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Abstract

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All larval stages except the 5th zoeal have been collected in the ocean off San Francisco January through March 1975-76, megalopae in the San Francisco-San Pablo Bay-complex in April and May 1975-76, and first post-larval crabs in San Pablo Bay in May 1975-76. Eighty percent of 1975 year-class crabs entered the Bay-complex to use it as a nursery ground. Staghorn sculpin, starry flounder, big skate, and brown smoothhound were the principal fish predators on megalopae and juveniles.

Multi-variate correlations comparing crab landings with an array of oceanographic parameters and the crab density dependent factor show that from March through May, when late stage larvae prevail, the most significant correlating factors were sea level and atmospheric pressure for central California and, for northern California, the density dependent factor and sea surface temperature. Analyses of crab tissues for contaminants revealed petroleum hydrocarbon burdens, Ag, Se, Cd, and PCB's higher in central California crabs, while DDE was found in higher amounts in northern California crab tissue.

SAN FRANCISCO BAY: CRITICAL TO THE DUNGENESS CRAB?

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Because of the decline in harvestable yield of Dungeness crab (*Cancer magister*) in the San Francisco area since 1961, a study has been undertaken to determine critical stages in the crab's life history and environmental factors affecting survival.

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The central California Dungeness crab (*Cancer magister*) resource has yielded harvestable crabs at drastically low levels for 15 seasons beginning with the 1961-62 season (Fig. 1). From 1915 to 1949 the average seasonal landings were 2.5 million lb (1.14×10^6 tonnes), and from 1949-50 to 1961-62 they were 5 million lb (2.27×10^6 t) (Orcutt et al. 1976). The need to understand the causes of the catastrophic condition of the central California Dungeness crab resource is very real in terms of the economics crucial to the lives of the fishermen, the economic values to society, and the well-being of the renewable resource.

The California Department of Fish and Game (DFG) was mandated (State Senate Bill 1606) to investigate the causes of the decline and in 1974 established the Dungeness Crab Research Program. The objectives of this program are 1) determine the factors causing the decline and continued low levels of central California's Dungeness crab resource, and 2) make management recommendations to protect and increase the resource.

The program has two distinct projects. The first, termed the Crab Critical Stage Project, has as its major objectives the determination of distribution and relative abundance of Dungeness crab zoeae, megalopae, and post-larval instars; the importance of the San Francisco-San Pablo Bay-complex as a nursery ground for recruitment into the commercial fishery; predators and their effects on the crab population; racial composition of Pacific Coast crab stocks with emphasis on the relation between northern and central California; and growth rates of juvenile crabs in Bay waters. The second, termed the Crab Environment Project, has as its major objective the investigation of the natural and/or man-caused factors which induce or contribute to changes in the crab population in the San Francisco area.

The central California Dungeness crab fishery has exploited only males since 1897 and has

had a closed season (period of maximum male molting) and size limits since 1903. Mating in Dungeness crab takes place between a hard-shelled male and a soft-shelled (recently molted) female. The mating season ranges from late February to July with most mating occurring March to May. Sperm are transferred to the female during mating and are retained in the spermathecae until the eggs mature. Males generally molt late June through October with peak molting in July and August. Fertilization occurs as the eggs pass out through the oviduct and pass the spermathecae. Most spawning occurs October to February and the eggs become attached to the abdomen of the female

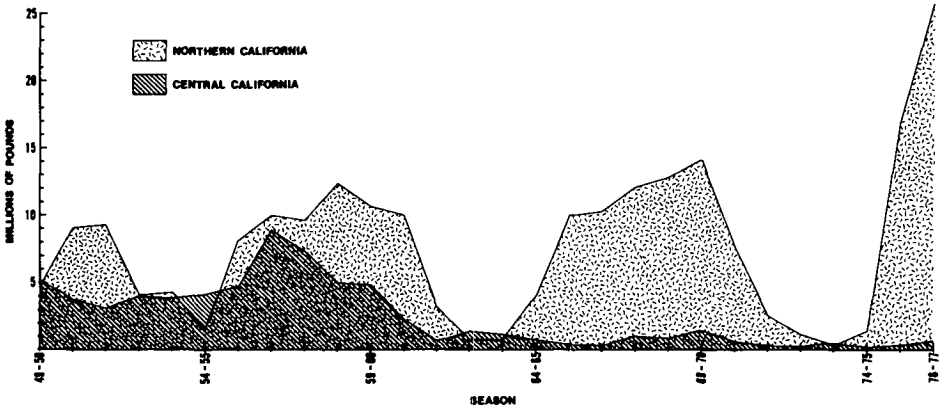

Fig. 1. Dungeness crab landings of northern and central California by seasons since 1949.

in a sponge-like mass. There are approximately 1.5 million eggs on an average-sized female. Hatching of the eggs generally takes place December through January. For convenience, the birthdate of January 1 is given to all members of a designated year class (e.g. 1977 year-class crabs - born 1 January 1977). There are seven Dungeness crab larval stages (1 prezoeal, 5 zoeal, and 1 megalopal) with a combined pelagic existence of 90 to 120 d. Metamorphosis to the first post-larval instar (resting or intermolt) stage occurs May-June.

The study area encompasses the Gulf of the Farallones from Pt. Reyes to Pt. San Pedro (Fig. 2) and the San Francisco-San Pablo Bay-complex (Fig. 3). The program was formally initiated 1 July 1975, and will conclude 1 September 1979.

This paper presents a brief overview of our activities to date (June 1977) and some of the results generated by studies thus far. Most information presented here has been abstracted from the Program's first two annual reports (Orcutt et al. 1975, 1976).

CRAB CRITICAL STAGE STUDIES

Methods and Materials

Crab larvae and associated zooplankters. During pre-program studies in spring 1975 we developed our plankton collecting gear and procedures. Generally, we opted for 0.5-m, 505-μ mesh cylinder-cone nets, with opening-closing capabilities, to test for horizontal stratification of zoeal and megalopal stages. In 1977 we experimented with 30-cm Clarke-Bumpus samplers and a 1-mm mesh plankton net adapted to a sled. The Clarke-Bumpus samplers were rejected eventually because they were awkward and inefficient. The sled arrangement has been incorporated into our routine sampling plan when plankton samples near the bottom are needed.

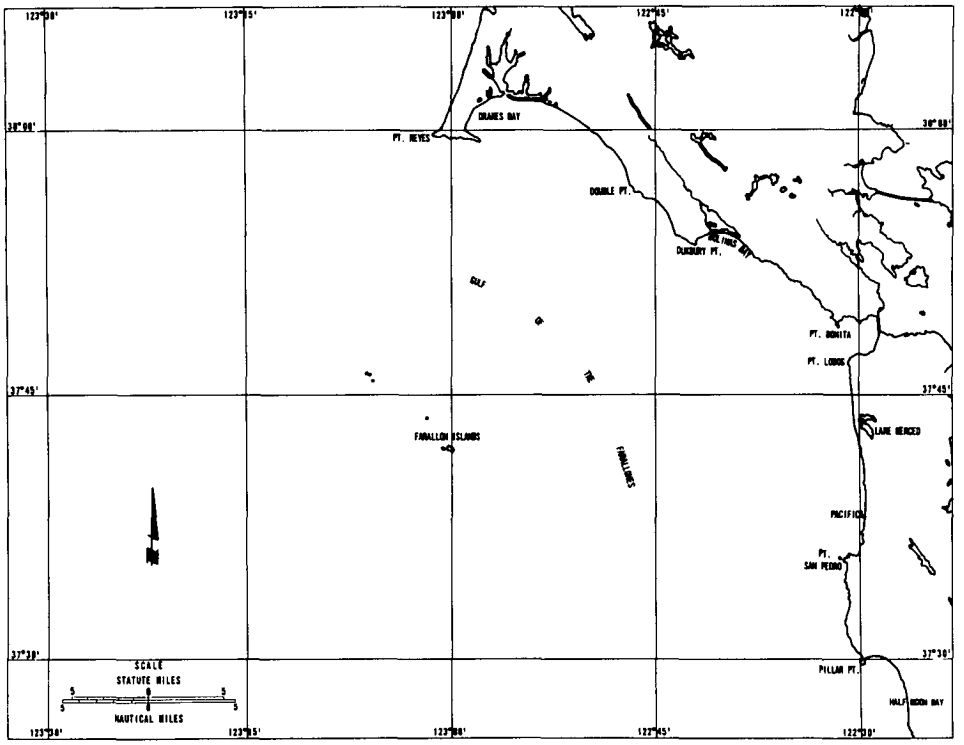

Fig. 2. Study area, Gulf of the Farallones.

Plankton collecting cruises are scheduled December to June when crab larvae are most abundant. Collections are made from Department research vessels, patrol boats, and chartered vessels. Permanent stations in the Gulf of the Farallones are spaced 9.3 km apart in a grid pattern along transects perpendicular to the coastline. Bay stations were selected with regard to bottom depth, vessel maneuverability, and prevailing currents. Sampling procedures frequently include a variety of tow types, e.g. discrete depth horizontal tows, oblique tows from bottom to surface, and bottom-sled tows. Towing times vary with regard to previously computed zooplankton densities, and flowmeters attached to the nets give us a record of the amount of water filtered. Samples are preserved in buffered 10% formalin and transported to the Menlo Park Laboratory for analysis. All zooplankters are identified to the lowest taxa possible, enumerated, and all information computerized and stored in our data banks.

Juvenile and adult crabs. To collect post-larval instar crabs, we use 5- and 13-m semi-balloon otter trawls, 2.5-m beam trawls, commercial crab pots, and hoop or ring nets. Captured crabs are enumerated, measured, sexed, and either returned to the water or retained for special studies.

Cruises designed to investigate the juvenile crab population are scheduled intermittently throughout the year. Two cruises are scheduled in spring when the crabs are metamorphosing from the megalops to the first post-larval instar stage. An additional cruise is conducted in autumn using catch-per-unit-of-effort (CPUE) to determine the extent to which crabs of the year entered the Bay-complex to utilize it as a nursery ground. The distribution of current year-class crabs within the Bay-complex is monitored monthly by trawling from small boats and ring-netting from shore-based stations.

Predation. Fishes for gut content analysis are selected primarily from trawl catches. Occasionally hook- and line-caught fish from the recreational sportfishery are analyzed. The fishes are identified and measured to the nearest mm total length (TL). Their stomachs are removed, preserved in 10% formalin, and returned to the laboratory.

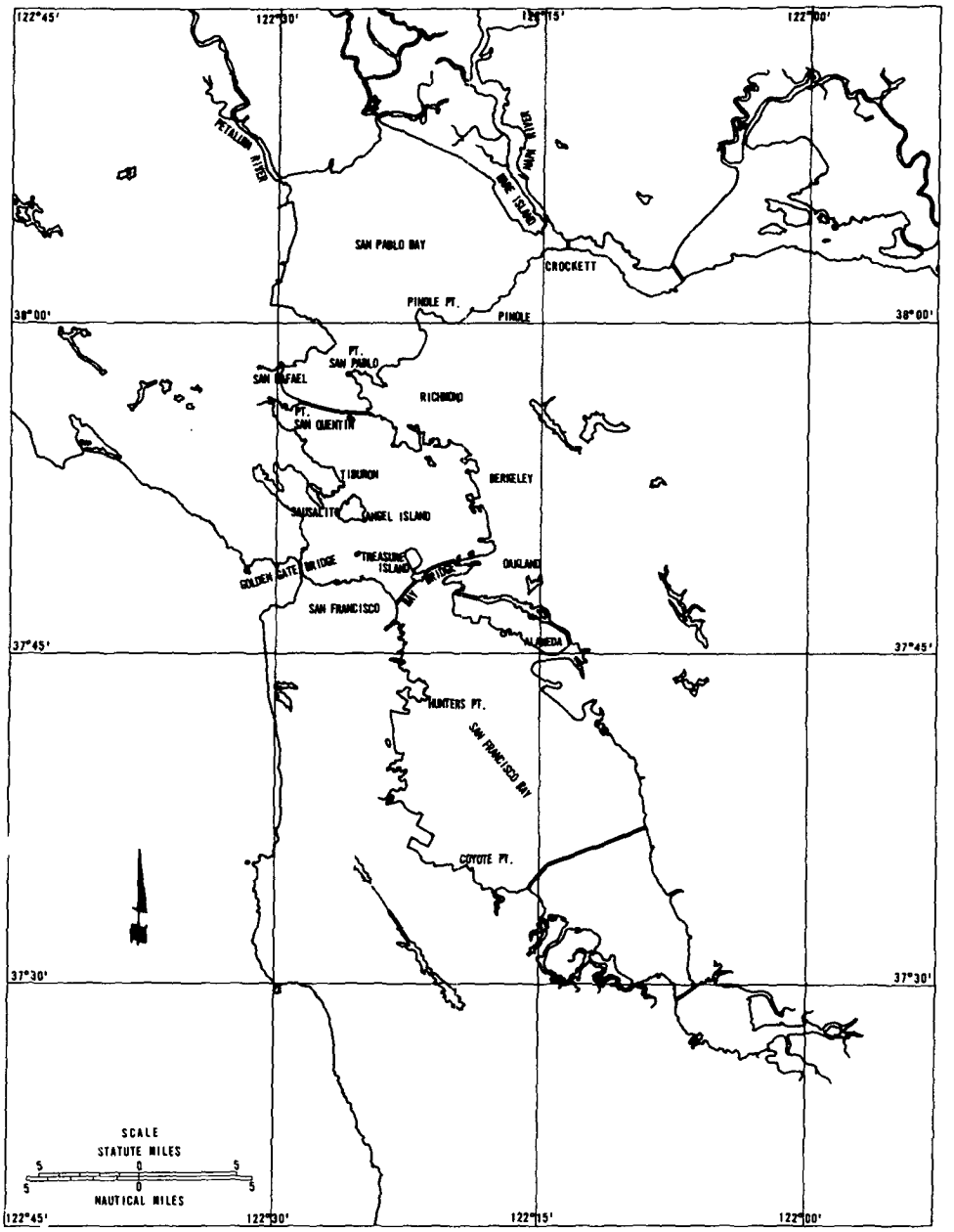

Fig. 3. Study area, San Francisco-San Pablo Bay complex.

Oceanographic Parameters. Salinity and temperature measurements of the water column are taken at each location where sampling occurs. We frequently measure these parameters at the surface, 5, 15, 25 m, and bottom (if possible). In 1975 ocean sampling, water samples were taken at discrete depths and salinities determined by an induction salinometer; water temperature profiles were recorded with an expendable bathythermograph (XBT) system. Since 1976 we have used an InterOcean conductivity-salinity-temperature-depth (CSTD) recorder. A field portable temperature-salinity (TS) meter is used at the shallower Bay stations. We gather data on these parameters to determine if they correlate to distribution or abundance of Dungeness crab larvae.

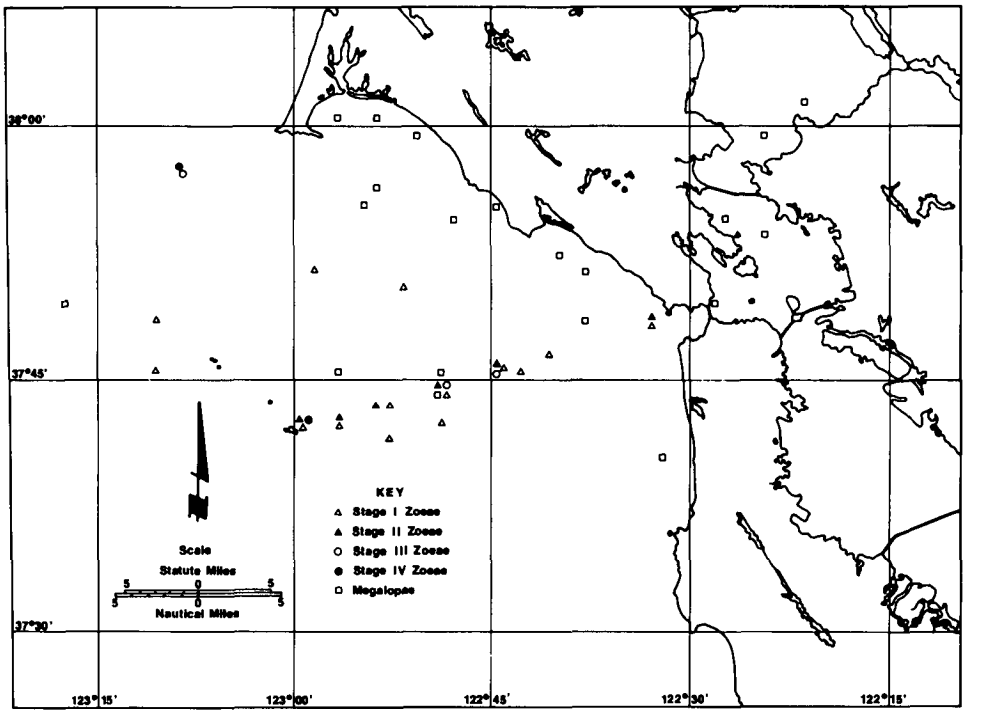

Fig. 4. Occurrences of *C. magister* larval stages from plankton tows and fish stomachs, January-June 1975-76.

Results and Discussion

Distribution. During pre-program cruises in April and July 1975, approximately 200 plankton samples were collected from the study areas (Figs. 2, 3). This sampling effort yielded only 12 megalopae, all from the Gulf. Over 100 bottom trawls were made and they collected approximately 1000 early post-larval instar crabs, the vast majority of which were collected in the Bay-complex. Twenty megalopae were found in fish stomachs, most of these from Gulf-caught fish.

Investigation of the 1976 year class began in mid-December 1975 with bi-weekly cruises. Each cruise consisted of a single transect from the Golden Gate Bridge to and slightly beyond the Farallon Islands. These cruises resulted in a substantial collection (ca. 2000) of early zoeal stages. Subsequently we conducted a 2-wk cruise in March during which we collected 183 plankton samples. These samples contained only a dozen zoeal stages, a mixture of early and late.

From late April through early May, we conducted three additional 2-wk cruises in which we slowly decreased the number of plankton stations and increased our trawling efforts. One hundred seventy plankton samples were collected yielding a mere 14 megalopae; fish stomachs yielded an additional seven megalopae. One hundred forty-three bottom trawls captured only 160 early post-larval instar crabs. Again, as in 1975, the vast majority of these were caught in the Bay-complex.

Some discernable patterns of distribution begin to emerge upon inspection of the data. Larval forms are concentrated in the Gulf and juvenile stages in the Bay-complex. All larval forms from 1975 and 1976 with the exception of four megalopae and one stage II zoea were found in Gulf stations (Fig. 4). There is also some indication that as the zoeae develop from stage I through stage V they move progressively offshore. CPUE studies conducted in autumn determined the extent to which juveniles moved into the Bay.

Data from over 400 plankton tows and approximately 150 bottom trawl tows made in 1977 have not been evaluated to date (June 1977). However, cursory inspection of these data indicates that the data substantiate the aforementioned conclusions.

Relative abundance. The maximum zoeal density recorded at any station has been $9 \cdot m^{-3}$ water filtered for stage I zoeae. The maximum density for megalopae has been $0.47 \cdot m^{-3}$. Most samples averaged considerably less. The only observable trend has been a lowered density as the zoeal stages develop. The megalopae are not included in this pattern.

Catch-per-unit-of-effort (fishing) data generated by a cruise in September 1975 indicated that nearly four out of five 1975 year-class crabs entered the Bay-complex to utilize it as a nursery ground (Table 1). We caught 60% less crabs in 1976 with similar fishing effort and during the

TABLE 1. CATCH-PER-UNIT-OF-EFFORT (CPUE) DATA FOR 1975.

	Ring-net				Trawl				Combined	
Station locations	No. crabs collected	Crabs/ set	Crabs/ net	CPUE (%)	No. crabs collected	Crabs/ set	Crabs/ net	CPUE (%)	Non-adjusted[a] CPUE (%)	Adjusted[b] CPUE (%)
San Francisco and San Pablo Bays	152	12.7	2.5	74	312	26.0	13.0	83	78.5	78.4
Gulf of Farallones	63	4.5	0.9	26	77	5.5	2.8	17	21.5	21.6

[a] Sum of percentages divided by 2.
[b] Percentages weighted by number of crabs caught by each method.

same time period. Although the data indicate that 1976 year-class crabs were equally distributed between Bay and Gulf, the statistical reliability of the data is suspect because of the low number of crabs caught. Another indication of the weakness of the 1976 year class can be seen when we pool all available trawl data, without regard to type of trawl used, from the summers of 1975 and 1976 (Table 2). The CPUE dropped more than 85% in 1976.

Predation. A study of 750 demersal fish stomachs collected in 1975 and 1976 has suggested that the major predators on Dungeness crab are Pacific staghorn sculpin (*Leptocottus armatus*), starry flounder (*Platichthys stellatus*), big skate (*Raja binoculata*), white croaker (*Genyonemus lineatus*), brown smoothhound (*Mustelus henlei*), and sturgeon (*Acipenser* spp.) (see also Smith and Kato 1979).

Growth. Carapace width data have been collected regularly in San Francisco and San Pablo bays since 1971. These data have been incorporated into an age and growth study which, along

TABLE 2. COMPARATIVE TRAWL CATCH-PER-UNIT-OF-EFFORT (CPUE) DATA, 1975 vs. 1976 YEAR CLASSES.

Year-class	Month	No. crabs collected	Trawling effort (min.)	CPUE (crabs per min.)
1975	May	281	225	1.25
	June	497	420	1.18
	September	312	240	1.30
	TOTAL	1090	885	1.23
1976	May	1	210	0.01
	June	150	680	0.22
	September	56	240	0.23
	TOTAL	207	1130	0.18

with a 1972-73 tagging study, is in manuscript (P. Collier in prep.).

Racial composition. Electrophoretic studies were conducted to survey the variability and geographic distribution of gene products (proteins) for approximately 20 gene loci from *C. magister* to determine the structure of the various natural Dungeness crab populations. The results of 18 months of investigation of 2,000 crabs from Alaska to Morro Bay indicated that there is virtually no electrophoretic polymorphism in *C. magister* and that electrophoresis is of no value in illuminating the population structure (M. Soulé unpublished).

CRAB ENVIRONMENT STUDIES

Methods and Materials

Oceanographic factors. Initial emphasis was placed on compiling data on nearshore ocean and bay temperatures, salinities, upwelling, sea level, wind stress curl, atmospheric pressure and river flows into the ocean and bays. Most historical information concerning temperature, salinities, and sea level was provided by the National Ocean Survey (NOS) (unpublished data) (Fig. 5). National Marine Fisheries Service (NMFS) has provided upwelling indicates from 1946-74 for 10 stations (Bakun 1973) (Fig. 6). River flow rates were compiled for the Sacramento River Delta, Smith River, Klamath River, and Eel River. These parameters, plus a density-dependent factor (autocorrelation of crab landings) were correlated with yearly (1948 to 1975) crab landings using 3- and 4-yr lag times (Boeing Computer Services 1975). In addition some simple regressions were made of crab landings using varying lag times.

Hundreds of mature female crabs were collected and retained, some alive and the remaining quick-frozen, for studies on the relationship between spawning success and water temperature and to assess differences in ovary development and mating success between Eureka and San Francisco area crabs.

Environmental toxicants. A literature review on environmental toxicants was directed first toward data sources and research papers on a variety of toxicants including trace and major elements, pesticides, polychlorinated biphenyls (PCB's), petroleum hydrocarbons, municipal and industrial effluents, chlorinated waste, and biostimulants. The results of this review indicated that there was very little information on levels or effects of potentially toxic materials on crabs or related organisms and scant historical data which document these factors when the crab population was high in the San Francisco area. Therefore it was decided to evaluate whether present levels

found in crab tissues are having significant effects on the crab population.

Making the basic assumption that crabs from the northern California population are healthy, much of 1975 was spent collecting crabs from the San Francisco and Eureka areas and preparing to test the crab samples for current levels of these toxicants.

Studies on elements were conducted by the Water Pollution Control Laboratory of DFG and by Moss Landing Marine Laboratories (San Jose State University); pesticide and PCB levels are

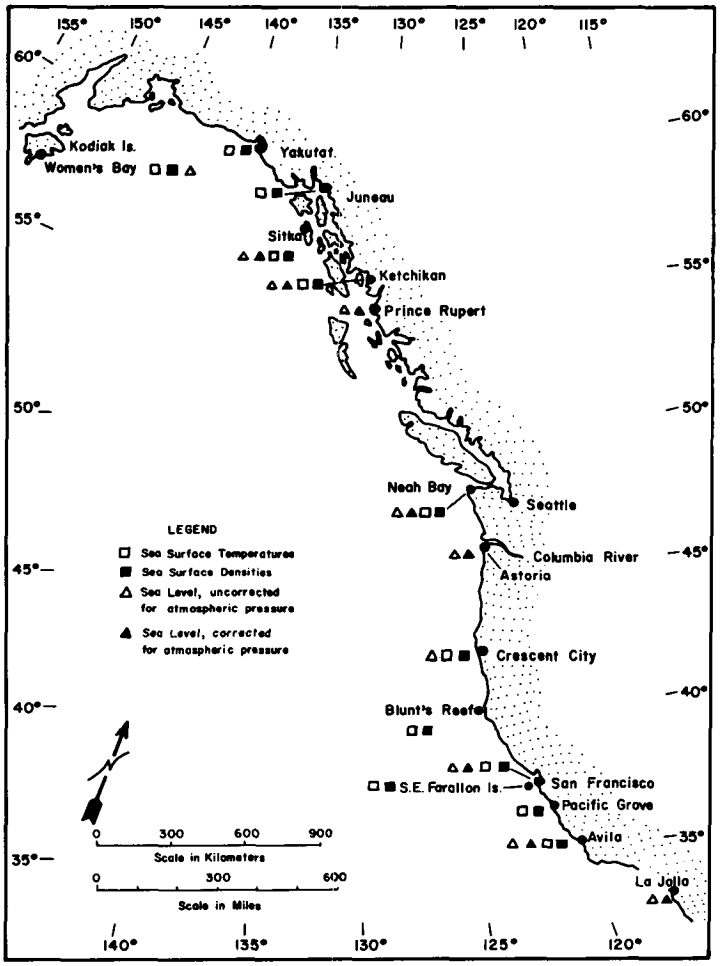

Fig. 5. Oceanographic shore station locations for sea surface temperature, density, and sea level from California to Alaska (NOS).

being determined by the DFG Pesticide Laboratory. The Naval Biosciences Laboratory (University of California Berkeley) was awarded a contract to investigate petroleum hydrocarbons. The effects of effluents, chlorinated wastes, and biostimulants are being studied by the Sanitary Engineering Research Laboratory (SERL) of the University of California, Berkeley.

In general, our approach in assessing the role of environmental toxicants in preventing the recovery of San Francisco area Dungeness crab stocks is to compare tissue burdens of various

toxicants in crabs from the San Francisco area with those from Eureka. Statistically significant differences between the two areas will suggest where laboratory experimentation such as bioassays may be useful in evaluating the biological significance of the differences in toxicant levels.

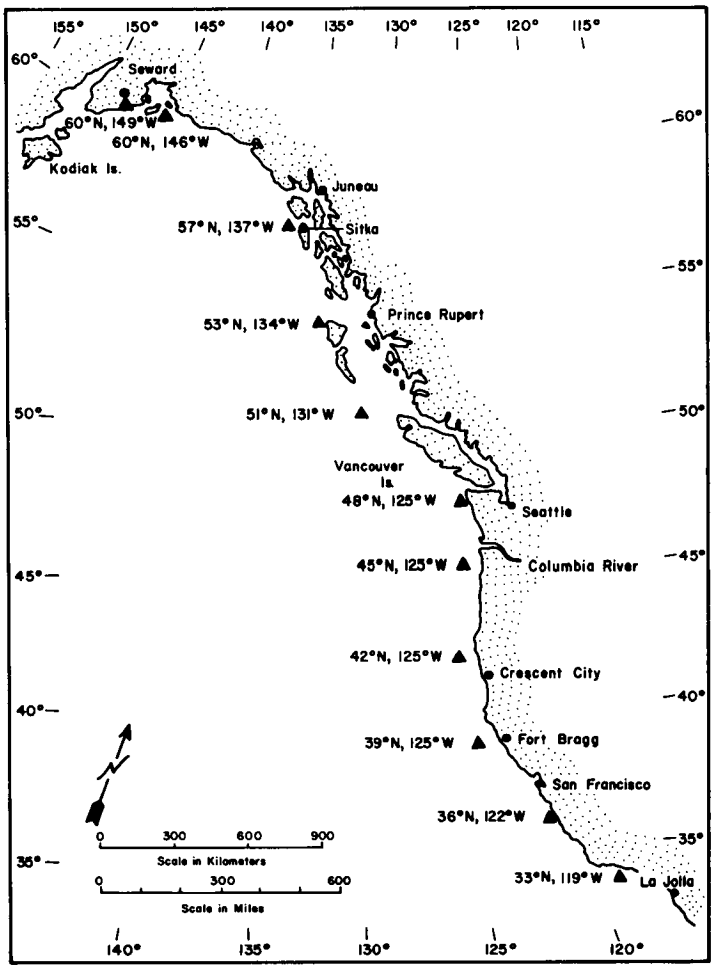

Fig. 6. Locations of computed upwelling indices (black triangles) from California to Alaska.

In testing for major or trace elements, muscle and hepatopancreas samples from crabs of the San Francisco and Eureka areas were tested for levels of As, Ba, Br, Cd, Ca, Co, Cu, Fe, Hg, K, Mn, Ni, Pb, Se, Ag, Sr, and Zn. Analyses were conducted by atomic absorption and X-ray fluorescence. Tissues from 25 adult crabs of each sex and from each area were analyzed individually, whereas juvenile crab tissues were composited and represented 50 of each sex from each area. Approximately 7,300 analyses were performed.

Five crab-egg samples from the San Francisco area and two from the Eureka area were analyzed for tissue concentrations of 38 elements by X-ray fluorescence and neutron activation analysis.

Results and Discussion

Oceanographic factors. The best multivariate correlation coefficient obtained for oceanographic factors and crab landings was 0.67 for central California with the significant factors being uncorrected sea level and atmospheric pressure. In northern California, a correlation coefficient of 0.76 was obtained with a density dependent factor and sea surface temperatures being the major contributors to the correlation. The results suggest the possibility of a relation between oceanographic conditions, late stage larval survival, and year-class strength in central California, while in northern California biotic factors inherent in the crab population may be more important to year-class strength than effects of environmental conditions on late stage larval survival.

While these first efforts are encouraging, more complete analysis and interpretation of the results will be possible when correlations have been made for all of the possible life stages and oceanographic phenomena we plan to compare, and a better index of year-class strength is achieved. Data from DFG pre-season crab cruises 1958-74 are being analyzed currently to see if such an index is available.

The study to determine the relationship between spawning success and water temperature proved unsuccessful; a more extensive study is currently underway at DFG's Marine Culture Laboratory. Also, the series of experiments designed to assess the differences in ovary development and mating success between Eureka and San Francisco Bay area crabs was inconclusive; however, the study shows promise and will continue through 1978.

Environmental toxicants. Although data from the analyses of major and trace elements have not been analyzed statistically yet, some generalizations can be made. In all samples tested, the concentrations of Pb, Cr, Co, and Ba were below detection limits. Tissue concentrations of the elements tested were higher in adult animals (an exception was Mn) and higher in the hepatopancreas than in the muscle (exceptions were As, K, and Zn). The highest concentrations of most elements tested were found in the hepatopancreas of adult females.

The most obvious differences in tissue burdens of potentially toxic elements between San Francisco and the Eureka areas were found in comparisons of levels of Ag, Cd, and Se in adult female hepatopancreas (Table 3). In general, concentrations of nearly all elements averaged higher in the egg masses of San Francisco crabs than in those from Eureka, although there is more variability within the San Francisco samples than between the two areas. Bioassays of acute and chronic effects of Cd, Ag, and Se on juvenile crabs are underway currently at the DFG Bioassay Laboratory.

The levels of chlorinated hydrocarbon pesticide and PCB's of the muscle and hepatopancreas of juvenile crabs collected from San Francisco and Humboldt bays were determined. The only

TABLE 3. CONCENTRATIONS OF SELECTED ELEMENTS IN HEPATOPANCREAS OF ADULT FEMALE DUNGENESS CRABS FROM SAN FRANCISCO AND EUREKA AREAS.

Area	Silver[a] (ppm) range	mean	Cadmium[a] (ppm) range	mean	Selenium[b] (ppm) range	mean
San Francisco	9.9 - 49.9	24.0	22.1 - 241.0	76.9	2.8 - 24.8	9.75
Eureka	4.2 - 25.3	10.4	8.3 - 90.7	27.2	0 - 6.3	2.75

[a] Determinations made by Moss Landing Marine Laboratories.
[b] Determinations made by DFG Water Pollution Control Laboratory personnel at California State Dept. Agriculture facilities.

pesticide residue found was DDE, a metabolite of DDT. Levels of DDE and PCB's were higher in the hepatopancreas than in the muscle. Crabs from Humboldt Bay had higher mean levels of DDE residue than those from San Francisco Bay; however, PCB residues averaged higher in San Francisco Bay crabs (Table 4). The levels of DDE and PCB's reported here are lower than those found in crab tissues in earlier studies and may reflect the more stringent controls on releases of DDT and PCB's into the environment. Thus, it seems unlikely that DDT or PCB's are responsible for preventing the recovery of the San Francisco area Dungeness crab population.

TABLE 4. TISSUE LEVELS OF DDE AND PCB'S IN DUNGENESS CRABS FROM SAN FRANCISCO AND HUMBOLDT BAYS.[a]

Area	Tissue	DDE (ppm) range	DDE (ppm) mean	PCB's[b] (ppm) range	PCB's[b] (ppm) mean
San Francisco Bay	muscle	.001 - .020	.004	.005 - .079	.028
	hepatopancreas	.016 - .58	.075	.32 - 1.8	.82
Humboldt Bay	muscle	.001 - .020	.007	.007 - .025	.013
	hepatopancreas	.027 - .32	.15	.18 - .79	.36

[a] Determinations made by DFG Wildlife Management Branch, Pesticide Section personnel.
[b] PCB's - a total of Aroclors 1248 + 1254/1260 mixture.

The results from the analyses of petroleum hydrocarbon burdens in muscle, hepatopancreas, and gonadal (or egg mass) tissues of crabs from the San Francisco and Eureka area (L. DiSalvo et al. unpublished) show no statistically significant difference between males and females of the same region. There was no significant difference in hydrocarbon burden between different tissues in the Eureka samples, although hepatopancreas tissue in San Francisco crabs showed higher hydrocarbon levels than did muscle and gonadal tissue. In comparing different regions, the San Francisco adult crabs contained significantly higher burdens than did Eureka crabs. Large juvenile crabs appeared to follow the same trend, although further work is required to obtain statistical validity. Identification of the various fractions that constitute the petroleum hydrocarbon burden in San Francisco area Dungeness crabs and bioassays is slated for 1978-79.

A study of the effects of chlorinated waste effluents on juvenile crabs will be conducted in 1978-79 by SERL. The need for this study arose when it was demonstrated that "significant increases in chlorine usage by municipal wastewaster treatment plants directly proceeded (*sic*) failure of the regional Dungeness crab population" (Russell and Horne 1977).

MARINE CULTURE LABORATORY

Dungeness crab culture studies are directed toward developing the capability of growing sufficient numbers of larval and post-larval crabs for studies of development and behavior, experiments in testing effects of environmental factors, and bioassays of selected environmental toxicants. In 1975 crab eggs showed 36.6% survival to the megalopal stage in a flow-thru system; of these, 92% survived to the first post-larval instar. In 1976, it was determined that larval crab densities in the flow-thru culture systems could be increased by a factor of nearly six and yield favorable results. Although the percentage developing to the megalopal stage was lower at these increased densities than that of the best previous culture system tested, the number of larvae developing to the megalopal stage was nearly double. Based on results obtained from three high larval density flow-thru

culture systems that were tested, an estimation of the present capability, and requirements, to cultivate larval crabs to the megalopal stage can be made (average values): twelve hundred newly hatched crab larvae, distributed in an 8.5-liter culture container should yield 163 larvae to the megalopal stage in about 63 days.

CONCLUSIONS

It appears from our continuing studies that San Francisco Bay is a "critical" or essential element in the life history of our local Dungeness crab population. We cannot say definitely whether the environmental quality of the Bay is such that it has been instrumental in causing the decline of, or in preventing the recovery of, the local Dungeness crab fishing stock.

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