1 INSTANTANEOUS SOURCE.
      DL=2000.
C     TAT TIME STEP IN HOURS
      TAT=24.
      TD=20.
      T=LL*1440.
      KAL=0
C     KAL=0 - NO OIL MOVEMENT ON THE BOTTOM, 1 OIL ADVECTED ON BOTTOM
C     KU - CURRENT INDEX, SEE CUROIL; KA - TURBULENCE INDEX(NOT USED);
C     LU - PRINT SCALING INDEX
      KU=3
      KA=1
      LU=0
      UI=0.
      VI=0.
      CALL OILBOT(S7,LL,TD,DL,C,S8,IB,BLO,UI,VI,KU,KAL,T,KA,TAT)
      IF(LL.GT.1) GO TO 55
C
      DO 54 N=1,NE
      DO 54 M=1,ME
      ISL(N,M)=0
      IF(C(N,M).GT.0) ISL(N,M)=1
   54 CONTINUE
C
   55 UI=60.
      VI=8.
      IF(KAL.NE.1)GO TO 31
      CALL CUROIL(S8,KU,UI,VI,DL,LL,BLO,T,KAL)
   31 DO 33 N=1,NE
      DO 33 M=1,ME
   33 TARS(N,M)=S8(N,M)
      CALL FEDOIL(IFEDOL)
      J=1
 1200 DO 1000 I=1,4
      IT(I)=0
 1000 CONTINUE
      DO 1201 N=1,NE
      DO 1201 M=1,ME
      IF(OILCON(J,N,M).LT.5.0)GO TO 1201
      IF(OILCON(J,N,M).GE.5.0)IT(1)=IT(1)+4
      IF(OILCON(J,N,M).GE.10.)IT(2)=IT(2)+4
      IF(OILCON(J,N,M).GE.50.)IT(3)=IT(3)+4
      IF(OILCON(J,N,M).GT.100.)IT(4)=IT(4)+4
 1201 CONTINUE
      WRITE(9,/)LL,J
      WRITE(9,/)(IT(I),I=1,4)
      IF(J.EQ.13)GO TO 778
      J=13
      GO TO 1200
 1303 FORMAT(15X,2A6,1X,5I8)
 1307 FORMAT(15X,2A6,1X,5I8//)
  778 LL=LL+1
      IF(LL.LE.LLMAX)GO TO 30
      CLOSE(9,DISP=KEEP)
C
 9999 STOP
      END
      BLOCK DATA
```

```
      COMMON/INPBIO/BIOLC(3,16)
      COMMON/VALUES/FDCOMP(16),TJ(16),K2(16)
      REAL K2
      DATA BIOLC/ 1409.,521.,1551., 1121.,414.,1234.,
     &3708.,2322.,3261., 11007.,6893.,9675., 424.,279.,307.,
     &730.,330.,240., 831.,555.,819., 2004.,1472.,1650.,
     &922.,615.,908., 2004.,1472.,1650., 861.,461.,681.,
     &664.,222.,432., 1656.,553.,1078., 5970.,4995.,6075.,
     &13930.,11655.,14175., 19150.,13750.,19250./
      DATA FDCOMP/1.00,.95,.55,.72,.81,.43,.20,.20,.15,.25,.30,
     *.30,.10,0.0,0.0,0.0/
      DATA TJ/.016,.010,.012,.007,.015,.012,.012,.012,.006,.006,
     *.007,.012,.006,.019,.006,.006/
      DATA K2/.198040,.132027,.198040,.132027,.198040,.1664,.1664,.1664,
     &.1109,.1109,.132027,.334234,.222823,.198042,.03460,.06930/
      END
      SUBROUTINE FEDOIL(IFEDCL)
      COMMON/OIL/WSF(32,34),TARS(32,34)
      COMMON/ELKBIO/LOC,ACTBIO(16)
      COMMON/ELKOIL/OILCON(16,32,34)
      COMMON/ELKNEW/NEWOIL(16,32,34)
      COMMON/ELK1/NE,ME,K,LL,ISL(32,34)
      COMMON/VALUES/FDCOMP(16),TJ(16),K2(16)
      COMMON/ELKTAB/MS(16,9),AREA(16,9),FRCCON(16,9,2)
      DIMENSION CR(14),CCR(14),TCH(16),S1(32,34)
      REAL MS,K2,NEWOIL
C     DATA CR/10.,7.51,7.5,5.01,5.0,2.51,2.5,1.01,1.,0.11,0.1,0.011,0.01
C    &,.001/
C     DATA CCR/10.,7.51,7.5,5.01,5.0,2.51,2.5,1.01,1.,0.11,0.1,0.011,0.0
C    &1,.001/
      DATA CR/100.,50.01,50.,10.01,10.,5.01,5.,1.01,1.,0.11,0.1,0.011,0.
     &01,0.001/
      DATA CCR/100.,50.01,50.,10.01,10.,5.01,5.,1.01,1.,0.11,0.1,0.011,0
     &.01,0.001/
C
C       ART/FEDCL13 - THIS IS THE 'BCF VERSION' OF FEDOIL IN WHICH ONLY
C       K2, AND BCF ARE USED IN COMPUTING UPTAKE AND DEPURATION.
C
C       K2(J) IS THE DEPURATION RATE CONSTANT FOR SPECIES J
C
C       BCFPEL IS THE BIOCONCENTRATION FACTOR OF EACH PELAGIC SPECIES J
C
C       BCFDEM IS THE BIOCONCENTRATION FACTOR OF EACH DEMERSAL SPECIES J
C
C       FRCNAP IS THE FRACTION OF WSF THAT IS NAPHTHALENES.
C
C       FRCNAD IS THE FRACTION OF TARS THAT IS NAPHTHALENES.
C
C-----------------------------------------------------------------------
C
C     SET CONSTANTS
C
      RAD=0.01745329
      ALP=30.*RAD
      GKAP=175.*RAD
      VALCA=COS(ALP*K-GKAP)
      FRCNAP=.50
      FRCNAD=.10
      BCFPEL=170.
      BCFDEM=170.
```

```
C
C-----------------------------------------------------------------------
C
C      COMPUTE UPTAKE AND DEPURATION OF OIL CONTAMINANTS. FOR OUTPUT,
C      ALL CONCENTRATIONS ARE IN PPM AND ACTBIO IS IN KG
C-----------------------------------------------------------------------
C
      DO 99 J=1,16
C
      DO 100 I=1,9
      MS(J,I)=0.
      AREA(J,I)=0.
      FRCCON(J,I,1)=0.
      FRCCON(J,I,2)=0.
  100 CONTINUE
C
      RATEXP=EXP(-K2(J))
      TOH(J)=TJ(J)+(0.35*TJ(J)*VALCA)
      TONS=(ACTBIO(J)*4.0)/1000.
C
      TAREA=0.
      TTONS=0.
      TCOUNT=0.
      DO 10 N=1,NE
      DO 10 M=1,ME
      IF(ISL(N,M).EQ.0) GO TO 10
      VALUE=0.0
      S1(N,M)=0.0
      TAREA=TAREA+4.0
      TTONS=TTONS+TONS
      TCOUNT=TCOUNT+1.0
      IF(FODCMP(J).GT.0..AND.FODCMP(J).LT.1.0) GO TO 20
      IF(FODCMP(J).EQ.1.0) GO TO 30
      CO=TARS(N,M)*FRCNAD
      VALUE=CO*BCFDEM*2.0
      IF(J.EQ.16) VALUE=CO*BCFDEM
      GO TO 130
   20 PEL=FODCMP(J)
      DEM=1.0-PEL
      CO1=MSF(N,M)*FRCNAP
      CO2=TARS(N,M)*FRCNAD
      VALUE1=(CO1*BCFPEL)
      VALUE2=(CO2*BCFDEM)
      VALUE=(PEL*VALUE1+DEM*VALUE2)
      GO TO 130
   30 CO=MSF(N,M)*FRCNAP
      VALUE=(CO*BCFPEL)
  130 CONTINUE
      OILCON(J,N,M)=VALUE*(1.0-RATEXP)+NEWOIL(J,N,M)*(RATEXP)
      NEWOIL(J,N,M)=OILCON(J,N,M)
      S1(N,M)=OILCON(J,N,M)
      IF(IFEDCL.NE.1.AND.IFEDCL.NE.3) GO TO 10
      IF(S1(N,M).LT.CCR(14)) MS(J,9)=MS(J,9)+TONS
      IF(S1(N,M).LT.CCR(14)) AREA(J,9)=AREA(J,9)+4.0
      IF(S1(N,M).LE.CCR(13).AND.S1(N,M).GE.CCR(14))
     &MS(J,8)=MS(J,8)+TONS
      IF(S1(N,M).LE.CCR(13).AND.S1(N,M).GE.CCR(14))
     &AREA(J,8)=AREA(J,8)+4.0
      IF(S1(N,M).LE.CCR(11).AND.S1(N,M).GE.CCR(12))
     &MS(J,7)=MS(J,7)+TONS
```

```
      IF(S1(N,M).LE.CCR(11).AND.S1(N,M).GE.CCR(12))
     &AREA(J,7)=AREA(J,7)+4.0
      IF(S1(N,M).LE.CCR(9).AND.S1(N,M).GE.CCR(10))
     &MS(J,6)=MS(J,6)+TONS
      IF(S1(N,M).LE.CCR(9).AND.S1(N,M).GE.CCR(10))
     &AREA(J,6)=AREA(J,6)+4.0
      IF(S1(N,M).LE.CCR(7).AND.S1(N,M).GE.CCR(8))
     &MS(J,5)=MS(J,5)+TONS
      IF(S1(N,M).LE.CCR(7).AND.S1(N,M).GE.CCR(8))
     &AREA(J,5)=AREA(J,5)+4.0
      IF(S1(N,M).LE.CCR(5).AND.S1(N,M).GE.CCR(6))
     &MS(J,4)=MS(J,4)+TONS
      IF(S1(N,M).LE.CCR(5).AND.S1(N,M).GE.CCR(6))
     &AREA(J,4)=AREA(J,4)+4.0
      IF(S1(N,M).LE.CCR(3).AND.S1(N,M).GE.CCR(4))
     &MS(J,3)=MS(J,3)+TONS
      IF(S1(N,M).LE.CCR(3).AND.S1(N,M).GE.CCR(4))
     &AREA(J,3)=AREA(J,3)+4.0
      IF(S1(N,M).LE.CCR(1).AND.S1(N,M).GE.CCR(2))
     &MS(J,2)=MS(J,2)+TONS
      IF(S1(N,M).LE.CCR(1).AND.S1(N,M).GE.CCR(2))
     &AREA(J,2)=AREA(J,2)+4.0
      IF(S1(N,M).GT.CCR(1)) MS(J,1)=MS(J,1)+TONS
      IF(S1(N,M).GT.CCR(1)) AREA(J,1)=AREA(J,1)+4.0
   10 CONTINUE
C
      IF(IFEDCL.NE.1.AND.IFEDCL.NE.3) GO TO 250
      DO 200 I=1,9
      FRCCON(J,I,1)=MS(J,I)/TTONS
      FRCCON(J,I,2)=AREA(J,I)/TAREA
  200 CONTINUE
C
C-----------------------------------------------------------------------
C      PRINT OIL CONCENTRATION FIELDS
C-----------------------------------------------------------------------
C
  250 IF(IFEDCL.NE.2.AND.IFEDCL.NE.3) GO TO 99
      PRINT 1005,J,LL
 1005 FORMAT("1CONTAMINATION INDEX (PPM) IN FEDOIL FOR SPECIES #"I2,2X,"
     &TIME STEP #"I2)
      PRINT 1006,((S1(N,M),M=1,14),N=1,NE)
 1006 FORMAT(2X,14F9.5)
      PRINT 1008,((S1(N,M),M=15,ME),N=1,NE)
 1008 FORMAT(13F9.5)
C
   99 CONTINUE
C
C-----------------------------------------------------------------------
C-----------------------------------------------------------------------
C
C
      IF(IFEDCL.NE.1.AND.IFEDCL.NE.3) GO TO 999
      ICOUNT=1
      DO 300 J=1,16
      ITAB=LL
      IF(ICOUNT.GT.1) GO TO 1320
      PRINT 1121,ITAB,TCOUNT
 1121 FORMAT(1H1,//6X,"TABLE",I3,".--- AREA COVERED BY   INTERNAL   CONC
     &ENTRATIONS FOR SELECTED LEVELS OF CONTAMINATION"/,19X,"ACCIDENT SC
     &ENARIO; EACH GRID POINT IS 2 KM BY 2 KM; GRID COUNT = ",F6.0)
```

```
      GO TO 116
 1320 PRINT 1119,ITAB,ICOUNT
 1119 FORMAT(///6X,"TABLE",I3,".--- AREA COVERED BY   INTERNAL   CONCENT
     &RATIONS FOR SELECTED LEVELS OF CONTAMINATION"/,19X,"ACCIDENT SCENA
     &RIO; EACH GRID POINT IS 2 KM BY 2 KM; GRID COUNT = ",F6.0)
  116 IF(LOC.NE.1) GO TO 324
      PRINT 118,LL
  118 FORMAT(19X,"LOCATION: FORT MOLLER, TIME STEP: DAY",I3)
      GO TO 328
  324 IF(LOC.NE.2) GO TO 326
      PRINT 220,LL
  220 FORMAT(19X,"LOCATION: FORT HEIDEN, TIME STEP: DAY",I3)
      GO TO 328
  326 PRINT 222,LL
  222 FORMAT(19X,"LOCATION: CAPE NEWENHAM, TIME STEP: DAY",I3)
  328 PRINT 223
  223 FORMAT(19X,"(CONTAMINATED BIOMASS IS SUMMED OVER THE GRID AND GIVE
     &N IN TONS)")
      GO TO (224,224,224,224,225,225,225,224,224,224,225,225,224,225,225
     &,225)J
  224 PRINT 124,J,ACTBIO(J)
  124 FORMAT(///6X,"SPECIES NO.",I3," - A MIGRATING SPECIES (BIOMASS",F9
     &.2," KG/KM2)")
      GO TO 226
  225 PRINT 221,J,ACTBIO(J)
  221 FORMAT(///6X,"SPECIES NO.",I3," - A NON-MIGRATING SPECIES (BIOMASS
     &",F9.2," KG/KM2)")
  226 PRINT 123
  123 FORMAT(/8X,"CONCENTRATIONS IN PPM (MG/KG)",28X,"TOTAL CONTAMINATED
     & BIOMASS")
      PRINT 2225
 2225 FORMAT(58X,"BIOMASS(TONS)",18X,"AREA(KM2)")
      PRINT 323
  323 FORMAT(55X," BIOMASS ",5X,"FRACTION",5X,"  AREA   ",6X,"FRACTION")
      PRINT 122,CR(1),MS(J,1),FRCCON(J,1,1),AREA(J,1),
     &FRCCON(J,1,2)
  122 FORMAT(/6X,24HCONT.INDEX GREATER THAN ,F9.3,8X,F16.2,6X,F8.3,6X,F8
     &.2,6X,F8.3)
      PRINT 125,CR(2),CR(1),MS(J,2),FRCCON(J,2,1),AREA(J,2),
     &FRCCON(J,2,2)
  125 FORMAT(6X,10HCONT.INDEX,F9.3,2X,3HTO ,F9.3,8X,F16.2,6X,F8.3,6X,F8.
     &2,6X,F8.3)
      PRINT 125,CR(4),CR(3),MS(J,3),FRCCON(J,3,1),AREA(J,3),
     &FRCCON(J,3,2)
      PRINT 125,CR(6),CR(5),MS(J,4),FRCCON(J,4,1),AREA(J,4),
     &FRCCON(J,4,2)
      PRINT 125,CR(8),CR(7),MS(J,5),FRCCON(J,5,1),AREA(J,5),
     &FRCCON(J,5,2)
      PRINT 125,CR(10),CR(9),MS(J,6),FRCCON(J,6,1),AREA(J,6),
     &FRCCON(J,6,2)
      PRINT 125,CR(12),CR(11),MS(J,7),FRCCON(J,7,1),AREA(J,7),
     &FRCCON(J,7,2)
      PRINT 125,CR(14),CR(13),MS(J,8),FRCCON(J,8,1),AREA(J,8),
     &FRCCON(J,8,2)
      PRINT 126,CR(14),MS(J,9),FRCCON(J,9,1),AREA(J,9),
     &FRCCON(J,9,2)
  126 FORMAT(6X,"CONT.INDEX LESS THAN     ",F9.3,8X,F16.2,6X,F8.3,6X,F8.2
     &,6X,F8.3)
C
      ICOUNT=ICOUNT+1
```

```
      IF(ICOLNT.EQ.3) ICOUNT=1
  300 CONTINUE
C
C
C-----------------------------------------------------------------------
C                              END SUBROUTINE
C-----------------------------------------------------------------------
C
C
  999 RETURN
      END
      SUBROUTINE OILBOT(S,K,TC,DL,D,AC,TB,BLC,UI,VI,KU,KAL,T,KA,TAT)
      COMMON/BLKBIC/LOC,ACTBIC(16)
      DIMENSION S(32,34),D(32,34),AC(32,34),TB(4),PLD(2),W(3)
C     D-DEPTH
C     AO-OIL ON THE BOTTOM
C     TB-BOTTOM TEMPERATURE, FOUR VALUES GIVEN
C     PLD-THERMOCLINE DEPTH, TWO VALUES
C     W-WIND SPEED, THREE VALUES
C     KT-INDEX OF TB VALUE CHOSEN FOR THE RUN
C     KP-INDEX OF PLD VALUE
C     KW-INDEX OF WIND VALUE
C     BLC=1 INSTANTANEOUS SOURCE, =2 CONTINUOUS SOURCE
C     UI-SURFACE CURRENT SPEED
C     KAL=1 COMPUTATION OF OIL MOVEMENT ON BOTTOM
C     LU=1 DEPTH DATA
C     LU=2 DECAY OF OIL ON THE BOTTOM
C     LU=3 OIL ON THE BOTTOM BEFORE ADVECTION
C     LU=4 OIL ON THE BOTTOM,LAYER THICKNESS DECREASING, ADVECTED
C     LU=5 ADVECTED OIL ON THE BOTTOM
C     LU=6 CONTAMINATION INDEX, PELAGIC FOOD
C     LU=7 CONTAMINATION INDEX, DEMERSAL FOOD
      NE=32
      ME=34
      MO=10
C     MO IS THE M LOCATION OF BLOWOUT
C     SIMULATION OF DEPTH,
C     KB-AREA NUMBER FOR TANKER ACCIDENT, 4 TO 6
   16 KB=LOC+3
      IF(KB-5)305,330,360
  305 DO 319 N=1,NE
      DO 319 M=1,ME
      SDS=M
      IF(N-17)306,306,307
  306 D(N,M)=70.-0.35*SDS
      GO TO 319
  307 IF(N-26)308,308,311
  308 IF(M-20)309,309,310
  309 D(N,M)=62.-1.0*SDS
      GO TO 319
  310 D(N,M)=62.-1.5*SDS
      GO TO 319
  311 IF(M-20)312,312,313
  312 D(N,M)=54.-1.2*SDS
      GO TO 319
  313 D(N,M)=54.-1.4*SDS
  319 CONTINUE
      ALPHA=0.9
      CALL SILITA(D,ALPHA,NE,ME,S,1)
      GO TO 10
```

```
CXXXXXXXXXXXXXXXX
  330 DO 359 N=1,NE
      DO 359 M=1,ME
      SDS=M
      IF(N-22)331,331,332
  331 D(N,M)=50.-1.0*SDS
      GO TO 359
  332 IF(M-25)333,333,334
  333 D(N,M)=45.-1.6*SDS
      GO TO 359
  334 D(N,M)=0.
  359 CONTINUE
      ALPHA=0.9
      CALL SILITA(D,ALPHA,NE,ME,S,1)
      GO TO 10
CXXXXXXXXXXXXXXXX
  360 DO 379 N=1,NE
      DO 379 M=1,ME
      SDS=M
      IF(N-12)361,361,362
  361 D(N,M)=38.
      GO TO 379
  362 D(N,M)=45.
  379 CONTINUE
      ALPHA=0.9
      CALL SILITA(D,ALPHA,NE,ME,S,1)
CXXXXXXXXXXXXXXXXXXXXXX
   10 LU=1
      IF(K-1)17,17,20
      IF(K-1)9,9,20
    9 CALL PRIMFS(D,T,UI,VI,CL,K,KA,KAL,BLO,LU,NE,ME)
CXXXXXXXXXXXXXXXXXXXXXXX
   17 DO 18 N=1,NE
      DO 18 M=1,ME
      AC(N,M)=0.
   18 CONTINUE
C     INPUT PARAMETERS
   20 TB(1)=1.
      TB(2)=4.
      TB(3)=8.
      TB(4)=12.
      PLO(1)=20.
      PLO(2)=40.
      W(1)=5.
      W(2)=10.
      W(3)=15.
C     PP - RELATIVE CONC. OF PLANKTON
C     R - INDEX OF SUSPENDED MATTER
C     BB - BOTTOM TYPE INDEX
      PP=1.5
      R=40.
      BB=0.8
C     SETTING OF INDICES FOR INPUT PARAMETERS
      KT=3
      KP=1
      KW=2
CXXXXXXXXXXXXXXXXXXXXXXX
C     DECAY OF OIL ON THE BOTTOM
      IF(K-2)30,25,25
   25 DO 29 N=1,NE
```

```
      DO 29 M=1,ME
      IF(D(N,M))29,29,290
  290 IF(AO(N,M))29,29,26
   26 TFA=(TB(KT)**2.7)*0.0001
      DFA=0.15/SQRT(D(N,M))
      EFA=-(TFA+DFA)
      AO(N,M)=AO(N,M)*EXP(EFA)
      IF(TAT-12.)29,29,27
   27 AO(N,M)=AO(N,M)*EXP(EFA)
   29 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXX
      LU=2
C     CALL PRIMFS(AO,T,UI,VI,DL,K,KA,KAL,ELO,LU,NE,ME)
CXXXXXXXXXXXXXXXXXXXXXXXXXX
   30 IF(BLO-1)31,31,51
C     INSTANTANEOUS SOURCE (TANKER ACCIDENT)
   31 DO 45 N=1,NE
      DO 45 M=1,ME
      IF(D(N,M))45,45,291
  291 IF(PLD(MF)-D(N,M))40,33,33
C      NO PYCNOCLINE
   33 SK=K
   35 STK=SK/(3.+0.2*SK)
   56 BCF=0.0015
      CCF=0.15
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      FS=(BCF*W(KW)+CCF/(D(N,M)**0.7))*STK
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)45,45,131
  131 IF(TAT-12.)45,45,37
   37 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      GO TO 45
C     THERMOCLINE PRESENT
   40 IF(K-1)45,45,38
   38 SK=K
      TDK=SK/(3.+0.5*SK)
      BCF=0.001
      CCF=0.20
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      FDD=(BCF*W(KW)+CCF/(D(N,M)**0.7))*TDK
      AO(N,M)=AO(N,M)+S(N,M)*FDD*PP*RR*BB
      IF(K-1)45,45,132
 132  IF(TAT-12.)45,45,44
   44 AO(N,M)=AO(N,M)+S(N,M)*FDD*PP*RR*BB
   45 CONTINUE
      GO TO 70
C     CONTINUOUS SOURCE (BLOWOUT)
   51 DO 65 N=1,NE
      DO 65 M=1,ME
      IF(D(N,M))65,65,292
  292 DIS=((M-MO)*0.001*DL)
      IF(DIS)53,53,54
   53 DIS=0.001
   54 APD=2.5
C     NO COMPUTATION IN IMMEDIATE AREA OF BLOWOUT
C     I.E. 2.5KM FROM THE SOURCE
      IF(DIS-APD)65,59,59
   59 IF(PLD(MF)-D(N,M))60,55,55
C     NO PYCNOCLINE
```

```
   57 STK=SK/(3.+C.2*SK)
   58 BWF=C.0016
      CDF=C.15
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      DIFAC=(DIS+4.)/(20.+0.1*DIS)
      FS=(BWF*W(KW)+CDF/(D(N,M)**C.7))*STK*(DIFAC)
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)65,65,69
   69 IF(TAT-12.)65,65,71
   71 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      GO TO 65
C     COMPUTATION WITH THERMOCLINE PRESENT
   6C APD=2.5
      IF(DIS-APD)65,61,61
   61 SK=K
   62 STK=SK/(3.+0.5*SK)
   64 BWF=C.001
      CDF=C.2C
      DDP=D(N,M)**C.74
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      DIFAC=(DIS+4.)/(2C.+0.1*DIS)
      FS=(BWF*W(KW)+CDF/DDP)*STK*(DIFAC)
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)65,65,66
   66 IF(TAT-12.)65,65,67
   67 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
   65 CONTINUE
CXXXXXXXXXXXXXXXXXXX
   7C ALPHA=0.78
      CALL SILITA(AO,ALPHA,NE,ME,C,C)
CXXXXXXXXXXXXXXXXXXXXXXXXXX
      LU=3
C     CALL PRIMFS(AO,T,UI,VI,DL,K,KA,KAL,BLO,LU,NE,ME)
CXXXXXXXXXXXXXXXXXXXXXXXXXX
  10C RETURN
      END
      SUBROUTINE CUROIL(S,KU,UI,VI,DL,K,BLO,T,KAL)
      DIMENSION S(32,34),PF(32,34),D(32,34)
CXXXXXXXXXXXXXXXXXXXX
C     INDICES
C     KG-GRID SIZE 1-2KM;2-4KM
C     KT-TIME STEP 1-2CMIN, 2-40MIN.
C     KF-FLUCTUATION PARAMETER (FAF);PERIOD 15 MIN,KF=1,FAF=0.4
C        30 MIN,KF=2,FA=0.2
C     KA-LAMINAR FLOW OR INCREASING LAYER  1-LAMINAR; 2-INCREASING LAYER
C     KU-UNIDIRECTIONAL                 CURRENT 1-UNIDIRECTIONAL,U-DIRECTION
C        2-UNIDIRECTIONAL V-DIRECTION, 3-UNIDIRECTIONAL AT 45 DEG. ANGEL
C     KR-UNIDIRECTIONAL OR ROTATING, 1-UNIDIRECTIONAL, 2-ROTATING
C     KS-SPEED COUNTER FOR 4 DIFERENT SPEEDS
C     CURRENT SPEED IN, M/SEC
CXXXXXXXXXXXXXXXXXXX
C     THIS SUBROUTINE HAS BEEN USED FOR COMPUTATION OF
C     DISTRIBUTION OF SMELL FROM BAITS
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      KG=1
      KT=1
      KF=1
      KA=1
      KR=1
CXXXXXXXXXXXXXXXXXX
```

```
      NE=32
      NEH=NE-1
      ME=34
      MEH=ME-1
      IF(KG-1)1,1,2
    1 DL=2000.
      GO TO 3
    2 DL=4000.
    3 IF(KT-1)4,4,5
    4 TD=20.
C     IAC=3
C     IPR=36
      IAC=9
      IPR=3*24
      GO TO 6
    5 TD=40.
      IAC=2
      IPR=18
    6 IF(KF-1)7,7,8
    7 FAF=0.4
      GO TO 9
    8 FAF=0.2
    9 CON=0.0174533
      ALPHA=0.82
      ALP=FAF*CON
      TCAP=45.*CON
      SD=100.
CXXXXXXXXXXXXXXXX
C     ADVECTION COMPUTED FOR 24 HOURS
      TSTD=24.*60.
      TI=0.
C     TF=10080.+TD
CXXXXXXXXXXXXXXXXX
      KS=1
      KKK=0
      TURC=0.02
C     XXXXXX
C     CURRENT SPEED INPUT
      IF(KR-1)12,12,16
   12 IF(KL-2)13,14,15
   13 UA=0.1*UI
      VA=0.1*VI
      GO TO 18
   14 UA=0.15*UI
      VA=0.15*VI
      GO TO 18
   15 UA=0.15*UI
      VA=0.15*VI
      GO TO 18
   16 UA=0.15*UI
      VA=0.15*VI
      ADD=0.008
      AROT=ADD*CON
      AKADI=90.*CON
      APARP=180.*CON
      DL=4000.
      TF=14400.
CXXXXXXXXXXXXXXXX
C     KAL=1, OIL MOVEMENT ON THE BOTTOM
      IF(KAL)18,18,519
```

```
CXXXXXXXXXXXXXXXXX
   18 T=T+TD
      TI=T
  515 ITC=0
      ITCP=0
      TI=TI+TI
   10 ITC=ITC+1.
      ITCP=ITCP+1
   20 IF(KR-1)41,41,47
   41 IF(KU-2)42,43,44
   42 U=UI+UA*COS(ALP*TI)
      V=VI*COS(ALP*TI+TCAP)
      GO TO 49
   43 V=VI+VA*COS(ALP*TI)
      U=UI*COS(ALP*TI+TCAP)
      GO TO 49
   44 U=UI+UA*COS(ALP*TI)
      V=VI+VA*COS(ALP*TI+TCAP)
      GO TO 49
   47 U=UI*COS(ARCT*TI+AKADI)
      V=VI*COS(ARCT*TI+APARP)
   49 CONTINUE
      IF(KAL-1)253,27,27
  253 IF(BLO-1)250,250,252
C     100 UNITS OF OIL ADDED EACH TIME STEP (SO=100.)
  252 S(12,10)=S(12,10)+SO
      GO TO 27
CXXXXXXXXXXXXXXXXXXXXXX
  250 IF(K-1)251,251,27
  251 S(12,10)=600.

CXXXXXXXXXXXXXXXXXXXXX
   27 SUS=0.
      SUA=0.
   30 DO 50 N=2,NEH
      DO 50 M=2,MEH
      SUA=SUA+S(N,M)
      IF(U)32,31,31
   31 SH=(S(N,M)-S(N,M-1))/DL
      GO TO 33
   32 SH=(S(N,M)-S(N,M+1))/DL
   33 IF(V)34,36,36
   34 SV=(S(N,M)-S(N-1,M))/DL
      GO TO 35
   36 SV=(S(N,M)-S(N+1,M))/DL
   35 S(N,M)=S(N,M)-(TD*ABS(U)*SH)-(TD*ABS(V)*SV)
      SUS=SUS+S(N,M)
   50 CONTINUE
      IF(SUS)80,80,95
   95 IF(ITC-IAC)80,55,80
CXXXXXXXXXXXXXXXXXX
   55 IF(KAL-1)550,551,551
  551 ALPHA=0.78
CXXXXXXXXXXXXXXXXXXXX
  550 CALL SILITA(S,ALPHA,NE,ME,D,1)
      ITC=0
      U1=SUA/SUS
      DO 60 N=1,NE
      DO 60 M=1,ME
      S(N,M)=S(N,M)*U1
```

```
   60 CONTINUE
C     EFFECTS OF INCREASING LAYER THICKNESS,APPROXIMATE
C     FACTOR -CTR REFERRES TO KILOMETERS FROM SOURCE
C     OBS. N AND M ARE LOCATION OF SOURCE
CXXXXXXXXXXXXXXX
C     THE FOLLOWING SECTION NOT USED IN OIL PROBLEMS
CXXXXXXXXXXXXXXX
      CTR=0.015
      IF(KA-1)81,81,61
   61 DO 131 N=1,NE
      DO 131 M=1,ME
      PF(N,M)=S(N,M)
  131 CONTINUE
      IF(KR-1)62,62,69
   62 IF(KU-2)63,65,67
   63 DO 64 N=1,NE
      DO 64 M=1,ME
      DIS=(M-10)*0.01*DL
      IF(DIS)51,51,52
   51 RRC=1.
      GO TO 53
   52 RRC=(1.-(CTR*DIS))
   53 PF(N,M)=PF(N,M)*RRC
   64 CONTINUE
      GO TO 81
   65 DO 66 N=1,NE
      DO 66 M=1,ME
      DIS=(N-20)*0.01*DL
      IF(DIS)54,54,56
   54 RRC=1.
      GO TO 57
   56 RRC=(1.-(CTR*DIS))
   57 PF(N,M)=PF(N,M)*RRC
   66 CONTINUE
      GO TO 81
   67 DO 68 N=1,NE
      DO 68 M=1,ME
      IF(M-10)58,58,59
   58 RRC=1.
      GO TO 82
   59 IF(N-10)58,58,83
   83 DIS=SQRT((M-10)**2.+(N-10)**2.)*0.01*DL
      RRC=(1.-(CTR*DIS))
   82 PF(N,M)=PF(N,M)*RRC
   68 CONTINUE
      GO TO 81
   69 DO 84 N=1,NE
      DO 84 M=1,ME
      IF(M-10)86,86,87
   86 RRC=1.
      GO TO 88
   87 DIS=(M-10)*0.01*DL
      RRC=(1.-(0.5*CTR*DIS))
   88 PF(N,M)=PF(N,M)*RRC
      IF(N-20)89,89,91
   89 RRC=1.
      GO TO 94
   91 DIS=(N-20)*0.01*DL
      RRC=(1.-(0.5*CTR*DIS))
   94 PF(N,M)=PF(N,M)*RRC
```

```
   84 CONTINUE
   81 ITC=0.
   80 IF(ITOP-IPR)590,85,590
C       XXXXXXX)XXXXXXX
  590 TI=TI+TC
      IF(TSTC-TI)100,10,10
C 590 T=T+TD
C     IF(TF-T)100,10,10
C      XXXXXX)XXXXXXX
   85 IF(KA-1)122,122,121
  121 LU=4
C     CALL PRIMFS(PF,T,UI,VI,CL,K,KA,KAL,BLC,LU,NE,ME)
      DO 132 N=1,NE
      DO 132 M=1,ME
      S(N,M)=PF(N,M)
  132 CONTINUE
      GO TO 123
  122 LU=5
C     CALL PRIMFS(S,T,UI,VI,CL,K,KA,KAL,BLC,LU,NE,ME)
  123 ITOP=0
  100 RETURN
      END
      SUBROUTINE SILITA (S,ALPHA,NE,ME,D,I)
      DIMENSION S(32,34),D(32,34)
      NEH=NE-1
      MEH=ME-1
      BET=(1.-ALPHA)/4.
      DO 123 N=2,NEH
      DO 123 M=2,MEH
      IF(I-1)101,102,102
  101 IF(D(N,M))124,124,103
  102 IF(S(N,M))124,124,103
  103 IF(1-N)105,107,105
  105 VALP=S(N-1,M)
      GO TO 108
  107 VAUP=S(N,M)
  108 IF(NE-N)110,112,110
  110 VALO=S(N+1,M)
      GO TO 113
  112 VALO=S(N,M)
  113 IF(1-M)115,116,115
  115 VALE=S(N,M-1)
      GO TO 117
  116 VALE=S(N,M)
  117 IF(ME-M)119,121,119
  119 VARI=S(N,M+1)
      GO TO 122
  121 VARI=S(N,M)
  122 S(N,M)=ALPHA*S(N,M)+BET*(VAUP+VALO+VALE+VARI)
      GO TO 123
  124 S(N,M)=0.
  123 CONTINUE
      RETURN
      END
      SUBROUTINE PRIMFS(S,T,UI,VI,CL,K,KA,KAL,BLC,LU,NE,ME)
      DIMENSION S(32,34),IS(32,34)
C     IF(LU-1)202,401,420
      IF(LU-1)270,401,420
  202 PRINT 201,K,T,UI,VI,DL,KA,KAL
  201 FORMAT(1H1,5X,18HOIL CONCENTRATIONS,2X,2HK=,I5,3X,2HT=,F6.0,3X,3HU
```

```
     2I=,F6.4,3X,3HVI=,F6.4,3X,3HCL=,F6.0,3X,3HKA=,I3,3X,4HKAL=,I3)
  270 PRINT 271,K,CL
  271 FORMAT(1H1,5X,18HOIL CONCENTRATIONS,2X,2HK=,I5,3X,3HCL=,F6.0)
C     PRINT 203
      PRINT 504
  203 FORMAT(/5X,12HCONC. IN PPB/)
  504 FORMAT(5X,19HPRINT FACTOR = 0.1,4X,7HPPB/10./)
CXXXXXXXXXXXXXXXXXXXXX
      GO TO 212
  401 PRINT 402
  402 FORMAT(1H1,5X,16HDEPTHS IN METERS,)
      GO TO 320
  420 IF(LU-3)421,425,430
  421 PRINT 422,K
  422 FORMAT(1H1,5X,34HDECAY OF OIL ON THE BOTTOM, PERIOD,I5)
      GO TO 212
  425 PRINT 426,K
  426 FORMAT(1H1,5X,41HNEW OIL ON BOTTOM BEFORE ADVECTION,PERIOD,I5)
      GO TO 212
  430 IF(KAL-1)202,431,431
  431 PRINT 432,K
  432 FORMAT(1H1,5X,34HADVECTED OIL ON THE BOTTOM, PERIOD,I5)
      PRINT 272,UI,VI
  272 FORMAT(5X,3HUI=,F5.2,3X,3HVI=,F5.2)
      GO TO 212
CXXXXXXXXXXXXXXXXXXXXX
      IF(KA-1)210,210,215
  210 PRINT 211
  211 FORMAT(5X,12HLAMINAR,FLOW/)
      GO TO 212
  215 PRINT 216
  216 FORMAT(5X,26HLAYER THICKNESS INCREASING/)
CXXXXXXXXXXXXXXXXXXXXX
C 212 IF(KAL-1)230,220,220
  212 IF(KAL-1)530,220,220
  220 IF(BLO-1)250,250,252
  250 DO 225 N=1,NE
      DO 225 M=1,ME
      IS(N,M)=S(N,M)*1000.
  225 CONTINUE
      PRINT 260
  260 FORMAT(5X,16HPRINT FACTOR = 1/)
      GO TO 240
  252 DO 253 N=1,NE
      DO 253 M=1,ME
      IS(N,M)=S(N,M)*100.
  253 CONTINUE
      PRINT 261
  261 FORMAT(5X,18HPRINT FACTOR = 0.1,4X,7HPPB/10./)
      GO TO 240
  320 DO 321 N=1,NE
      DO 321 M=1,ME
      IS(N,M)=S(N,M)
  321 CONTINUE
      GO TO 240
  230 DO 205 N=1,NE
      DO 205 M=1,ME
      IS(N,M)=S(N,M)*1000.
  205 CONTINUE
  530 DO 531 N=1,NE
```

```
      DO 531 M=1,ME
      IS(N,M)=S(N,M)*100.
  531 CONTINUE
  240 IF(ME-40)610,640,640
  640 PRINT 206,(M,M=1,40)
  206 FORMAT(/4X,40I3)
      PRINT 207,(N,(IS(N,M),M=1,40),N=1,50)
  207 FORMAT(/1X,I2,1X,40I3)
C    XXXXXXXXXXXXXXXXXX
      GO TO 300
C    XXXXXXXXXXXXXXXXXXX
      PRINT 208,(M,M=41,50)
  208 FORMAT(1H1,//4X,10I3)
      PRINT 209,(N,(IS(N,M),M=41,50),N=1,50)
  209 FORMAT(/1X,I2,1X,10I3)
C     XXXXXX
      GO TO 300
  610 PRINT 611,(M,M=1,34)
  611 FORMAT(/4X,34I3)
      PRINT 612,(N,(IS(N,M),M=1,34),N=1,32)
  612 FORMAT(/1X,I2,1X,34I3)
  300 RETURN
      END
```

```
$RESET FREE
$SET OWN CWNAFRAYS
FILE  1(KIND=DISK,TITLE="CCSEAP/CILCON/LOC1",FILETYPE=7)
FILE  2(KIND=DISK,TITLE="CCSEAP/CILCON/LOC2",FILETYPE=7)
FILE  3(KIND=DISK,TITLE="OCSEAP/OILCON/LOC3",FILETYPE=7)
FILE  6(KIND=PRINTER)
FILE  8(KIND=DISK,NEWFILE=.TRUE.)
FILE  9(KIND=DISK,NEWFILE=.TRUE.)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     THIS VERSION HAS MIGRATIONS (OVER A 64X68 GRID)
C       BUT ONLY TWO SPECIES:
C          SPECIES 1 (JUVENILE HERRING) AND
C          SPECIES 13 (ADULT CRABS)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      COMMON/ELK1/NE,ME,K,LL
      COMMON/ELKBIC/LCC,ACTBIO(2)
      COMMON/INPBIO/BIOLC(2)
      COMMON/ELKOIL/OILCON(2,32,34)
      COMMON/ELKNEW/NEWOIL(2,32,34)
      COMMON/OIL/WSF(32,34),TARS(32,34)
      DIMENSION ISL(32,34),D(32,34),TE(4),S7(32,34),S8(32,34),
     &IS(32,34)
C
C     SET MIGRATION PARAMETERS
C
      RP=.95; ME=2; ANG=45; VEL=10.
C
C     DATA STATEMENT FOR SUBROUTINE FEDOIL. IFEDOL=0 FOR NO PRINTING OF
C     OUTPUT; IFEDOL=1 FOR PRINTING OF SUMMARY TABLE ONLY; IFEDOL=2 FOR
C     PRINTING OF CONCENTRATIONS AT EACH GRID POINT ONLY; IFEDOL=3 FOR
C     PRINTING OF BOTH.
C
      DATA IFEDOL/0/
C
      REAL NEWOIL
      NE=32;ME=34;K=8;LL=1;LLMAX=50;LCC=2
C
      DO 25 J=1,2
      ACTBIO(J)=BIOLC(J)
   25 CONTINUE
C
   30 IF(LL.GT.10) GO TO 35
      READ(LCC,/) NHRS
      READ(LCC,/) ((WSF(N,M),M=1,ME),N=1,NE)
      GO TO 40
C
   35 DO 38 N=1,NE
      DO 38 M=1,ME
      WSF(N,M)=WSF(N,M)*EXP(-0.3)
      S7(N,M)=WSF(N,M)
   38 CONTINUE
      GO TO 42
C
C
```

```
C   CHANGE OIL CONCENTRATIONS FROM PPB TO PPM
C
C
   40 CONTINUE
      DO 32 N=1,NE
      DO 32 M=1,ME
      WSF(N,M)=WSF(N,M)/1000.
   32 S7(N,M)=WSF(N,M)
C
C   COMPUTE OIL ON THE BOTTOM
C
   42 CONTINUE
      BLO=1.
C     BLO=2 CONTINUOUS SOURCE, BLO=1 INSTANTANEOUS SOURCE.
      DL=2000.
C     TAT TIME STEP IN HOURS
      TAT=24.
      TD=20.
      T=LL*1440.
      KAL=0
C     KAL=0 - NO OIL MOVEMENT ON THE BOTTOM, 1 OIL ADVECTED ON BOTTOM
C     KU - CURRENT INDEX, SEE CURCIL; KA - TURBULENCE INDEX(NOT USED);
C     LU - PRINT SCALING INDEX
      KU=3
      KA=1
      LU=0
      UI=0.
      VI=0.
      CALL OILBOT(S7,LL,TD,DL,D,S8,T8,BLO,UI,VI,KU,KAL,T,KA,TAT)
      IF(LL.GT.1) GO TO 55
C
      DO 54 N=1,NE
      DO 54 M=1,ME
      ISL(N,M)=0
      IF(D(N,M).GT.0) ISL(N,M)=1
   54 CONTINUE
C
   55 UI=60.
      VI=0.
      IF(KAL.NE.1)GO TO 31
      CALL CURCIL(S8,KU,UI,VI,DL,LL,BLO,T,KAL)
   31 DO 33 N=1,NE
      DO 33 M=1,ME
   33 TARS(N,M)=S8(N,M)
      CALL FETCIL(IFECOL)
      CALL MIGR(RF,KE,ANG,VEL)
  778 LL=LL+1
      IF(LL.LE.LLMAX)GO TO 30
      CLOSE(8,DISP=KEEP)
      CLOSE(9,DISP=KEEP)
C
 5999 STOP
      END
      BLOCK DATA
      COMMON/INPBIO/BIOLC(2)
      COMMON/VALUES/FOOCMP(2),TJ(2),K2(2)
      REAL K2
      DATA BIOLC/330.,1472./
      DATA FOOCMP/1.00,.10/
      DATA TJ/.016,.006/
```

```
      DATA K2/.198040,.222823/
      END
      SUBROUTINE MIGR(RP,KE,ANG,VEL)
C
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C                    MIGRATION SUBROUTINE
C
C   SET UP FOR MIGRATIONS OF 45,135,225, OF 315 DEGREES
C             (0=TOWARDS EAST;  90=TOWARDS NORTH)
C
C        USES TWICE NORMAL GRID SIZE   RP=MIGRATION FRACTION
C
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      DIMENSION ISPC(2),S1(64,68),S2(64,68),S3(64,68),DAT(2,64,68),IT(4)
      COMMON/OIL/WSF(32,34),TARS(32,34)
      COMMON/ELKOIL/OILCON(2,32,34)
      COMMON/ELKNEW/NEWOIL(2,32,34)
      COMMON/ELK1/NE,ME,K,LL
      COMMON/VALUES/FODCMP(2),TJ(2),K2(2)
      DATA ISPC/1,13/
      REAL NEWOIL
      RAD=0.0174533
      A=ANG
      IF(KE.EQ.1) A=ANG+180.
      NNE=64;MME=68
      IF(A.EQ.45)GO TO 1
      IF(A.EQ.135)GO TO 2
      IF(A.EQ.225)GO TO 3
      M1=1
      N1=1
      GO TO 4
    1 M1=1
      N1=33
      GO TO 4
    2 M1=35
      N1=33
      GO TO 4
    3 M1=35
      N1=1
    4 MM=(M1-1)+34
      NN=(N1-1)+32
      MO=0;NO=0
      IF(M1.GT.1)MO=34
      IF(N1.GT.1)NO=32
      A=A*RAD
      U=COS(A)*VEL
      V=SIN(A)*VEL
C
C
      DO 999 J=1,2
      RATEXP=EXP(-K2(J))
      DO 801 N=N1,NN
      NX=N-NO
      DO 801 M=M1,MM
      MX=M-MO
  801 DAT(J,N,M)=NEWOIL(J,NX,MX)
      DO 5 N=1,NNE
      DO 5 M=1,MME
    5 S1(N,M)=DAT(J,N,M)
```

```
      DO 65 N=1,NNE
      DO 65 M=1,MME
      IF(S1(N,M).GT.0.)GO TO 64
      S1(N,M)=0.
      S2(N,M)=0.
      S3(N,M)=0.
      GO TO 65
   64 S2(N,M)=S1(N,M)*RP
      S3(N,M)=S1(N,M)-S2(N,M)
   65 CONTINUE
      CALL RANNAK (J,L,V,S2)
C     S2 - SPECIES (PORTION WHICH MIGRATED)
C     ISL-SEA-LAND TABLE
C
C     ADDING NONMIGRATING PORTION
      SUMNEW=0.
      DO 63 N=1,NNE
      DO 63 M=1,MME
      S1(N,M)=S3(N,M)+S2(N,M)
   63 CONTINUE
 1200 DO 1000 I=1,4
      IT(I)=0
 1000 CONTINUE
      DO 1201 N=1,NNE
      DO 1201 M=1,MME
      IF(S1(N,M).LT.5.0)GO TO 1201
      IF(S1(N,M).GE.5.0)IT(1)=IT(1)+4
      IF(S1(N,M).GE.10.)IT(2)=IT(2)+4
      IF(S1(N,M).GE.50.)IT(3)=IT(3)+4
      IF(S1(N,M).GT.100.)IT(4)=IT(4)+4
 1201 CONTINUE
      WRITE(9,/)LL,ISPC(J)
      WRITE(9,/)(IT(I),I=1,4)
      IF(LL.NE.5.AND.LL.NE.10.AND.LL.NE.20.AND.LL.NE.30)GO TO 70
      WRITE(8,/)LL,ISPC(J)
      WRITE(8,/)((S1(N,M),M=1,MME),N=1,NNE)
   70 DO 778 N=1,NE
      NX=N+NC
      DO 778 M=1,ME
      MX=M+MC
      NEWOIL(J,N,M)=S1(NX,MX)
  778 S1(NX,MX)=0.
      DO 779 N=1,NNE
      DO 779 M=1,MME
  779 DAT(J,N,M)=S1(N,M)*RATEXP
C
  999 CONTINUE
 8888 RETURN
      END
      SUBROUTINE RANNAK(J,L,V,S8)
      DIMENSION S8(64,68),ANEW(64,68),OLD(64,68)
      COMMON/OIL/WSF(32,34),TARS(32,34)
      COMMON/BLK1/NE,ME,K,LL
C     ISL- SEA-LAND TABLE
C     S8 - (SPECIES)
C     KRC - NUMBER OF MIGRATIONS PER DAY
      AL=2.0
      NNE=64;MME=68
C
C
```

```
C   U,V VELOCITY COMPONENTS
C
C   KE IS INDICATOR OF SEASON
C   KE=1 IF MIGRATION IS TO SHALLOWER WATER; KE=2 FOR MIGRATION TO DEEP
C
   20 TD=.125
      NEH=NNE-1
      MEH=MME-1
C
C   MIGRATE 8 TIMES PER DAY (TD=.125 DAYS)
C
C   S8 IS MIGRATING CONTAMINATION
C
      DO 254 MRC=1,8
C
C   CALCULATE MIGRATION AT EACH GRID POINT
C
      DO 133 N=1,NNE
      DO 133 M=1,MME
      OLD(N,M)=S8(N,M)
C
C   DETERMINE GRID POINT TO GO TO
C
      IF(U)230,231,232
  230 IM=-1
      GO TO 233
  231 IM=0
      GO TO 233
  232 IM=1
  233 IF(V)234,235,236
  234 IN=1
      GO TO 237
  235 IN=0
      IF(IM.EQ.0)GO TO 133
      GO TO 237
  236 IN=-1
C
C   GX,GY ARE AMTS LEAVING IN X,Y DIRECTION
C   OLD IS ORIGINAL CONTAMINATION LEFT AT GRIDPOINT N,M
C   ANEW IS FIELD OF MIGRATED CONTAMINATION
C
  237 IF(M.EQ.1 .AND. IM.GT.0)GO TO 2000
      IF(M.EQ.MME .AND. IM.LT.0)GO TO 2000
      GONX=(S8(N,M)-S8(N,M-IM))
      GO TO 2001
 2000 GONX=(S8(N,M+IM)-S8(N,M))
 2001 IF(N.EQ.NNE .AND. IN.LT.0)GO TO 2002
      IF(N.EQ.1 .AND. IN.GT.0)GO TO 2002
      GONY=(S8(N,M)-S8(N-IN,M))
      GO TO 2003
 2002 GONY=(S8(N+IN,M)-S8(N,M))
 2003 GX=GONX*ABS(U)*TD/AL
      IF(GX.LT.0.)GX=0.
      GY=GONY*ABS(V)*TD/AL
      IF(GY.LT.0.)GY=0.
      IF(OLD(N,M).LT.1.)GO TO 991
      IF(M.EQ.MME .AND. IM.GT.0)GO TO 991
      IF(M.EQ.1 .AND. IM.LT.0)GO TO 991
      ANEW(N,M+IM)=ANEW(N,M+IM)+GX
  991 IF(OLD(N,M).LT.1.)GO TO 133
```

```
      IF(N.EG.1 .ANC. IN.LT.C)GO TC 992
      IF(N.EG.NNE .ANC. IN.GT.C)GC TC 992
      ANEW(N+IN,M)=ANEW(N+IN,M)+GY
  992 OLD(N,M)=OLC(N,M)-GX-GY
      IF(CLD(N,M).LT.C.)OLD(N,M)=C.
  133 CONTINUE
  591 CO 751 N=1,NNE
      CO 751 M=1,MME
      SB(N,M)=OLD(N,M)+ANEW(N,M)
      OLD(N,M)=0.
      ANEW(N,M)=0.
  751 CONTINUE
  254 CONTINUE
      RETURN
      END
      SUBROUTINE FECOIL(IFEDCL)
      COMMON/CIL/WSF(32,34),TARS(32,34)
      COMMON/ELKBIC/LCC,ACTBIC(2)
      COMMCN/ELKOIL/OILCON(2,32,34)
      COMMON/ELKNEW/NEWOIL(2,32,34)
      COMMON/ELK1/NE,ME,K,LL
      COMMCN/VALUES/FCDCMP(2),TJ(2),K2(2)
      DIMENSION TCH(2),S1(32,34)
      REAL MS,K2,NEWOIL
C
C      ART/FECCL13 - THIS IS THE *BCF VERSION* OF FECCIL IN WHICH ONLY
C      K2, ANC BCF ARE USED IN COMPUTING UPTAKE AND DEPURATION.
C
C      K2(J) IS THE DEPURATION RATE CONSTANT FCR SPECIES J
C
C      BCFPEL IS THE BIOCONCENTRATION FACTOR OF EACH PELAGIC SPECIES J
C
C      BCFDEM IS THE BIOCONCENTRATION FACTOR OF EACH DEMERSAL SPECIES J
C
C      FRCNAP IS THE FRACTION OF WSF THAT IS NAPHTHALENES.
C
C      FRCNAD IS THE FRACTION OF TARS THAT IS NAPHTHALENES.
C
C-----------------------------------------------------------------------
C
C      SET CONSTANTS
C
      RAD=0.01745329
      ALP=30.*RAD
      GKAP=175.*RAD
      VALCA=COS(ALP*K-GKAP)
      FRCNAP=.50
      FRCNAD=.10
      BCFPEL=170.
      BCFDEM=170.
C
C-----------------------------------------------------------------------
C
C      COMPUTE UPTAKE AND DEPURATION OF OIL CONTAMINANTS. FOR OUTPUT,
C      ALL CONCENTRATIONS ARE IN PPM AND ACTBIO IS IN KG
C-----------------------------------------------------------------------
C
      DO 99 J=1,2
C
      DO 100 I=1,9
```

```
  10C CONTINUE
C
      RATEXP=EXP(-K2(J))
      TOH(J)=TJ(J)+(0.35*TJ(J)*VALCA)
      TONS=(A(TBIC(J)*4.0)/1CCC.
C
      TAREA=C.
      TTCNS=0.
      TCOUNT=C.
      DO 10 N=1,NE
      DC 10 M=1,ME
      VALUE=C.0
      S1(N,M)=C.0
      TAREA=TAREA+4.0
      TTCNS=TTCNS+TCNS
      TCCUNT=TCCUNT+1.C
      IF(FCDCMF(J).GT.0..AND.FCDCMP(J).LT.1.0) GC TC 20
      IF(FCDCMP(J).EQ.1.0) GC TO 30
      CO=TARS(N,M)*FRCNAD
      VALUE=CC*BCFCEM*2.0
      GO TC 13C
   2C PEL=FODCMP(J)
      CEM=1.0-PEL
      CO1=WSF(N,M)*FRCNAP
      CO2=TARS(N,M)*FFCNAC
      VALUE1=(CO1*BCFPEL)
      VALUE2=(CO2*BCFCEM)
      VALUE=(PEL*VALUE1+DEM*VALUE2)
      GC TO 13C
   3C CO=WSF(N,M)*FRCNAP
      VALUE=(CC*BCFPEL)
  130 CONTINUE
      OILCON(J,N,M)=VALUE*(1.0-RATEXP)+NEWOIL(J,N,M)*(RATEXP)
      NEWOIL(J,N,M)=OILCON(J,N,M)
      S1(N,M)=OILCON(J,N,M)
C-----------------------------------------------------------------------
C                                EAD SUBRCUTINE
C-----------------------------------------------------------------------
C
  10  CONTINUE
  99  CONTINUE
  999 RETURN
      END
      SUBRCUTINE OILBOT(S,K,TC,DL,D,AC,TB,BLC,UI,VI,KU,KAL,T,KA,TAT)
      COMMCN/ELMBIO/LCC,ACTBIC(2)
      DIMENSION S(32,34),D(32,34),AC(32,34),TB(4),PLC(2),W(3)
C     D-DEPTH
C     AO-OIL CN THE BOTTOM
C     TB-BOTTOM TEMPERATURE, FOUR VALUES GIVEN
C     PLC-THERMOCLINE DEPTH, TWO VALUES
C     W-WIND SPEED, THREE VALUES
C     KT-INDEX OF TB VALUE CHOSEN FOR THE RUN
C     KP-INDEX OF PLD VALUE
C     KW-INDEX OF WINC VALUE
C     BLD=1 INSTANTANEOUS SOURCE, =2 CONTINUOUS SOURCE
C     UI-SURFACE CURRENT SPEED
C     KAL=1 COMPUTATION OF OIL MOVEMENT ON BOTTOM
C     LU=1 DEPTH DATA
C     LU=2 DECAY OF OIL ON THE BOTTOM
C     LU=3 OIL ON THE BOTTOM BEFORE ADVECTION
```

```
C      LU=4 OIL ON THE BOTTOM,LAYER THICKNESS DECREASING, ADVECTED
C      LU=5 ADVECTED OIL ON THE BOTTOM
C      LU=6 CONTAMINATION INDEX, PELAGIC FOOD
C      LU=7 CONTAMINATION INDEX, DEMERSAL FOOD
       NE=32
       ME=34
       MO=10
C      MO IS THE M LOCATION OF BLOWOUT
C      SIMULATION OF DEPTH,
C      KB-AREA NUMBER FOR TANKER ACCIDENT, 4 TO 6
    16 KB=LOC+3
       IF(KB-5)305,330,360
   305 DO 319 N=1,NE
       DO 319 M=1,ME
       SDS=M
       IF(N-17)306,306,307
   306 D(N,M)=70.-0.35*SDS
       GO TO 319
   307 IF(N-26)308,308,311
   308 IF(M-20)309,309,310
   309 D(N,M)=62.-1.0*SDS
       GO TO 319
   310 D(N,M)=62.-1.5*SDS
       GO TO 319
   311 IF(M-20)312,312,313
   312 D(N,M)=54.-1.2*SDS
       GO TO 319
   313 D(N,M)=54.-1.4*SDS
   319 CONTINUE
       ALPHA=0.9
       CALL SILITA(D,ALPHA,NE,ME,S,1)
       GO TO 10
CXXXXXXXXXXXXXXXX
   330 DO 359 N=1,NE
       DO 359 M=1,ME
       SDS=M
       IF(N-22)331,331,332
   331 D(N,M)=50.-1.0*SDS
       GO TO 359
   332 IF(M-25)333,333,334
   333 D(N,M)=45.-1.6*SDS
       GO TO 359
   334 D(N,M)=0.
   359 CONTINUE
       ALPHA=0.9
       CALL SILITA(D,ALPHA,NE,ME,S,1)
       GO TO 10
CXXXXXXXXXXXXXXXX
   360 DO 379 N=1,NE
       DO 379 M=1,ME
       SDS=M
       IF(N-12)361,361,362
   361 D(N,M)=38.
       GO TO 379
   362 D(N,M)=45.
   379 CONTINUE
       ALPHA=0.9
       CALL SILITA(D,ALPHA,NE,ME,S,1)
CXXXXXXXXXXXXXXXXXXXXXX
    10 LU=1
```

```
      IF(K-1)17,17,20
      IF(K-1)5,9,20
    9 CALL PRIMFS(D,T,UI,VI,CL,K,KA,KAL,BLO,LU,NE,ME)
CXXXXXXXXXXXXXXXXXXXXXXXX
   17 DO 18 N=1,NE
      DO 18 M=1,ME
      AO(N,M)=0.
   18 CONTINUE
C     INPUT PARAMETERS
   20 TB(1)=1.
      TB(2)=4.
      TB(3)=8.
      TB(4)=12.
      PLD(1)=20.
      PLD(2)=40.
      W(1)=5.
      W(2)=10.
      W(3)=15.
C     PP - RELATIVE CONC. OF PLANKTON
C     R - INDEX OF SUSPENDED MATTER
C     BB - BOTTOM TYPE INDEX
      PP=1.5
      R=40.
      BB=0.8
C     SETTING OF INDICES FOR INPUT PARAMETERS
      KT=3
      KP=1
      KW=2
CXXXXXXXXXXXXXXXXXXXXXXXX
C     DECAY OF OIL ON THE BOTTOM
      IF(K-2)30,25,25
   25 DO 29 N=1,NE
      DO 29 M=1,ME
      IF(D(N,M))29,29,290
  290 IF(AO(N,M))29,29,26
   26 TFA=(TB(KT)**2.7)*0.0001
      DFA=0.15/SQRT(D(N,M))
      EFA=-(TFA+DFA)
      AC(N,M)=AC(N,M)*EXP(EFA)
      IF(TAT-12.)29,29,27
   27 AO(N,M)=AO(N,M)*EXP(EFA)
   29 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXX
      LU=2
C     CALL PRIMFS(AC,T,UI,VI,CL,K,KA,KAL,BLO,LU,NE,ME)
CXXXXXXXXXXXXXXXXXXXXXXXXXXX
   30 IF(BLO-1)31,31,51
C     INSTANTANEOUS SOURCE (TANKER ACCIDENT)
   31 DO 45 N=1,NE
      DO 45 M=1,ME
      IF(D(N,M))45,45,291
  291 IF(PLD(MF)-D(N,M))40,33,33
C      NO PYCNOCLINE
   33 SK=K
   35 STK=SK/(3.+0.2*SK)
   56 BCF=0.0015
      CCF=0.15
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      FS=(BCF*W(KW)+CCF/(D(N,M)**0.7))*STK
      AC(N,M)=AC(N,M)+S(N,M)*FS*PP*RR*BB
```

```
      IF(K-1)45,45,131
  131 IF(TAT-12.)45,45,37
   37 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      GO TO 45
C     THERMOCLINE PRESENT
   40 IF(K-1)45,45,38
   38 SK=K
      TDK=SK/(3.+0.5*SK)
      BCF=0.001
      CCF=0.20
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      FDD=(BCF*W(KW)+CCF/(D(N,M)**0.7))*TDK
      AO(N,M)=AO(N,M)+S(N,M)*FDD*PP*RR*BB
      IF(K-1)45,45,132
  132 IF(TAT-12.)45,45,44
   44 AO(N,M)=AO(N,M)+S(N,M)*FDD*PP*RR*BB
   45 CONTINUE
      GO TO 70
C     CONTINUOUS SOURCE (BLOWOUT)
   51 DO 65 N=1,NE
      DO 65 M=1,ME
      IF(D(N,M))65,65,292
  292 DIS=((M-MO)*0.001*DL)
      IF(DIS)53,53,54
   53 DIS=0.001
   54 APD=2.5
C     NO COMPUTATION IN IMMEDIATE AREA OF BLOWOUT
C     I.E. 2.5KM FROM THE SOURCE
      IF(DIS-APD)65,59,59
   59 IF(PLD(KF)-D(N,M))60,55,55
C     NO PYCNOCLINE
   55 SK=K
   57 STK=SK/(3.+0.2*SK)
   58 BWF=0.0016
      CDF=0.15
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      DIFAC=(DIS+4.)/(20.+0.1*DIS)
      FS=(BWF*W(KW)+CDF/(D(N,M)**0.7))*STK*(DIFAC)
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)65,65,69
   69 IF(TAT-12.)65,65,71
   71 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      GO TO 65
C     COMPUTATION WITH THERMOCLINE PRESENT
   60 APD=2.5
      IF(DIS-APD)65,61,61
   61 SK=K
   62 STK=SK/(3.+0.5*SK)
   64 BWF=0.001
      CDF=0.20
      DDP=D(N,M)**0.74
      RR=(R+0.2*D(N,M))/SQRT(D(N,M))
      DIFAC=(DIS+4.)/(20.+0.1*DIS)
      FS=(BWF*W(KW)+CDF/DDP)*STK*(DIFAC)
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)65,65,66
   66 IF(TAT-12.)65,65,67
   67 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
   65 CONTINUE
CXXXXXXXXXXXXXXXXXXXX
```

```
   7C ALPHA=C.78
      CALL SILITA(AC,ALPHA,NE,ME,C,C)
CXXXXXXXXXXXXXXXXXXXXXXXX
      LU=3
C     CALL PRIMFS(AC,T,UI,VI,CL,K,KA,KAL,ELO,LU,NE,ME)
CXXXXXXXXXXXXXXXXXXXXXXXX
  100 RETURN
      END
      SUBROUTINE CUROIL(S,KU,UI,VI,CL,K,BLO,T,KAL)
      DIMENSION S(32,34),PF(32,34),D(32,34)
CXXXXXXXXXXXXXXXXXXXX
C     INDICES
C     KG-GRID SIZE 1-2KM;2-4KM
C     KT-TIME STEP 1-20MIN, 2-40MIN.
C     KF-FLUCTUATION PARAMETER (FAF);PERIOD 15 MIN,KF=1,FAF=0.4
C        30 MIN,KF=2, FA=0.2
C     KA-LAMINAR FLOW OR INCREASING LAYER  1-LAMINAR; 2-INCREASING LAYER
C     KU-UNIDIRECTIONAL               CURRENT 1-UNIDIRECTIONAL,U-DIRECTION
C        2-UNIDIRECTIONAL V-DIRECTION, 3-UNIDIRECTIONAL AT 45 DEG. ANGEL
C     KR-UNIDIRECTIONAL OR ROTATING, 1-UNIDIRECTIONAL, 2-ROTATING
C     KS-SPEED COUNTER FOR 4 DIFERENT SPEEDS
C     CURRENT SPEED IN, M/SEC
CXXXXXXXXXXXXXXXXXXX
C     THIS SUBROUTINE HAS BEEN USED FOR COMPUTATION OF
C     DISTRIBUTION OF SMELL FROM BAITS
C     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      KG=1
      KT=1
      KF=1
      KA=1
      KR=1
CXXXXXXXXXXXXXXXXXX
      NE=32
      NEH=NE-1
      ME=34
      MEH=ME-1
      IF(KG-1)1,1,2
    1 DL=2000.
      GO TO 3
    2 DL=4000.
    3 IF(KT-1)4,4,5
    4 TD=20.
C     IAC=3
C     IPR=36
      IAC=9
      IPR=3*24
      GO TO 6
    5 TD=40.
      IAC=2
      IPR=18
    6 IF(KF-1)7,7,8
    7 FAF=0.4
      GO TO 9
    8 FAF=0.2
    9 CON=0.0174533
      ALPHA=0.82
      ALP=FAF*CON
      TCAP=45.*CON
      SO=100.
CXXXXXXXXXXXXXXXXXX
```

```
C       ADVECTICN CCMPUTED FOR 24 HCURS
        TSTC=24.*60.
        TI=0.
C       TF=1C08C.+TD
CXXXXXXXXXXXXXXXXX
        KS=1
        KKK=0
        TURC=0.C2
C       XXXXXX
C       CURRENT SPEED INPUT
        IF(KR-1)12,12,16
    12  IF(KU-2)13,14,15
   13   UA=0.1*UI
        VA=0.1*VI
        GO TC 18
   14   UA=0.15*UI
        VA=0.15*VI
        GO TC 18
    15  UA=0.15*UI
        VA=0.15*VI
        GO TC 18
   16   UA=0.15*UI
        VA=0.15*VI
        ADO=C.CC8
        ARCT=ADO*CON
        AKADI=9C.*CCN
        APARP=18C.*CON
        DL=4COC.
        TF=144CC.
CXXXXXXXXXXXXXXXX
C       KAL=1, OIL MOVEMENT ON THE BOTTCM
        IF(KAL)18,18,519
CXXXXXXXXXXXXXXXXX
    18  T=T+TD
        TI=T
   519  ITC=0
        ITOP=0
        TI=TI+TC
    10  ITC=ITC+1.
        ITCP=ITCP+1
    20  IF(KR-1)41,41,47
    41  IF(KU-2)42,43,44
    42  U=UI+UA*COS(ALP*TI)
        V=VI*COS(ALP*TI+TCAP)
        GO TC 49
    43  V=VI+VA*COS(ALP*TI)
        U=UI*COS(ALP*TI+TCAP)
        GO TO 49
    44  U=UI+UA*COS(ALP*TI)
        V=VI+VA*COS(ALP*TI+TCAP)
        GO TO 49
    47  U=UI*COS(ARCT*TI+AKADI)
        V=VI*COS(ARCT*TI+APARP)
    49  CONTINUE
        IF(KAL-1)253,27,27
   253  IF(BLO-1)250,250,252
C       100 UNITS OF OIL ADDED EACH TIME STEP (SO=100.)
   252  S(12,10)=S(12,10)+SO
        GO TC 27
CXXXXXXXXXXXXXXXXXXXXXXX
```

```
  250 IF(K-1)251,251,27
  251 S(12,10)=600.
C XXX)XXXXXXXX))XX XXXXX
   27 SUS=0.
      SUA=0.
   30 DO 50 N=2,NEH
      DO 50 M=2,MEH
      SUA=SUA+S(N,M)
      IF(U)32,31,31
   31 SH=(S(N,M)-S(N,M-1))/DL
      GO TO 33
   32 SH=(S(N,M)-S(N,M+1))/DL
   33 IF(V)34,36,36
   34 SV=(S(N,M)-S(N-1,M))/DL
      GO TO 35
   36 SV=(S(N,M)-S(N+1,M))/DL
   35 S(N,M)=S(N,M)-(TD*ABS(U)*SH)-(TD*ABS(V)*SV)
      SUS=SUS+S(N,M)
   50 CONTINUE
      IF(SUS)80,80,95
   95 IF(ITC-IAC)80,55,80
C XXX)XXXXXXXX))XX XXX
   55 IF(KAL-1)550,551,551
  551 ALPHA=0.78
C XXX)XXXXXXXXX))XX XXXX
  550 CALL SILITA(S,ALPHA,NE,ME,C,1)
      ITC=0
      U1=SUA/SUS
      DO 60 N=1,NE
      DO 60 M=1,ME
      S(N,M)=S(N,M)*U1
   60 CONTINUE
C      EFFECTS OF INCREASING LAYER THICKNESS,APPROXIMATE
C      FACTOR -CTR REFERRES TO MILOMETERS FROM SOURCE
C      OBS. N AND M ARE LOCATION OF SOURCE
C XXX)XXXXXXXX))XX
C      THE FOLLOWING SECTION NOT USED IN OIL PROBLEMS
C XXX)XXXXXXXX))XX
      CTR=0.015
      IF(KA-1)81,81,61
   61 DO 131 N=1,NE
      DO 131 M=1,ME
      PF(N,M)=S(N,M)
  131 CONTINUE
      IF(KR-1)62,62,69
   62 IF(KU-2)63,65,67
   63 DO 64 N=1,NE
      DO 64 M=1,ME
      DIS=(M-10)*0.01*DL
      IF(DIS)51,51,52
   51 RRC=1.
      GO TO 53
   52 RRC=(1.-(CTR*DIS))
   53 PF(N,M)=PF(N,M)*RRC
   64 CONTINUE
      GO TO 81
   65 DO 66 N=1,NE
      DO 66 M=1,ME
      DIS=(N-20)*0.01*DL
```

```
      IF(DIS)54,54,56
   54 RRC=1.
      GO TO 57
   56 RRC=(1.-(CTR*DIS))
   57 PF(N,M)=FF(N,M)*RRC
   66 CONTINUE
      GO TO 81
   67 DO 68 N=1,NE
      DO 68 M=1,ME
      IF(M-10)58,58,59
   58 RRC=1.
      GO TO 82
   59 IF(N-10)58,58,83
   83 DIS=SQRT((M-10)**2.+(N-10)**2.)*0.01*DL
      RRC=(1.-(CTR*DIS))
   82 PF(N,M)=FF(N,M)*RRC
   68 CONTINUE
      GO TO 81
   69 DO 84 N=1,NE
      DO 84 M=1,ME
      IF(M-10)86,86,87
   86 RRC=1.
      GO TO 88
   87 DIS=(M-10)*0.01*DL
      RRC=(1.-(0.5*CTR*DIS))
   88 PF(N,M)=FF(N,M)*RRC
      IF(N-20)89,89,91
   89 RRC=1.
      GO TO 94
   91 DIS=(N-20)*0.01*DL
      RRC=(1.-(0.5*CTR*DIS))
   94 PF(N,M)=FF(N,M)*RRC
   84 CONTINUE
   81 ITC=0.
   80 IF(ITOP-IPR)590,85,590
C      XXXXXXX))XX)XXX
  590 TI=TI+TD
      IF(TSTO-TI)100,10,10
C 590 T=T+TD
C     IF(TF-T)100,10,10
C      XXXXXX))XXXXXX
   85 IF(KA-1)122,122,121
  121 LU=4
C     CALL PRIMFS(PF,T,UI,VI,DL,K,KA,KAL,ELO,LU,NE,ME)
      DO 132 N=1,NE
      DO 132 M=1,ME
      S(N,M)=FF(N,M)
  132 CONTINUE
      GO TO 123
  122 LU=5
C     CALL PRIMFS(S,T,UI,VI,DL,K,KA,KAL,BLO,LU,NE,ME)
  123 ITOP=0
  100 RETURN
      END
      SUBROUTINE SILITA (S,ALPHA,NE,ME,D,I)
      DIMENSION S(32,34),D(32,34)
      NEH=NE-1
      MEH=ME-1
      BET=(1.-ALPHA)/4.
      DO 123 N=2,NEH
```

```
      DO 123 M=2,ME
      IF(I-1)101,102,102
  101 IF(D(N,M))124,124,103
  102 IF(S(N,M))124,124,103
  103 IF(1-N)105,107,105
  105 VAUP=S(N-1,M)
      GO TO 108
  107 VAUP=S(N,M)
  108 IF(NE-N)110,112,110
  110 VALO=S(N+1,M)
      GO TO 113
  112 VALO=S(N,M)
  113 IF(1-M)115,116,115
  115 VALE=S(N,M-1)
      GO TO 117
  116 VALE=S(N,M)
  117 IF(ME-M)119,121,119
  119 VARI=S(N,M+1)
      GO TO 122
  121 VARI=S(N,M)
  122 S(N,M)=ALPHA*S(N,M)+BET*(VAUP+VALO+VALE+VARI)
      GO TO 123
  124 S(N,M)=0.
  123 CONTINUE
      RETURN
      END
      SUBROUTINE PRIMFS(S,T,UI,VI,DL,K,KA,KAL,BLO,LU,NE,ME)
      DIMENSION S(32,34),IS(32,34)
C     IF(LU-1)202,401,420
      IF(LU-1)270,401,420
  202 PRINT 201,K,T,UI,VI,DL,KA,KAL
  201 FORMAT(1H1,5X,18HOIL CONCENTRATIONS,2X,2HK=,I5,3X,2HT=,F6.0,3X,3HU
     2I=,F6.4,3X,3HVI=,F6.4,3X,3HDL=,F6.0,3X,3HKA=,I3,3X,4HKAL=,I3)
  270 PRINT 271,K,DL
  271 FORMAT(1H1,5X,18HOIL CONCENTRATIONS,2X,2HK=,I5,3X,3HDL=,F6.0)
C     PRINT 203
      PRINT 504
  203 FORMAT(/5X,12HCONC. IN PPB/)
  504 FORMAT(5X,19HPRINT FACTOR = 0.1,4X,7HPPB/10./)
CXXXXXXXXXXXXXXXXXXXXXX
      GO TO 212
  401 PRINT 402
  402 FORMAT(1H1,5X,16HDEPTHS IN METERS,)
      GO TO 320
  420 IF(LU-3)421,425,430
  421 PRINT 422,K
  422 FORMAT(1H1,5X,34HDECAY OF OIL ON THE BOTTOM, PERIOD,I5)
      GO TO 212
  425 PRINT 426,K
  426 FORMAT(1H1,5X,41HNEW OIL ON BOTTOM BEFORE ADVECTION,PERIOD,I5)
      GO TO 212
  430 IF(KAL-1)202,431,431
  431 PRINT 432,K
  432 FORMAT(1H1,5X,34HADVECTED OIL ON THE BOTTOM, PERIOD,I5)
      PRINT 272,UI,VI
  272 FORMAT(5X,3HUI=,F5.2,3X,3HVI=,F5.2)
      GO TO 212
CXXXXXXXXXXXXXXXXXXXXXXX
      IF(KA-1)210,210,215
  210 PRINT 211
```

```
  211 FORMAT(5X,12HLAMINAR,FLOW/)
      GO TO 212
  215 PRINT 216
  216 FORMAT(5X,26HLAYER THICKNESS INCREASING/)
CXXXXXXXXXXXXXXXXXXXXXXX
C 212 IF(KAL-1)230,220,220
  212 IF(KAL-1)530,220,220
  220 IF(BLO-1)250,250,252
  250 DO 225 N=1,NE
      DO 225 M=1,ME
      IS(N,M)=S(N,M)*1000.
  225 CONTINUE
      PRINT 260
  260 FORMAT(5X,16HPRINT FACTOR = 1/)
      GO TO 240
  252 DO 253 N=1,NE
      DO 253 M=1,ME
      IS(N,M)=S(N,M)*100.
  253 CONTINUE
      PRINT 261
  261 FORMAT(5X,18HPRINT FACTOR = 0.1,4X,7HPPB/10./)
      GO TO 240
  320 DO 321 N=1,NE
      DO 321 M=1,ME
      IS(N,M)=S(N,M)
  321 CONTINUE
      GO TO 240
  230 DO 205 N=1,NE
      DO 205 M=1,ME
      IS(N,M)=S(N,M)*1000.
  205 CONTINUE
  530 DO 531 N=1,NE
      DO 531 M=1,ME
      IS(N,M)=S(N,M)*100.
  531 CONTINUE
  240 IF(ME-40)610,640,640
  640 PRINT 206,(N,N=1,40)
  206 FORMAT(/4X,40I3)
      PRINT 207,(N,(IS(N,M),M=1,40),N=1,50)
  207 FORMAT(/1X,I2,1X,40I3)
C     XXXXXXXXXXXXXXXXXX
      GO TO 300
C     XXXXXXXXXXXXXXXXXX
      PRINT 208,(N,N=41,50)
  208 FORMAT(1H1,//4X,10I3)
      PRINT 209,(N,(IS(N,M),M=41,50),N=1,50)
  209 FORMAT(/1X,I2,1X,10I3)
C     XXXXXX
      GO TO 300
  610 PRINT 611,(N,N=1,34)
  611 FORMAT(/4X,34I3)
      PRINT 612,(N,(IS(N,M),M=1,34),N=1,32)
  612 FORMAT(/1X,I2,1X,34I3)
  300 RETURN
      END
```

SUBROUTINE/PLOTR

```
$RESET FREE
      SUBROUTINE PLOTR(DX,DY,X,Y,S1)
      DIMENSION S1(4,50),X(50),Y(14),S2(50)
      DATA SIZW,SIZH/.12,.185/
C
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C  SUBROUTINE TO DRAW LINE PLOTS
C
C  DY IS UNITS PER X INCREMENT
C  DY IS UNITS PER Y INCREMENT
C  Y IS ARRAY OF VALUES FOR Y INCREMENTS
C  X IS ARRAY OF VALUES OF X INCREMENTS
C  S2 IS ARRAY OF DATA TO BE PLOTTED
C  SIZW,SIZH ARE SIZES (IN INCHES) OF CHARACTER WIDTH OR HEIGHT
C
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C   THIS PLOT USES PLOTCOMP PLOTTING PACKAGE ROUTINES
C          CAN BE ADAPTED TO CALCOMP
C            ALL UNITS ARE INCHES
C
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      CALL PLOT(6.,0.,2)
      CALL PLOT(0.,0.,3)
      CALL PLOT(0.,4.,2)
      CALL PLOT(0.,0.,3)
      DO 10 I=1,50
      CALL PLOT(X(I),.1,3)
      CALL PLOT(X(I),-.1,2)
      IF(MOD(I,10).NE.0)GO TO 10
      FI=I
      XX=X(I)-SIZH
      CALL NUMBER(XX,-.25,SIZH,FI,0.,-1)
   10 CONTINUE
      DO 20 I=1,14
      CALL PLOT(-.1,Y(I),3)
      CALL PLOT(.1,Y(I),2)
      IF(MOD(I,5).NE.0)GO TO 20
      FI=I*100.
      FACT=3.
      IF(FI.GE.1000.)FACT=4.
      XX=.2+(FACT*SIZW)
      YY=Y(I)-.06
      CALL NUMBER(-XX,YY,SIZH,FI,0.,-1)
   20 CONTINUE
      DO 30 I=1,50
   30 S2(I)=(S1(1,I)/100.)*DY
      CALL NEWPEN(2)
      CALL PLOT(0.,0.,3)
      DO 40 I=1,50
   40 CALL PLOT(X(I),S2(I),2)
      DO 50 I=1,50
   50 S2(I)=(S1(2,I)/100.)*DY
      CALL NEWPEN(1)
      CALL PLOT(0.,0.,3)
      DO 60 I=1,50
      CALL PLOT(X(I),S2(I),2)
```

```
      CALL SPCSYM(X(I),S2(I),SIZH,88,0.,-1)
      CALL PLOT(X(I),S2(I),3)
60    CONTINUE
      DO 70 KNT=1,2
      KK=KNT+2
      DO 71 I=1,50
71    S2(I)=(S1(KK,I)/100.)*DY
      IDSH=KNT+1
      CALL DASHPT(0.,0.,-1)
      DO 72 I=1,50
72    CALL DASHPT(X(I),S2(I),IDSH)
70    CONTINUE
      RETURN
      END
```

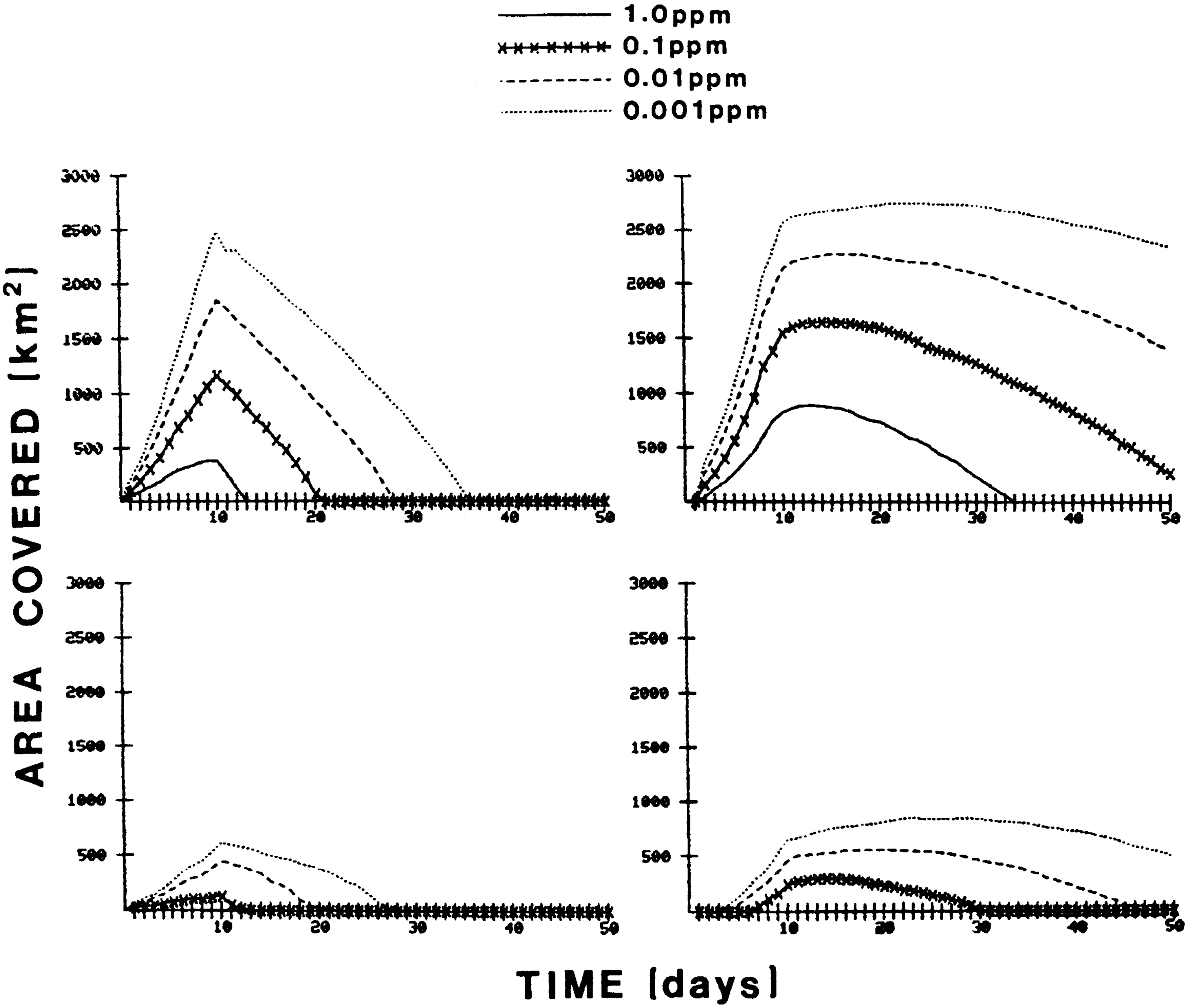


Figure 1.--Example of plot drawn using SUBROUTINE/PLOTR. In this example, DX = (length of x-axis)/50 and DY = (length of y-axis)/30.

Laevastu, T. and H.A. Larkins.

1981. Marine Fisheries Ecosystem, Its Quantitative Evaluation and Management. Fishing News Books Ltd., Farnham, Surrey, U.K., 162 pp.

Moriarity, F.

1975. Organochlorine Insecticides: Persistent Organic Pollutants. Academic Press, London, 302 pp.

Pola, N.B., R.K. Miyahara, and A.F. Gallagher, Jr.

1985. Spatial and temporal extent of hydrocarbon contamination in marine species of Bristol Bay. Natl. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA, Processed Rep. 85-08, 40 pp.

Swan, Nancy Pola.

1984. Biological Impact of an Oil Spill (BIOS) model documentation. Part 1: Fish migrations and exposure to contamination. Nat. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA., Program Documentation No. 21, 17 pp.

Teal, John M.

1977. Food chain transfer of hydrocarbons. In: Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystem and Organisms (D.A. Wolfe, Ed.), pp 71-77.

Wilson, K.W.

1975. The laboratory estimation of the biological effects of organic pollutants. Proc. R. Soc. Lond. B., 189:459-477.

ESTIMATED IMPACTS OF HYPOTHETICAL OIL SPILL ACCIDENTS OFF PORT MOLLER, PORT HEIDEN AND CAPE NEWENHAM ON EASTERN BERING SEA YELLOWFIN SOLE

by

Francis M. Fukuhara
University of Washington
and
Natural Resource Consultants
Seattle, Washington

Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 643

July 1985

This report is from a series of processed reports and program documentation produced by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, in Seattle, Washington, and is individually available as Processed Report 85-15 from that source.

This study was funded by Minerals Management Service through an interagency agreement with NOAA.

TABLE OF CONTENTS

NWAFC PROCESSED REPORT 85-15
This report does not constitute a publication and is for information only.
All data herein are to be considered provisional.

LIST OF TABLES

LIST OF FIGURES

ESTIMATED IMPACTS OF HYPOTHETICAL OIL SPILL ACCIDENTS OFF PORT MOLLER, PORT HEIDEN AND CAPE NEWENHAM ON EASTERN BERING SEA YELLOWFIN SOLE

by

Francis M. Fukuhara

INTRODUCTION

The yellowfin sole (Limanda aspera) is a flounder of the family Pleuronectidae and is the most abundant of the commercially important species of the eastern Bering Sea benthos. The species ranked first or second in abundance of all fish taken in the trawl surveys of the National Marine Fisheries Service (NMFS), Northwest and Alaska Fisheries Center (NWAFC) trawl surveys in 1975-80. Although information for more recent years was not available, their abundance ranking probably remains unchanged.

This large biomass is ubiquitously distributed over the eastern Bering Sea, therefore, any oil spill scenario in Bristol Bay will contaminate some of the species' habitat. The impact of such contamination on the productivity of the eastern Bering Sea yellowfin sole stock will depend upon the concentrations and duration of exposure as well as the physiological state and life history stage of the animals in the contaminated area. Considerable knowledge has been compiled on the life history, distribution, abundance and fishery of yellowfin sole in the eastern Bering Sea (Fadeev 1970a & b, Bakkala 1981, Wakabayashi 1985). The purpose of this report is to summarize information from these and other sources to provide relevant background information for estimating the impact of specific quantities and types of petroleum released at three sites in Bristol Bay on the productivity of the eastern Bering Sea yellowfin sole population.

DISTRIBUTION

Overall Distibution

Yellowfin sole (Limanda aspera) are widely distributed in the northern North Pacific Ocean and adjacent seas. They are typically found over sandy and sandy-silt bottom and never found in large numbers on gravel or purely silty sediments (Fadeev 1970a). In Asia, the species occurs on the shelf from the east coast of the Korean Peninsula northward in the Sea of Japan, Okhotsk Sea and along the Pacific coast of Siberia to Bering Strait. In the eastern North Pacific Ocean, yellowfin sole occur on the North American continental shelf from off central British Columbia and Alaska as far north as the Chukchi Sea (Fig. 1). The largest biomass of yellowfin sole occurs on the broad shelf of eastern Bering Sea with only minor centers of abundance found off the western coast of Kamchatka, off the southeastern coast of Sakhalin and in the northernmost parts of the Sea of Japan (Kasahara 1961). Eastern Pacific stocks other than those of eastern Bering Sea are also minor.

Distribution in the Eastern Bering Sea

Yellowfin sole are very broadly distributed over the continental shelf and slope of the eastern Bering Sea at depths of 5 m to 360 m (Fadeev 1970) although the most dense concentrations and the commercial fishery occur generally south of 60°N (Fig. 1). The distribution of yellowfin sole varies by stock, season and age.

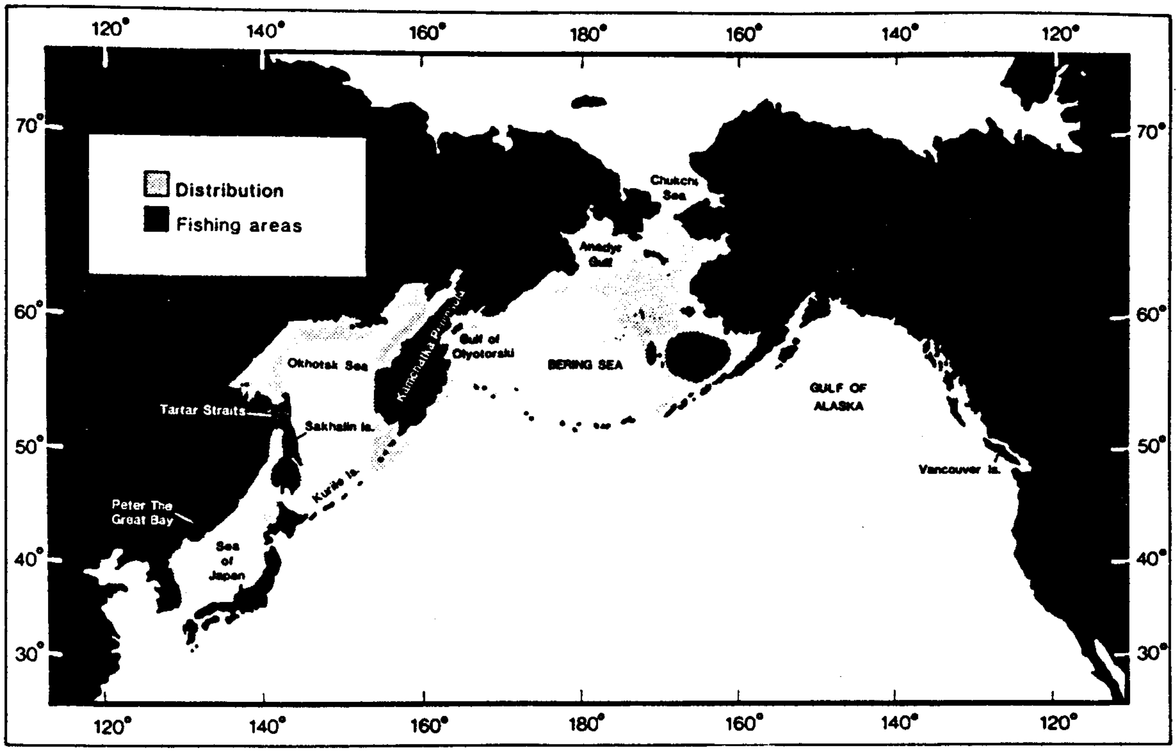


Figure 1. Overall distribution and areas of commercial fishing for yellowfin sole.

During the winter, adults aggregate in large dense schools on the outershelf and upper slope at depths of 100-270 m (max. depth, 360 m). Wintering adults are found in temperatures of 2° to 6°C (Fadeev 1970a). In April and May (sometimes as early as March), these aggregations of adult fish migrate generally northeastward to shallower waters of the eastern Bering Sea shelf (Fig. 2).

With the approach of summer, there is a progressive movement of the fish toward Bristol Bay and northward. By summer the main body of yellowfin sole is broadly distributed over the inner shelf of southeastern Bering Sea at bottom depths of 100 m and less (Fig. 3). Yellowfin occur in bottom temperatures of -1.0° to 13°C with highest catches at -1° to 7°C according to Bakkala (1981) and 1° to 6°C according to Fadeev (1970b). Distribution extends well into Bristol Bay with dense concentrations off Togiak, the Egegik River estuary and the northern Aleutian Shelf in some years (e.g., 1980).

Stimulus for spring migrations is apparently not temperature per se because sole move from relatively warm deep water (3.5°-4.0°C in April) to cooler shelf waters (0°C)in April and May (Fadeev 1970a). Maximum winter chilling of shelf water occurs in March-April. Large concentrations of sole may be aggregations of fish near the borders of cold water masses.

Bakkala (1981) has presented evidence that the distribution and spring migration of sole is associated with seasonal changes in the ice covering of the eastern Bering Sea.

Movements of the Japanese fishery also illustrate the seasonal changes in the distribution of eastern Bering Sea yellowfin sole (Fig. 4).

In addition to these seasonal movements, yellowfin sole are known to migrate vertically through the water column. They have been observed near the

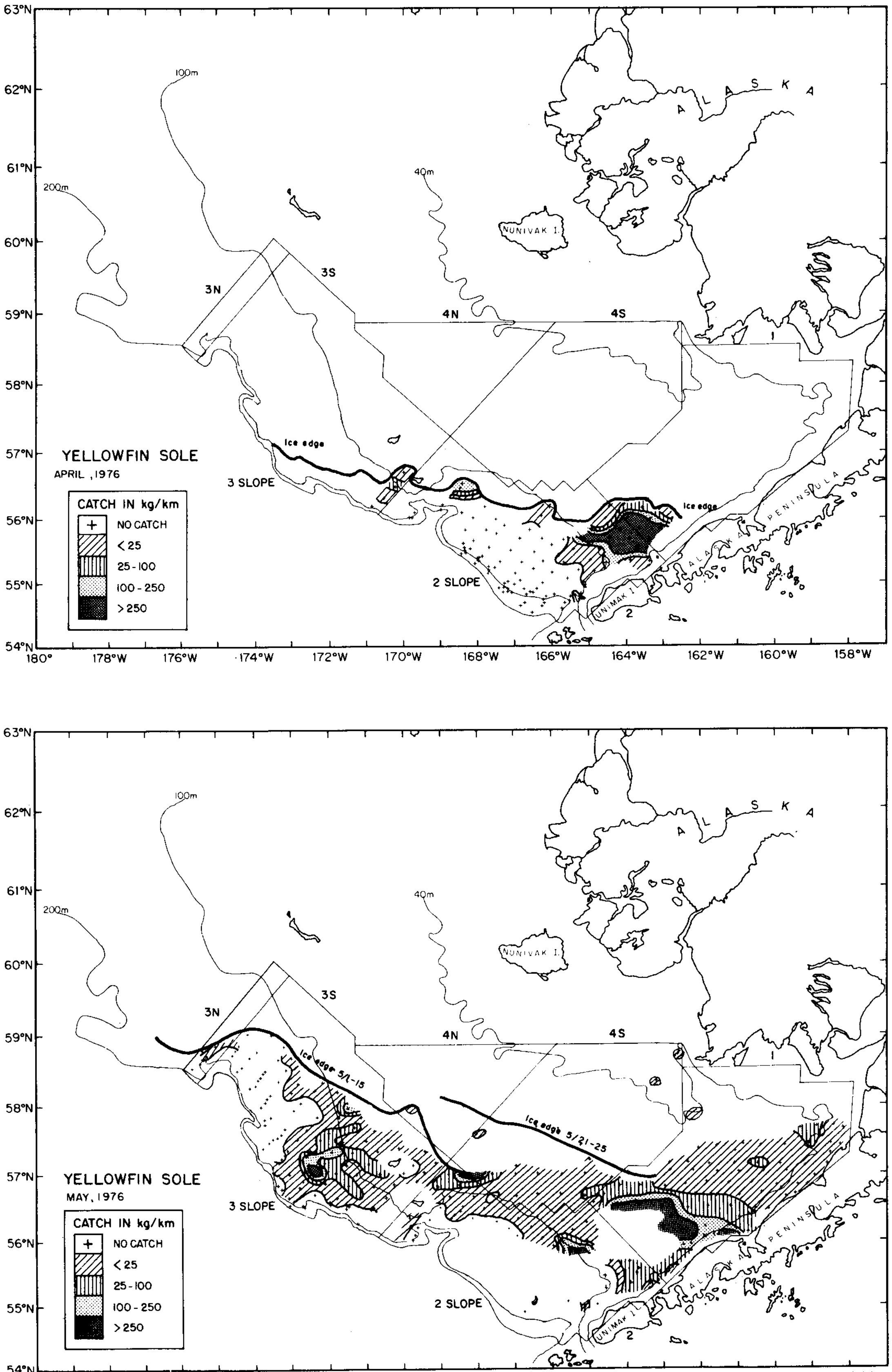
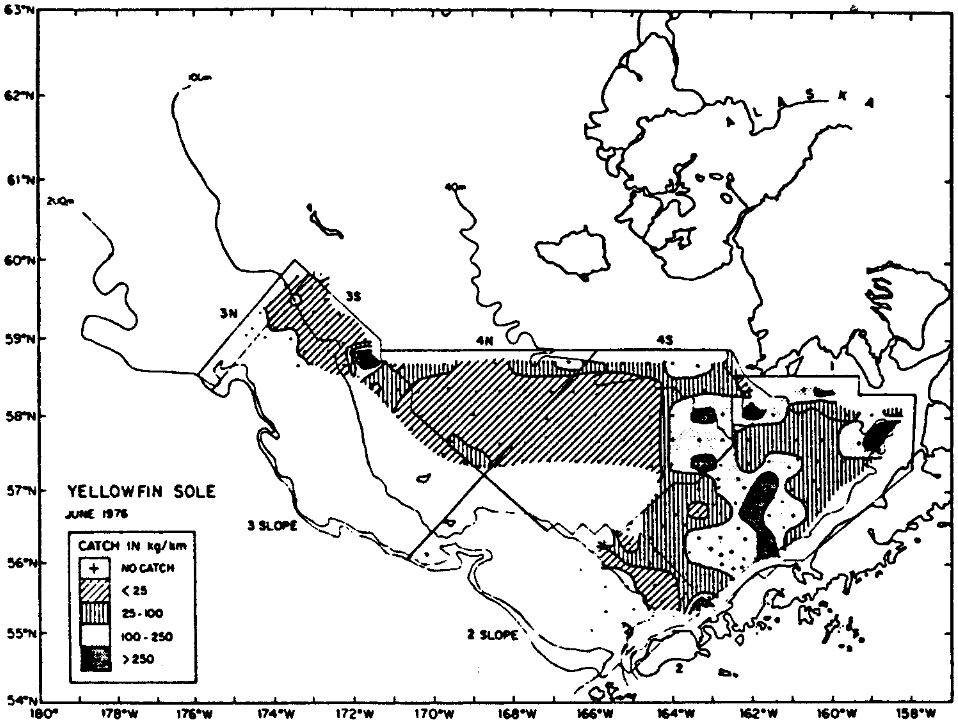


Figure 2. Seasonal changes in relative abundance of yellowfin sole as shown by NWAFC trawl surveys.



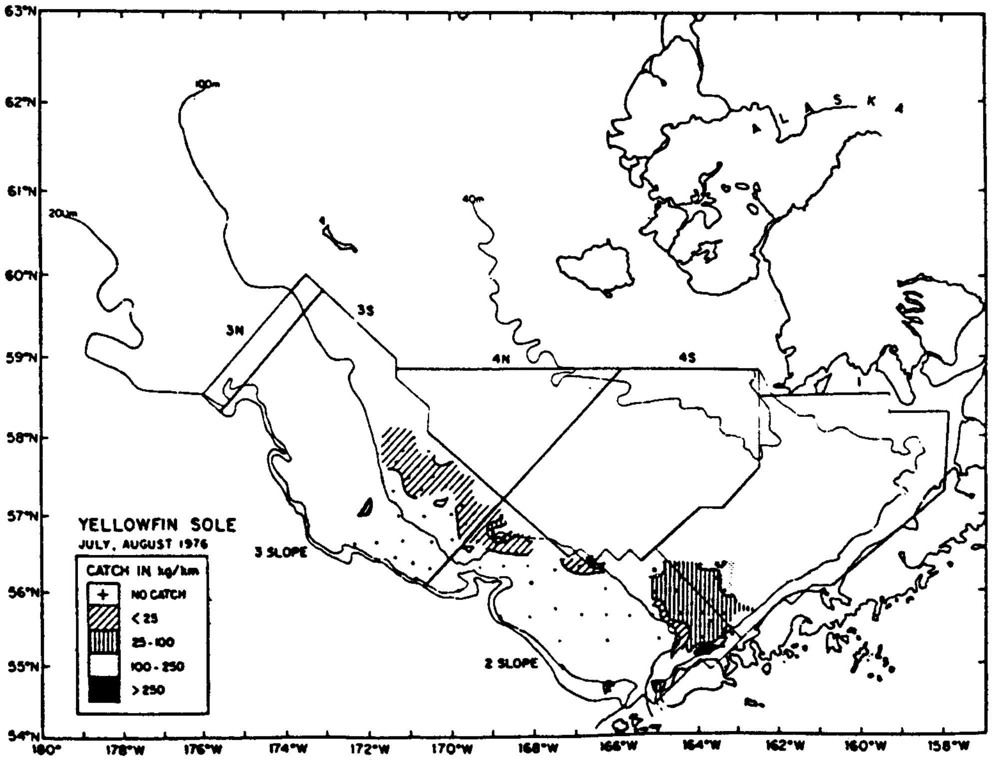


Figure 2. Continued.

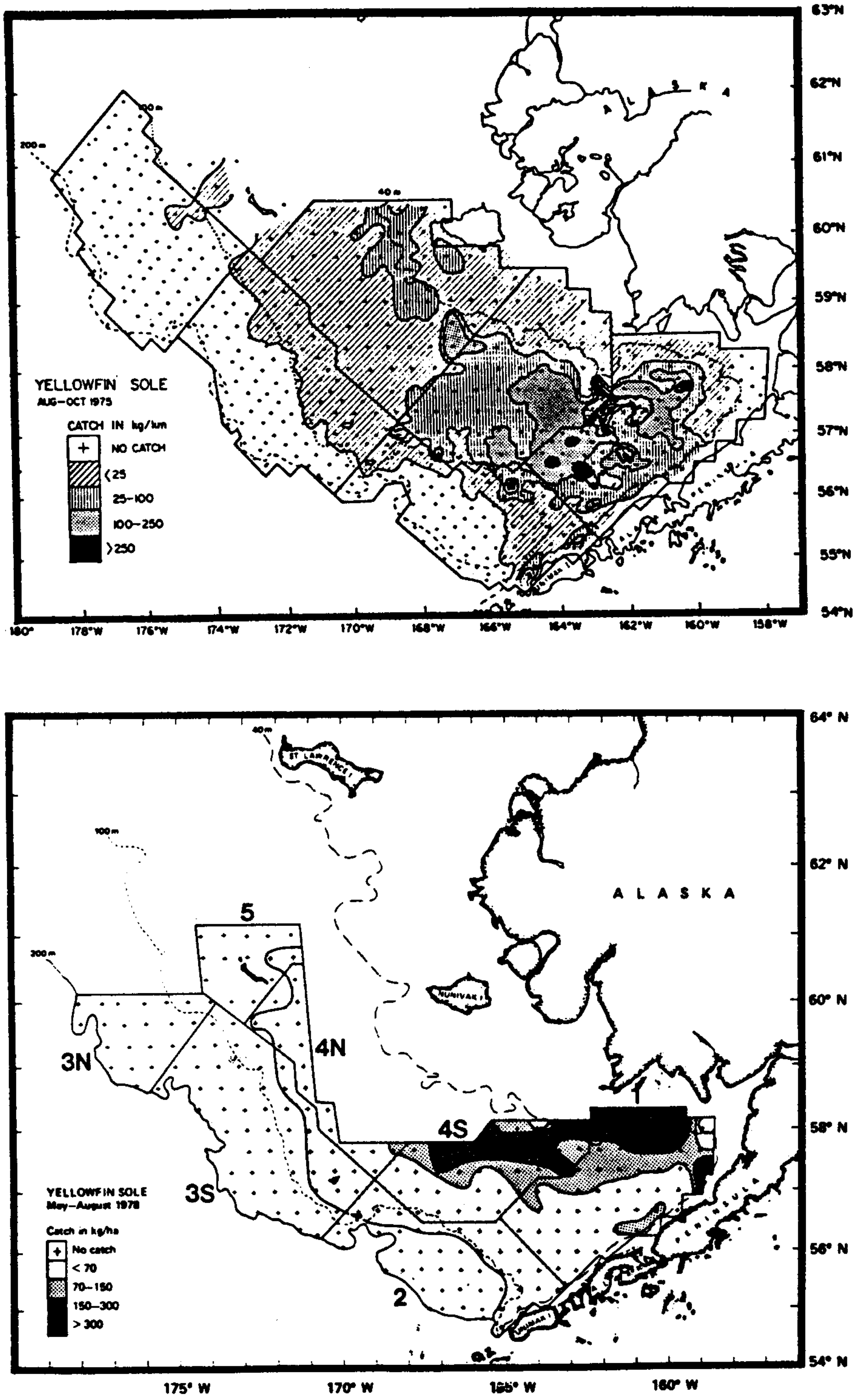


Figure 3. Distribution and relative abundance by weight of yellowfin sole in the eastern Bering Sea.

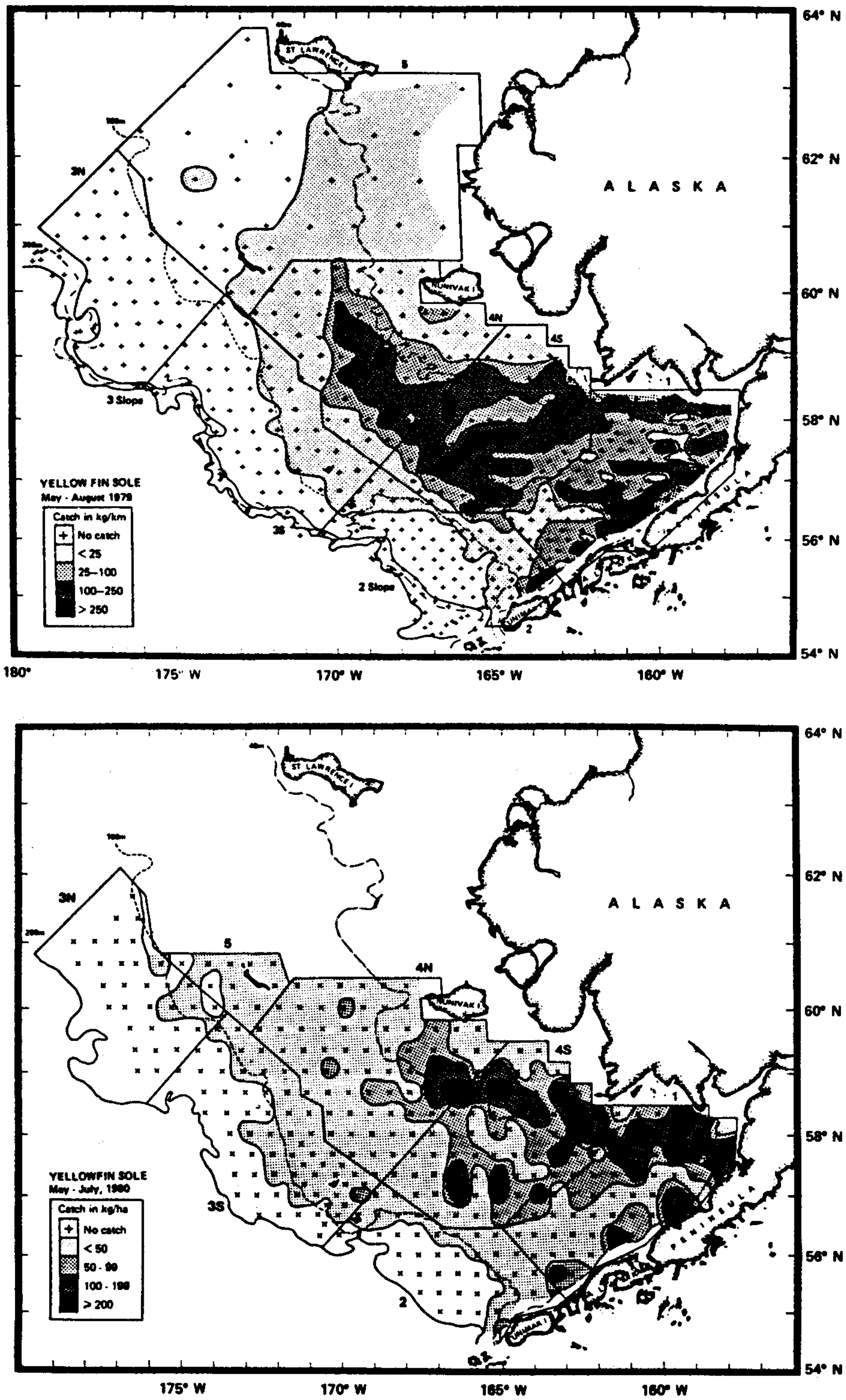


Figure 3. Continued.

surface in spawning areas and during the winter rising to the surface at night and descending to the bottom during daylight hours (Fadeev 1970a). Occurrence of yellowfin sole well off the bottom has been confirmed by Japanese and United States investigations (Salveson and Alton 1976).

Available evidence indicates that juveniles are year round residents of the inner shelf. As juveniles mature, they move from shallower to deeper waters (Bakkala 1981).

Stock Structure and Seasonal Migrations

There is evidence that the eastern Bering Sea yellowfin sole population is composed of more than one stock. As mentioned in the previous paragraph, adults aggregate in deeper water during the winter. Three such aggregations were reported by Soviet scientists, the largest off Unimak Island, another west of the St. Paul Island and a comparatively small and poorly defined concentration south or east of St George Island (Fadeev 1970a, Wakabayashi 1974). Tagging studies have shown that the Unimak and St. George Island wintering groups combine in spring before onshore migrations (Wakabayashi et al. 1977). The juvenile concentrations in Bristol Bay are thought to be a part of the Unimak-St. George group (Bakkala 1981).

The Unimak-St. George school moves to shallower water in April and May (as early as March) and with the approach of summer, there is progressive movement toward Bristol Bay and northward. By summer, most yellowfin sole are on the inner shelf of southeast Bering Sea at bottom depths of 100 m and less.

The St. Paul Island wintering group apparently remains relatively independent of the Unimak-St. George group. This group forms summer concentrations in shallow waters around Nunivak Island.

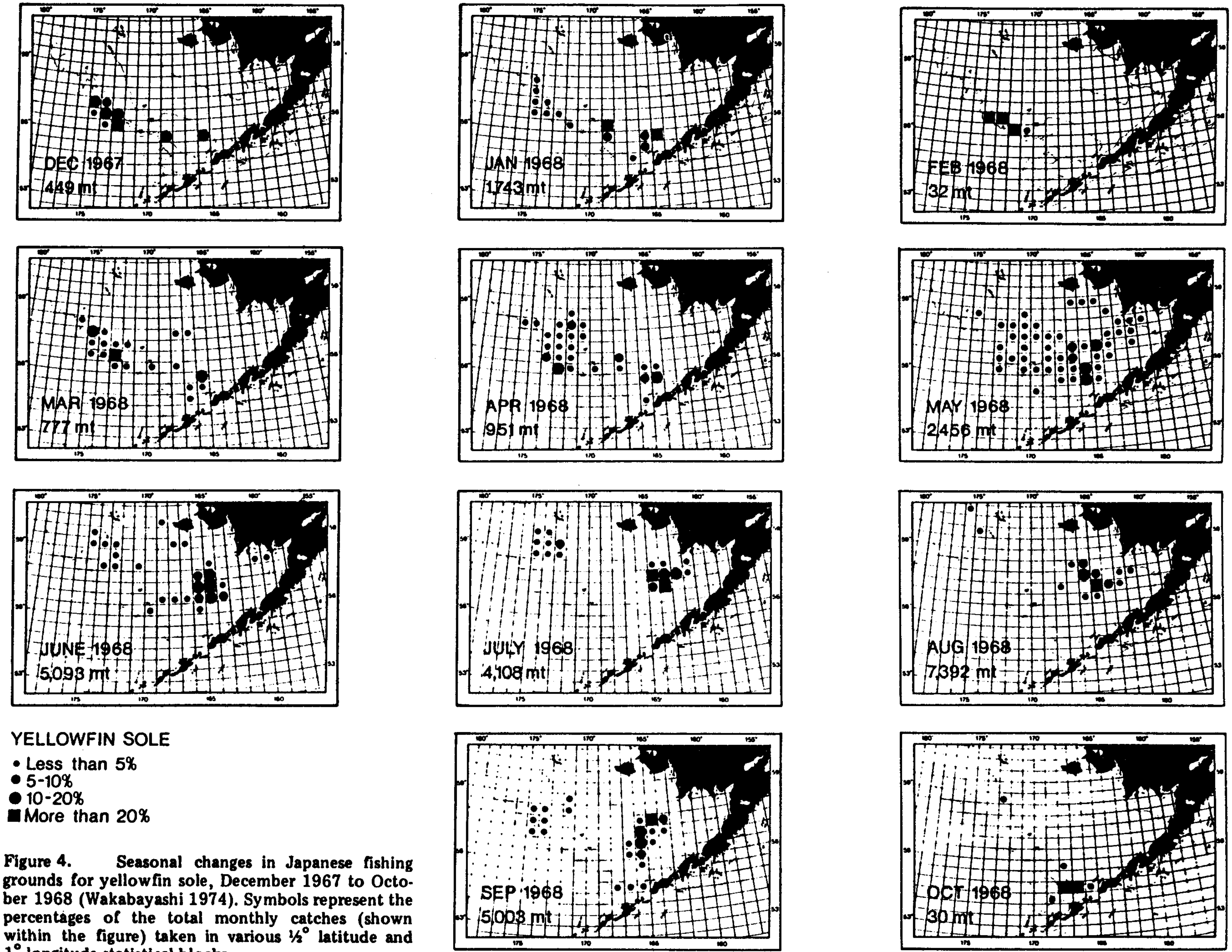


Figure 4. Seasonal changes in Japanese fishing grounds for yellowfin sole, December 1967 to October 1968 (Wakabayashi 1974). Symbols represent the percentages of the total monthly catches (shown within the figure) taken in various ½° latitude and 1° longitude statistical blocks.

Tagging studies (Wakabayashi 1974, Wakabayashi et al. 1977) and differences in morphometric measurements (Kashkina 1965, Wakabayashi 1974) indicated that these populations constitute a northern (St. Paul) and southern (Unimak-St. George) stock of yellowfin sole. Other biological studies (Fadeev 1970a, Wakabayashi 1974, Grant et al. 1978) and more recent tagging studies, suggest that the eastern Bering Sea yellowfin sole constitute a single stock.

Distibution by Subareas in Northwest and Alaska Fisheries Center (NWAFC) Trawl Surveys

The history of resource surveys in the eastern Bering Sea was described by Alton (1976). Surveys have occurred since 1890, however, the most comprehensive in area and consistent in time are the trawl surveys of the NWAFC which have occurred annually and included demersal fish assessments since about 1971. Subareas of the NWAFC eastern Bering Sea trawl surveys in recent years (since 1975) are shown in Figure 5. As indicated in this figure, the Port Heiden and Port Moller spill scenario sites are located within Subarea 1 and the Cape Newenham spill site in Subarea 4S. The following discussion will, therefore, emphasize the population characteristics of the yellowfin sole within these two Subareas.

Distribution of Biomass By Subareas

The mean estimated biomass of yellowfin sole in the eastern Bering Sea is given in Table 1. The mean biomass almost doubled from 1 million t in 1975 to 1.9 million t in 1979. The biomass remained essentially the same through 1981. From 1981 to 1982, the biomass increased by 63% and again from 1982 and 1983 the biomass increased by almost 19%. The increase in biomass from 1981 to 1982 was far more than could be explained by population growth

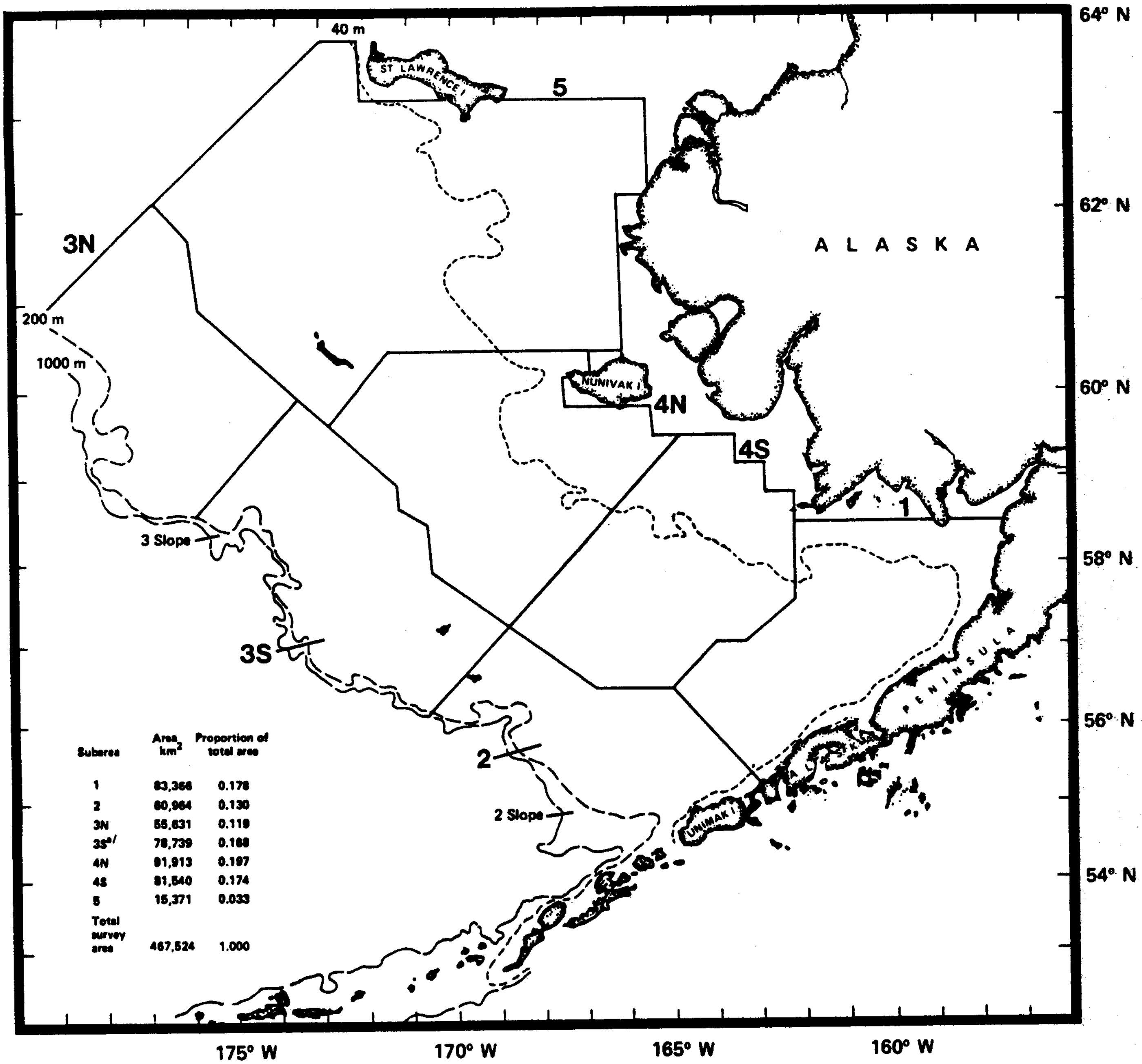


Figure 5. National Marine Fisheries Service trawl survey subareas showing locations of hypothetical oil spill sites off Port Moller, Port Heiden and Cape Newenham.

Table 1. Biomass estimates from research vessel surveys, 1975-84.

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	2,039,900	1,791,000 - 2,288,800
1982	3,322,500	2,675,900 - 3,970,100
1983	3,951,500	3,459,200 - 4,443,900
1984	3,365,900	2,972,000 - 3,759,800

Source: Bakkala and Wespestad, 1984.

increments. This increase was attributed in part to improved bottom tending qualities of the trawl and an increase in the area sampled during the 1982 survey (Bakkala and Wespestad 1984a).

The distribution of yellowfin sole biomass by subareas of the eastern Bering Sea is summarized in Table 2 with the percentage of estimated biomass in each of the 7 subareas shown in Figure 6. During the period of the surveys (spring-fall), 90% (1976) to 98% (1978) of the biomass was estimated to be on the inner shelf (primarily Subareas 1, 4S and 4N). Subareas 1 and 4S combined accounted for 69% (1983) to 96% (1978) of the total biomass. Estimated biomass was generally largest in Subarea 1 which includes the Port Moller and Port Heiden hypothetical spill sites. Estimated biomass in Subarea 1 constituted 33% (1979) to 79% (1976) of the total, although the latter was considered to be an overestimate (Smith and Bakkala 1982). The average percentage of biomass in Subarea 1 for 1975-83 (excluding 1976 and 1977) was 43%.

Excluding 1976 and 1977, the percentage of the eastern Bering Sea yellowfin sole biomass occupying Subarea 4S (Cape Newenham spill site) ranged from 31% (1975) to 46% (1981) with the average 37% for the 7 years considered.

Distribution of Life History Groups

Spawning Populations and Eggs and Larvae

Knowledge concerning the timing and areas of spawning of yellowfin sole has been obtained primarily from observations of the distribution of their eggs and larvae. The distribution of yellowfin sole eggs and larvae taken in Soviet plankton surveys is shown in Figure 7. Spawning begins in early July and probably ends in September (Musienko 1963). Eggs are distributed over a

Table 2. Estimated biomass of yellowfin sole in the eastern Bering Sea, 1975-83.

Subarea/Year	1975[1]	1976[2]	1978[3]	1979[4]	1980[5]	1981[6]	1982[6]	1983[6]
Inner Shelf								
5			10	24,872	1,742	1,076	1,073	81,320
4N	105,800	44,249	30,367	414,050	343,291	154,746	591,547	976,568
4S	319,000	88,151	694,943	790,749	677,458	948,406	1,052,146	1,343,322
1	540,100	939,471	937,829	634,061	821,490	827,670	1,376,102	1,438,319
Total	964,900	1,071,871	1,663,149	1,863,732	1,843,981	1,931,898	3,020,868	3,839,529
	(93)	(90)	(98)	(96)	(96)	(94)	(91)	(95)
Outer Shelf								
3N	t	120,753	0	0	24	47	19	39
3S	5,800		4,555	11,476	21,649	18,072	16,615	47,546
2	67,700	-	37,006	57,349	47,321	114,492	285,295	163,150
Total	73,500	120,753	41,561	68,825	68,994	132,611	301,929	210,735
	(7)	(10)	(2)	(4)	(4)	(6)	(9)	(5)
All Areas Total	1,038,400	1,192,624	1,704,710	1,932,557	1,912,975	2,064,509	3,322,797	4,050,264

1/ Pereyra et al. 1976
2/ Smith and Bakkala 1982.
3/ Bohle and Bakkala 1978.
4/ Bakkala, et al. 1982
5/ Umeda and Bakkala 1983
6/ Unpublished data, RACE Division, NWAFC.

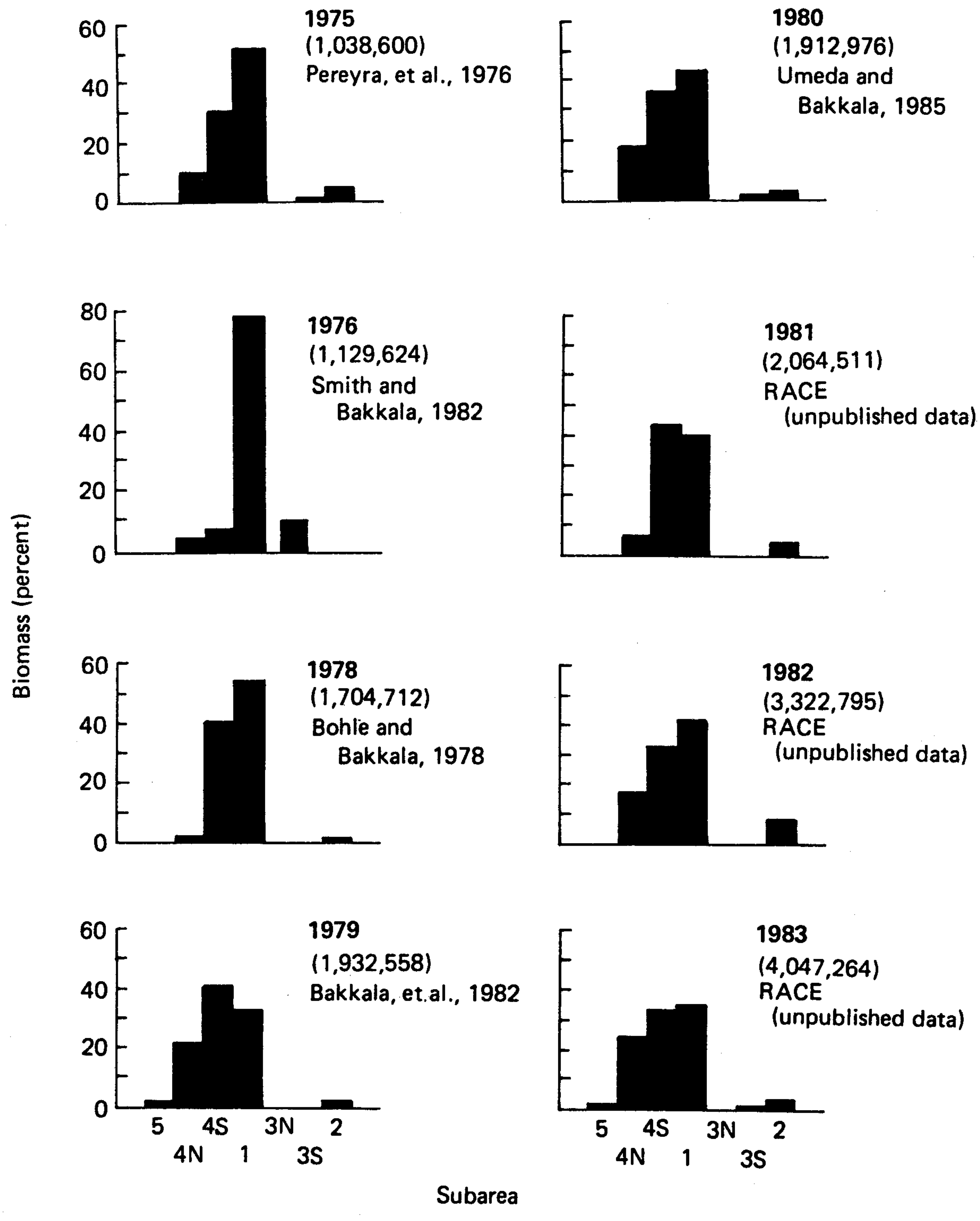


Figure 6. Percentage distribution of biomass of yellowfin sole in subareas of the NWAFC eastern Bering Sea trawl survey.

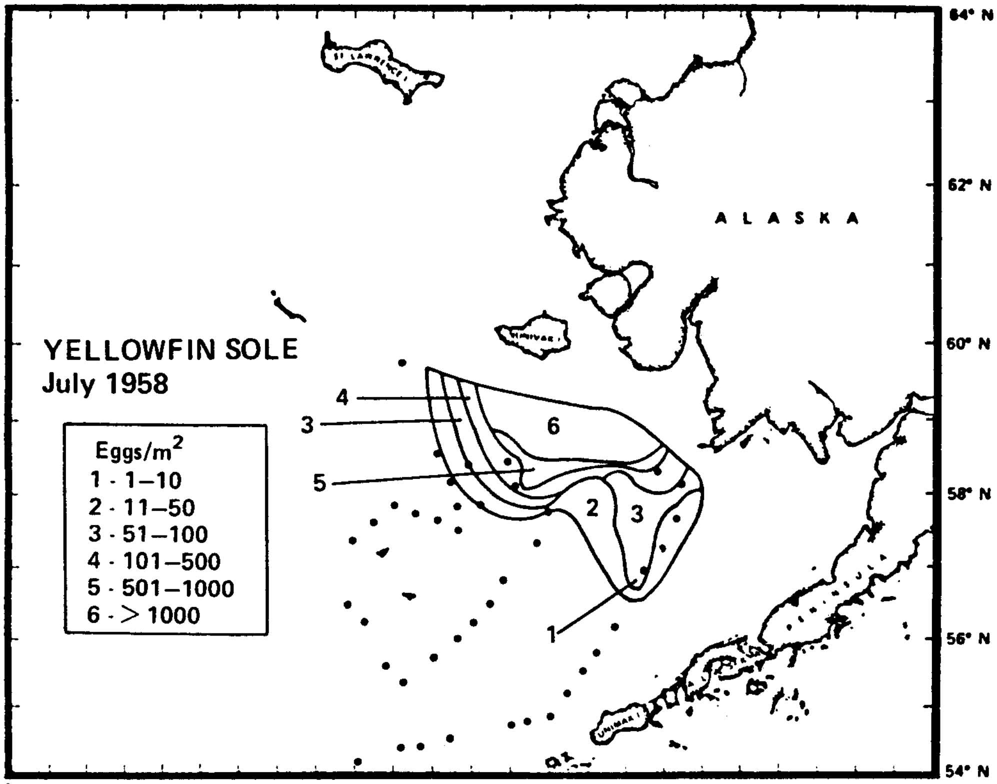


Figure 7. Distribution of yellowfin sole eggs as shown by plankton surveys.

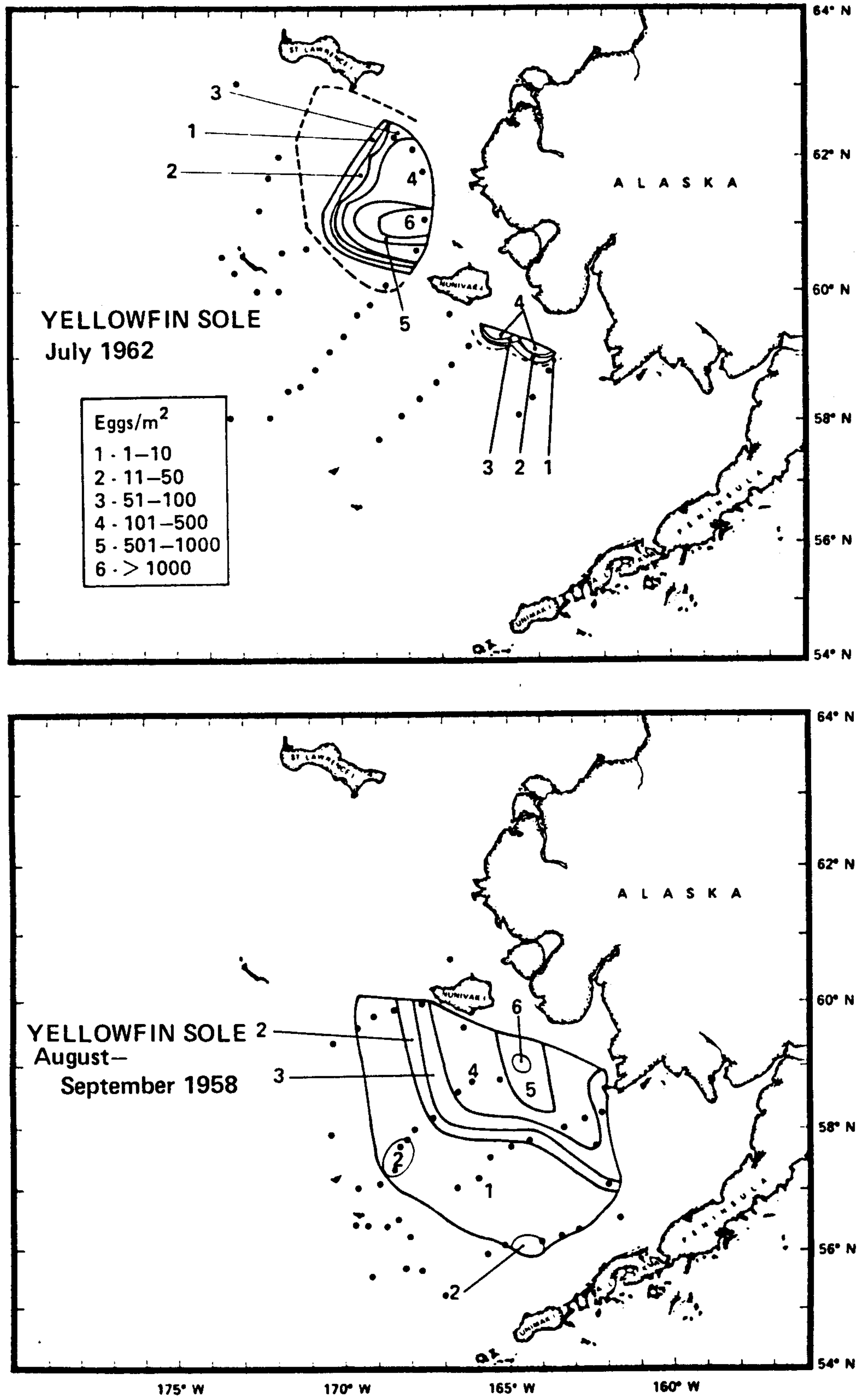


Figure 7. Continued

broad area of the eastern Bering Sea shelf from off Bristol Bay to Nunivak Island. Density of eggs was greatest south and southeast of Nunivak I. Depth of spawning ranged from 15-75 m (Bakkala 1981).

The eggs of yellowfin sole are pelagic, hatch in about 4 days at 13°C and larvae absorb their yolk sacs in about 3 day (Pertseva-Ostroumova 1961). The distribution of yolk-sac larvae is presumed to be similar to that of the eggs.

Young Juveniles (3 yrs and younger)

The time elapsed from hatching to metamorphosis is not known, although partially metamorphosed yellowfin sole have been taken in plankton hauls. Juvenile fish larger than this size are presumed to have begun a bottom existence even though metamorphosis may not be completed. Although there are no quantitative estimates of their relative abundance or numbers, 2 and 3 year old yellowfin sole have been taken in relatively small numbers in shallow waters of inner Bristol Bay (Fig. 8).

Prerecuits (4 & 5 yrs) and Adults

Yellowfin sole of sizes equivalent to ages 3-5 years have been found to be broadly distributed in inner Bristol Bay from off Port Moller to waters north of northern Bristol Bay (Fig. 8). At these ages, yellowfin sole begin to disperse to offshore waters. By 5 to 8 years of age which is roughly the age at sexual maturity, they join the adult population (Fig. 8). This group winters in the the deeper waters of the outer shelf and upper slope and migrates to the inner shelf in the spring with spawning occurring in midsummer to early autumn (Bakkala 1981).

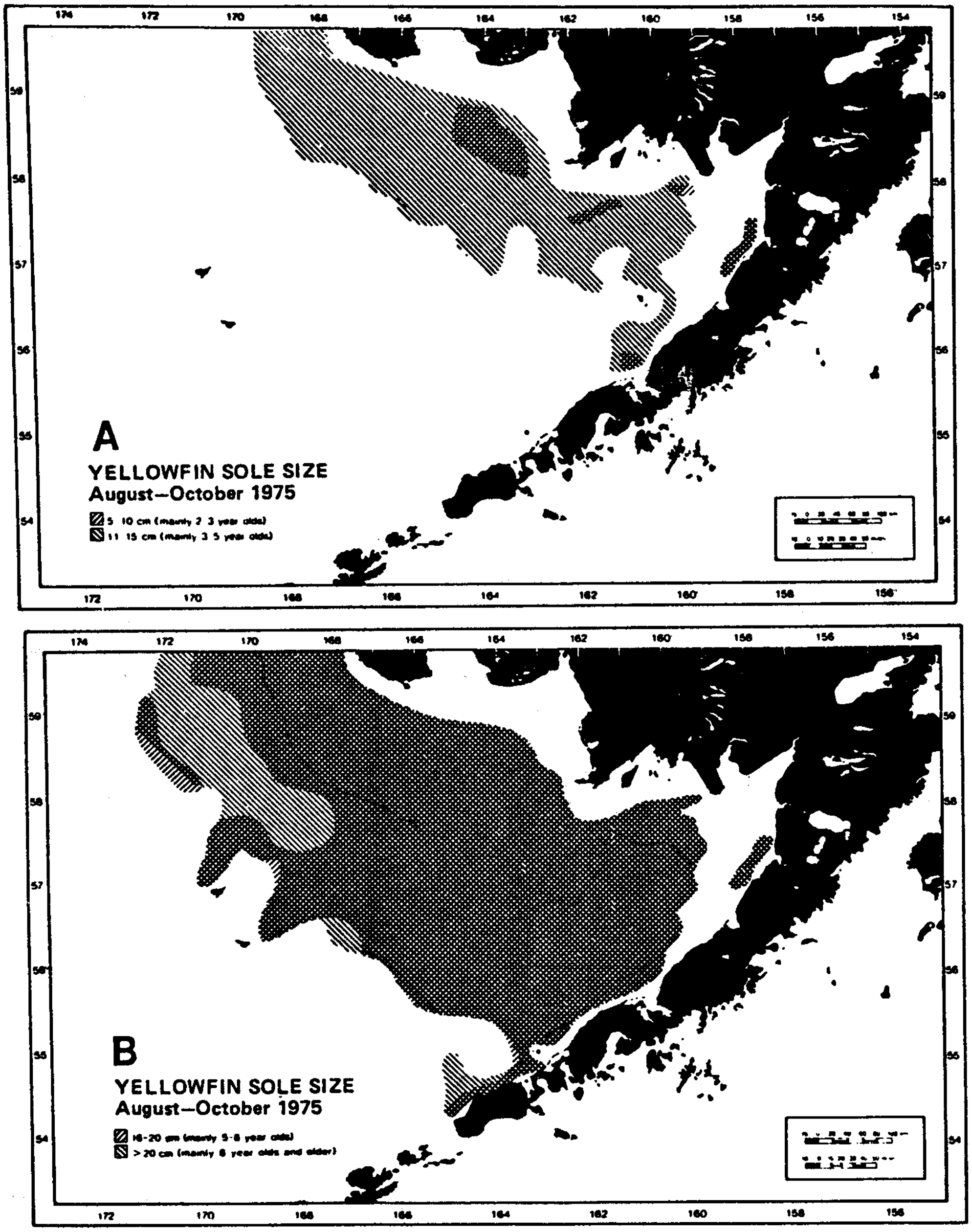


Figure 8. Distribution of yellowfin sole by size group, August-October 1975.

BIOLOGICAL CHARACTERISTICS

Sex Ratios

From data averaged over all areas of eastern Bering Sea, in summer hauls, females dominated males by 2.8 in 1958 to 1.1 in 1959. The sexes were more equally represented in 1961-63 and males were somewhat more numerous in all winter hauls (Fadeev 1970a). The ratio of females to males by regions and seasons is shown in Table 3. In Bristol Bay, the area of primary interest to these studies, and where fish are small, males were subordinate in numbers in the winter but dominant in spring. The ratio of females to males for All Areas, Subarea 1 and Subarea 4S are given in Table 4.

Table 4. Sex ratios (F/M) in All Subareas, Subarea 1 and Subarea 4S, 1981-83.

Year	All Areas	Subarea 1	Subarea 4S
1981	1.1	0.7	1.2
1982	1.0	0.6	1.1
1983	1.0	0.7	0.9

Source: Data on file in RACE Div., Northwest and Alaska Fisheries Center.

For these recent 3 years the sexes have been about equally represented in catches in the entire survey. Males have dominated the catch in Subarea 1 and females outnumber males slightly in Subarea 4S (excepting 1983).

The fecundity of yellowfin sole increases with size (Table 5).

Table 3. Ratio of yellowfin sole females and males by regions and seasons.

Region and time of catch	1958		1959-1961		1962-1964	
	Ratio of females to males	Average number of fish	Ratio of females to males	Average number of fish	Ratio of females to males	Average number of fish
Unimak bank	-	-	1.2	1464	0.7	1454
Slope west of the Pribilof Islands						
winter and spring. . . .	-	-	1.1	437	1.5	769
Bristol Bay						
winter	-	-	0.6	273	1.4	392
spring	-	-	0.8	693	0.6	398
North bank						
May.	-	-	1.4	783	-	-
February	-	-	-	-	3.1	200
Central shallows						
June	-	-	1.9	1098	1.3	295
July	2.8	905	0.5	388	2.9	323
September.	-	-	1.5	400	-	-

Source: Fadeev 1970a.

Table 5. Fecundity of yellowfin sole in the eastern Bering Sea (10^3).

Length (cm)	Fecundity ($X10^3$ eggs)
15 - 20	--
20 - 25	--
25 - 30	1293.7
30 - 35	1707.6
35 - 40	2413.4
40 - 45	3319.2
45 - 50	--

The relationship of fecundity to total length was estimated by Wakabayashi(1974) to be:

$$\text{Fecundity (in 1000 egggs)} = 0.0747565 \text{ (total length in cm)}^{2.86517}$$

An estimate of the potential number of eggs which might be produced by yellowfin sole in Subareas 1 and 4S was calculated from data on the female yellowfin sole population estimated from the 1983 NWAFC trawl survey (Table 6). From these data, about a third of the total female population occurred in both Subareas 1 and 4S during the period of the survey. This would indicate that about one third of the estimated potential number of 8.6×10^{15} eggs were produced in each of Subareas 1, 4S and 4N. As discussed earlier, however, there is little evidence from ichthyoplankton surveys that any spawning occurs in Subarea 1.

Eggs, Larvae and Juveniles

Fertilization of eggs is external. Fertilized eggs are pelagic with diameters ranging from 0.68 to 0.90 mm (Kashkina 1965).

Table 6. Estimated number of eggs produced by eastern Bering Sea yellowfin sole in 1983[1/].

Length (cm)	Average fecundity ($X10^3$)[2/]	Est. no. of females ($X10^6$) Subareas 1	4S	All subareas	Est. no. of eggs ($X10^9$) Subareas 1	4S	All subareas
<25	-	1,047.70	1,493.53	3,677.21			
25-30	1293.7	1,454.75	1,396.55	4,235.21	1,882,010	1,806,716	5,479,091
30-35	1707.6	466.36	428.13	1,659.29	796,356	731,075	2,833,404
35-40	2413.4	39.01	39.20	123.18	94,147	96,605	297,283
40-45	3319.2	0.00	0.48	2.06	-	1,593	6,837
Total		3,007.82	3,357.89	9,686.95	2,772,513	2,635,989	8,616,615

1/ Based on trawl survey population estimate (data on file at NWAFC, NMFS, NOAA).
2/ From Fadeev (1970).

Eggs of yellowfin sole from Peter the Great Bay were fertilized and observed under experimental conditions by Pertseva-Ostroumova (1961). Incubation time was about 4 days at an average water temperature of 13°C. The lower temperature threshhold for egg hatching was 4°C. Newly hatched larvae ranged in size from 2.25 to 2.80 mm (ave. = 2.55 mm). These larvae were transparent, had large yolk sacs and were capable of swimming. After about 3 days, larvae attained lengths of 3.29 to 3.84 mm, absorbed their yolk sacs and were actively feeding.

In the eastern Bering Sea, yellowfin sole eggs were encountered at surface temperatures of 6.4° to 11.4°C (Kashkina 1965, Musienko 1970). Prolarvae collected in Bering Sea ranged from 2.2 to 3.1 mm (Musienko 1963).

Details regarding the metamorphosis of yellowfin sole from pelagic larvae to bottom dwelling juveniles are not known. Partially metamorphosed juveniles 16.5 to 17.4 mm in length have been captured in plankton hauls. Juveniles larger than this (until about 5 cm in length) have not been captured in plankton hauls and are assumed to have begun a benthic existence in shallow, nearshore waters.

Juvenile yellowfin sole 5-10 cm in length (2 and 3 yrs) are first observed in research vessel bottom trawls in inshore waters (Fig. 8). They occur in low abundance off Kuskokwim Bay, in Bristol Bay and along the Alaska Peninsula. At lengths of 16-20 cm (5-8 yrs), they occupy the same waters as larger fish.

Growth

Von Bertalanffy growth curves (Fig. 9) and parameters (Table 7) from Bakkala (1981) show the similarity in growth of males and females. Mean

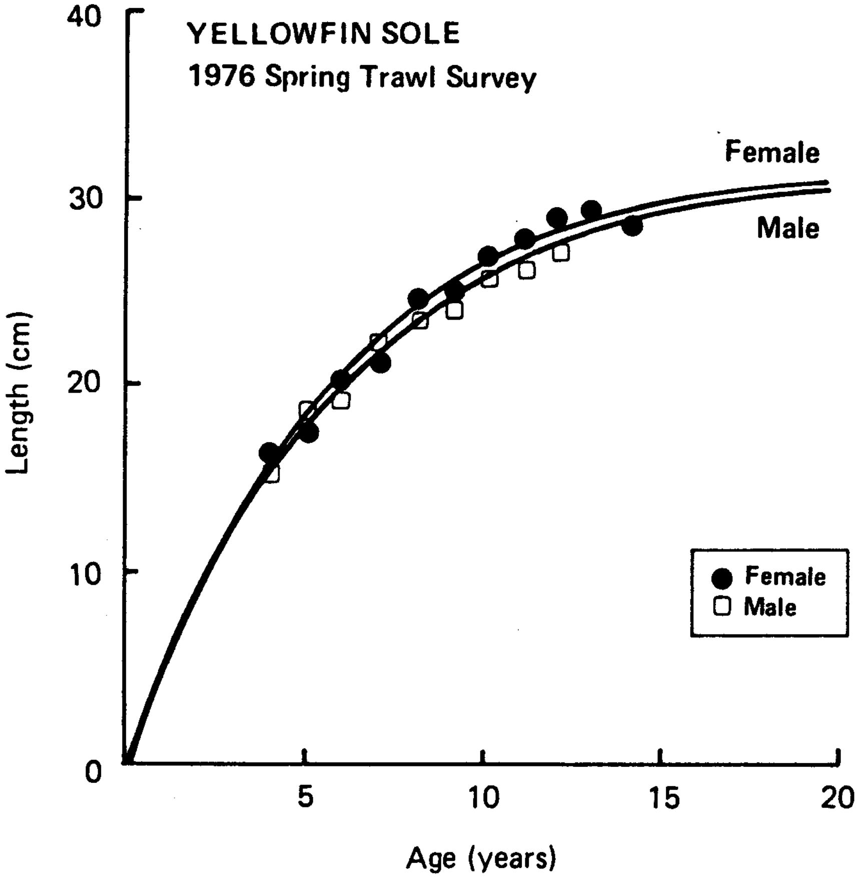


Figure 9. Von Bertalanffy growth curves for yellowfin sole taken during spring 1976 (Bakkala and Smith 1978).

Table 7. Parameters of the von Bertalanffy growth curve for yellowfin sole of the eastern Bering Sea (data of Pereyra et al. 1976, Bakkala and Smith 1978).

Sex	Year	Number of age readings	Age range	Length range (cm)	Standard error of curve fit	Parameter		
						L_∞	K	t_0
Male	1975	609	0,8-15	0,17-30	1.50	40.79	0.11	0.22
	1976	507	0,4-12	0,13-33	0.31	31.88	0.17	-0.02
Female	1975	707	0,8-15	0,19-39	0.80	40.28	0.11	-0.09
	1976	600	0,4-14	0,13-36	0.66	32.23	0.18	0.10

Source: Bakkala 1981.

lengths and weights of yellowfin sole sampled from catches of the NWAFC trawl surveys of 1973-78 were also given by Bakkala (Table 8). The annual growth increment in length decreases to less than 2.0 cm after age 6 and to less than 1.0 cm after age 13. Annual weight increment increases rapidly from ages 4 to 6, ranges from 22.4 to 34.9 gm from ages 7 through 13 and declines, thereafter. Laevastu and Livingston (1978) have shown growth rate to decline between ages 7 and 8 which they attributed to the diversion of energy for growth to the production of sex products.

The oldest yellowfin sole captured in eastern Bering Sea were a 17 year old male and a 19 year old female (Salveson and Alton 1976).

Size and Age at Maturity and Recruitment to the Fishery

Male yellowfin sole attain sexual maturity at a smaller size and earlier age than females. Males begin to mature at 11 cm and females at 19 cm (Wakabayashi 1974). About half the males at a length of about 13 cm and half the females at 26-27 cm are mature (Wakabayashi 1974). These lengths correspond to ages of less than 4 for males (Fadeev 1970a) and 9 years for females.

Yellowfin sole first enter the fishery at 13-14 cm which corresponds to ages 4 or 5. They are fully recruited to the fishery at age 7 (Laevastu and Favorite 1978) when the the biomass of the exploitable stock is at its maximum (Wakabayashi 1975).

Natural Mortality

Instantaneous natural mortality of yellowfin sole 4 years and older was estimated by Fadeev (1970) as 0.29 (25% annual mortality rate) for the population in 1958, prior to the intensive exploitation of the stock(s).

Table 8. Six-year means of observed lengths and calculated weights at age for yellowfin sole of the eastern Bering Sea from NWAFC survey data of 1973-78.

Age	Mean length (cm)	Annual increment (cm)	Mean weight (g)	Annual increment (g)
3	12.0		19.5	
4	14.1	2.1	32.3	12.8
5	16.6	2.5	51.7	19.4
6	19.3	2.7	81.5	29.8
7	21.0	1.7	103.9	22.4
8	22.4	1.4	126.4	22.5
9	23.9	1.5	154.2	27.8
10	25.2	1.3	181.0	26.8
11	26.4	1.2	206.3	25.3
12	27.4	1.0	230.3	24.0
13	28.7	1.3	265.2	34.9
14	29.1	0.4	278.3	13.1
15	29.4	0.3	286.6	8.3

Source: Bakkala 1981.

Subsequently, Wakabayashi (1975) estimated instantaneous natural mortality for fish 4 years and older as 0.25 which corresponds to an annual mortality rate of about 22 %. If these estimates are reliable, the decrease in natural mortality may be a consequence of the intense fishery for yellowfin sole since 1958-59 (Pereyra et al. 1976).

Predators, Prey and Associated Species

Predators

Novikov (1964) found the distribution of Pacific halibut (*Hippoglossus stenolepis*) closely associated with yellowfin sole in spring and autumn. Yellowfin sole occurred in 33 to 70 percent of the halibut stomachs and constituted 30 to 55 percent of the weight of the stomach contents in fish examined by Novikov. Although there are no doubt other predators on yellowfin sole, particularly during the egg, larval and juvenile stages, they have not been documented (Bakkala 1981).

Prey

Yellowfin sole feed on a broad range of organisms from the benthos (bivalves and worms), in the water column (amphipods, euphausids and mysids) to the pelagia (smelt and capelin). About 50 different taxa were found in the stomachs of yellowfin sole by Skalkin (1963).

Feeding generally stops in winter although some instances of intense winter feeding have been recorded (Fadeev 1970a). Feeding is more intense as they migrate onto the central shelf.

Primary food of yellowfin sole are bivalves, echurid and polychaete worms and amphipods (Table 9).

Table 9. Stomach contents (in grams) by size group of yellowfin sole collected in the eastern Bering Sea in 1970 (Wakabayashi 1974).

Food	Size group 101-200 mm	201-300 mm	>300 mm	Total
Gadidae	-	60.3	26.8	87.1
Osmeridae	-	12.7	-	12.7
Ammodytidae	-	12.5	56.4	68.9
Other Pisces	-	36.4	18.4	54.8
Amphipoda	22.6	180.2	45.3	248.1
Euphausiacea	1.6	61.7	38.1	101.4
Macrura	3.7	22.8	24.1	50.6
Mysidacea	0.4	-	0.2	0.6
Brachyura	-	39.4	7.8	47.2
Anomura	1.7	51.5	18.3	71.5
Crangonidae	0.3	10.0	0.8	11.1
Polychaeta	31.4	360.9	63.1	455.4
Cephalopoda	-	-	1.7	1.7
Bivalvia	6.5	403.6	553.1	963.2
Gastropoda	-	1.3	10.4	11.7
Ophiuroidea	2.3	36.1	1.4	39.8
Scutellidae	6.4	33.2	17.2	56.8
Echiurida	9.2	245.4	398.4	653.0
Ascidia	0.2	13.7	4.2	18.1
Holothuroidea	-	34.8	3.5	38.3
Sand[1]	7.2	91.9	13.7	112.8
Others	12.8	108.2	163.6	284.6
Indistinct	12.9	64.2	27.7	104.8
Total	119.2	1,878.3	1,496.7	3,494.2
No. of stomachs	275	1,708	374	2,357

[1]Possibly tubes of Polychaeta.

Associated Species

Species closely associated with yellowfin sole are shown in Table 10. Alaska plaice (Pleuronectes quadrituberculatus) is the only species which showed affinity to yellowfin sole in all studies. Pacific halibut, which were indicated to be closely associated with yellowfin sole by Novikov (1964), was not mentioned by any of the authors in Table 10.

ABUNDANCE BY YEAR, SUBAREAS, AGE AND YEAR CLASSES

Annual Biomass Estimates

The biomass of the exploitable stock (6 yrs and older) of eastern Bering Sea yellowfin sole prior to the intensive post World War II trawl fisheries of the late 1950s and early 1960s was estimated to be 1.3 to 2.0 million t (Alverson et al. 1964, Wakabayashi 1975). The stock declined in abundance, presumably as a consequence of excessive removals in 1960-62 and fluctuated at relatively low levels of abundance until recently.

Biomass of eastern Bering Sea yellowfin sole in 1975 through 1984 was estimated from annual trawl surveys of the NWAFC (discussed previously and given in Table 1). The subareal distribution of yellowfin for 1975-83 was also discussed in the same section and shown in Table 2.

The age composition of the yellowfin sole as estimated from sampling the catches of the annual trawl surveys and commercial landings is given in Fig. 10. The strong year classes of 1966-70 have dominated the catches of both the research vessels and commercial fisheries. These year classes have ranged from 13 to 17 years in the 1983 commercial catch and constituted 45% of the commercial catch of 1982 (Bakkala and Wespestad 1984a). The 1973-77 year classes were well represented in the 1982 trawl survey catches. These year

Table 10. Species showing close association with yellowfin sole as indicated by recurrent group analysis.

Authority	Season	Years of study	Species showing affinity with yellowfin sole
Kihara (1976)	Summer	1966-71, 1974	Alaska plaice (Pleuronectes quadrituberculatus) Rock sole (Lepidopsetta bilineata) Flathead sole (Hippoglossoides elassodon) Pacific cod (Gadus macrocephalus) Walley pollock (Theragra chalcogramma) Cottidae Agonidae
Mito (1977)	Winter	1972, 1974-75	Alaska plaice (P. quadrituberculatus) Rock sole (L. bilineata) Yellow Irish Lord (Hemilepidotus jordani) Plain sculpin (Myoxocephalus jaok)
Pereyra et al. (1976)	Summer	1975	Alaska plaice (P. quadrituberculatus) Pacific herring (Clupea pallasi)
Bakkala and Smith (1978)	Spring	1976	Alaska plaice (P. quadrituberculatus) Pacific herring (C. pallasi) Sturgeon poacher (Podothecus acipenserinus) Capelin (Mallotus villosus)

Source: Bakkala 1981.

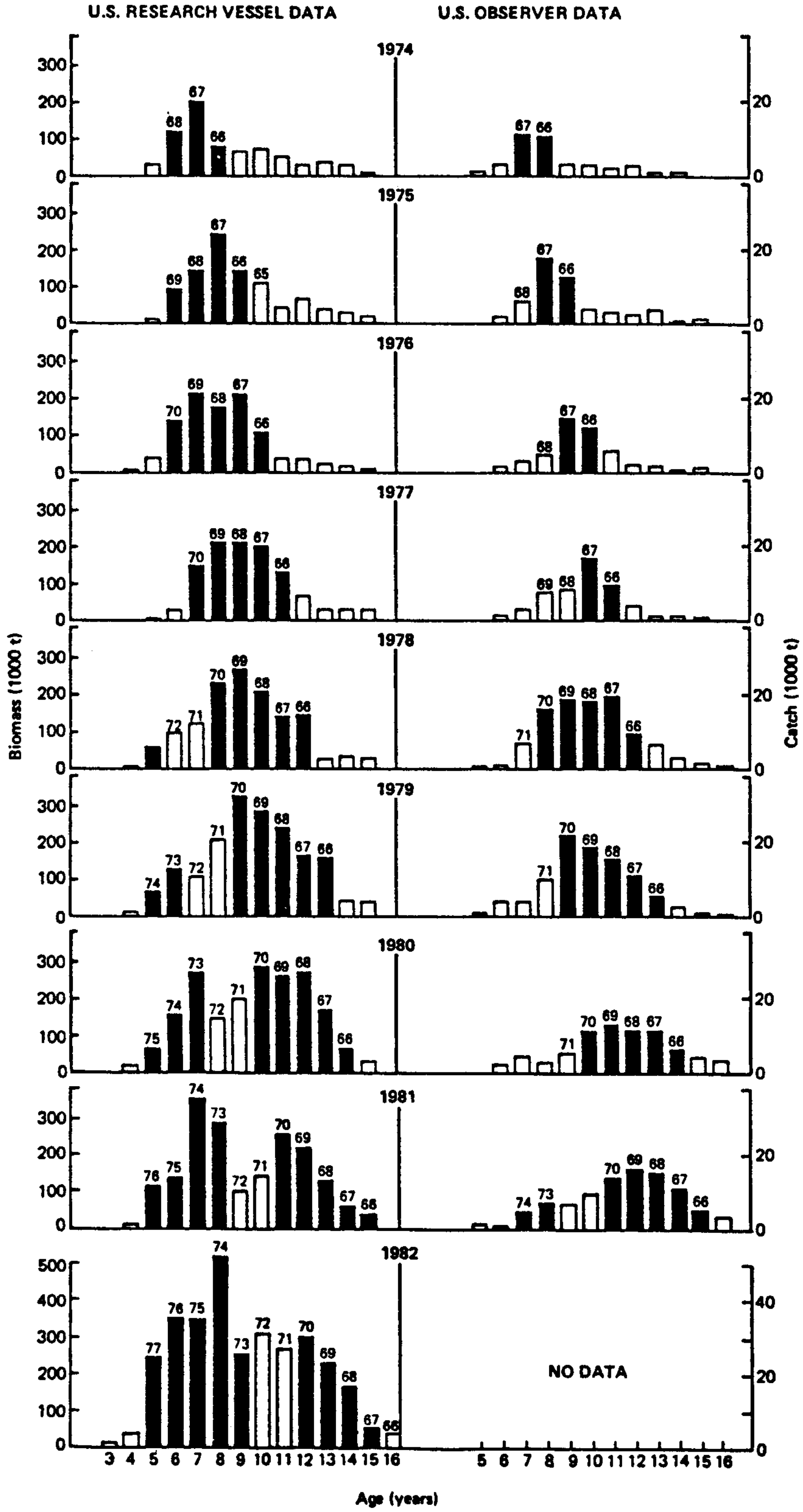


Figure 10. Age composition of yellowfin sole of the eastern Bering Sea as shown by data from trawl surveys of the Northwest and Alaska Fisheries Center and by U.S. observer data from the commercial fishery.

classes appear to be even more abundant than the 1966-70 year classes and contributed substantially to the increase in population abundance in 1981-83.

There is evidence that the strong year classes of 1966-70 were associated with warm bottom temperatures (2.5°-4°C) whereas the weaker year classes were associated with cooler bottom temperatures (Bakkala 1981).

Population Estimates from Cohort Analyses

Estimates of the eastern Bering Sea yellowfin sole in numbers and weight are given in Tables 11 and 12, respectively. According to these analyses, yellowfin sole were most numerous in 1977 due to the large contributions of the 1974-77 year classes (Table 11). Total estimated biomass was lowest in 1970 and highest in 1981, the last year included in the analysis (Table 12). Biomass of the exploitable population (7 years and older) was also largest in 1981.

Relative Abundance (Catch per Unit Effort)

The catch per unit effort (CPUE) of Japanese pair trawlers and NWAFC trawl surveys is shown in Fig. 11. The CPUE of pair trawlers in the September-December fishery peaked at over 50 t/1000 hp-hrs in 1980 and dropped rather sharply to less than 20 t/1000 hp-hrs in 1983. CPUE in the July-October fishery peaked in 1979 at about 30 t/1000 hp-hrs and declined to about 15 t/1000 hp-hrs in 1983.

The CPUE of the NWAFC trawl survey increased to about 80 kg/ha in 1983 with a modest decline in 1984. There has been no evaluation of the inconsistency in the two measures of relative abundance. Bakkala and Wespestad (1984b) do not believe the CPUE of the pair trawlers accurately represent the abundance of yellowfin sole. These authors have, however,

Table 11. Estimated numbers of yellowfin sole (billions of fish) in the eastern Bering Sea, 1959-81, based on cohort analysis.

Age (yr)	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
1	2.040	1.620	0.931	1.407	1.108	1.047	1.320	1.519	2.394	2.779	3.693	5.662
2	2.308	1.810	1.437	0.826	1.248	0.983	0.928	1.171	1.347	2.123	2.465	3.275
3	2.826	2.047	1.605	1.275	0.733	1.107	0.871	0.823	1.039	1.195	1.883	2.186
4	1.029	2.506	1.815	1.424	1.130	0.650	0.976	0.773	0.730	0.921	1.060	1.670
5	1.382	0.912	2.223	1.599	1.263	1.003	0.565	0.865	0.685	0.648	0.817	0.940
6	1.856	1.226	0.809	1.947	1.406	1.119	0.871	0.501	0.767	0.608	0.574	0.724
7	1.865	1.640	1.063	0.696	1.596	1.223	0.945	0.771	0.444	0.668	0.538	0.501
8	1.565	1.632	1.342	0.793	0.376	1.383	0.959	0.832	0.670	0.358	0.565	0.471
9	1.234	1.336	1.282	0.792	0.363	0.273	1.006	0.809	0.697	0.501	0.289	0.410
10	0.923	0.989	0.950	0.579	0.366	0.233	0.190	0.809	0.624	0.480	0.379	0.166
11	0.625	0.670	0.588	0.324	0.256	0.241	0.148	0.147	0.570	0.401	0.353	0.172
12	0.377	0.419	0.320	0.174	0.114	0.168	0.151	0.104	0.097	0.308	0.283	0.160
13	0.213	0.245	0.165	0.098	0.045	0.063	0.105	0.104	0.058	0.059	0.210	0.111
14	0.118	0.138	0.084	0.059	0.021	0.016	0.042	0.074	0.056	0.028	0.034	0.113
15	0.063	0.079	0.044	0.036	0.013	0.004	0.009	0.031	0.045	0.021	0.014	0.006
16	0.038	0.042	0.025	0.022	0.008	0.002	0.002	0.006	0.022	0.021	0.009	0.004
17	0.019	0.026	0.012	0.014	0.005	0.000	0.002	0.002	0.003	0.012	0.012	0.000
	18.482	17.337	14.695	12.064	10.051	9.513	9.089	9.343	10.250	11.130	13.177	16.571

Age (yr)	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
1	6.117	3.542	2.390	5.964	6.791	5.461	7.389	2.674	0.000	0.000	0.000
2	5.022	5.425	3.141	2.120	5.289	6.023	4.843	6.554	2.372	0.000	0.000
3	2.905	4.454	4.812	2.786	1.880	4.691	5.342	4.196	5.813	2.104	0.000
4	1.939	2.576	3.950	4.268	2.471	1.668	4.161	4.738	3.810	5.155	1.866
5	1.481	1.719	2.285	3.504	3.785	2.192	1.479	3.690	4.201	3.379	4.572
6	0.833	1.313	1.521	2.024	3.107	3.356	1.940	1.308	3.261	3.720	2.993
7	0.629	0.715	1.134	1.336	1.787	2.753	2.963	1.711	1.147	2.870	3.283
8	0.380	0.402	0.572	0.921	1.157	1.562	2.418	2.610	1.455	0.998	2.514
9	0.323	0.240	0.336	0.425	0.751	0.986	1.358	2.105	2.191	1.244	0.867
10	0.254	0.190	0.177	0.242	0.332	0.560	0.799	1.171	1.759	1.859	1.064
11	0.116	0.127	0.145	0.120	0.195	0.215	0.444	0.642	0.946	1.482	1.588
12	0.101	0.077	0.092	0.091	0.086	0.141	0.167	0.349	0.472	0.782	1.258
13	0.071	0.044	0.056	0.046	0.069	0.064	0.118	0.133	0.273	0.376	0.648
14	0.055	0.021	0.029	0.022	0.030	0.046	0.049	0.100	0.098	0.220	0.293
15	0.050	0.002	0.012	0.013	0.012	0.016	0.039	0.041	0.077	0.080	0.174
16	0.002	0.007	0.002	0.004	0.006	0.006	0.010	0.033	0.032	0.064	0.064
17	0.000	0.000	0.006	0.001	0.002	0.002	0.004	0.008	0.027	0.027	0.048
	20.276	20.856	20.659	23.885	27.751	29.743	33.524	32.163	27.932	24.359	21.232

Source: Bakkala and Wespestad 1984.

Table 12. 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 (yr)	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
1	10	8	5	7	6	5	7	8	12	14	18	28
2	21	16	13	7	11	9	8	11	12	19	22	29
3	51	37	29	23	13	20	16	15	19	22	34	39
4	34	83	60	47	37	21	32	26	24	30	35	55
5	77	51	124	90	71	56	32	48	38	36	46	53
6	163	108	71	171	124	98	77	44	68	53	51	64
7	209	184	119	78	179	137	106	86	50	75	60	56
8	211	220	181	107	51	187	129	112	90	48	76	64
9	196	212	204	126	58	43	160	129	111	80	46	65
10	171	183	176	107	68	43	35	150	115	89	70	31
11	131	141	124	68	54	51	31	31	120	84	74	36
12	88	97	74	40	26	39	35	24	23	71	66	37
13	56	65	43	26	12	17	28	28	15	16	55	29
14	33	39	24	16	6	5	12	21	16	8	9	32
15	19	23	13	11	4	1	3	9	13	6	4	2
16	13	15	9	8	3	1	1	2	8	8	3	1
17	7	10	4	5	2	0	1	1	1	4	5	0
	1491	1492	1273	938	723	733	711	744	735	664	675	622
7+	1135	1189	971	592	461	523	540	593	562	489	469	353

Age (yr)	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
1	31	18	12	30	34	27	37	13	0	0	0
2	45	49	28	19	48	54	44	59	21	0	0
3	52	80	87	50	34	84	96	77	105	38	0
4	64	85	130	141	82	55	137	156	126	170	62
5	83	96	128	196	212	123	83	207	235	189	256
6	73	116	134	178	273	295	171	115	287	327	263
7	70	80	127	150	200	308	332	192	128	321	368
8	51	54	77	124	156	211	326	352	196	135	339
9	51	38	53	68	119	157	216	335	348	198	138
10	47	35	33	45	61	104	148	217	326	344	197
11	24	27	30	25	41	45	93	135	199	311	334
12	24	18	21	21	20	33	39	81	109	181	292
13	19	12	15	12	18	17	31	35	72	99	171
14	15	6	8	6	8	13	14	28	27	62	82
15	15	1	3	4	4	5	12	12	23	24	51
16	1	3	1	1	2	2	4	12	11	23	23
17	0	0	2	0	1	1	2	3	10	10	17
	666	717	890	1071	1314	1534	1783	2029	2224	2432	2593
	317	273	371	456	631	895	1216	1401	1450	1708	2012

Source: Bakkala and Wespestad 1984.

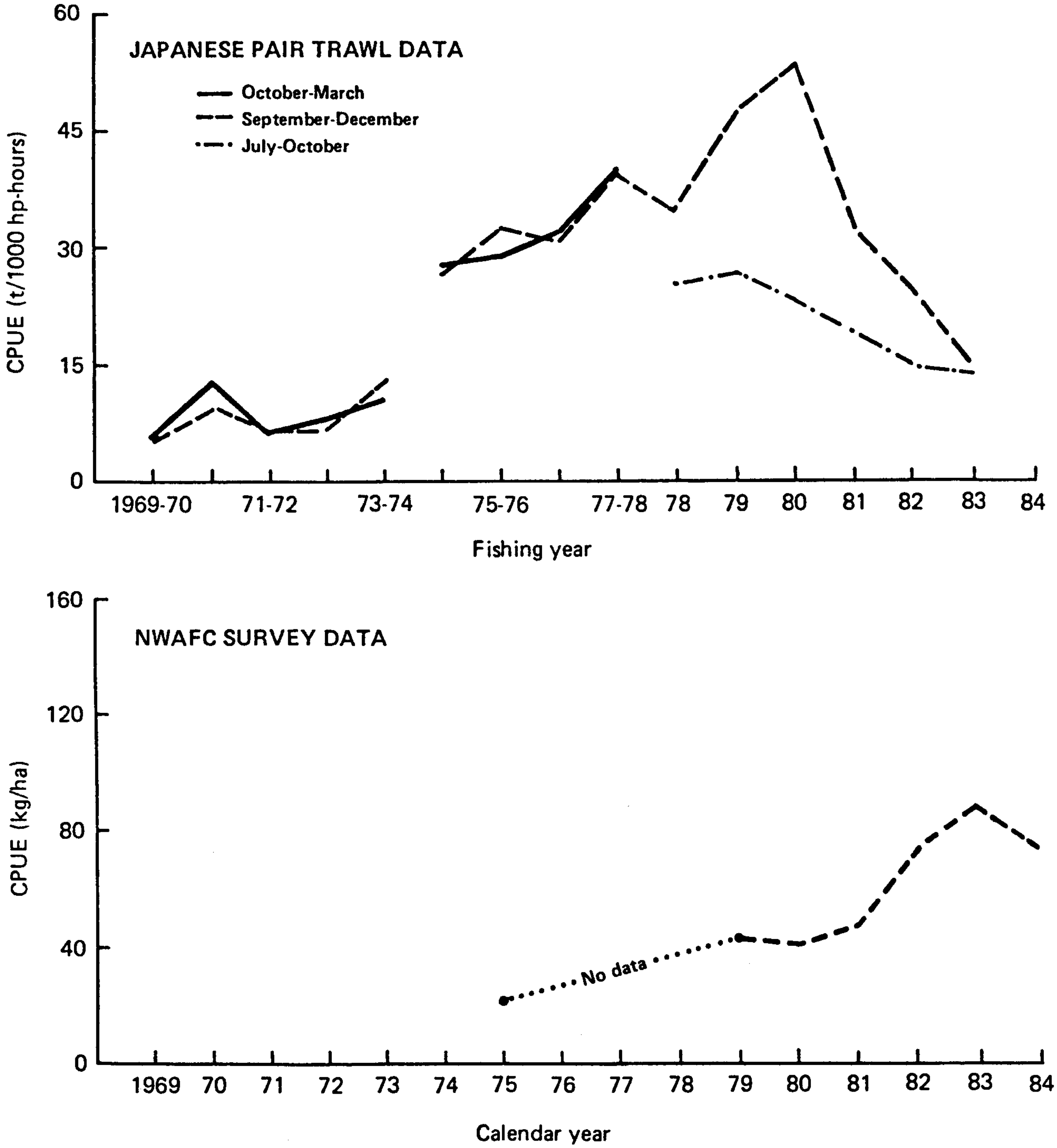


Figure 11. Relative abundance (CPUE) for Japanese pair trawlers and NWAFC trawl surveys.

presented evidence which suggests that the apparent increase in abundance reflected by the NWAFC trawl surveys after 1981 may be attributable to the better bottom tending qualities of the sampling gear (Bakkala and Wespestad 1984a and 1984b). This probably resulted in better estimates of the population since 1981, however, the siginificance of the abundance trend is questionable due to underestimation of the yellowfin sole population prior to 1982.

THE COMMERCIAL FISHERY

Yellowfin sole were first taken by Japanese trawlers which fished for flounders in the eastern Bering Sea beginning in 1929 (Kibesaki 1965). From 1933 through 1937, one factory ship (fish and meal) and accompanying trawlers were involved in a full scale reduction fishery. Japanese trawling in eastern Bering Sea was interrupted during World War II.

In 1954, the trawl fishery in eastern Bering Sea was resumed when Japanese trawlers caught about 12,500 t of yellowfin sole (Table 13). Until 1958 the Japanese fishery occurred on the eastern Bering Sea shelf during a short period during the summer and the fish were frozen for human consumption.

In 1958 the fishery was intensified and the catch reduced to meal as well as frozen for food. The Soviet Union also commenced fishing yellowfin sole in this year.

From 1960 through 1962, the combined catch of Japan and the Soviet Union exceeded 420,000 t (max. > 550,000 t). In 1963, however, the total catch of yellowfin sole dropped to 85,810 t (about 20% of the catch in 1962). Since then, total annual catches have been between 167,000 t (1969) and 42,000 t

Table 13. Annual catches of yellowfin sole in the eastern Bering Sea (east of long. 180° and north of lat. 54°N) in metric tons.[a]

Year	Japan	USSR	ROK[b]	Others	Joint venture	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	-			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
1982	68,009		10,277	45	17,381	95,712
1983	64,824		21,050		22,511	108,385

[a]Source of catch data: 1954-76, Wakabayashi and Bakkala 1978; 1977-79, data submitted to the United States by fishing nations; 1980-82, French et al. 1981, 1982; Nelson et al. 1983, 1984.
[b]Republic of Korea.

(1974). Except for a token catch in 1980, the Soviet fishery for yellowfin sole was essentially terminated in 1979.

The Republic of Korea (R.O.K.) began fishing for yellowfin sole in the eastern Bering Sea in 1976, however, catches were very modest through 1979 and have remained at less than 22,000 t, thereafter.

The combined annual catches of foreign countries other than the three mentioned above have ranged from 3 to 269 t.

United States fishing vessels involved in joint-ventures with foreign fishing companies have fished yellowfin sole since 1980. Annual landings by these vessels has increased from 9600 t in 1980 to 22,500 t in 1983.

Monthly distribution of Catch

In the recent six years 1979-84, most of the yellowfin sole catches were made after June (Table 14). More than 75% of the annual catch in all three years was taken in the last two quarters of the calendar year (Table 14).

Fishery Management

Prior to enactment of the Fishery Management and Conservation Act of 1976 (FCMA), the domestic and foreign fisheries for groundfish in the eastern Bering Sea were subject to regulations which included gear restrictions, licensing of vessels and gear, time-area closures, requirements for reporting catches or landings and quotas on the catch for some species in some years. The Fishery Management Plan (FMP) for the Groundfish Fishery in the Bering Sea/Aleutian Islands Area (October 1983) prepared by the North Pacific Fisheries Management Council (NPFMC) contains a detailed summary of historical regulations. The FMP also describes the rationale and management of current foreign and domestic fisheries in the 3 to 200 mile economic zone.

Table 14. Yellowfin sole catch by month, 1979-84

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Q-1	Q-2	Q-3	Q-4	Total
								Foreign reported catch									
1979	3152	3344	1412	2295	282	1341	10686	15293	20141	22265	10217	1889	7908	3918	46120	34370	92316
1980	3699	3567	3250	2090	2005	3102	13801	11007	11826	10461	4736	4843	10516	7197	36633	20039	74385
1981	1819	2506	2943	3923	2548	4333	8597	9374	11248	10472	9970	9364	7268	10805	29219	29806	77097
1982	3795	1504	2947	1708	1676	2933	8727	8551	9540	10313	12113	7887	8246	6316	26819	30313	71695
1983	718	1451	2816	3371	3561	2974	10360	13366	10328	10148	9107	15139	4986	9906	34054	34394	83339
1984	783	1134	3353	7927	4887	2269	11854	21476	13339	21389	15589	15342	5270	15083	46669	52320	119342
1985	8530	2315	6192	4643													
NOTE: 1984 and 1985 are from "Observer" estimate file.																	
							Joint-venture: best blend estimate of catch										
1979	No observer data file																
1980	+	0	2	12	254	2084	2868	2546	1857	0	0	0	2	2350	2019	0	4371
1981	0	0	0	+	2702	1546	4153	3679	3966	+	0	0	0	4248	11798	+	16046
1982	0	0	6	1098	1431	7077	4073	2791	904	1	+	0	6	9606	7768	1	17381
1983	0	+	1893	1742	4353	6153	3566	4401	338	0	0	0	1893	12252	8304	0	22449
1984	+	12	107	2289	6426	8895	4168	5282	5199	338	0	0	119	17610	14648	338	32715
1985	+	21	195	4885													
				Bering Sea Area I - Catch of yellowfin sole (Total directed and joint-venture)													
1979	3152	3344	1412	2295	282	1341	10686	15293	20141	22265	10217	1889	7908	3918	46120	34370	92316
1980	3699	3567	3252	2102	2259	5186	16669	13553	13683	10461	4736	4843	10518	9547	38652	20039	78756
1981	1819	2506	2943	3923	5250	5879	12750	13053	15214	10472	9970	9364	7268	15053	41017	29806	93143
1982	3795	1504	2953	2806	3107	10010	12800	11342	10444	10314	12113	7887	8252	15922	34587	30314	89076
1983	718	1451	4709	5113	7914	9127	13926	17767	10666	10148	9107	15139	6879	22158	42358	34394	105788
1984	783	1146	3460	10216	11313	11164	16022	26758	18538	21727	15589	15342	5389	32693	61317	52658	152057
1985	8530	2336	6387	9528													

Source: Data on file, Observer Program, NWAFC, Seattle, WA.

Priority objectives of the FMP for the management of groundfish fisheries of eastern Bering Sea are to:

1. Provide for the rational and optimal use, in a biological and socio-economic sense, of the region's fisheries resources as a whole;

2. Minimize the impact of groundfish fisheries on prohibited species (including halibut, herring salmonids, shrimps, scallops, snails, king crab, Tanner crab, Dungeness crab, corals surf clams, horsehair crab and lyre crab) and continue the rebuilding of the Pacific halibut resources;

3. Provide for the opportunity and orderly development of domestic groundfish fisheries, consistent with 1. and 2. above and;

4. Provide for foreign participation in the groundfish fishery, consistent with all three objectives above, to take the portion of the total allowable catch (TAC) not utilized by domestic fishermen.

The following management actions pertain specifically to the yellowfin sole fishery of the eastern Bering Sea.

Total Allowable Catch (TAC)

The TAC of yellowfin sole in the Bering Sea/Aleutian region and its allocation to foreign and domestic fisheries under the FCMA is shown in Table 15. Except in 1978 (when the catch exceeded TAC by 12,000 t), annual catches have been less than the TAC. Most of the TAC has been allocated to foreign fisheries, although catches have been less than allocations for all years except 1978. Until 1980, the total allocation was to foreign fisheries. Since 1980, domestic production and the joint venture fisheries have taken a comparatively small but increasing proportion of the TAC.

Table 15. Total allowable catch of yellowfin sole and its allocation under the FCMA.

Year	Total Allowable Catch (OY)	Total Catch	U.S. Allocation DAP	U.S. Allocation JVP	J-V Catch	Foreign Fisheries Allocation	Foreign Catch	Reserves
1977	106,000	58,373	0	0	-	102,900	58,373	3,100
1978	126,000	138,433	0	0	-	126,000	138,433	0
1979	106,000	99,017	0	0	-	106,000	99,017	0
1980	117,000	87,391	100	15,614	9,623	101,286	77,768	0
1981	117,000	97,301	200	17,000	16,046	99,800	81,255	0
1982	117,000	95,712	1,200	18,000	17,381	96,400	78,331	1,400 (non-allocated)
1983		108,385			22,511		85,874	

Source: Data on file, NWAFC.

Annual catches in the years 1981-83 has been less than both the "most likely" maximum sustainable yield (MSY) of 150,000 to 175,000 t and the equilibrium yield of 310,000 t for the 1984 standing stock suggested by Bakkala and Wespestad (1984).

Fishing is terminated when the allocation of target species is taken or when the allocation of bycatch species is exceeded.

Time and Area Restrictions

Time and area closures for trawl fisheries and, therefore, to yellowfin sole fishing are shown in Fig. 12. A large sector of the North Aleutian Shelf has been designated as the Bristol Bay Pot Sanctuary which is closed year-round to foreign trawl fisheries. The waters north of the eastern Aleutians, eastward of 170°W is closed to foreign trawling from December 1 to May 31 for the protection of juvenile halibut.

STATUS OF THE EASTERN BERING SEA YELLOWFIN SOLE STOCK

The available evidence indicates that the eastern Bering Sea yellowfin sole stock is presently in excellent condition. The average total biomass for 1981-83 of 3.1 million t is the highest of recorded biomass estimates. The present population has an exploitable biomass which is equal to and perhaps greater than the exploitable biomass of the virgin stock. Furthermore, the age structure of the population indicates that yields may remain stable at high levels for at least the next few years. The strong year classes of 1966-70 still contribute substantially to the catch and a new series of year classes (1973-77) which may be even stronger are now entering the fishery. Catches in recent years have been less than TAC (117,000 t in 1982) and

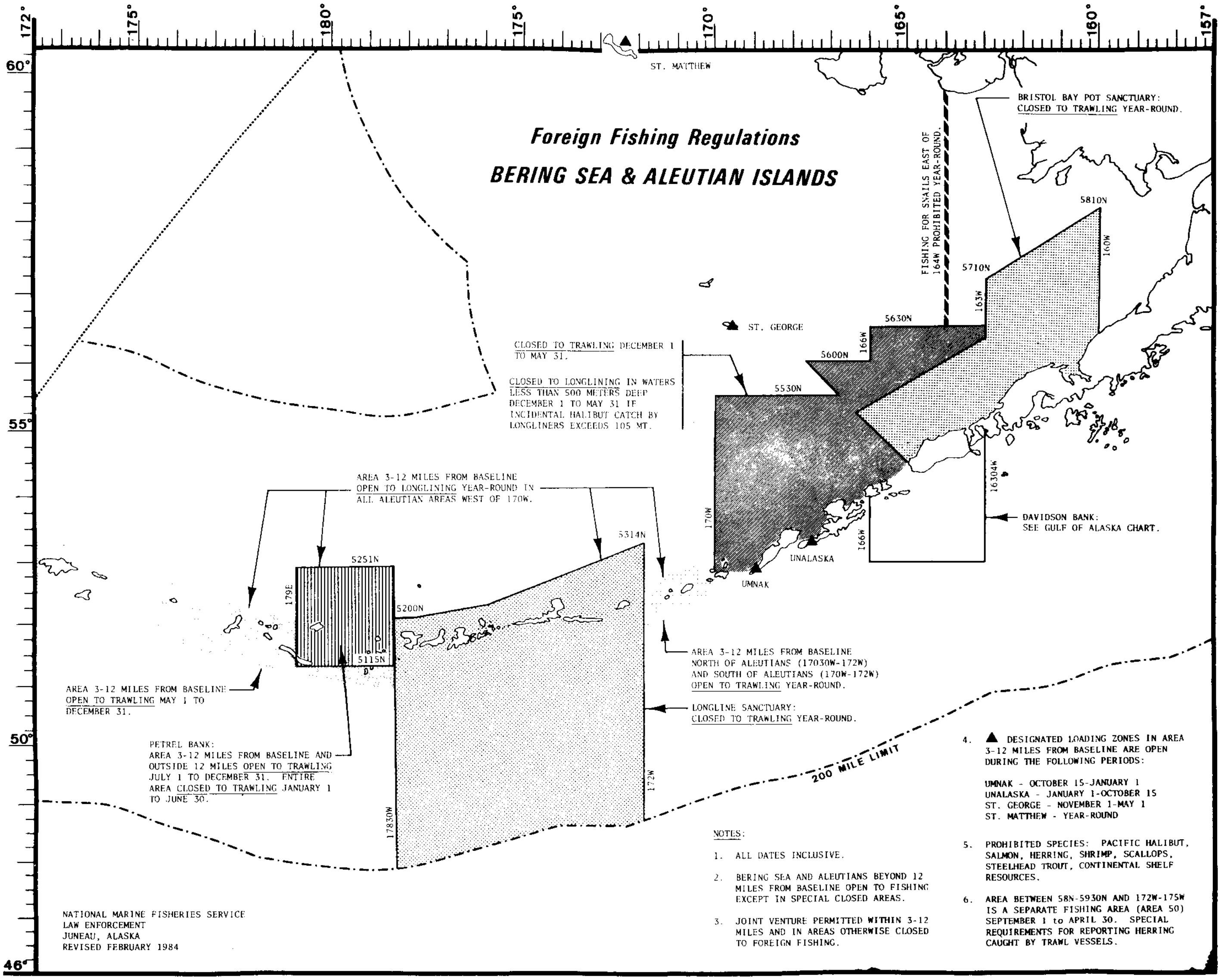


Figure 12. Time area restrictions applicable to non-U.S. groundfish fisheries in the eastern Bering Sea and Aleutian Islands regions.

considerably below estimated MSY (150,000-175,000 t) and present equilibrium yield of 310,000 t.

Forecasts of yellowfin sole abundance in the eastern Bering Sea are given in Table 16. The assumed catch of 214,500 t is considerably greater than the actual catch of recent years and both assumed recruitment levels are less than the estimated average recruitment of 2.1 billion fish for the 1973-80 period (Bakkala and Wespestad 1984a).

SENSITIVITY OF FLATFISH TO PETROLEUM AND DISTILLATES

The effects of oil on fish have been observed after some past oil spills and studied in the laboratory, however, I found no studies relating specifically to yellowfin sole. There have, however, been studies on other flatfish, the results of which may be applicable to assessing the impact of oil on yellowfin sole.

As a general rule, eggs and larvae of both fish and shellfish have been found to be more sensitive to petroleum hydrocarbons than adults.

Sensitivity of Eggs and Larvae

The 1978 year class of flatfish originating in the year of the spill of the Amoco Cadiz (March 16-17, 1978) was totally absent in subsequent years (Desaunay 1979, Conan & Friha 1979, Laubier 1980). Although there was no direct supporting evidence, this was indicative of total mortality to eggs and larvae as a consequence of oil contamination from the spill of the Amoco Cadiz.

Malins et al. (1981) exposed flatfish eggs to saltwater soluble fraction (SWSF) of slightly weathered Prudhoe Bay crude oil (PBCO) with renewal of SWSF

Table 16. Forecast of yellowfin sole abundance in the eastern Bering Sea, 1982-89, with constant catches of 214,500 t, natural mortality = 0.12, assuming lower (upper table) and higher recruitment estimates 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[a]	F[b]	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
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

[a]E = Exploitation rate for fished population (ages 8-17).
[b]F = Fishing mortality.

Source: Bakkala and Wespestad 1984

at mid-incubation. High embryo and larval mortality, gross abnormalities or pathological changes occurred at 100-500 ppb. At average concentrations of 130-165 ppb, percent hatching was high but all hatched larvae were either abnormal or dead. Test fish were similar to control fish only at concentrations of 80 ppb and less. Sandsole (Psettichthys melanostictus) embryos exposed to 164 ppb SWSF of weathered PBCO showed retinal and brain pathological changes.

Mazmanidi and Bazhashvili (1975) exposed Black Sea flounder (Platichthys luscus) at various stages to Water Soluble Fraction (WSF) of crude oil at concentrations of 2.5 to 0.025 ppm. All concentrations greater than 0.025 ppm were found to be toxic. Eggs exposed in the gastrulation stage died immediately. Embryos in more advanced stages hatched but died soon after. Surviving larvae exhibited scoliosis, reduced activity and rate of yolk absorption as well as abnormalities in heart rate and pigment configuration.

Similar experiments were done by Kanter et al. 1983 in which eggs, larvae and adults of California halibut (Paralichthys californicus) were exposed to 3 concentrations, of Santa Barbara crude oil (Table 17) which has a chemical composition very similar to Middle Eastern and Alaskan (Cook Inlet (CICO) and Prudhoe Bay) crude oils.

After 72 hours of exposure, halibut embryo showed a marked accumulation of petroleum hydrocarbons, particularly at the medium (91.3 ppb) and high (761 ppb) concentrations. Embryo mortality was directly related, and hatching success inversely related, to oil concentration. Size of hatched larvae was significantly smaller at the highest concentrations. The frequency of malformed larvae was significantly higher than controls at all concentrations of oil exposure and markedly higher at the highest concentration.

Table 17. Petroleum hydrocarbon uptake expressed as counts per minute (cpm) of radioactive tracer, embryo mortality, hatching success, total length of newly-hatched (mm), and malformed newly-hatched California halibut larvae following 72 hours of embryonic test solution exposure. All stared (*) elements were statistically significantly different from control values.

Concentration	Petroleum hydrocarbon uptake	Mean % embryo mortality	Mean % hatching success	Mean length mm) of newly-hatched larvae	Mean % malformed newly-hatched larvae
Control	2.8	13.3	86.7	2.29	1.9
Low	16.0	16.4	83.2	2.34	5.7*
Medium	85.2*	22.0*	78.0*	2.33	6.7*
High	267.7*	29.0*	71.0*	1.99*	20.6*

Source: Kanter et al. 1983

Larvae of California halibut were exposed to petroleum hydrocarbon concentrations of 10.5, 69.5 and 606 ppb. Survival of larvae was inversely proportional to concentration and duration of exposure. Halibut survived less than 7 days in the high regime and less than 14 days in medium concentrations. Some halibut survived the entire 18 days of the experiment in the low concentration regime, however, survival was significantly less than in the controls. Larvae exposed to the high concentration were smaller and less well developed. Larvae exposed to the medium concentration regime for 7 days had reduced growth and higher incidence of structural abnormalities. Larvae in the low concentration regime had significantly reduced growth rate but no evidence of delayed or abnormal development. Reduced growth of halibut larvae exposed to the medium concentration was closely associated with reduced or delayed development, abnormal swimming behavior and failure to feed. These observations indicate that a combination of reduced development and abnormal feeding behavior resulted in reduced growth rates. All medium concentration larvae died soon after yolk absorption, suggesting that impaired feeding due to petroleum hydrocarbon exposure was the primary cause.

Plaice (*Pleuronectes platessa*) and flounder (*Platichthys flesus*) exposed to crude oil for even short periods (1-15 hrs) developed deformed notochords and severe abnormalities in the head region (Lonning 1977).

Sensitivity of Juvenile Flatfish

The effect of the *Amoco Cadiz* spill was reported to be greatest among young sole (*Solea vulgaris*) and adult plaice. Up to 80% of the fish examined showed fin rot up to 9 months after the spill (Conan and Friha 1981). Growth rate was also reduced in adults as well as younger flatfish. It is not known whether or how much these factors contribute to the mortality of flatfish. Other evidence such as the absence of the 1978 year class in catches indicate oil-imposed mortality to the flatfish populations in some areas of the *Amoco Cadiz* accident. Although reduced growth rates were observed, there was no verifiable evidence of large mortalities to either juvenile or adult flatfish.

The available experimental evidence indicates that juvenile flatfish have far greater tolerance to petroleum than do eggs and larvae and are comparable to adults in that respect. Juvenile English sole (*Parophrys vetulus*) exposed for up to 7 days to sediments impacted with CICO and juvenile starry flounder (*Platichthys stellatus*) exposed to PBCO impacted sediments up to 6 weeks caused no change in disease resistance.

Sensitivity of Adults

Acute Toxicity

Rice et al. 1979 estimated the 96TLm for starry flounder to be 5.34 ppm of total aromatics CICO.

Sublethal Effects

Sublethal effects of petroleum hydrocarbons on flatfish include reduction in feeding, vitality and resistance to disease, alterations in behavior (including spawning) and tainting. Animals are known to accumulate and biomagnify hydrocarbons as well as to convert certain compounds to carcinogenic and mutagenic metabolites.

McCain et al. (1978) exposed three species of flatfish to sediments mixed with 0.2% (v/v) Prudhoe Bay crude oil. Adult rock sole and starry flounder showed no petroleum-related adverse effects. During the first month, half the English sole developed cellular abnormalities in the liver. Fish exposed to oil-sediment weighed significantly less than control fish. During the 4 month duration of the experiment, no control fish died whereas 18% of the oil-exposed fish died or were moribund and emaciated. Poor feeding and weight loss was greatest in the first 30 days when the total extractable petroleum hydrocarbon (TEPH) was between 400-700 μg/g (dry weight). Winter flounder (Pseudopleuronectes americanus) exposed to freshly oiled sediments were also observed to have reduced feeding rates (Fletcher et al. 1981).

Growth was almost arrested for a year in plaice (P. platessa) and reduced in dab (Limanda limanda) after the Amoco Cadiz spill. The reductions in observed growth were partially due to a scarcity of benthic prey and partly to a state of physiological deterioration (Desaunay 1979).

Prespawning, female starry flounder, exposed to WSF of monoaromatic hydrocarbons (ave. conc. = 117 ppb) for one week had an average concentration of monocyclic aromatics of 5.26 ppm in mature ovaries. The ripest female had an accumulation 236 times the water concentration of monoaromatics. Monocyclics were low or undectable in testes and immature ovaries (Whipple et al. 1978). There were no mortalities among females but they appeared to be stressed and had faster and more irregular ventilation rates. Eggs were pale and dead and opaque ovaries were observed after 4 days. There were no apparent effects on testes or on sperm motility. Flounders were thought to accumulate low boiling point compounds much more rapidly through the water column than through molluscan food items.

In the experiment with California halibut by Kanter et al. (1983), petrogenic hydrocarbons were accumulated in the gill, liver, digestive tract, muscle, gonad and eye from exposure to the high exposure (417 ppb) level. Only gill (7000 ng/g dry weight) and liver (about 5500 ng/g dry weight) tissue were damaged by petroleum hydrocarbon exposure.

ESTIMATED IMPACT OF HYPOTHETICAL OIL SPILL SCENARIOS OFF PORT MOLLER, PORT HEIDEN AND CAPE NEWENHAM ON EASTERN BERING SEA YELLOWFIN SOLE

In previous sections we have presented the available knowledge concerning distribution, life history and fishery of yellowfin sole. Although no information was available on the effects of oil on yellowfin sole, results of some studies on the sensitivity of other flatfish to different kinds and concentrations of petroleum hydrocarbons was discussed. By collating this information with estimates of the areas and concentrations of contamination expected from the hypothetical spill scenarios off Port Moller, Port Heiden and Cape Newenham, we can obtain provisional estimates of the impact of these spills on the productivity of yellowfin sole in eastern Bering Sea.

At this point, it may be useful to summarize and reiterate some factors relevant to such an assessment.

1. The Port Moller and Port Heiden hypothetical spill sites are located in the southerly portions of the NWAFC trawl Subarea 1 and the Cape Newenham site is slightly east of the middle of Subarea 4S. No other subareas will be impacted by these spill scenarios and, as will be shown later, only very small proportions of Subareas 1 and 4S are expected to be contaminated.

2. The yellowfin sole stock of eastern Bering Sea is very abundant (biomass greater than 3 million t) and broadly distributed over the shelf and upper slope. The stock is presently in excellent condition, the catch in recent years has been less than the allowable catch and the exploitation rate below the level for estimated equilibrium and maximum sustainable yields.

3. Adults inhabit deeper waters of the outer shelf and upper slope during late fall through early spring (November-March) and then migrate toward the inner shelf occupying these waters through summer and early autumn (May-September). Adults, therefore, are not in the area contaminated by the spill during the late autumn to early spring months when the liklihood of severe storms and tanker accidents is greatest. The average biomass percentage of the total eastern Bering Sea yellowfin sole in Subareas 1 and 4S as estimated by the NWAFC trawl surveys during May-October (1975, 1978-83) was 43% and 37%, respectively.

4. Yellowfin sole are found on sandy bottom and never on muddy or silty bottom. Longer term pollution is known to persist for longer periods over muddy and silty bottoms.

5. Spawning occurs from July-September, primarily in waters of northern Bristol Bay and northward (Subareas 4S, 4N and 5).

6. There is little knowledge regarding the distribution and life history of younger juveniles (<3 yrs). The available evidence indicates they are in bays and the shallower waters of Bristol Bay throughout the year, however, there are no estimates of their numbers or temporal-spatial distribution.

7. Yellowfin sole have high fecundity with estimates of the number of eggs per female ranging from 1.3 million (body length 25-30 cm) to 3.3 million (body length 40-45 cm). Although no estimates are available, natural mortality to eggs and larvae must be extremely high. Both eggs and larvae are pelagic.

8. Most foreign fishing for yellowfin sole has occurred after June with about 75% to 80% of the catch taken in the last two quarters of the calendar year (1981-84). In May-September, the fishery on the inner shelf is primarily

in Subarea 4S. Little or no foreign fishing has occurred in thode portions of Subarea 1 which might be impacted by spills, either at Port Moller or Port Heiden because a large part of Subarea 1 has been designated a pot sanctuary and is closed to foreign fishing year round. The domestic fishery, however, can and does operate in that area. Domestic catches (joint-venture fisheries) have been highest during the second and third quarters.

Fishing in October-April occurs mainly on the outer shelf and inner slope, well outside the areas which can reasonably be expected to be contaminated by the hypothetical spill scenarios.

Information regarding the effect of oil on flatfish is summarized in Table 18. Acute toxicity in flatfish eggs occurred at concentrations as low as 25 ppb (Black Sea flounder, Mazmanidi & Bazhashvili 1975) to greater than 606 ppb (California halibut, Kanter et al. 1983). The variation is undoubtedly attributable to differences in the species, petroleum and conditions of the experiments. Whether any of the results apply to yellowfin sole in eastern Bering Sea is uncertain. For purposes of this discussion, the results of Malins et al. (1981) will be considered to be most applicable for no other reason than their experiment subjected subarctic North Pacific species of flatfish of the same family as yellowfin sole to weathered PBCO. Based on their results and for the sake of simplicity, the lethal concentration of WSF of PBCO is assumed to be 100 ppb or 0.1 ppm. Although there is some evidence that larvae may be more sensitive than certain egg stages, the same concentration will be assumed to be lethal to 100% of the larvae in the contaminated area.

Rice et al. (1979) have estimated the 96TLm for adult starry flounder to be 5.34 ppm (total aromatics, CICO). For these discussions, it will be

Table 18. Summary of effects of petroleum hydrocarbons on flatfish.

Stage	Oil/conc.	Effect	Authority
Embryo	WSF crude/25 ppb	Immediate mortality in gastrulation stage. Latent death of later stages. Surviving larvae deformed or physiologically defective.	Mazmanidi & Bazhashvili (1975)
	SWSF PBCO/80 ppb	Similar to controls	
	SWSF PBCO/130-165 ppb	Percent hatching high but all larvae abnormal or dead.	Malins et al. (1981)
	SBCO/10.2 & 91.3 ppb	Embryo mort = 16.4-22%, malformed larvae signif. greater than in controls (5.7-6.7%).	Kanter et al. (1983)
	SBCO/606 ppb	Signif. smaller larvae. Mean mortality = 29%. Mean % malformed larvae = 20.6%	
Larvae	SBCO/10.5 ppb	Survival signif. less than in controls. Reduced growth but no abnormal development.	Kanter et al. (1983)
	SBCO/69.5 ppb	Reduced growth rate after 7 day exposure. All died in less than 14 days after yolk absorption.	
	SBCO/606 ppb	Significantly smaller, less developed and all died after 7 days.	
Adults	SBCO/7.5-46.6 ppb	Little or no accumulation in tissues. Some mortality after 4-5 weeks of exposure.	Kanter et al. (1983)
	SBCO/417 ppb	Significant accumulation in gills (6900 ng/g), liver (5400 ng/g) and digestive tract (1250 ng/g). Marked mortality after 4 weeks of exposure with total mortality in 7 weeks.	
	CICO/>5.34 ppm (total aromatics)	50% mortality in 96 hrs.	Rice et al. (1979)

assumed that 50% of the yellowfin sole in WSF and TARS concentrations greater than 5.0 ppm will die of acute oil toxicity.

The spill scenarios involve Prudhoe Bay crude oil and automotive diesel fuel. Prudhoe Bay crude oil is much more viscous than Cook Inlet crude oil and automotive diesel fuel a much less viscous and volatile petroleum product. The scenarios are summarized in Table 19.

The areas contaminated by various concentrations of water soluble fractions (WSF) from these oil spill scenarios were estimated by the Rand Corporation. Using this and certain biological information, the contamination, uptake and depuration of hydrocarbons by various commercially valuable species or species groups in eastern Bering Sea were simulated by Gallagher and Pola (1985) and Pola, Miyahara and Gallagher (1985). Estimated concentrations and areas contaminated in the hypothetical spills as given by Gallagher and Pola are summarized in Table 20. The proportions of Subareas 1 and 4S (which are approximately the same size, i.e., 83,366 km^2 and 81,540 km^2, respectively) contaminated by the blowout and accident scenarios is also given in this table.

The biomass of yellowfin sole has been estimated from trawl hauls made at a number of stations broadly distributed over 467,000 km^2 and several months. Although estimates of biomass are available by subareas, the distribution of that biomass in smaller time and space intervals is not available. For purposes of making first approximations of the impacts of these oil spill scenarios, I will assume that eggs and larvae, juveniles and adult yellowfin sole are uniformaly distributed in time and space throughout Subareas 1 and 4S. Given this assumption, the proportion of the subarea

Table 19. Hypothetical oil spill scenarios.

Scenario	Oil Type	Volume	Duration	Temperature	Grid	Bristol Bay
Well blowout	Prudhoe Bay crude	20,000 bbl/day	15 days	9.3°C	(50 x 50)	Port Moller Port Heiden Cape Newenham
Tanker accident	Automotive diesel	200,000 bbl (instantaneous)	10 days	9.3°C	(32 x 34)	Port Moller Port Heiden Cape Newenham

Source: Gallagher & Pola (1985)

contaminated by the spill approximates the proportion of the total yellowfin sole population within each area impacted by the spill.

Acute Toxic Mortality

Blowout Scenario

In the blowout scenario, WSF and TAR concentrations never exceeded 0.34 ppm. At this level, all contaminated eggs and larvae will be killed, but no acute toxic mortality would be expected to juveniles and adults. Since eggs and larvae are pelagic, only the WSF is pertinent. In the areas of spill impact, spawning occurs only in Subarea 4S and only during the third quarter. WSF of 0.34 ppm is estimated to persist for 17 days in 0.4% of the waters in Subarea 4S. Assuming their uniform distribution, mortality of eggs and larvae in subarea 4S from the blowout off Cape Newenham would also be 0.4%. This estimated mortality rate applies only to the eggs and larvae in the area during the 17 day interval of the blowout. Considering that spawning can occur over a period of 3 months, the total mortality to eggs and larvae produced in subarea 4S would probably be considerably less than 0.4%. Also, because as much or more spawning occurs north of Subarea 4S, a blowout off Cape Newenham would kill a considerably smaller proportion of the total eggs and larvae produced by eastern Bering Sea yellowfin sole.

Accident Scenario

The area contaminated was estimated to be similar in accident scenarios off Port Moller, Port Heiden and Cape Newenham. Since the total areas of the potentially impacted Subareas 1 and 4S were also quite similar (83,366 km^2 and 81,540 km^2, respectively), the proportion of each of these subareas that would becontaminated by spills at any one site is also approximately the same

(Table 20). There are, however, differences in the quantity and life history groups of yellowfin sole inhabiting the two subareas.

An accident at any of the hypothetical spill sites is expected to result in concentrations of WSF greater than 0.1 ppm over an area of 1000 km^2 for 15 days, contaminating 1.2% of subarea 1 or 4S. Since eggs and larvae are pelagic, only WSF and not TARS is of concern. Also, as noted above, there is little or no spawning in Subarea 1 and spawning in Subarea 4S occurs only during the third quarter. Assuming uniform distribution of eggs and larvae throughout Subarea 4S during the 15 day period of contamination from a tanker accident off Cape Newenham, a mortality of 1.2% can be expected (Table 21). Except for the remote possibility that all yellowfin sole spawning coincided exactly with the time of the spill, actual mortality within Subarea 4S would be expected to be substantially less than 1.2% because the normal duration of spawning (3 months) is 6 times the duration of WSF concentrations lethal to eggs and larvae. Also, because much spawning occurs to the north of Subarea 4S, an accident off Cape Newenham would be expected to inflict mortalities on far less than 1.0% of the total egg and larvae produced by the eastern Bering Sea yellowfin sole stock.

Natural mortality of eggs and larvae for species of flatfish other than yellowfin sole has been estimated to equal or exceed 99% (Cushing 1974, Bannister et al. 1974). Considering their very high fecundity, natural mortality in yellowfin sole can be expected to be as great. Thus, it is highly improbable that an oil imposed mortality of less than 1.0% can be isolated from the huge background of ongoing natural mortality. Even if detectable and measurable, the impact of oil imposed mortality on yellow fin

Table 20. Estimated concentrations and area contaminated by simulated oil spills at Port Heiden, Port Moller and off Cape Newenham

Scenario	Conc./days[1]	Area contaminated[1] km^2	Proportion of Subareas 1 & 2 contaminated[2]
Blowout			
WSF	max. 0.34 ppm/17	300	0.004
TARS	max. 0.34 ppm/8	300	0.004
Accident			
WSF	max. >5 ppm/4	50	0.0006
	1 - 5 ppm/12	450	0.005
	0.1 - 1 ppm/15	1000	0.012
TARS	5 ppm/15	225	0.003
	1 - 5 ppm/28	825	0.010
	0.1 - 1 ppm/30	1200	0.014

1/ Source: Summarized from Gallagher & Pola (1985).

2/ Subarea 1 = 83,366 km^2, Subarea 4s = 81,540 km^2

sole eggs and larvae to recruitment and stock productivity would be virtually impossible to assess, considering variations in survival rate.

Juvenile and adult yellowfin sole are known to migrate vertically through the water column from the bottom to the surface, and they can therefore be contaminated by both WSF and tars. The area contaminated by concentrations (>5.0 ppm) which are assumed to kill 50% of juvenile and adult yellowfin sole is 50 km^2 for WSF and 225 km^2 for TARS (Table 20). These spill fields represent 0.06% and 0.3%, respectively, of Subareas 1 and 4S. Assuming they are uniformly distributed, .03% (one-half of 0.06%) of the juvenile and adult yellowfin sole inhabiting Subareas 1 or 4S during the 4 day duration of lethal WSF concentrations would perish from acute hydrocarbon toxicity (Table 21). An additional mortality of 0.15% (1/2 of 0.3%) would be attributable to TARS concentrations exceeding 5.0 ppm. As a first approximation, it is estimated that an accident at any one of the three hypothetical spill sites would inflict acute toxic mortality to 0.18% of the juvenile and or adult yellowfin sole inhabiting Subareas 1 or 4S during the period of contamination.

Juveniles are year round residents of Subareas 1 and 4S and could therefore be impacted during any quarter but adults winter on the outer shelf and upper slope and would be imapcted by an accident in Subarea 1 or 4S only during the second and third quarters. An accident during either of these quarters will then result in an estimated mortality of 0.18% of the adults in the impacted subarea (Table 21). The current exploitable biomass of yellowfin sole in eastern Bering Sea is estimated to be about 3.3 million t. The average percentage of the total biomass occupying Subareas 1 and 4S during the late spring-early autumn months is 43% and 37% or a biomass of 1,419,000 t and

Table 21. Estimated percentage of mortality from acute toxicity in yellowfin sole in the accident scenarios at Port Moller, Port Heiden and Cape Newenham by life history group and quarter.

A. Percentage Mortality at Port Moller or Port Heiden Spill Sites

QUARTERS	1		2		3		4	
STAGE	WSF	TARS	WSF	TARS	WSF	TARS	WSF	TARS
EGGS & LARVAE	0	0	0	0	0	0	0	0
JUVENILES	.03	.15	.03	.15	.03	.15	.03	.15
ADULTS	0	0	.03	.15	.03	.15	0	0

B. Percentage Mortality at Cape Newenham Spill Site

QUARTERS	1		2		3		4	
STAGE	WSF	TARS	WSF	TARS	WSF	TARS	WSF	TARS
EGGS & LARVAE	0	0	0	0	1.2	0	0	0
JUVENILES	.03	.15	.03	.15	.03	.15	.03	.15
ADULTS	0	0	.03	.15	.03	.15	0	0

1,221,000 t, respectively. The estimated loss of adults from an accident would be about 2,554 t in subarea 1 and 2,198 t in Subarea 4S.

The estimated oil-related mortality rate of 0.18% is a small fraction of the total annual mortality rate which is estimated to be 22% (Wakabayashi 1975). A loss of 2,554 t would be about 2% of the estimated total catch in 1984, perhaps less than the error in estimating the catch. Considering the very large number of fish in the eastern Bering Sea yellowfin sole population, their broad distribution and the relatively small area impacted by any one of the hypothetical spills, the estimated kill of adults probably would be of very small consequence as far as the productivity of the yellowfin sole stock is concerned.

Summary of Estimated Impacts of Oil Imposed Lethality to Eastern Bering Sea Yellowfin Sole

Only accidents at the Cape Newenham site are expected to impact eggs and larvae. The accident scenario was estimated to impose a mortality of about 1% to the eggs and larvae within Subarea 4S during the 15 day duration of WSF concentration greater than 100 ppb. As much or more spawning occurs north of the subarea, therefore, the percentage mortality imposed upon the total eggs and larvae of yellowfin sole in the eastern Bering Sea is expected to be far less than 1%. This a very small fraction, indeed, of total natural mortality which in marine eggs and larvae has been estimated to equal or exceed 99%.

The impact of spill scenarios at Port Moller, Port Heiden and Cape Newenham on juveniles cannot be estimated because there is little reliable information on the distribution or quantity of juveniles three years old and younger. An accident at any one of the three sites may kill about 2,500 t of the exploitable juveniles within either Subareas 1 or 4S. This is about 2% of the total catch in 1984 and a small fraction of the estimated biomass of the exploitable stock eastern Bering Sea yellowfin sole.

Considering the magnitude and variability of natural mortality mortality and its subsequent impacts on recruitment variability in marine fishes, it is doubtful that mortalities of these magnitudes can be detected, let alone evaluated for their effects on the productivity of the yellowfin sole stock. The difficulties and impracticalities of isolating the effects of oil imposed mortality from ongoing natural mortality has been discussed by Ware (1982).

The foregoing estimates of acute mortality to yellowfin sole were based on assumptions concerning the applicability of laboratory and field observations on the toxicity of oil to other flatfish to eastern Bering Sea yellowfin sole. It is generally recognized that the transferring of laboratory results for the assessment of oil on commercially imporatant fish and shellfish in the field is extremely difficult. In addition, the estimates carried additional assumptions regarding the abundance and time-space distribution of eggs and larvae, juvenile and exploitable yellowfin sole. As previously mentioned, quantitative information on eggs, larvae and young juveniles is almost totally lacking, estimates of the exploitable population are not without uncertainties. Available knowledge will not permit rigorous evaluation of assumptions relating to the quantitative estimation of the various components of the eastern Bering Sea yellowfin sole in time and space. For these reasons, the foregoing estimates must be considered first approximations which do, however, indicate that acute mortality and projected impact on the productivity of yellowfin sole from accident scenarios considered in these studies is of a magnitude which cannot be measured or evaluated.

Sublethal Effects of Oil on Flatfish

In the previous section (Sensitivity of Flatfish to Petroleum and Distillates), examples of some sublethal effects of petroleum hydrocarbons which have been observed in the field and in laboratory studies were briefly discussed. Observations on some short term effects such as tainting may be of some use in evaluating the possible impact of oil on the marketability of yellowfin sole concaminated by oil spills in Bristol Bay. In most cases, however, due to differences in experimental animals, oils and experimental procedures, field observations or the results of laboratory experiments cannot be directly extrapolated to reliably estimate the impacts of oil to assess either acute or sublethal effects of oil on yellowfin sole in eastern Bering Sea (see Rice et al. 1976, National Research Council 1985). Although the consequences of sublethal effects on the productivity and welfare of eastern Bering Sea yellowfin sole cannot be predicted with any reliability, they are briefly mentioned here because of the possibility that under some spill conditions and ecological circumstances, sublethal effects may have some long term consequences to the eastern Bering Sea resources.

After the *Amoco Cadiz* spill (March 16-17, 1978), a pronounced reduction was observed in the growth rate of the 1977 year class of plaice in the stock impacted by the spill. In addition, there was a marked increase in the incidence of fin rot, hemorrhagic fins and bent or scarred fin rays (Desaunay 1979) as well as some alterations of gonadal tissues (Laubier 1980).

Flounders (*P. flesus*) in the deeper soft bottom areas showed concentrations of 50 ppm in liver and muscle tissue even a year after the Tsesis spill. Flounders are known to feed very heavily on *Macoma* which were very heavily contaminated by oil. Chromatographic profiles of flounder flesh closely resembled that of *Macoma* (Linden et al. 1979).

The results of studies on the sublethal effects of petroleum hydrocarbons on a number of organisms has been summarized by Connell and Miller (1981), Malins (1981), Rice (1981) and most recently by the National Research Council (1985). Among these sublethal effects are alterations in behavior, physiological and pathological effects and tainting of flesh from bioaccumulation of petroleum hydrocarbons. Other effects which are external to the fish are the temporary or longer term destruction of habitat or the reduction or elimination of prey.

Malins et al. (1981) have summarized results of several experiments on the effects of Prudhoe Bay crude oil on some subarctic North Pacific species of flatfish. Roubal et al. (1978) showed that large amounts of low molecular weight hydrocarbons were acumulated in the muscle of starry flounder. Certain hydrocarbons have been found to accumulate in the skin and muscles of English sole (*P. vetulus*). The bioaccumulation of hydrocarbons was also observed in California halibut (Kanter et al. 1983) and in starry flounder (Whipple et al. 1977). The significance of such bioaccumulation to the welfare of the flatfish, its applicability to the condition and productivity of contaminated yellowfin sole stock is not known.

The metabolism of petroleum hydrocarbons in English sole (*P. vetulus*) was discussed by Varanasi and Gmur (1981). Relating hydrocarbons in the fish is complicated by the metabolic conversion of hydrocarbons in the environment by organs such as the liver. These hydrocarbons were taken up from oil-contaminated sediments and entensively metabolized to a number of compounds which are known to be carcinogenic and mutagenic to mammals.

The tainting of fish from the hypothetical spill scenarios is discussed in a report on the simulation of oil uptake and depuration (see Pola et al. 1985).

LITERATURE CITED

Alton, M.

1976. History of research on demersal fishery resources. In: Pereyra, W. T., J. E. Reeves, R. G. Bakkala, Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Proc. Rep. Oct. 1976.

Alverson, D. L., A. T. Pruter, and L. L. Ronholt.

1974. A study of demersal fishes and fisheries of the northeastern Pacific Ocean. H. R. MacMillan Lect. Ser. Fish. Univ. B.C.

Bannister, R. C. A., D. Harding, and S. J. Lockwood.

1974. Larval mortality and subsequent year-class strength in the plaice (Pleuronectes platessa L.), p, 21-37. In: J. H. S. Blaxter (ed.) The early life history of fish. Springer-Verlag, Berlin.

Bakkala, R. G.

1981. Population characteristics and ecology of yellowfin sole. In: The Eastern Bering Sea Shelf: Oceanography and Resources Vol. 1. Univ. Wash. Press.

Bakkala, R.G., T.M. Sample, M.S. Bohle, J.A. June , A.M. Shimada and Y. Umeda

1982 Data Report: 1979 demersal trawl survey of the eastern Bering Sea continental shelf and slope. NOAA Tech. Memo. NMFS F/NWC-30:200 pp.

Bakkala, R. G., and V. G. Wespestad.

1984a. Yellowfin sole. In: R. G. Bakkala and L. L. Low (editors), Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands Region in 1983. Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Unpubl. Rep.

1984b. Yellowfin sole. In: Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands Region in 1984. Nat. Mar. Fish. Cent., Northwest and Alaska Fish. Cent., Unpub. Rep. (submitted to International North Pacific Fisheries Commission in Oct. 1984).

Bohle, M.S., and R.G. Bakkala

1984 Data Report: 1978 bottom trawl survey of the eastern Bering Sea groundfish. NOAA Tech. Memo. NMFS F/NWC-55:164 pp.

Conan, G., and M. Friha.

1979. Effects of hydrocarbon pollution from the oil tanker Amoco Cadiz on the growth of soles and plaices in the estuary of the Benoit River mouth. From: Amoco Cadiz: Fates and effects of the oil spill. Proc. of the Int. Symp., Cent. Oceanologique de Bretagne, Brest, France. November 19-22, 1979.

Connell, D. W., and G. J. Miller.

1981. Petroleum hydrocarbons in aquatic ecosystems - Behavior and effects of sublethal concentrations: Part 1. CRC Critical Reviews in Environmental Control Vol. 11, Issue 1:37-104.

1981. Petroleum hydrocarbons in aquatic ecosystems - Behavior and effects of sublethal concentrations: Part 2. CRC Critical Reviews in Environmental Control Vol. 11 Issue 2:105-162.

Cushing, D. H.

1974. The possible desnity-dependence of larval mortality and adult mortality in fishes. P. 103-111. In: J. H. S. Blaxter (ed.) The early life history of fish. Springer-Verlag, Berlin.

Desaunay, Y.

1979. Evolution of flatfish stocks in the area contaminated by the Amoco Cadiz. From: Amoco Cadiz: Fates and Effects of the Oil Spill. Proc. of the Int. Symp., Cent. Oceanologique de Bretagne, Brest, France. November 19-22, 1979.

Fadeev, N.S.

1970a. The fishery and biological characteristics of yellowfin sole in the eastern part of the Bering Sea. Tr. Vses Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanog. 70 (Izv. Tikookeau. Nauchno-Issled. Inst. Rybn. Khoz. Okeanog. 72):327-90.

1970b. The distribution pattern of yellowfin sole (Limanda aspera, Pall.) in the northern part of the Pacific Ocean. Izv. Tikhookean. Nauchno-Issled. Inst. Rybn. Khoz. Okeanogr. 74:3-21.

Fletcher, G. L. J. W. Kiceniuk, and U. P. Williams.

1981. Effects of oiled sediments on mortality, feeding and growth of winter flounder (Pseudopleuronectes americanus). Mar. Ecol. Prog. Ser. Vol. 4:91-96, 1981.

Gallagher, A. F., Jr., and N. B. Pola.

1985. The uptake and depuration of petroleum hydrocarbons in marine species. A simulation study of the uptake and depuration of petroleum hydrocarbons and its effect on selected marine species in the Bristol Bay ecosystem.Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Proc. Rep.

Grant, S. R., R. Bakkala, and F. Utter.

1978. Examination of biochemical genetic variation in yellowfin sole (Limanda aspera) of the eastern Bering Sea. Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, WA. Unpubl. MS.

Kanter, R. G., R. C. Wingut, W. H. Vick, M. L. Sowby and C. J. Foley.

1983. California commercial/sport fish and shellfish oil toxicity study. Vol. 1. Exec. Summ. MBC Applied Environmental Sciences, La Jolla, CA. Study supported by Min. Manag. Serv., Dept. Int. Contract 14-12-0001-29105.

Kasahara, H.

1961. Fishery resources of the North Pacific Ocean. Part I. H. R. MacMillan Lect. Fish. Univ. B.C., 135 pp.

Kashkina, A. A.

1965. Reproduction of yellowfin sole (Limanda aspera, Pallas) and changes in its spawning stocks in the eastern Bering Sea. Tr. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 53):179-89.

Kibesaki, O.

1965. Demersal fish resources in the northern Pacific. Japanese Fish. Res. Conser. Assoc. Fish. Res. Ser. No. 11:1-45. (Prelim. transl., 1964, by U.S. Joint Public. Res. Serv. for Bur. Com. Fish., Seattle.)

Kihara, K.

1976 Studies on the formation of demersal fishing ground. 3. Recurrent group analysis of demersal fish in the eastern Bering Sea.Bull. Soc. Franco-Japanese Oceanogr. 14(1):11-22.

Laevastu, T., and F. Favorite.

1978. Fish biomass parameter estimations. Nat. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, WA. Proc. Rep.

Laevastu, T., and P. Livingston.

1978. Some heretofore unknown episodes of yellowfin sole in the eastern Bering Sea. Nat. Mar. Fish. Ser., Northwest and Alaska Fish. Cent. Proc. Rep.

Laubier, Lucien.

1980. The Amoco Cadiz oil spill: An ecological inpact study. Ambio Vol. 9 No. 6:268-276.

Linden, O., R. Elmgren, and P. Boehm.

1979. The Tsesis Oil Spill: its impact on the coastal ecosystem of the Baltic Sea. Ambio Vol. 8, No. 6 pp. 244-253, 1979.

Lønning, S.

1977. The effects of EKOFISK oil and oil products on marine fish larvae. Astarte 10:37-47.

Malins, D. C., S. L. Chan, H. O. Hodgins, U. Varanasi, B. B. McCain, D. D. Weber, and D. W. Brown.

1981. Sublethal effects of petroleum hydrocarbons and trace metals, including biotransformations, as reflected by morphological, chemical, physiological, pathological, and behavioral indices. Ann. Rep. Contract #7120819 RU #73 OCSEAP, U.S. Dept. Int., Bur. Land Manag. 84 pp.

Mazmanidi, N. D., and T. R. Bazhashvili.

1975. Effects of dissolved petroleum products on the embryonic development of the Black Sea flounder. Hydrobiol. J. 11(5):39-43.

McCain, B. B.

1978. The effects of Alaskan crude oil on flatfish, and the prevalence of fish pathology in Alaska waters. p.54-71. Marine Biol. Effects of Petrol. Devel. (D. A. Wolfe, ed.) NOAA Tech. Memo BRL OCSEAP-1:54-71.

McCain, B. B., H. O. Hodgins, W. D. Gronlund, J. W. Hawkes, D. W. Brown, M. S. Myers, and J. H. Vandermeulen.

1978. Bioavailability of crude oil from experimentally oiled sediments to English sole (Parophrys vetulus), and pathological consequences. J. Fish. Res. Bd. Can.:35(5):657-664.

Mito, K.

1977 Food relationships in the demersal fish community in the Bering Sea. I. Community structure and distributional patters of fish species. In: Fisheries biological production in the subarctic Pacific region. Res. Inst. N. Pac. Fis., Fac. Fish., Hokkaido Univ., Spec. Vol. 1977:205-58.

Musienko, L. N.

1963. Ichthyoplankton of the Bering Sea (data of the Bering Sea expedition of 1958-1959). Trs. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Koz. Okeanogr. 48 (Izv. Tikhookean. Nauchno-Issled Inst. Morsk. Rybn, Khoz. Okeanogr. 50):239-69.

National Research Council.

1985. Oil in the sea, inputs, fates, and effects. National Academy Press, Washington, D.C., 1985:601 pp.

Novikov, N. P.

1964. Basic elements of the biology of the Pacific halibut (Hippoglossus hippoglossus stenolepis Schmidt) in the Bering Sea. Trs. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 49(Izv. Tikhookean. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 51).

Pereyra, W. T., J. E. Reeves, and R. G. Bakkala.

1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, Wash. Proc. Rep.

Pertseva-Ostroumova, T. A.

1961. The reproduction and development of far-eastern flounders (Razmnozhenie i razvitie dal' nevostochnykh Kambal). Akad. Nauk. SSSR, Institute Okeanologii, 484 pp. 1961. Transl. Ser. No. 856, Fish Res. Bd. Can., 1967.

Pola, N. B., R. K. Miyahara, and A. F. Gallagher, Jr.

1985. Spatial and temporal extent of hydrocarbon contamination in marine species of Bristol Bay. Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Proc. Rep.

Rice, S. D.

1981. Review: Effects of oil on fish. Nat. Acad. Sci., Workshop on Petroleum in the Environment, Nov. 1981.

Rice, S. D., J. W. Short, and J. F. Karinen.

1976. Comparative oil toxicity and comparative animal sensitivity. From: Fates and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms. Proc. of Symp. Nov. 10-12, 1976, Olympic Hotel, Seattle, WA. Pergamon Press. Oxford/New York/Toronto/Sydney/Paris/Frankfurt.

Rice, S. D., A. Moles, T. L. Taylor, and J. Karinen.

1979. Sensitivity of 39 Alaskan marine species to Cook Inlet crude oil and No. 2 fuel oil. Paper presented at 1979 Conference on the Prevention and Control of Oil Spills, Los Angeles, CA.

Roubal, W. T., S. L. Stranahan, and D. C. Malins.

1978. The accumulation of low molecular weight aromatic hydrocarbons of crude oil by coho salmon (Oncorhynchus kisutch) and starry flounder (Platichthys stellatus). Arch. Environm. Contam. Toxicol. 7, 237-244 (1978).

Salveson, S. J., and M. S. Alton.

1976. Yellowfin sole (Family Pleuronectidae). In: Pereyra, W. T., L. E. Reeves, and R. G. Bakkala. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Nat. Mar. Fish. Serv. Northwest and Alaska Fish. Cent., Seattle, Wash. Proc. Rep.

Skalkin, V. A.

1963. Diet of flatfishes in the southeastern Bering Sea. Trs. Vses. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 48 (Izv. Tikhookean. Nauchno-Issled. Inst. Morsk. Rybn. Khoz. Okeanogr. 50):223-37.

Smith, G. B., and R. G. Bakkala.

1982. Demersal fish resources of the eastern Bering Sea: Spring 1976. NOAA Tech. Rep. (NMFS SSRF-754). 129 pp.

Umeda, Y. and R. Bakkala

1985 Data Report: 1979 demersal trawl survey of the eastern Bering Sea continental shelf.NOAA Tech. Memo. NMFS F/NWC-49 Oct. 1983.

Varanasi, U., and D. J. Gmur.

1981. Hydrocarbons and metabolites in English sole (*Parophrys vetulus*) exposed simultaneously to [^{3}H]Benzo[a]Pyrene and [^{14}C]Naphthalene in oil-contaminated sediment. Aquatic Toxicology, 1 (1981)49-67, Elsevier/North-Holland Biomedical Press.

Wakabayashi, K.

1974. Studies on resources of the yellowfin sole in the eastern Bering Sea. I. Biological characters. Japan Fishery Agency, Far Seas Fish. Res. Lab. Shimizu, Japan, Unpub. MS.

1975. Studies on the resources of the yellowfin sole in the eastern Bering Sea. II. Stock size estimates by method of virtual population analysis and its annual changes. Japan Fishery Agency, Far Seas Fish. Res. Lab., Shimizu, Japan, Unpubl. MS.

1985. Studies on the fishery biology of yellowfin sole in the eastern Bering Sea. Ph.D. Dissertation, U. of Tokyo, Dept. of Oceanography. 328 pp.

Wakabayashi, K., R. Bakkala, L. Low.

1977. Status of the yellowfin sole resources in the eastern Bering Sea through 1976. Nat. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, Wash. Unpubl. MS.

Ware, D. M.

1982. Recruitment variability - can we detect the effect of oil pollution? In: A. Longhurst (ed.), Consultation on the Consequences of Offshore Oil Production on Offshore Fish Stocks and Fishing Operation. Can. Technol. Rep. Fish. Aquat. Sci. 64-73.

Whipple, J. A., T. G. Yocom, P. E. Benville, D. R. Smart, M. H. Cohen, and M. E. Ture

1978 Transport, retention and effects of water-soluble fraction of Cook Inlet crude oil in experimental food chains (RU 389). In: Marine Biological Effects of OCS Petroleum Development, NOAA Tech. Memo., ERL, OCSEAP

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC
ADMINISTRATION
NATIONAL OCEAN SERVICE
701 C Street
Box 56
Anchorage, Alaska 99513

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-210

U.S.MAIL

PRINTED MATTER

CLASS OF POSTAL SERVICE

NOAA FORM 61-13
(9-84)