

Anatomy of an oil spill: long-term effects from the grounding of the barge Florida off West Falmouth, Massachusetts

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ABSTRACT

To determine carefully the effects on the marine and estuarine benthos of Number 2 fuel oil spilled by the barge FLORIDA off West Falmouth, Massachusetts, we sampled for many months along an onshore-offshore gradient of pollution, and less intensively at unoiled sites. Analyses of hydrocarbons established that pollution was greatest and most persistent in the intertidal and subtidal zones of Wild Harbor River, less severe in degree and duration at stations farthest from shore. A variety of concurrent analyses showed that disturbance of the fauna was most severe and longest lasting at the most heavily oiled sites, and least severe but perceptible at lightly oiled stations. Patterns of disturbance were not related to granulometry of the sediments. Plants, crustaceans, fish, and birds suffered both high mortality immediately after the spill, and physiological and behavioral abnormalities directly related to high concentrations of the fuel oil. Five years after the spill its effects on the biota were still detectable, and partly degraded #2 fuel oil was still present in the sediments in Wild Harbor River and estuary.

INTRODUCTION

Early in the morning of September 16, 1969, the barge *Florida* ran aground on a rocky shoal off Fassett's Point, West Falmouth, Massachusetts, and spilled 650,000 to 700,000 liters of Number 2 fuel oil into Buzzards Bay (Figs. 1-3). Strong SSW winds, common to this region, churned the oil into an oil-water emulsion and drove it northeastward into Wild Harbor River in North Falmouth. The oil spread over more than 1000 acres, including four miles of coastline (Souza, 1969). Mass mortality of at least the larger marine animals occurred immediately in the intertidal and subtidal zones of the river.

Water-based emulsifiers, claimed by the manufacturers to be nontoxic, were initially used to clean up the oil. The company hired to remove the oil first applied these emulsifiers in Wild Harbor on the evening of September 16, and made further applications the next day. On September 18 and 19 the company introduced emulsifiers into the waters from the beach south of Wild Harbor before being restrained

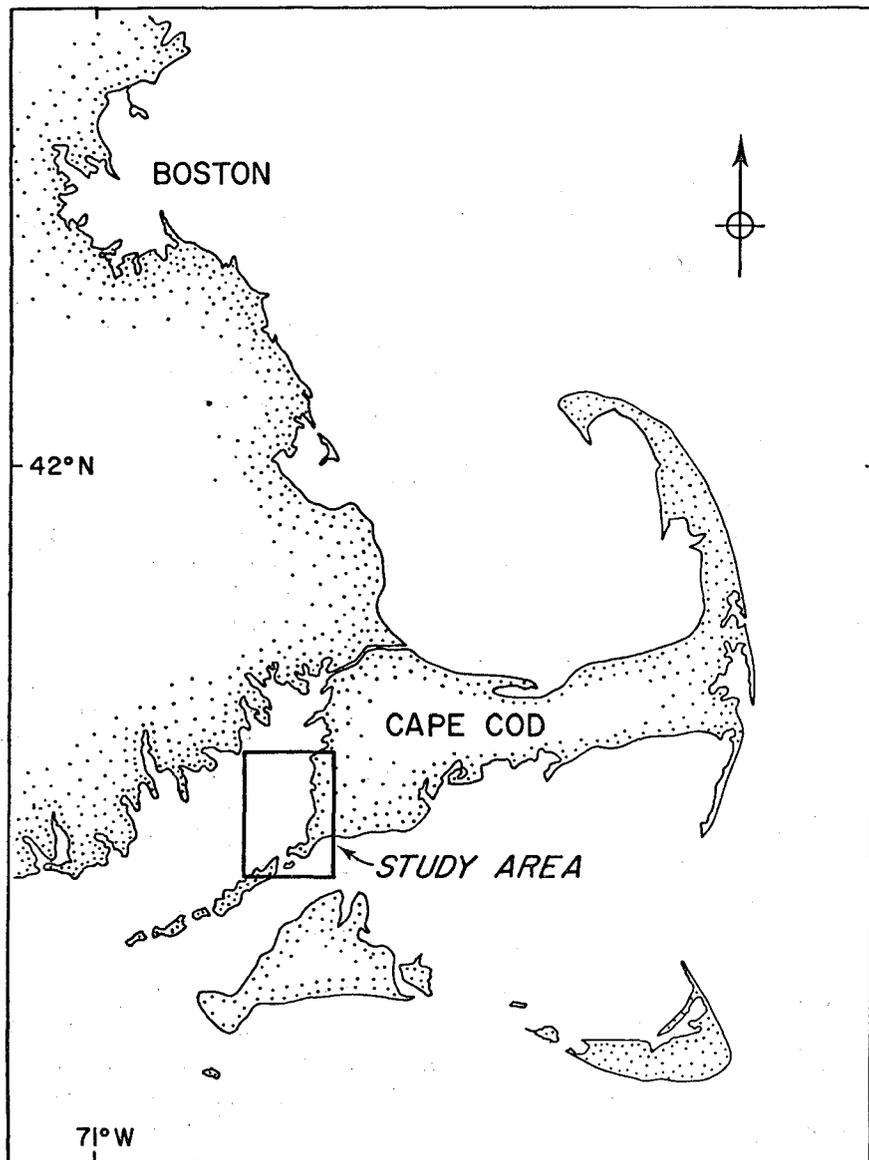


Figure 1. Map of Southeastern Massachusetts showing location of study area in Eastern Buzards Bay.

by official act on the grounds that the emulsifiers were toxic to shellfish. The company poured a total of 17,072 liters of emulsifiers into the waters in less than four days. These chemicals were not, however, the chief cause of death, for animals had already begun to die in large numbers at least four hours before the first emulsifiers

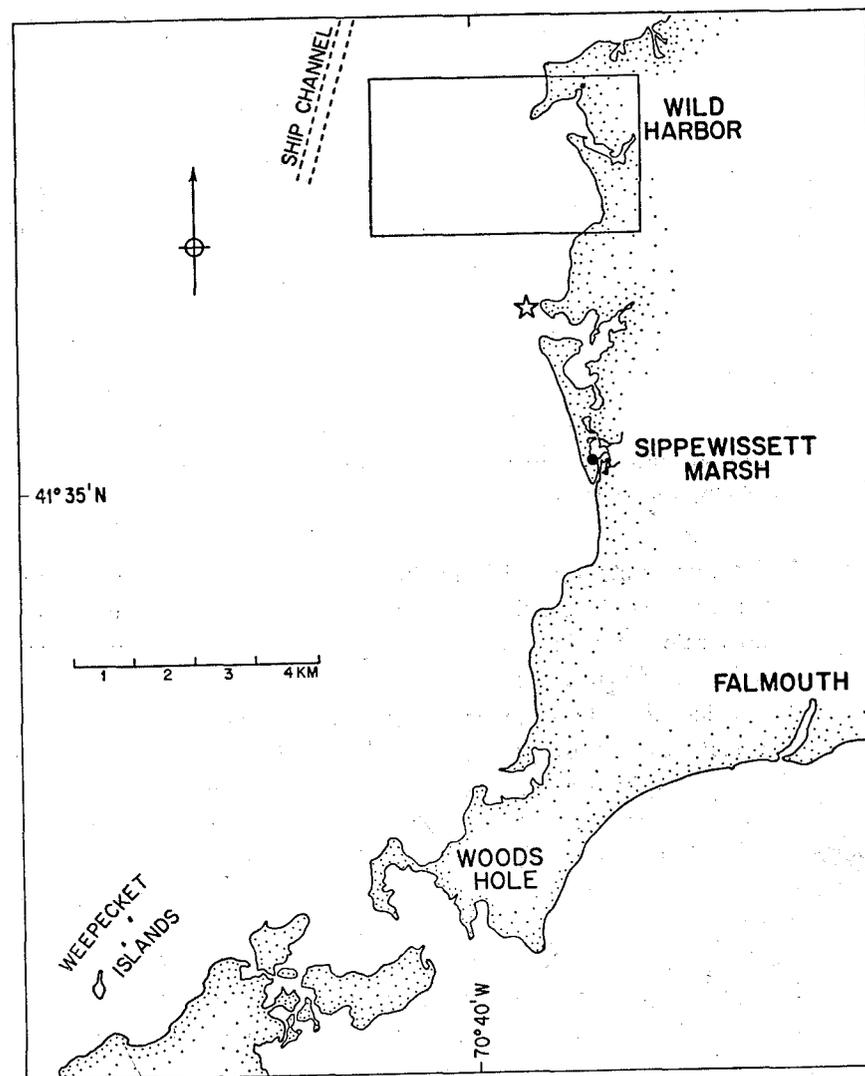


Figure 2. Map of study area showing site of grounding of barge *Florida* (star). Intensively sampled area in box.

were applied. As Murphy (1970) states, "... most spills of any magnitude of distillate fuel oils have resulted in a significant kill of marine life". (See also Adam, 1936; Tegelberg, 1964; North, Neushul, and Clendenning, 1965; Gooding, 1971; Croker, 1969).

This report may seem too detailed. It is our conscious purpose to give details. We wish to countervail against the all-too-common conclusions that are, at best, equivocal interpretations of insufficient and ambiguous data. Such inadequacies are usual

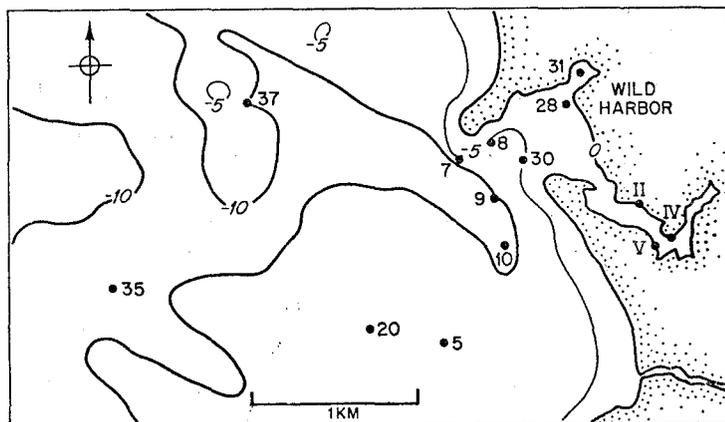


Figure 3. Intensively sampled Wild Harbor River area, showing location of stations and bathymetry. Contour interval is five meters.

in many pollution-related studies of benthic ecology, including those on which important decisions are based. Through detailed presentation and analysis of the data, we aim to demonstrate more than adequately the persistent, deleterious effects of Number 2 fuel oil on marine benthos.

In the initial period of study we made several observations. Within only eight to ten days at the relatively high temperatures of 18 to 21°C, carcasses of most soft-bodied animals completely decomposed. Skeletons were soon disarticulated and scattered. Both intertidal and subtidal sediments, particularly sands, became physically unstable, probably owing to disintegration of animal secretions and tubes, and death of vegetation and benthic algae that bound the sediment. Marsh grasses, reached by water-borne oil during the first three weeks after the spill, died. The pollution-indicator polychaete, *Capitella*, occupied the river bottom in very dense concentrations. By late spring and early summer of 1970 this polychaete population crashed, and a few other species were able to occupy this area. In the spring of 1970 the gonads of blue mussels, *Mytilus edulis*, surviving in the affected area were thin and sterile, whereas gonads of blue mussels in unpolluted Sippewissett Marsh were plump and ripe. Some mortality always attended oil in the sediments; the greater the concentration of oil, the heavier the mortality. In sediments saturated with oil, almost all of the benthic life was killed.

In order to study spatial and temporal changes in concentration and composition of the fuel oil, and like changes in density and character of the benthic fauna, our long-term strategy was monthly or bimonthly sampling at stations along a gradient from most severe effects in Wild Harbor River to least effects at offshore stations in Buzzards Bay. For the intensively sampled stations we considered granulometry of sediments, composition of hydrocarbons, and quantitative and qualitative changes

in the fauna (including patterns of dominance, constancy, numerical variability, and diversity).

In a paper that will be submitted to the Journal of Marine Research, we will provide a broader perspective for the *Florida* oil spill by making a critique of findings of oil pollution studies that are widely available, frequently cited, and often serve as a base for decision-making in public policy.

Throughout the body of this report, No. and # will be used interchangeably for "Number" as, for example, No. 2 fuel oil or U.S. Standard #50 mesh sieve.

1. Methods

Field work

On September 19, 1969, three days after the spill, we began to collect samples in the intertidal zone of Wild Harbor River, at six sites marked with stakes. Within the next week, we began collecting at many subtidal stations in the affected area. Within two months after the spill we were able to determine the onshore-offshore gradient of effects, and limited further sampling to stations along that gradient. These stations, 31, 9, 10, 5, 20, and 35, we marked with anchored buoys (Fig. 3). The three most offshore and minimally oiled stations 5, 20 and 35 served as reference or control stations for the more heavily oiled stations 9 and 10 and severely oiled station 31. Even though the buoys disappeared during the second winter, we were able to relocate stations to within a few feet by fathometer, bearings, compass bearings, and fixed-range radar. We later established a control area in the unoiled intertidal area of Sippewissett Marsh, well to the windward of Fassett's Point where the barge *Florida* ran aground (Fig. 2). Ice and rough seas sometimes prevented collecting during the winter. We collected 413 sets of samples, 42% of which were picked for animals. Each set of intertidal samples consisted of a principal 1/128 m² core for faunal analysis, a replicate sample of the same size, and surficial sediment for hydrocarbon and granulometric analyses. This third sample was taken with a spoon or trowel from a square 15 cm on a side to a depth of 4 cm (900 cc). Each set of subtidal samples consisted of one or two 1/25 m² Van Veen grab samples for faunal analysis, and another such sample for hydrocarbon and granulometric analyses. The uppermost 4 cm of this last grab sample was retained, the rest was discarded. In the field we noted the presence of oil in the sediments and on animals, the anaerobic condition of some substrata, and the presence or dead animals and plants. A total of 142 benthic faunal samples forming the critical information base of this study are listed chronologically by station in Table 1. The actual faunal composition of these samples can be obtained from the senior author.

Treatment of biological samples

We washed the samples for biological analysis on a U.S. standard #50 mesh (opening = 0.297 mm), preserved them in 5% buffered formalin, transferred them

Table 1. The benthic faunal samples and their sampling dates for the ten intensively studied stations that form the basis of the West Falmouth study.

	Intertidal Station IV	Intertidal Station II	Sippewissett Marsh	31	30	9	10	5	20	35
	9.21.69	9.19.69	2.24.70(1)	9.25.69	9.27.69	9.24.69	9.22.69	9.27.69	9.24.69	10.16.69
	10.9	9.26	(2)	10.24	10.10	10.14	10.14	10.22	10.16	11.13
	12.7	12.7	8.6	11.17	11.17	11.17	11.17	11.19	11.13	12.18
	2.22.70	2.24.70	8.13	12.22	12.17	12.18	12.18	12.18	12.18	3.19.70
	4.19	3.31	1.11.71	3.3.70	6.17.70	4.8.70	4.6.70	4.22.70	1.6.70	4.6
	5.20	6.16		5.12	9.30	5.15	5.10	6.17	3.19	5.12
	6.15	8.3(1)		6.12	2.22.71	6.12	6.12	7.14	4.6	6.12
		(2)		7.14		7.13	7.13	8.14	5.12	7.13
	7.14	10.1		8.18		8.11	8.11	1.4.71	6.12	8.11
	8.6	11.1		9.29		9.29	9.29	2.22	7.13	9.29
	10.2(1)	1.11.71		11.10		11.12	10.10		8.11	11.10
	(2)	3.1		12.22		12.22	12.22		9.29	1.4.71
	11.11	6.10		1.13.71		2.19.71	2.19.71		10.10	2.19
	12.12			3.3		4.26	6.10		12.22	8.25
	3.1.71			6.9		6.9	8.24		2.19.71	
	4.26			8.24		8.24	12.29(1)			
	6.4			12.29		12.29	(2)			
	7.8			3.23.72		3.23.72	3.23.72(1)			
	8.9			4.3			(2)			
	12.17			1.9.73						
	4.13.72									
	5.26									
Total Samples	21	13	5	20	7	18	19	10	15	14

after 24 hours to unbuffered 70% ethyl alcohol, and stained them with rose bengal. We picked the animals from the washed sediments under binocular microscopes. We extracted 280 species of animals, including 108 polychaetes, 34 bivalves, 39 gastropods, 47 amphipods, and 52 other taxa, a total of 347,165 individuals. Both the very abundant nematodes and other meiofauna were too small to be sampled adequately with a 0.297 mm sieve, and were omitted from the analyses.

Granulometric analysis

The sediments were analyzed to determine the extent to which faunal patterns were related to character of the substratum rather than to presence of oil. Analysis was limited to sediments from stations sampled for at least a year, stations II, IV, 31, 30, 9, 10, 5, 20, and 35. The approximate size of the samples was from five to 35 grams. Each sample taken for these and hydrocarbon analyses was homogenized, and a given quantity was removed for the hydrocarbon analysis. The remnant, if any, was used for sedimentary analysis. For statistical manipulation, we have used the phi scale, in which Wentworth scale of size classes was used in the descriptions. In this scale, each successively finer class is half the width arithmetically of its predecessor. For statistical manipulation, we have used the phi scale, in which the phi units are the logarithm to the base 2 of the Wentworth classes. Conversion tables appear in Folk (1974) and Krumbein (1939).

Samples from all stations except 31, which was much muddier than the others, were treated in the manner to be described.

First the sample was wet-sieved on #10 (2 mm, -1ϕ) and #230 (0.0625 mm, 4ϕ) U.S. standard meshes to separate it into the gravel, sand, and mud fractions. The gravel, freed of shells and plant debris, was dried and weighed. The sand was washed with acetone to remove organic molecules, dried, weighed, and put in the WHOI Rapid Sediment Analyzer (Schlee, 1966), which produced a strip chart which was analyzed for distribution of material among the five size classes of sand. The mud fraction was washed into a 1000-ml cylinder, 30 ml of 0.5 N sodium hexametaphosphate (Calgon) solution and enough water added to bring the level up to 1000 ml. After the mixture was thoroughly stirred and allowed to stand for 24 hours to check for flocculation, the mud and water were thoroughly stirred again, and 20 ml of the mixture was removed after 20 seconds from a depth of 20 cm by pipette, transferred to a beaker, dried, and weighed. This weight, multiplied by 50, gave the total weight of mud in the sample. At one minute and 49 seconds, 7 minutes and 15 seconds, 28 minutes and 59 seconds, 20 ml aliquots were withdrawn from a depth of 10 cm by pipette, released in beakers, dried, and weighed to give the proportions of clay and silt in the fine fraction.

Samples from station 31 were sandy muds containing large amounts of Number 2 fuel oil. They were first washed with acetone, dried, and weighed, then wet-sieved on a #230 mesh to separate sand from mud. The sand was dried and weighed. The

mud was centrifuged to separate silt from clay, and the silt was dried and weighed. Weight percents of sand, silt, and clay were calculated.

Cumulative curves were plotted on probability paper for all samples for which information was sufficient, and quartiles determined graphically for derivation of median, sorting, and skewness. Because the gravel and mud fractions were not analyzed in detail, it was impossible to fix the tails of the curves, and therefore impossible to use more sensitive measures to characterize the sediments. In the few cases in which mud constituted more than 25% by weight of the sample, the third quartile was estimated by continuing the line connecting the two previous points through the 75th percentile, and reading the phi value intersected. The phi-scale equivalents of Trask's sorting and skewness measures were calculated and described in terms set forth in Folk (1974). The central tendency was expressed by the median, the similarity among the central 50% of the grains by phi quartile deviation (sorting), and asymmetry of the distribution by phi quartile skewness.

Because the samples were small, special care was taken to avoid error. During sieving, fines were completely washed from the sands. A balance more accurate than necessary was used. To prevent samples from absorbing water from the air, fractions were stirred in a desiccator. In the RSA analysis, too large a sample resulted in artificial enhancement of the finer size classes, while too small a sample resulted in a low curve from which data were extracted only with difficulty. Any error in the pipette analysis of very small fractions of mud was magnified fifty fold, giving values less reliable than those for weightier fractions. In a few cases, replicate analyses by the same technique were run; agreement was very good. Measurement of the mud fractions are probably reliable within 2%, measurement by RSA probably are only slightly less reliable.

Analysis of hydrocarbons

Oil is almost infinitely complex. The thousands of different molecules in any crude oil, ranging from 16 to more than 20,000 in molecular weight, are products of diagenesis and bacterial action beneath the surface of the earth under anaerobic conditions over spans of thousands to millions of years. As Blumer and Sass (1972a) remark, "The diagenetic processes involved in petroleum formation at depth randomize the sedimentary organic matter through inter- and intramolecular scrambling and produce a hydrocarbon mixture of enormous complexity which cannot be resolved completely by present medium or high resolution chromatography." Most of the different molecules belong to a few major homologous groups of saturated hydrocarbons. Biogenic hydrocarbons, however, are synthesized through specific natural processes to yield a limited suite of compounds within a relatively narrow range of molecular weights. Up to at least C₂₂ biogenic hydrocarbons can be resolved into individual compounds by medium-resolution gas chromatography and mass spectrometry. Only a few members of each homologous group occur in any one kind

Table 2. Major differences between petroleum and biogenic hydrocarbons.

Hydrocarbon	Petroleum	Biogenic
<i>n</i> -Alkanes	Odd and even numbers of C atoms nearly equally abundant Adjacent members of series usually vary little in concentration	Odd numbers of C atoms much more abundant than even numbers
Aromatics	Many and complex (polybenzenes and naphthalenes, polynuclear aromatics with multiple alkyl substitutions, naphthene-aromatics)	Simple, with one or two alkyl substitutions at most
Cycloalkanes (Naphthenes)	Heterogeneous; those with substituted rings more abundant than their parent compounds	Uncommon; one- to three-chain rings
Alkenes (Olefins)	Usually absent in crude oil; may occur in refined petroleum	Major portion of biogenic hydrocarbons

of organism. Frequently, only one hydrocarbon group is present and commonly a single hydrocarbon predominates. The most diagnostic features of organic hydrocarbons in coastal sediments are the strong predominance of normal alkanes with odd numbers of carbon atoms (Stevens *et al.*, 1956) and the absence of the unresolved envelope typical of crude oil and its products. Biogenic hydrocarbons of this sort occurred in Buzzards Bay before the *Florida* spill (Clark and Blumer, 1967). The many differences between biogenic and petroleum hydrocarbons (Table 2) identify the source of hydrocarbons at a possibly polluted site.

Four processes, evaporation, dissolution, biodegradation, and chemical degradation, change oil. Dissolution as used here is defined operationally as the accommodation of the oil in water by true solution, emulsion, or any other process. Dissolution results in the removal of oil from the sediments to overlying or interstitial water or both.

Blumer and his colleagues used gas chromatography and mass spectrometry to identify the No. 2 fuel oil from the *Florida* and to measure rates of degradation of the different components with time (Blumer *et al.*, 1971; Blumer and Sass, 1972a, b, c; Blumer, Souza, and Sass, 1970a, b; Blumer, Souza, Sass, Sanders, Grassle, and Hampson, 1970).

They measured the mass of hydrocarbons in 100 g of dry sediment. The average concentration of biogenic hydrocarbons forming the normal background in Buzzards Bay is 5-7 mg/100 g dry sediment, with 10 mg nearly maximal (Blumer and Sass, 1972a). Sediments are considered polluted if concentrations perceptibly exceed this background. That concentrations are within the normal background need not mean that the hydrocarbons are biogenic. If the hydrocarbons are not the products of biogenic synthesis, then oil pollution has occurred. They studied the temporal changes

in the boiling point envelope. The lighter fractions of oil evaporate and dissolve more rapidly than the heavier fractions, so that the boiling point envelope retreats toward the higher carbon numbers and stabilizes there upon depletion of the lighter fractions (Blumer and Sass, 1972a). The envelope stabilizes more rapidly and at higher carbon numbers with increased temperature. Stabilization is also more rapid in coarser and well-sorted sediments. Unlike crude oil and its products, biogenic hydrocarbons do not appear in chromatograms as an unresolved boiling point envelope.

They measured the degradation of straight and branched alkanes. Straight alkanes are degraded more rapidly than their branched isomers in both the laboratory and field. The ratio of *n*-heptadecane (*n*-C₁₇) to pristane was a sensitive index of the initial stages of biodegradation in West Falmouth (Blumer, Souza, and Sass, 1970b). The value of this ratio for the unaltered #2 fuel oil spilled by the *Florida* was 1.67, but successively lower as biodegradation progressed.

They studied the degradation of adjacent homologues. Adjacent members of the same or adjacent homologous series break down at nearly the same rate; their relative concentrations vary only slightly as oil ages. Because oils (and their refined products) have different compositions, and therefore different concentration ratios, these ratios identify an oil and its refined products, regardless of age. Blumer and his colleagues used the ratio of the adjacent homologues of the branched isoprenoid alkane series, pristane (tetramethylpentadecane) and phytane (pentamethylpentadecane), to identify the polluting oil in its spread and degradation. Residues of the #2 fuel oil spilled by the *Florida* in Buzzards Bay and incorporated in the sediments contained isoprenoid alkanes from C₁₃ to at least C₂₀ (Blumer and Sass, 1972c). The members with the highest boiling points, pristane (C₁₉) and phytane (C₂₀), are little affected by solution at ambient temperatures. Decrease in amplitude of the pristane and phytane peaks relative to the unresolved background envelope represents biodegradation beyond the initial stage.

Lateral and temporal variation of the fauna

We used many graphic and mathematical techniques to analyze the stability of the fauna. Each method examined a different aspect of the changes in density and composition along the onshore-offshore gradient of pollution.

We examined changes in density and number of species at intertidal stations II and IV and subtidal stations 31, 30, 9, 10, 5, 20, and 35, and analyzed the degree and rapidity of fluctuations. We paid especial attention to the invasion and dominance of opportunistic species. Opportunists are those species which discover a habitat quickly, reproduce rapidly so as to exploit the resources sooner than can other species, and, having exhausted those resources or having befouled the habitat, die in great numbers or move to other areas (Wilson and Bossert, 1971). Opportunists are the index of ephemeral, unpredictable, and disturbed habitats. The chief

opportunists near West Falmouth were capitellid polychaetes, *Mediomastus ambiseta* and two or more sibling species of *Capitella* (Grassle and Grassle, 1977). *Mediomastus* was abundant offshore, *Capitella* in Wild Harbor River. We used BMD P1V one-way analysis of variance and covariance to evaluate rates of mortality at stations 9, 10, 20, and 35 in the year after July, 1970 (Dixon, 1973).

We studied changes in the proportions and identities of the subdominant species at most of these same stations and in Sippewissett Marsh, an unoiled control area for the intertidal stations in the Wild Harbor River Estuary. Modest seasonal variation in abundance of subdominants from year to year is indicative of minimally disturbed or undisturbed conditions. Successional assemblages making up a large portion of the partial fauna are signs of disturbance. We arbitrarily designated as subdominant any species which, in the absence of the one most abundant species, composed at least 10% of the fauna.

We also examined changes in density of ampeliscid amphipods. Counts of dead animals were based on fragments of heads retained on the #50 mesh sieve. These heads have four brightly pigmented, easily identifiable, decay-resistant eye lenses. Upon restudying our samples, we made small changes in the data previously published (Sanders, Grassle, and Hampson, 1972; Sanders, 1974). Trends remained unaltered, however. Owing to their high sensitivity to moderate quantities of oil (here, about 15 mg/100 g dry sediment), ampeliscid amphipods are excellent indicators of oil pollution (Stander and Ventner, 1968).

We used temporal changes in density to determine the effect of #2 fuel oil on the benthic fauna. To this end we measured the month-to-month variation at intensively sampled stations 31, 9, 10, 20, and 35 of a species with a mean abundance of three or more in 1/25 m² at one or more stations. We used the coefficient of variation (standard deviation/mean) to measure this variation. The more affected that species, the greater the variation in abundance and the greater the coefficient of variation.

We evaluated patterns of constancy of species from stations II, IV, 31, 9, 10, 5, 20, 35, and Sippewissett Marsh. Constancy measures the extent to which a species is a constant member of the biota at a station, and is the percentage of analyzed samples in which the species occurs. The samples from stations II, IV, and Sippewissett Marsh, each 1/128 m², are comparable among themselves, as are the samples from stations 31, 9, 10, 5, 20 and 35, each 1/25 m². The two sets are not comparable. All were retained on a #50 mesh sieve. We included only those species occurring in more than 45% of the samples from a station. Generally, species less constant than 0.45 were very much less constant. A high proportion of very constant species is indicative of a healthy, stable fauna; a high proportion of low-constancy species indicates a fluctuating, disturbed fauna.

We also used a weighted ratio to express the year-to-year differences in the density of each species. This weighted ratio is the discrepancy index, *Z_i*. For each species the index is composed of two parts: density, the sum of the mean densities of the

two years considered ($X_i + Y_i$), and disparity, the ratio of the larger mean density to the smaller (X_i/Y_i). The larger the value of this ratio, the greater the disparity. The formula for the discrepancy index is:

$$Z = (X_i + Y_i) (X_i/Y_i)$$

in which X_i is the larger mean density and Y_i is the smaller mean density of species in samples of a given size (here, $1/25 \text{ m}^2$) in the two years compared. This formulation of the index is a simplification of the discrepancy index already published (Sanders, 1978). When a species was absent in one of the years, we assigned one individual to that year, such that the mean density was one divided by the number of samples. At very low densities, a species absent in one of the years has a disproportionately large effect on the index; the replacement of null by one corrects the distortion index. For each of stations 31, 9, 10, 20, and 35 we arranged species in order of increasing discrepancy, cumulated discrepancies and densities in that order and plotted the points on logarithmic paper. The line having a slope of +1 and a y-intercept of 0 represents the case in which the mean densities of the species are the same in the two years. The degree of departure from this line is a measure of the discrepancy between the mean densities of the two years.

We used three indices to evaluate the diversity of samples from stations 31, 9, 10, 20, and 35. One is the commonly used Shannon-Wiener information function with the normally used log base 2:

$$H(s) = -\sum_j p_j \log p_j$$

in which s is the total number of species, and p_j is the observed proportion of individuals belonging to the j th species ($j = 1, 2, \dots, s$). Another index of diversity is the evenness function;

$$V' = H(s)/H_{\max}$$

in which H_{\max} is $\log s$. This index measures only the dominance component of diversity. The maximal value is 1.0, at which the individuals are distributed equally among species. The third index is Hurlbert's modification (1971) of the rarefaction method (Sanders, 1968), which predicts the number of species in a random sample without replacement, given a population N :

$$E \left[S_m | N \right] = \sum_{i=1}^k 1 - \frac{\binom{N_m - N_i}{m}}{\binom{N}{m}}$$

in which N_i is the finite population of species i ; N is (N_1, N_2, \dots, N_k) , a vector representing the entire finite population; N is the total number of individuals in the finite population,

$$\sum_{i=1}^k N_i;$$

and S_m is the random variable denoting the number of species in a sample of size m (Smith and Grassle, 1977).

There are many different indices for measuring either the variety of life in different habitats, or the relative "health" of an environment stressed by natural phenomena or pollutants. Among the more commonly used diversity indices are the Preston lognormal distribution (1948), the Margalef index (1957), the Fisher, Corbet, and Williams logarithmic series (1943), the Simpson diversity index (1949), the MacArthur broken-stick model (1957), the Shannon-Wiener information function (Shannon and Weaver, 1963), and the rarefaction method (Sanders, 1968, modified by Hurlbert, 1971).

The formulations of most indices involve assumptions about the way in which individuals are distributed among species in nature. The phenomenon measured is the closeness of agreement of a preconceived distribution with the natural one. The inherent danger is the mental ascendancy of the preconception over nature. A related difficulty is the unfortunate dependence of most diversity indices on size of sample, which for validity demands use of samples with identical numbers of individuals. The rarefaction method seeks to circumvent these two pitfalls: except at very low densities it is independent of sample size, and it does not make any assumptions about the distribution of individuals among species.

Most diversity indices have two components. One is dominance diversity, a measure of the evenness with which individuals are distributed among species, regardless of the number of species. The lower the degree of dominance, the more even this distribution, and the higher the diversity. The other component is species richness, a measure of the number of species in a sample. The greater the number of species, the greater the diversity (Whittaker, 1965). The relative contributions to these two components to the diversity value differ from one index to another.

The Shannon-Wiener information function reflects primarily the evenness of the five or six most abundant species. Smith, Grassle, and Kravitz (1979) show that the information function is essentially equal to the expected number of species in a random sample of 10 from a population, and equivalent to Hurlbert rarefaction at the level of 10 individuals. At this low density only the more abundant species are likely to be represented.

To determine the relative contributions of species richness and evenness to diversity at stations 31, 9, 10, 20, and 35, we ranked samples by diversity and by evenness from most diverse or even (1) to least diverse or even (71 in the analysis of the whole fauna, 70 in that of the fauna without the one most dominant species). Values of diversity were derived from the rarefaction curves, and are the inverse of the number of animals in 20 species. Values of evenness were calculated from the evenness function. The most diverse and most even fauna would have one ani-

mal for each of the 20 species. We used only those samples with at least 20 species. We then compared the rank positions of evenness and rarefaction diversity for each of the samples. If the rank positions by equitability and rarefaction were the same or nearly so, then evenness and species richness, the other component determining diversity, differed little in their contributions to the resulting diversity value. If, however, there was a large difference in the rank position of a sample in the two series, the diversity value was the resultant of large, opposite but equal effects of its two components. The higher rank component strongly increased diversity either as a result of greater evenness or greater species richness that, in turn, was equally opposed by the lower rank constituent reducing diversity by lower equitability or lower species richness. Mean rank diversity values together with relative contributions of equitability and species richness are given for three time periods: September 1969-June 1970, July 1970-June 1971 and July 1971-March 1972.

We used an agglomerative technique (Williams, 1971) to determine degree of faunal similarity among the various stations. In an agglomerative technique the most similar samples cluster most closely and first, less similar samples cluster less closely, and least similar samples most distantly and last. We used NESS, the Normalized Expected Species Shared, to assess faunal similarity (Grassle and Smith, 1976). This measure is sensitive to less common species, and is used to detect spatial and temporal relationships among samples on the basis of their species composition and on the number of these species shared among random subsamples of fixed size from each collection. We used a subsample size of 50, at which both rare and common species contribute to the measure. We included in the analysis only those samples with at least 100 animals. In some cases, the whole fauna of a sample had the required number of animals, but the fauna without the one most dominant species had too few animals; those sample were omitted from the analysis. Because it handles no more than 3000 entries, each species of each sample a separate entry, the program could analyze only three offshore stations at a time. Ideally, samples from an undisturbed station will cluster closely together and by season. The fauna at such a station undergoes seasonal oscillations and varies little from year to year. Samples from a station at which the fauna has been severely disturbed will cluster in temporal sequence, and more closely with the passage of time. At such a station the fauna undergoes successional changes, and varies from one year to the next.

There is a weak overlap or redundancy among some of the indices used. The Constancy and Coefficient of Variation Indices are related in the same way that the number of species is related to the diversity value in a sample. The Discrepancy Index can be thought of as a graphical display of similarity containing more information than a single similarity measure. Both the Shannon-Wiener Information Function and the Rarefaction Methodology modified by Hurlbert were used to calculate diversity. As pointed out elsewhere, the Information Function Index is essen-

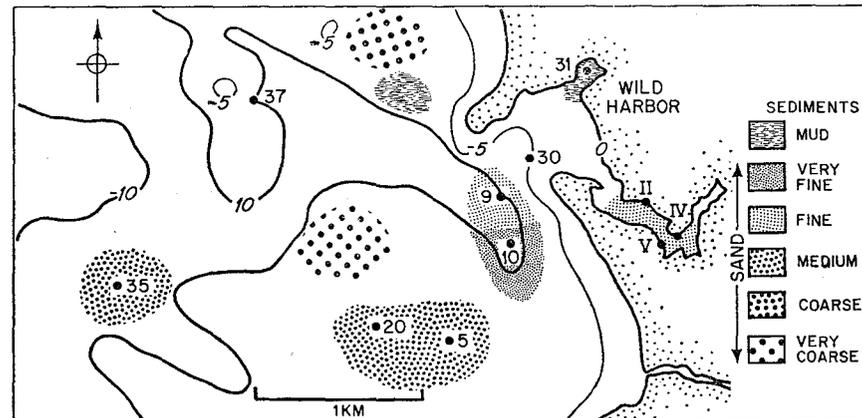


Figure 4. Distribution of sediments in intensively sampled area, with additional data from Hough (1940) and Moore (1963).

tially determined by the equitability of the few most abundant species. In contrast, each species contributes to the Rarefaction Index in proportion to its relative abundance. We believe the Rarefaction Index is the more appropriate measure of diversity. We have included the commonly used Information Function to provide a basis of comparison to the numerous other diversity studies that employed this index.

2. Results

Sediments

Eight of nine stations consisted of muddy sands mixed with small amounts of gravel and shell debris. At station 31 the sediment was sandy mud. Sediments at seven stations were studied in enough detail to provide some granulometric information. Secular changes were slight or absent. Figures 4 and 5 summarize the results.

At station IV the bottom was fine sand with an average median value of 2.40ϕ (0.16 mm). Gravel was absent. Some samples appear to have a minor mode in the mud class. Sands became finer with time, and were usually moderately well sorted and nearly symmetrical. In April, 1971, the sediment was poorly sorted and strongly fine skewed. The sediments seem to have been more strongly fine skewed in the early spring and late summer than in the late spring.

At station II sediments were fine and medium sands, coarser than those at station IV. Variation in the median size was not very great, 1.89 to 2.31ϕ (0.27 to 0.21 mm). These sands were about as well sorted as those at station IV, but seem to contain more mud. In March, 1971, as in the next month at station IV, the sediment was finer, more poorly sorted, and more fine skewed than usual. Only one sample was clearly bimodal, one was unimodal, and the other five had a minor mode in the

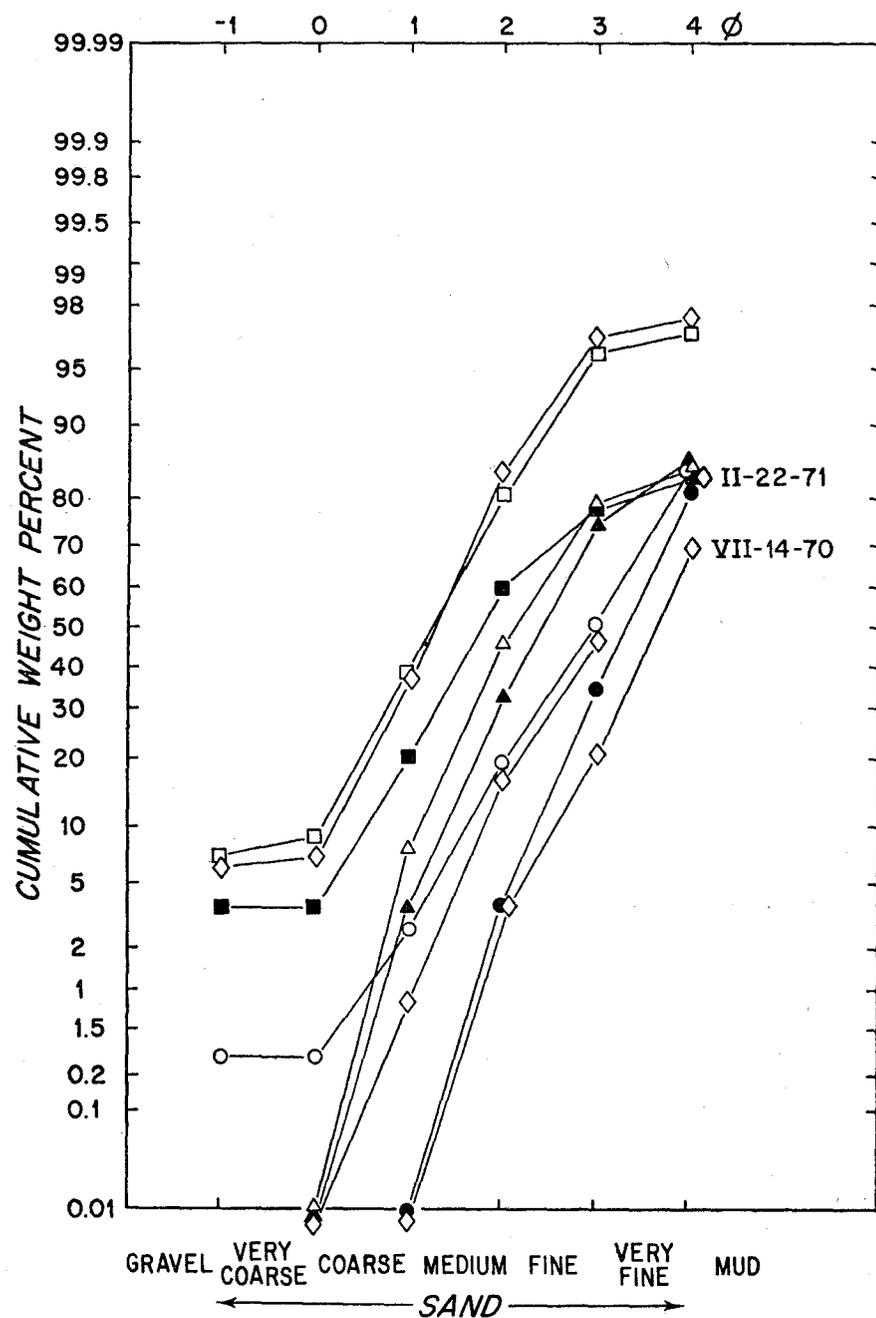


Figure 5. Cumulative curves for average samples at stations 5 (\diamond), 20 (\square), 35 (\blacksquare), II (\triangle), IV (\blacktriangle), 9 (\circ), and 10 (\bullet), and for the two unusually fine sediments from station 5 (\diamond).

mud size class. As at station IV, the sediments were granulometrically variable from sample to sample.

All seventeen samples from station 31 were sandy silts without gravel. The proportion of sand was variable (12.5 to 48.0%). The average sample was about 20% sand, 70% silt, and 10% clay. The four sandiest samples were taken in late spring (May, 1970; June, 1971) and in winter (December, 1971; March, 1972).

Six samples from station 30 appear most similar to the gravelly sands at stations 5 and 20.

Most sediments at stations 9 and 10 consisted of very fine sands, slightly finer at station 10. All samples had nearly symmetrical distributions; those at station 9 were usually slightly coarse skewed, those at station 10 slightly fine skewed. Small amounts of gravel were present at station 9 but not at station 10, where the sediment was always unimodal. Sorting was better at station 10. The sand at station 10 was very well sorted and devoid of mud in September, 1970, although the work sheet suggests that this resulted from procedural error. At station 9 the sediment became slightly coarser with time; at station 10 the sediment did not show temporal trends. The sediments at station 10 were less variable than those of any other station, even those of station 9 which they most closely resembled.

The sediments at station 5 and 20 were alike, most of them slightly gravelly medium sands moderately well to well sorted and symmetrically distributed. Mud was a minor constituent. The sands at station 20 were usually coarser than those at station 5. At both stations sediments were coarser in the late spring and early summer, and finer in mid- and late summer. Two samples from station 5 were unimodal very fine sands, similar to those at stations 9 and 10 (Fig. 5).

Sediments at station 35 varied from sample to sample in all textural aspects. All had a minor mode in the gravel class. The median size, medium and fine sand, was about as variable as those at stations 9 and II. Most samples were moderately well to poorly sorted, and on the whole more poorly sorted than samples from other stations. The proportion of mud was higher here than at other stations except station 31. Skewness toward the fines seems to have been greatest in late autumn and winter, when sorting was poorest. The great variability suggests that station 35 was on a lithofacies boundary. Because all samples were taken in the same way, and because the offshore stations were accurately relocated, it seems unlikely that the variability resulted from procedural error.

The one sample from the control station in Sippewissett Marsh most closely resembled sediments from intertidal stations II and IV, but was sandier.

Hydrocarbons

The oil spilled by the *Florida* contained normal alkanes which ranged from *n*-decane to *n*-docosane (C_{10} to C_{22}), with a maximum around C_{14} to C_{15} . Isomeric and homologous hydrocarbons, mostly aromatics and cycloalkanes, were so numer-

ous that their boiling points overlapped, a phenomenon expressed in the gas chromatograms as a broad unresolved envelope. Above this unresolved background were more or less defined peaks of homologous series of straight and branched alkanes. The $n\text{-C}_{17}$ /pristane value for the undegraded fuel oil was 1.67.

The oil which polluted Wild Harbor River and adjacent offshore areas was that spilled by the barge *Florida* on September 16, 1969. The pristane/phytane value established that all samples but one of petroleum hydrocarbons in the West Falmouth area were derived from this oil. Petroleum hydrocarbons from another source occurred at station 36 in November, 1970, and a large concentration of biogenic hydrocarbons appeared at station 10 in June, 1971. Presence of hydrocarbons having the boiling point range of the #2 fuel oil from the *Florida*, 170-370°C, showed that this oil became incorporated into the sediments of Wild Harbor River and adjacent parts of Buzzards Bay.

There was an onshore-offshore gradient in concentration of the #2 fuel oil. Concentrations were greatest at station 31 (Table 3), which remained heavily polluted with residues of this oil for at least two years (Blumer and Sass, 1972a, b, c). The concentration of relatively undegraded #2 fuel oil was particularly high in the late winter of 1970. Sediments at the three intertidal stations, II, IV, and V, also contained 1.4 to 19 times the maximal normal environmental background, 10 mg/100 g dry sediment, during the two years after the spill. Among the offshore stations, only stations 9 and 10 had quantities of hydrocarbons clearly in excess of the normal environmental background, and only in the first eleven months. Concentrations were intermediate or low at stations 7, 30, and 20; the mean hydrocarbon concentrations at stations 20, 35, and 37 were essentially unchanged in the first two years after the spill.

Degradation of the #2 fuel oil was slow, especially at the most heavily polluted stations, and the different modes of degradation proceeded at different rates along the gradient of pollution. At stations II, IV, V, and 31 the boiling point distribution of the hydrocarbons was very similar to that of the fresh oil for at least two years after the spill. The $n\text{-C}_{17}$ /pristane and pristane/phytane values at station 31 decreased very little for several months after the spill (Figs. 6, 7). At all four of these stations solution was retarded, and short-term toxicity did not decrease. Solution and reduction of short-term toxicity were slightly more rapid at stations 7, 9, and 10 than at the four most heavily oiled stations. Retreat of the boiling point envelope was slow for hydrocarbons from stations 7, 30, 10, and 20; hydrocarbons in the $\text{C}_{13}\text{-C}_{14}$ range were still detectable two years after the spill. Less-degraded fuel oil arrived at station 10 in August, 1971, as indicated by the reversal of the values of $n\text{-C}_{17}$ /pristane and pristane/phytane (Figs. 6, 7). At stations 7 and 20 (Fig. 6) the $n\text{-C}_{17}$ /pristane values were much lower than those at station 31. Biodegradation progressed relatively rapidly at stations 20, 35, and 37, and was six to eight months in advance of that at station 31. Such different rates of biodegradation indicate delayed bacterial

Table 3. Hydrocarbon content of sediments from Buzzards Bay, in mg hydrocarbons in 100 g dry sediment. All values rounded to two significant figures. After Blumer and Sass, 1972a.

Date	Stations												
	5	7	9	10	20	31	35	36	37	II	IV	V	
9/69		6.9			3.9	55				59	45		
10/69		19			4.4	110	4.6				55		
11/69		14	24	15	2.4	110	5.3	2.0	4.0				
12/69		12		25	4.5	110	6.0			76	150	180	
1/70								6.2	4.4				
2/70									3.8	51	120	15	
3/70						1240			3.5				
4/70		4.8		28	6.2	450	4.2	2.1	5.9		140	190	
5/70		6.5		25	3.5	210	4.9	7.0	7.0	52	40	77	
6/70		4.5		18	2.4	400	5.3	2.9	6.7	44	23	78	
7/70		7.4		14	2.5	240	6.4	4.3	5.7	75	150	40	
8/70				9.2		120		2.9	4.1				
9/70		2.6	5.9	9.4	4.9	210	7.9	6.1	4.2				
10/70										63	81	56	
11/70		4.3		9.8	3.1	300	11	6.8	8.5	22	18	45	
12/70		5.0	11	8.0	3.4	190				45	35	55	
1/71						160	5.4	4.0	5.0				
2/71		5.4	6.7	9.4	3.4		3.3	3.1	7.3				
3/71						200				39	34	29	
4/71	1.8	3.5	7.7	5.6	5.2	200				37	86		
5/71													
6/71		4.5	5.6	8.8	3.6	230	4.4	4.2	4.6	15	19	40	
7/71	3.3	1.1		4.6	2.3			6.0		34	27	16	
8/71	3.7	1.3	6.1	5.4	2.0	130	3.5		5.6	14	40	32	
9/71		3.0		8.4	5.4	130	4.5	3.9	4.6				
10/71										15	34	19	

attack in heavily oiled sediments. The fuel oil which first arrived at stations 20 and 35 was already somewhat altered and more degraded than that found contemporaneously at the more heavily polluted inshore stations. As the oil moved seaward, the very toxic benzenes and naphthalenes, which constitute the largest proportion of the aromatics in fuel oil, dissolved in the sea water. At stations 20, 35, 36, and 37, solution and reduction of the short-term toxicity of the benzene and naphthalene aromatics were relatively rapid. Through September, 1970, oil in the sediments at station 36 showed the characteristics of that spilled in September, 1969.

Michael, Van Raalte, and Brown (1975) studied the further weathering of the fuel oil from the *Florida* in the fifteen months from April, 1973, through June, 1974 (Table 4). Concentrations of hydrocarbons derived from this oil were two to six times the normal background at stations II, IV, and V. At station 31 hydrocarbon concentrations were six to sixty times the normal level; these hydrocarbons were derived from the #2 fuel oil, not from the fuel of motorboats. Hydrocarbon con-

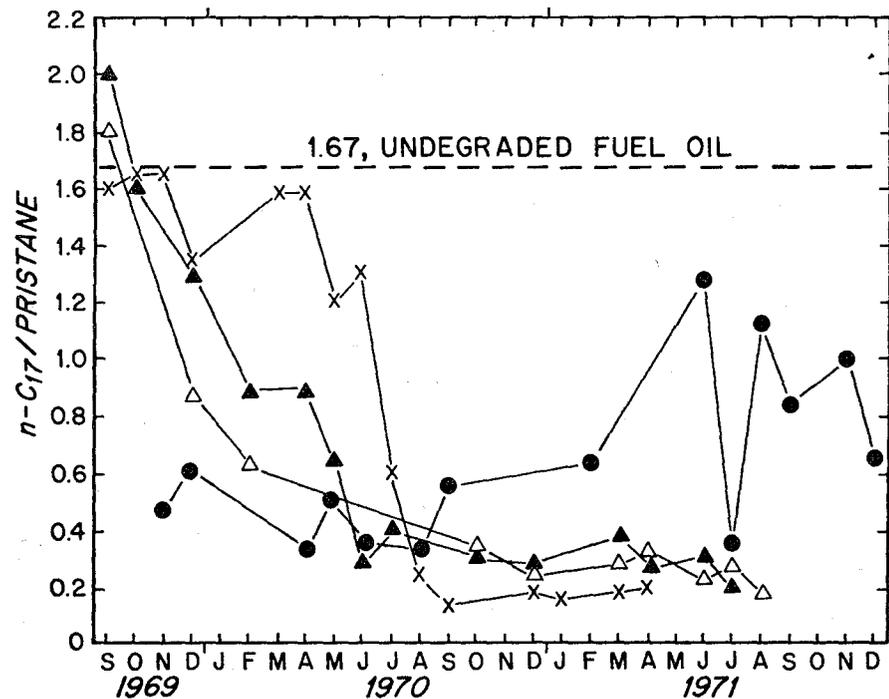


Figure 6. Changes in the value of $n\text{-C}_{17}$ /pristane at stations 31 (X), II (Δ), IV (\blacktriangle), and 10 (\bullet).

centrations at station 9 were at times somewhat above the normal background, but they were at or below that level at station 10. Weathered #2 fuel oil occurred at stations 9 and 10 as late as July, 1973, 46 months after the spill. Biogenic hydrocarbons were present at these two nearshore stations in November, 1973, and May,

Table 4. Hydrocarbon content of sediments from Buzzards Bay, in mg hydrocarbons in 100 g wet sediment. After Michael, Van Raalte, & Brown, 1975. Asterisks indicate that gas chromatographic analyses were also performed.

Date	Stations								
	9	10	20	31	35	II	IV	V	Sippe-wissett
4/73	15*	7	3*	507	8	55	43	59	10
7/73	21								
9/73				609					
11/73	3*	3	2	66	6	23	39	46	9
5/74	9	8	3	138*	7	22*	34*	51*	11*
6/74				350					

* Gas chromatographic analysis also performed.

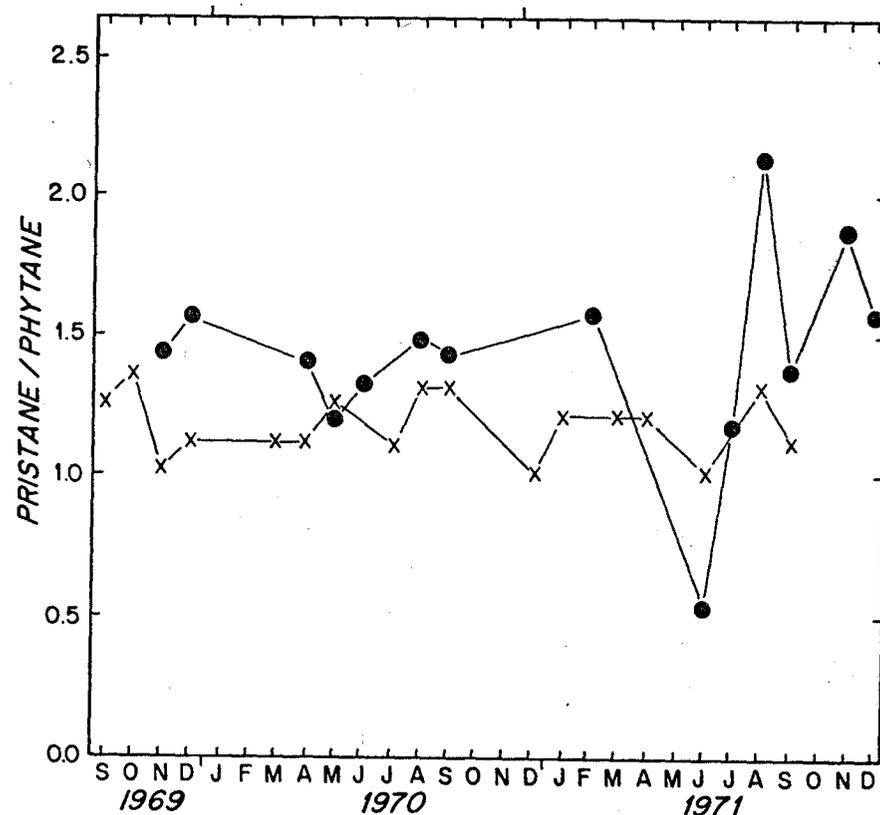


Figure 7. Changes in the value of pristane/phytane at stations 31 (X), and 10 (\bullet).

1974. Number two fuel oil was undetectable by gas chromatography at stations 20 and 35 and in Sippewissett Marsh in April, 1973, and hydrocarbon concentrations at these three sites were at or below the normal background level. As late as 1975, 217.1 mg/100 g wet sediment weight of petroleum hydrocarbons or 651.3 ± 108.6 mg/100 g dry sediment weight was still found to be present by Burns and Teal (1979) in the top 5 cms of sediment in the Wild Harbor River Marsh. They noted that eight years after the oil spill some sediment still contained more than 120 mg of hydrocarbons/100 g wet sediment weight (~ 360 g/100 mg dry sediment weight). These authors conclude—that the “. . . more persistent components of the oil, naphthenes and heavier aromatics, will be present in the ecosystem for many years to come.”

Oil continued to move in pulses from the more heavily polluted areas seaward into Buzzards Bay (Figs. 8-12) for several years after the spill. It is likely that oil incorporated in the sediments of the shallower reaches of Wild Harbor River was liberated by storms which roiled the bottom.

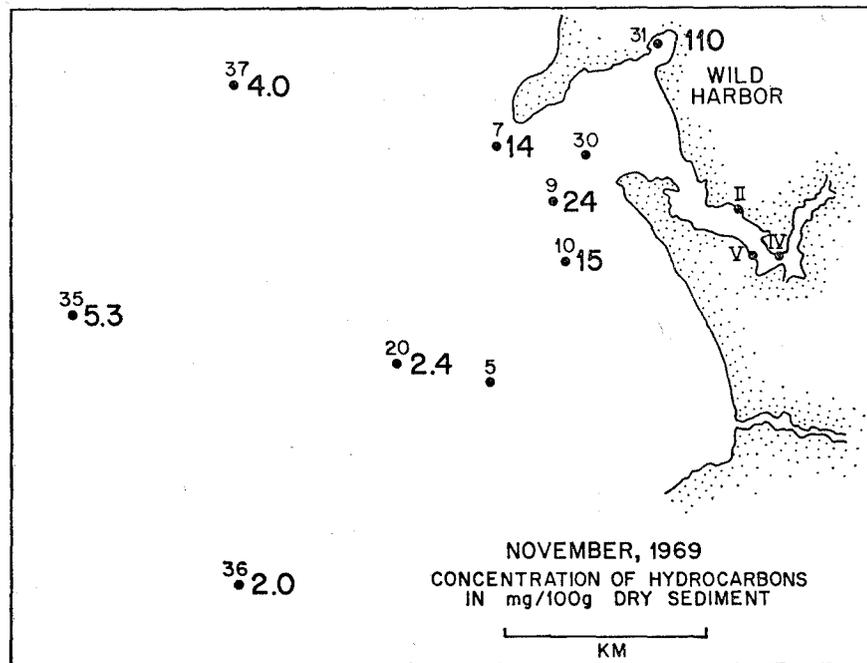


Figure 8. Concentrations of hydrocarbons during November, 1969, in Wild Harbor River and adjacent offshore areas, two months after the spill.

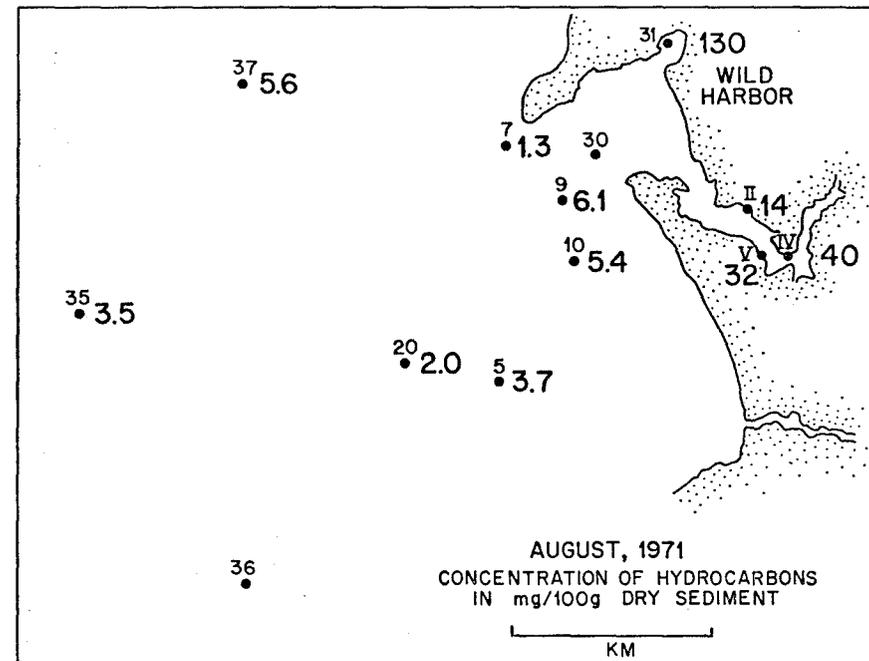


Figure 10. Concentrations of hydrocarbons during August, 1971, in Wild Harbor River and adjacent offshore areas. During that month less-degraded oil spread seaward to station 10 (●).

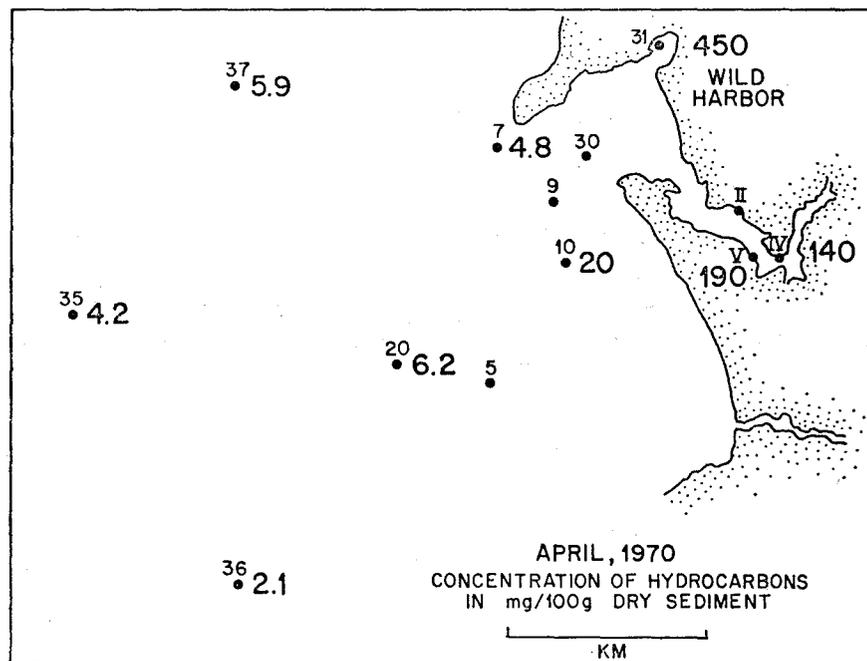


Figure 9. Concentrations of hydrocarbons during April, 1970, in Wild Harbor River and adjacent offshore areas. Oil was spreading seaward from the river.

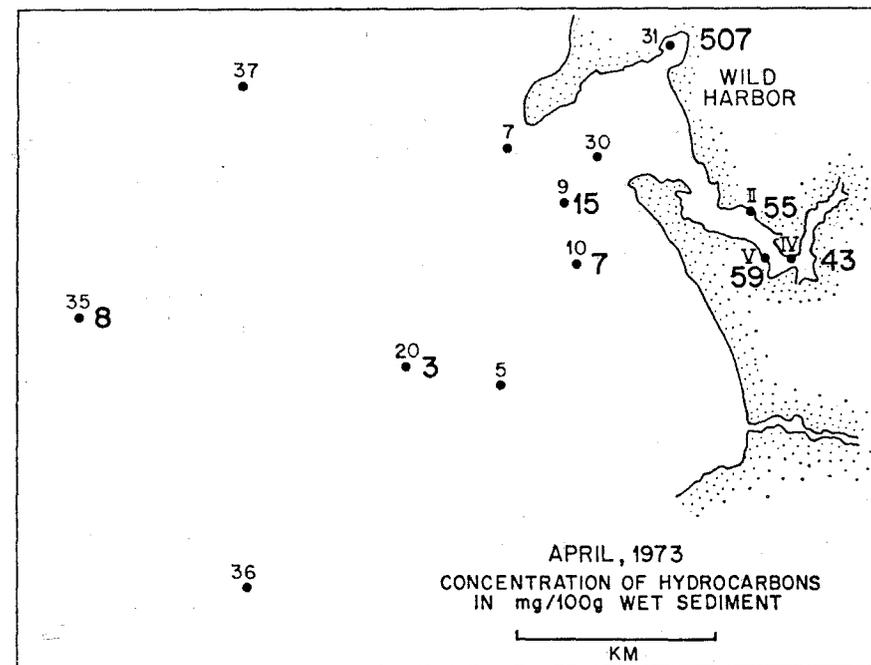


Figure 11. Concentrations of hydrocarbons during April, 1973, in Wild Harbor River and adjacent offshore areas. During this period, the concentrations rose in the river and harbor.

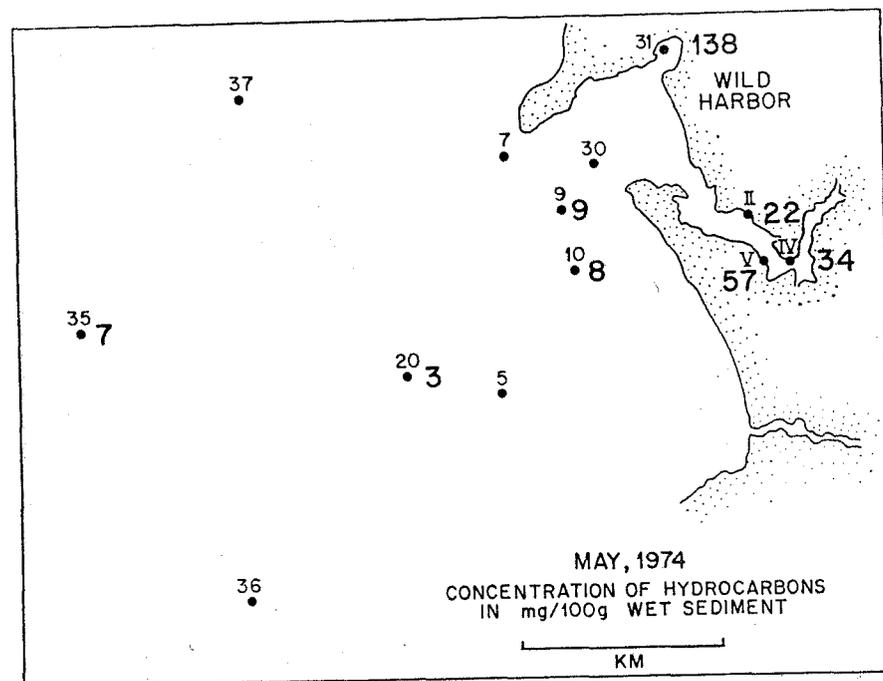


Figure 12. Concentrations of hydrocarbons in Wild Harbor River and adjacent offshore areas in May 1974. The concentrations in the river and the harbor still exceeded the normal environmental background level.

Burns and Teal (1971) studied by gas chromatogram the sediments, algae, marsh plants, fish, and gulls from Wild Harbor River and from unpolluted Sippewissett Marsh and Weepeket Islands in 1970 and 1971. Residues of #2 fuel oil were in all sedimentary and biologic samples from Wild Harbor River; all samples but one from Sippewissett Marsh were free of oil. The exception was the eel, *Anguilla rostrata*, a highly mobile animal which probably became contaminated with fresh fuel oil in Buzzards Bay. In Wild Harbor River, marsh grasses, *Spartina patens* and *S. alterniflora*, were dead at heavily oiled sites, but alive at lightly oiled ones during January, 1971. Residues in animals were more degraded than those in plants. Muscle and brain tissue of a juvenile herring gull, an animal at an upper trophic level, taken while feeding in Wild Harbor River one month after the spill, contained considerable quantities of hydrocarbons derived from the #2 fuel oil. An adult herring gull taken in June, 1971, from the colony on the Weepeket Islands (Fig. 2) contained pollutant hydrocarbons from some source other than the #2 fuel oil from the Florida.

Densities and numbers of species

Within ten days after the spill, numbers of species and animals at heavily oiled

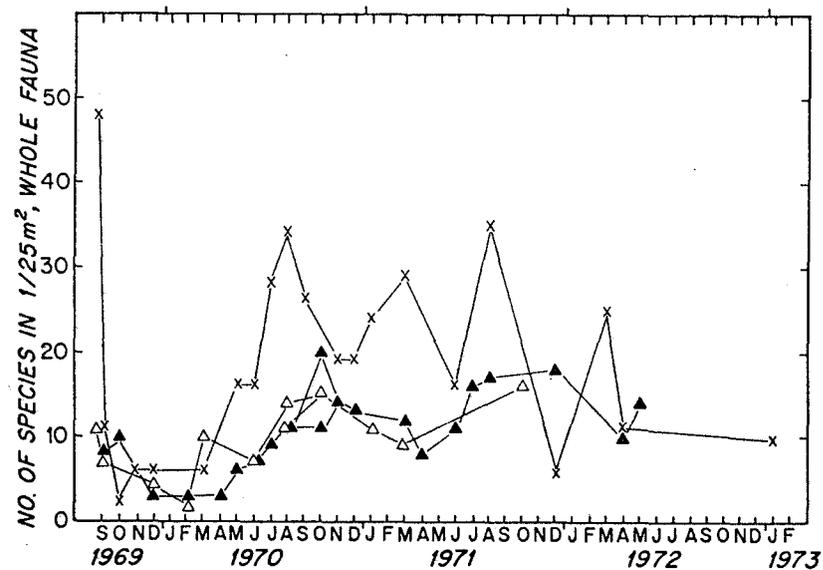


Figure 13. Number of species in $1/25 \text{ m}^2$ at station 31 (X), and in $1/128 \text{ m}^2$ at stations II (Δ) and IV (\blacktriangle), in Wild Harbor River.

stations 31, II, and probably IV dropped abruptly to very low levels (Figs. 13-16). Mass mortality was greatest at station II. At station 31 the number of species only three days after the spill was almost as high as that of lightly oiled stations offshore in the first post-spill year. The bloom of *Capitella* began almost immediately at the biologically denuded intertidal stations, but was delayed a month or two at most heavily oiled station 31. (Figs. 17-19). Five other species also became abundant at this subtidal station in the last months of 1969. In the winter of 1969-70 much of the fauna, including *Capitella*, died at the intertidal stations; ice may have caused this mass death. During the spring, the number of species was low at all three stations, and oscillated at station II. Density of the whole fauna rose sharply during the season of recruitment, which seems to have begun in June, a few weeks earlier than at offshore stations. *Capitella* constituted the vast majority of animals at stations II and IV, and at station 31 formed an almost unispecific culture. During the late summer and early autumn of 1970, *Capitella* crashed at all three stations, and remained relatively uncommon for the next two years, even in the later recruitment seasons. Numbers of species rose at stations II and IV during the second and third years. This number fluctuated widely at station 31, and by the middle of the fourth year had not risen to the level found three days after the spill. Density fluctuated at stations 31 and IV, and by the end of two or more years had not risen to the earliest levels.

Within a few days after the spill fairly large quantities of less-degraded #2 fuel

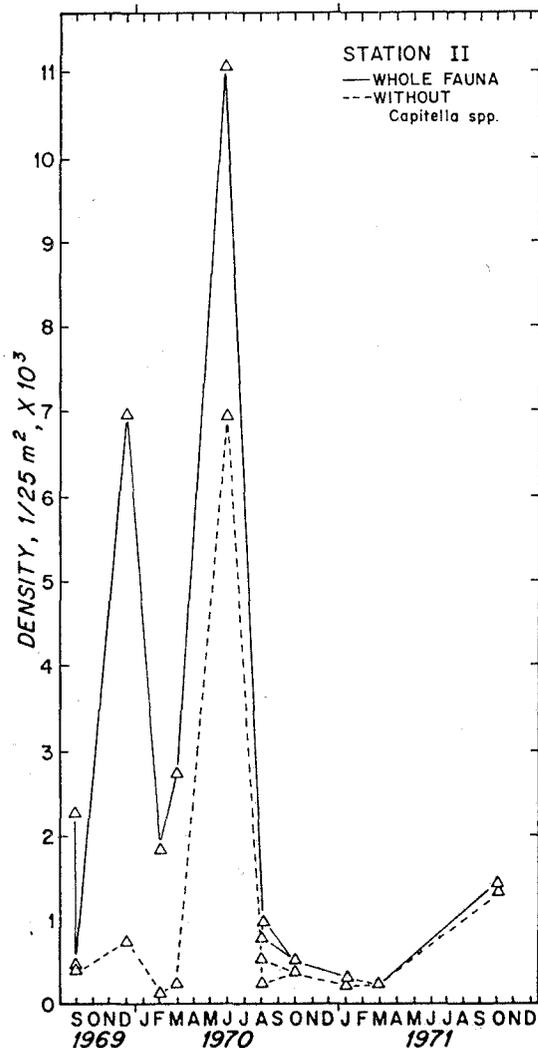


Figure 14. Density of the fauna with and without *Capitella*, in $1/25 \text{ m}^2$, at intertidal station II. Bifurcation of line indicates replicate samples.

oil spread to the sediments of offshore stations 30, 9, and 10. The fauna behaved the same way at all of these stations, even though the sediments at station 30 were apparently much coarser than those at the other two stations. Density and number of species (Figs. 20-23) declined sharply in the first eleven months to low levels, but not so low as those at the intertidal and subtidal river stations. Opportunists failed to colonize the bottom in this first span of time. During the first recruitment season after the spill, July and August, 1970, densities and numbers of species rose

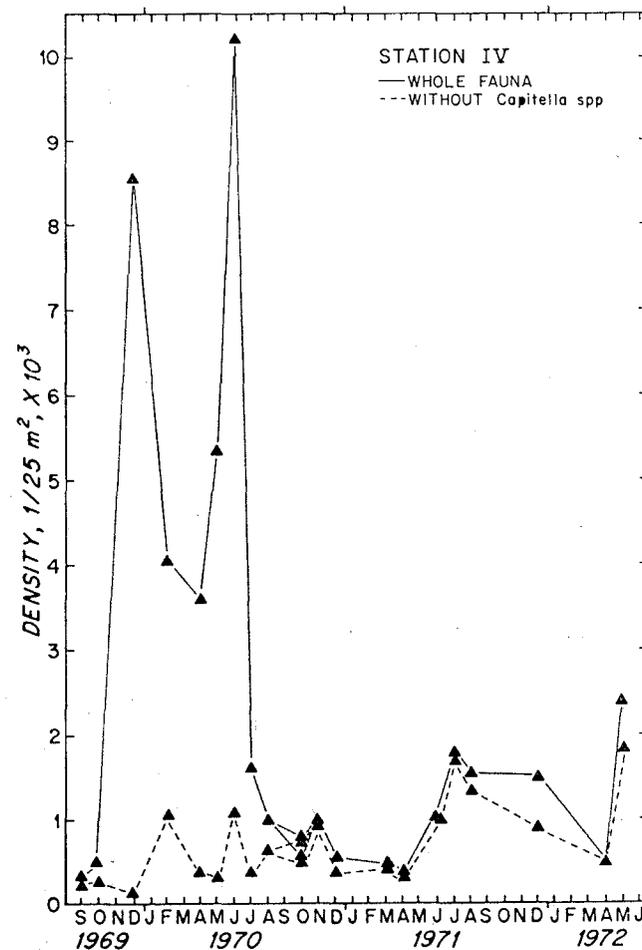


Figure 15. Density of the fauna with and without *Capitella*, in $1/25 \text{ m}^2$, at intertidal station IV. Bifurcation of line indicates replicate samples.

greatly, and *Mediomastus ambiseta* became abundant and dominant (Figs. 24, 25). At that time *Macoma tenta* was common at stations 9 and 10. At these two stations the fauna consisted almost entirely of juveniles. Within the next month numbers of species and animals, including *Mediomastus*, declined rapidly as a result of crowding. This bloom and decline was greatest at station 10. The number of species thereafter was intermediate to fairly high, and fluctuated widely at station 10. In August, 1971, the second season of recruitment after the spill, numbers of species and animals rose somewhat at station 9, and *Mediomastus* again became abundant and dominant. This polychaete decreased in dominance in the third year at station 9. During the second season of recruitment, a new infusion of less-degraded #2 fuel

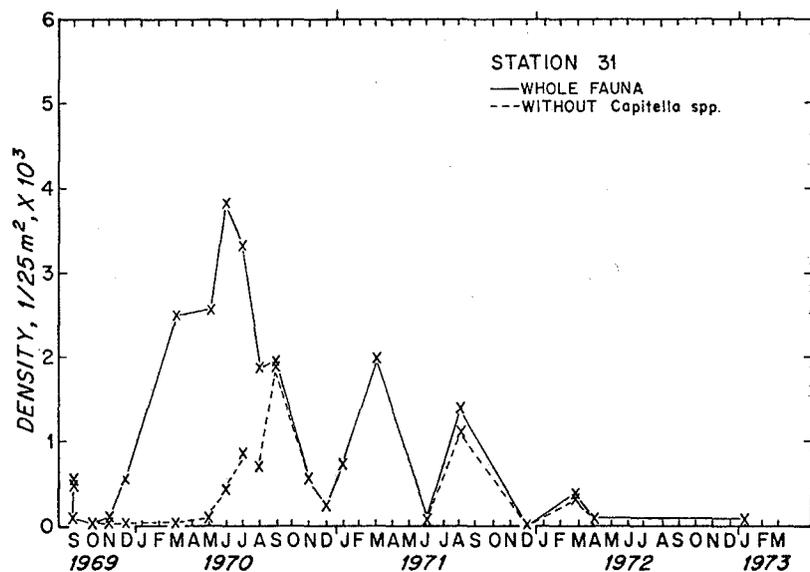


Figure 16. Density of the fauna with and without *Capitella*, in $1/25 \text{ m}^2$, at subtidal station 31. After August, 1971, *Capitella* was minor in every sample.

oil prevented the usual surge of numbers at station 10, although *Capitella* became fairly abundant in August, 1971. Although densities at stations 9 and 10 oscillated somewhat during the second and third years, numbers of both animals and species were considerably higher than in the first eleven months after the spill.

At offshore stations 5, 20, and 35, where concentrations of hydrocarbons were almost always within the range of the normal background, numbers of animals and species were generally higher at any one time than those of other stations (Figs. 26-29). Of these three stations, station 35 had the lowest densities, which were still higher than those at stations 9 and 10. Reduction in numbers of species and animals in the first eleven months was less severe at stations 5, 20, and 35 than elsewhere. As at stations 9, 10, and 30, *Mediomastus* first became abundant and dominant in the first season of recruitment (Figs. 30-32), July and August, 1970, when it constituted the majority of the benthic fauna. Aside from *Mediomastus*, density increased only slightly during this season, but numbers of species equaled or exceeded the numbers found shortly after the spill, before effects of the oil had become evident. The increase in density in August, 1970, was generally less marked at these offshore stations than at stations 9 and 10. During the winter of 1970-71, density and number of species decreased at all three stations, but rebounded in the spring and summer at station 35, the only one of these stations for which appropriate information exists. Density and numbers of species did not oscillate at these three distant offshore stations as they did at the stations nearer shore and in the river. By

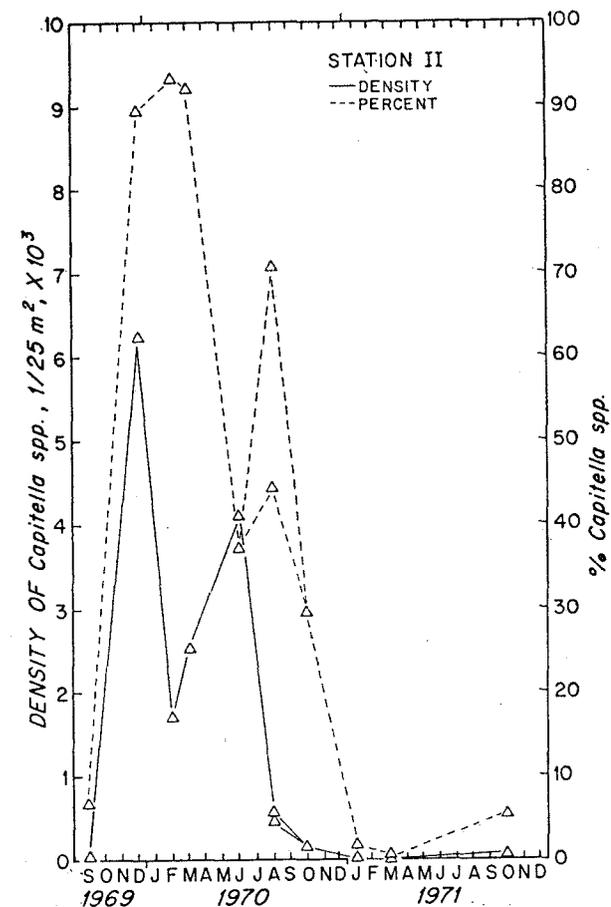


Figure 17. Density of *Capitella* at station II, in $1/25 \text{ m}^2$, and percent of whole fauna comprised by this polychaete.

the end of the period studied, number of species had declined below the initial level at station 5, but had increased above that level at stations 20 and 35.

Differential mortality

One-way analysis of variance and covariance of densities of *Mediomastus* at stations 9, 10, 20, and 35, from August, 1970, the first season of recruitment after the spill, through June, 1971, just before the second season, showed that rates of mortality of that polychaete were not significantly different at the 0.95 level of confidence, according to classical statistics. This lack of significance probably reflects the broad scatter and fewness of points for each regression curve. All four regressions were negative in slope. That for station 10 was steepest, -1649 , because the density was very much greater in August than in later months and three to five

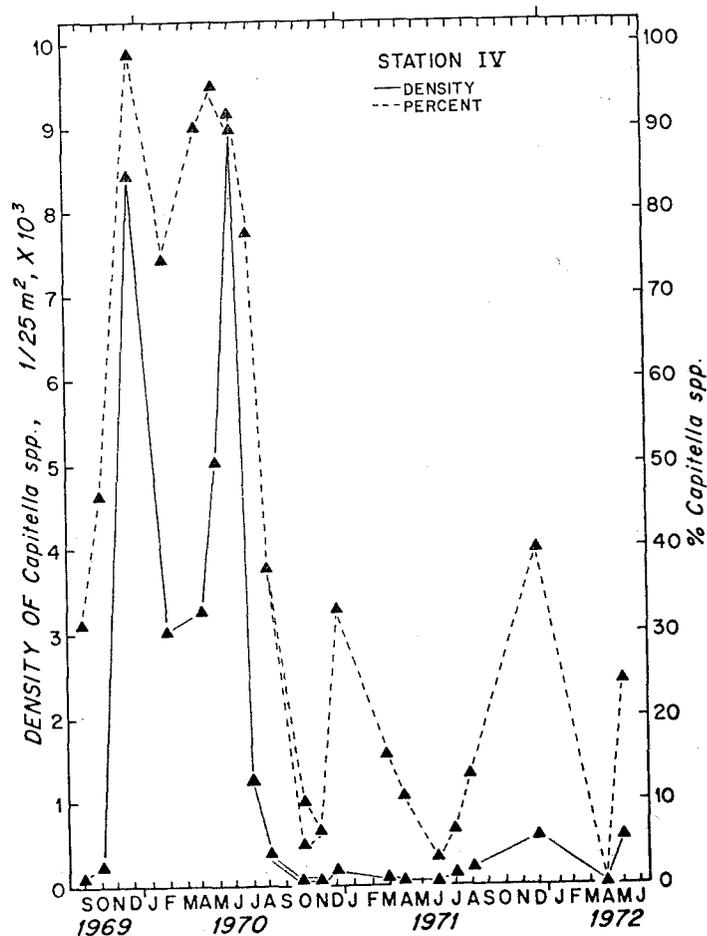


Figure 18. Density of *Capitella* at station IV, in $1/25 \text{ m}^2$, and percent of the fauna comprised by this polychaete.

times greater than densities at the other three stations. The curve described by the remaining points was similar to those of the other stations. The slope of the curve for station 9 was -796 , that for station 35 was -890 , and that for station 20 was -714 .

The same analysis of the density of the rest of the fauna at these same stations in the second year also showed that regressions were not significantly different from one another at the 0.95 level of confidence. The slopes of these regressions were much less than those for *Mediomastus*. The slope was greatest for station 10 (-343), less for station 9 (-199), slight for station 20 (-54). The slope for station 35 was positive ($+83$). The relatively high density at station 10 in August, 1970, considerably increased the slope of the curve.

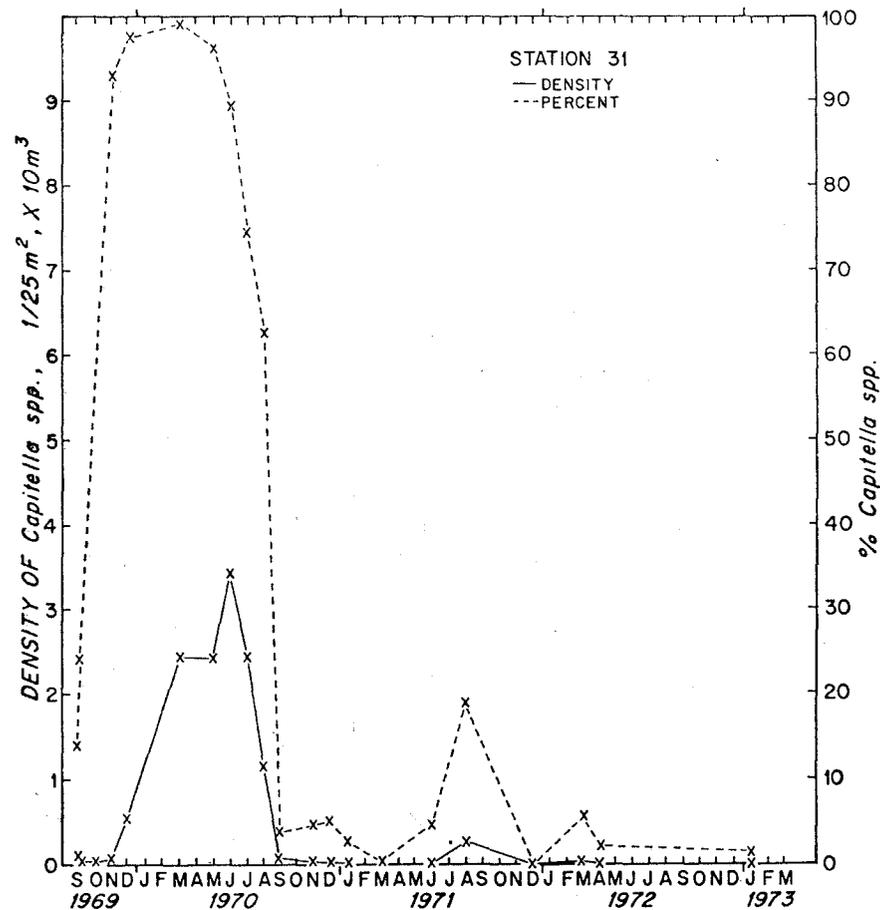


Figure 19. Density of *Capitella* at station 31, in $1/25 \text{ m}^2$, and percent of whole fauna comprised by this polychaete.

Subdominants

Subdominants here are those species which composed more than 10% of the fauna without the one most abundant species, either *Capitella* or *Mediomastus*.

At station 31 subdominants composed about 75% of the many samples in which there were subdominants (Fig. 33). Four samples lacked subdominants. There was no obvious tendency for the proportion of subdominants to decrease with the passage of time. In general, two species were subdominant in any one sample, especially in the later years. The subdominants belong to two major taxa, Polychaeta and Gastropoda. The *Polydora ligni-Microphthalmus aberrans* assemblage of the first months gave way in the summer of 1970 to the *Haminoea solitaria-Bittium alternatum* assemblage. By early 1973 *Streblospio benedicti* and *Nereis succinea* were

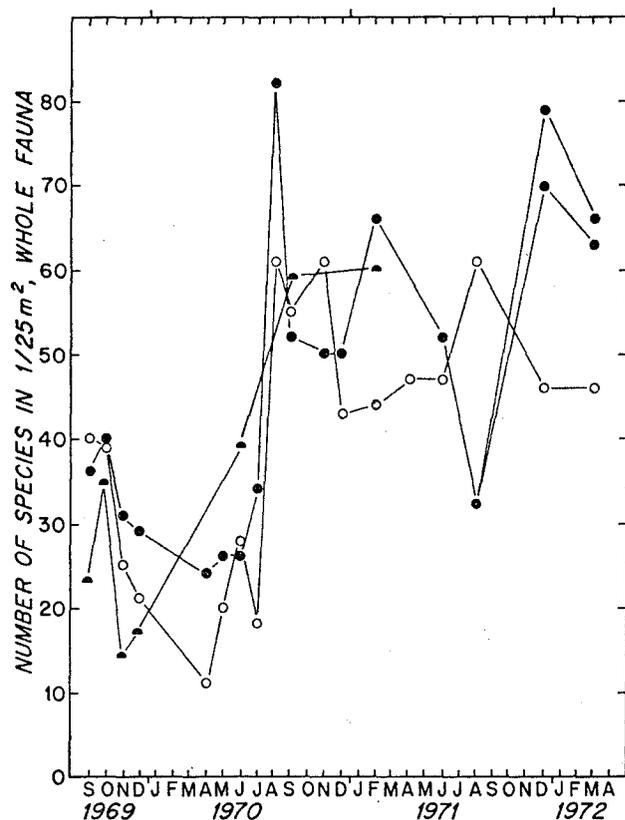


Figure 20. Number of species in $1/25 \text{ m}^2$, at nearshore subtidal stations 30 (▲), 9 (○), and 10 (●).

the chief subdominants. Several species were subdominant only occasionally, and no one species was subdominant in a large number of samples throughout the sampling period. Only *Microphthalmus aberrans* seems to have been seasonal in abundance. Eight of the eleven species subdominant at this station were subdominant at intertidal stations II and IV, despite differences in sediments and water depth.

At station 9 subdominants occurred in every sample, and composed slightly less than half of the fauna (Fig. 34). The number of subdominants in a sample decreased with time. The subdominants belong to four major taxa, Polychaeta, Gastropoda, Bivalvia, and Nemertinea. The *Tubulanus pellucidus* assemblage of the first few months gave way to the *Syllides verrilli-Nephtys incisa* assemblage. Gastropods became less common after the first year, and one species of *Odostomia* succeeded another. During the second year, the subdominant portion of the fauna decreased, especially after *Macoma tenta* waned. *Minuspio cirrifera* was the most constant subdominant in the late second and early third year. Most species were subdominant

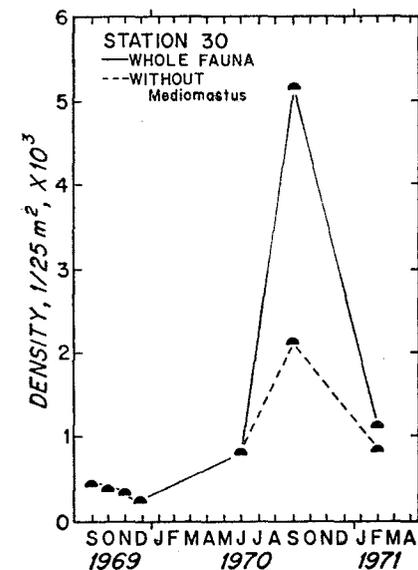


Figure 21. Density of the fauna with and without *Mediomastus* in $1/25 \text{ m}^2$, at station 30. *Mediomastus* was minor before June, 1970.

in only a few months, several were so in consecutive months. The subdominants of this station were not those of station 31.

The specific and temporal arrays of subdominants at station 10 (Fig. 35) were very similar to those at station 9. *Cylichna oryza* and *Sphaerosyllis hystrix* were more commonly subdominant at station 10, *Odostomia winkleyi* less so. Fewer species were subdominant at any one time at station 10, but on the average composed slightly more of the fauna here than at station 9. The tendency for reduction in numbers of species subdominant in a sample with the passage of time was less clear at station 10. As at station 9, subdominants occurred in every sample, and belonged to the same major taxa. *Capitella*, so abundant at station 31, was subdominant at station 10 only in August, 1971, when fuel oil reinvaded this site. The subdominants of station 10 were not those of station 31. *Sphaerosyllis hystrix* appears to have been seasonal in abundance.

All samples at station 5 contained subdominants, which comprised, on the average only about 40% of the fauna (Fig. 36). This proportion increased slightly with time. The number of subdominants in a sample was almost always two. At both this station and station 20, *Sphaerosyllis hystrix* was most common in the autumn, winter, and spring, whereas *Exogone verugera* was most common in the late spring and early summer. When the bottom sediments were unusually fine, the subdominants were unusual in their paucity (August, 1970) or identity (February, 1971). Members of two major taxa, Polychaeta and Gastropoda, were abundant. Whereas

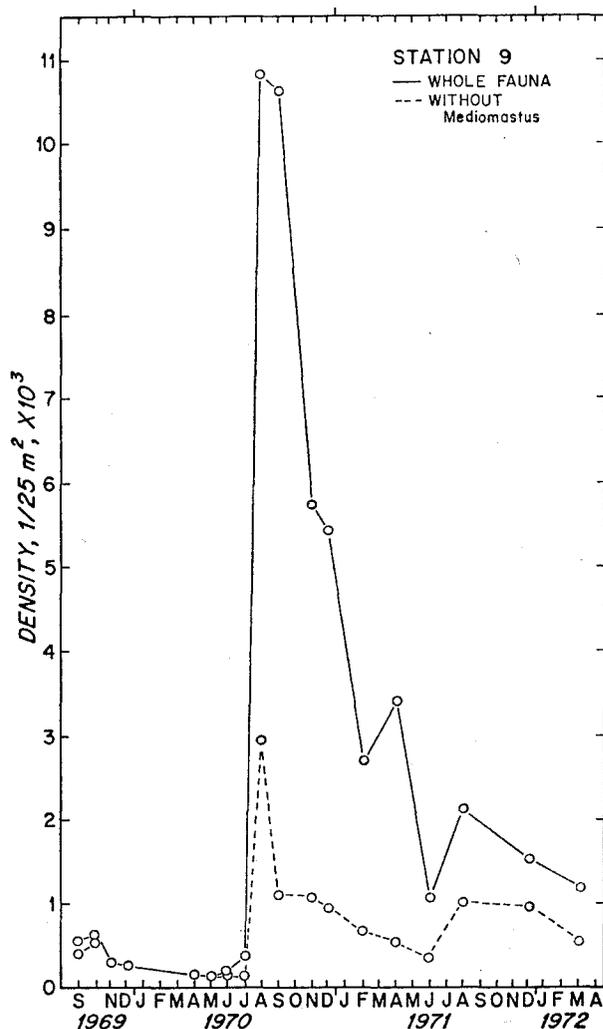


Figure 22. Density of the fauna with and without *Mediomastus* in $1/25 \text{ m}^2$, at station 9.

polychaetes were subdominant in every sample, gastropods became subdominant only in the second year. Some of the species subdominant at station 5 were the same as stations 9 and 10, but none was subdominant at station 31.

The eight species subdominant at station 20 belong to two major taxa, Polychaeta and Nemertinea, and on the average composed about 46% of the fauna (Fig. 37). This proportion increased somewhat in the latter half of the first year. Subdominants, usually two, occurred in every sample. *Parapionosyllis longicirrata*, also commonly subdominant at station 5, was subdominant for a longer time at station 20. Most of the species subdominant at this station were so at station 5 as well. Station 20

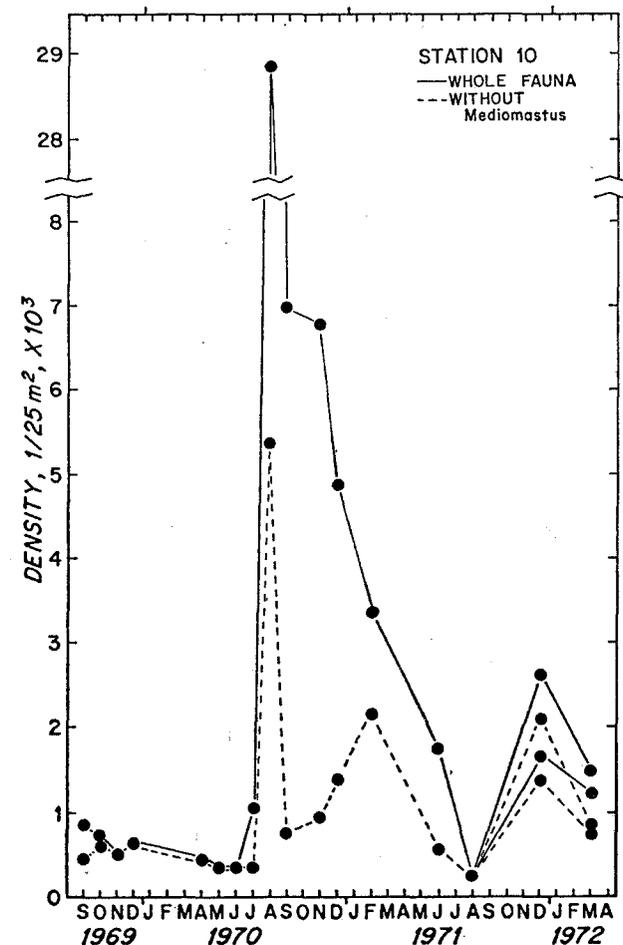


Figure 23. Density of the fauna with and without *Mediomastus* in $1/25 \text{ m}^2$, at station 10. Bifurcation of lines indicates replicate samples.

shared only *Pectinaria gouldii* and *Sphaerosyllis hystrix* as subdominants with stations 9 and 10. None of the species subdominant at station 20 was so at station 31.

The average proportion of the fauna comprised by subdominants was only one-third at station 35 (Fig. 38). The change in this proportion was slight and seemingly seasonal. Subdominants, usually two, were in every sample. *Sphaerosyllis hystrix* was abundant in the autumn, winter, and early spring here as at stations 5 and 20. *Ampelisca vadorum* was usually subdominant in the spring and early summer, whereas *A. abdita* prevailed in colder seasons. Gastropods did not appear until late in the second year, along with a polychaete different from its predecessors. Some of the subdominants at station 35 were also subdominant at station 20, 5, 9, and 10.

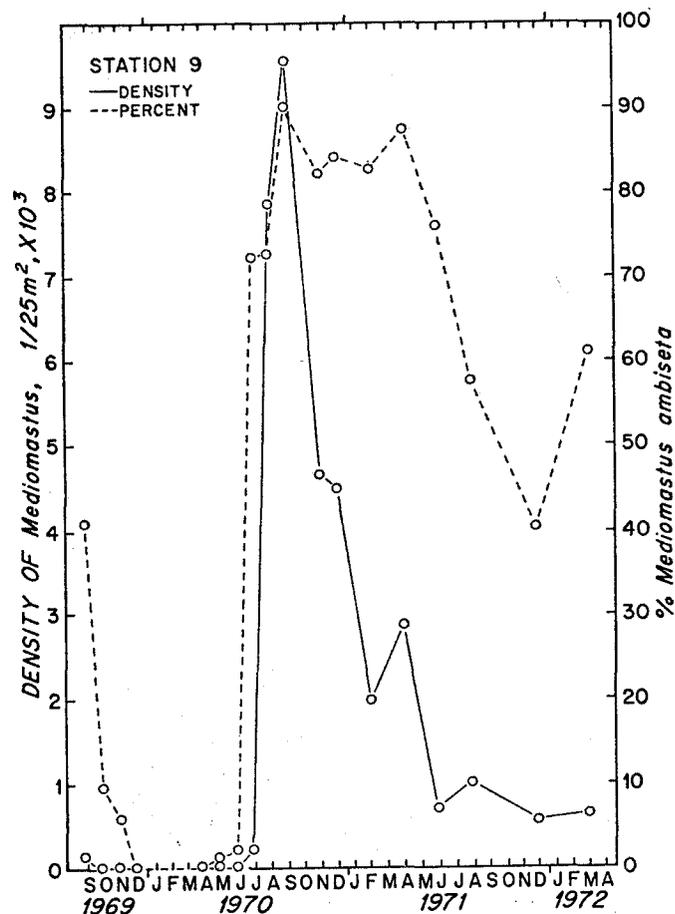


Figure 24. Density of *Mediomastus* in $1/25\text{ m}^2$, at station 9, and percent of whole fauna comprised by this polychaete.

None was in common with station 31. Of the subtidal stations, station 35 was unusual in its high proportion of amphipods.

At intertidal station II subdominants composed, on the average, 75% of those samples which had subdominants (Fig. 39). The percentage decreased slightly in the second year. Two samples lacked subdominants. As at station 31 and IV, the number of subdominants in a sample was fairly variable; it increased slightly with the passage of time. *Gemma gemma* was subdominant only in the first few days after the spill. *Hydrobia totteni* was the only species which was subdominant in several samples; others occurred sporadically. In the second year the *Nereis succinea*-*Streblospio benedicti* assemblage became subdominant. Many species subdominant at this station were so at station 31.

At intertidal station IV subdominants composed almost 80% of the samples

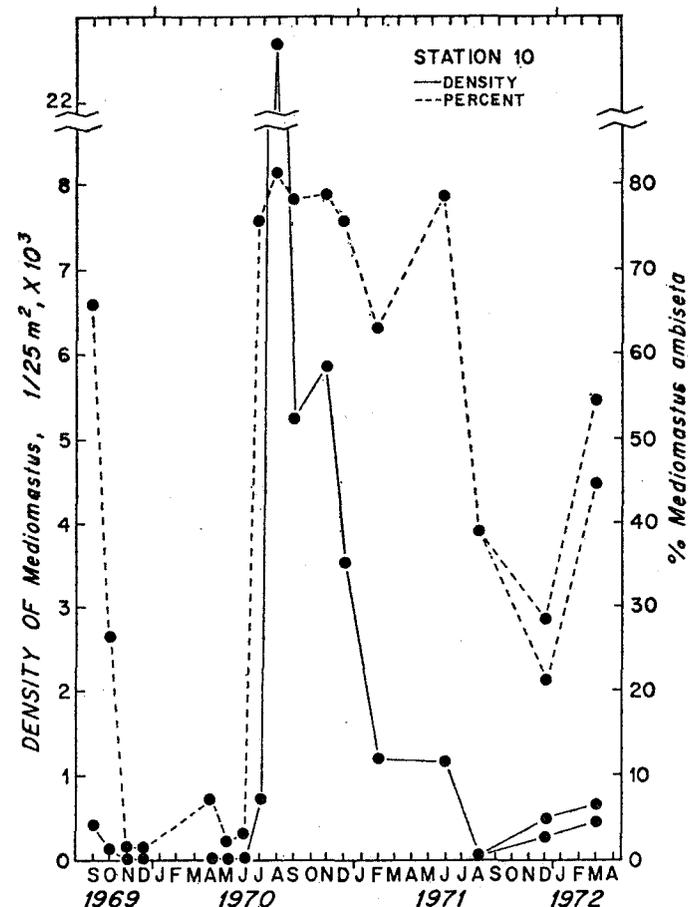


Figure 25. Density of *Mediomastus* in $1/25\text{ m}^2$, at station 10, percent of whole fauna comprised by this polychaete. Bifurcation of lines indicates replicate samples.

which had subdominants; the proportion fluctuated somewhat (Fig. 40). Six samples were too sparse to have subdominants. The number of subdominants in a sample increased with the passage of time. As at station II, *Gemma gemma* was common only in the first few days after the spill. *Hydrobia totteni* and *Syllides verrilli* were subdominant in several samples. *Nereis succinea* and *Streblospio benedicti* occurred together here, as at station II, but their relative proportions were reversed. Both here and at station 31, *Spio filicornis* became abundant in the third year. Several species were subdominant infrequently.

At the control station in Sippewissett Marsh two species composed more than 10% of a sample, and together made up about 77% of the fauna (Fig. 41). This percentage varied, but did not show any temporal trend. *Hydrobia totteni* occurred in all samples and was dominant in three. The suite of species which together com-

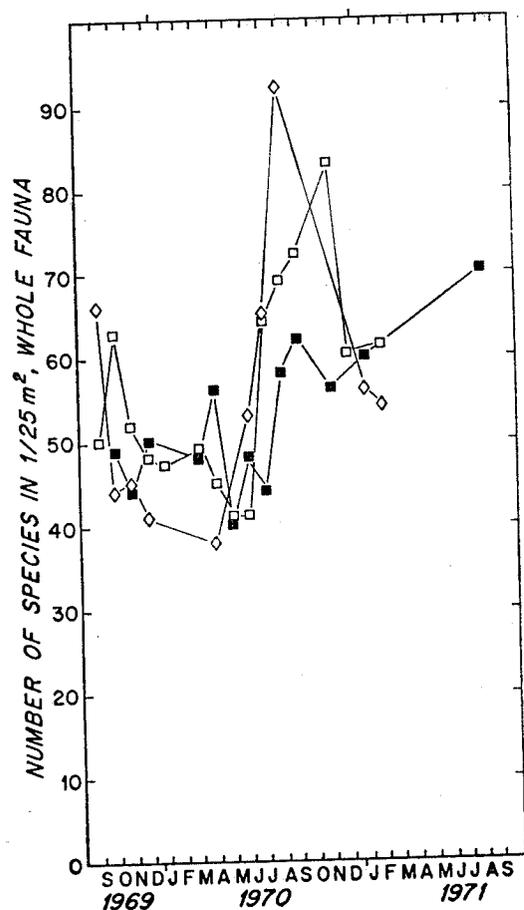


Figure 26. Number of species in $1/25 \text{ m}^2$ at subtidal stations 5 (◊), 20 (◻), and 35 (■) farther offshore.

posed about 90% of the fauna was almost always the same. *Capitella* was abundant only when it invaded from test plots. Several species which were abundant in Sippewissett Marsh were subdominant in the intertidal zone of Wild Harbor River as well, but the minor species at the control station were different.

Ampeliscid amphipods

At station 31 five living ampeliscids were taken in a trawl sample three days after the spill. From September 25, 1969, to January, 1973, these animals were absent from this station. Living ampeliscids were absent from station 30 in the first months after the spill. Their appearance in later months was sporadic.

At station 9 these amphipods died almost immediately after the spill (Fig. 42). From October, 1969, through July, 1970, only dead ampeliscids were found. With-

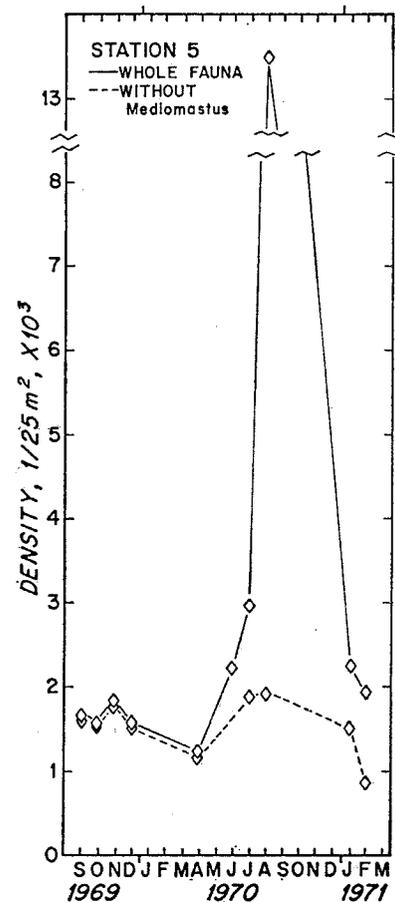


Figure 27. Density of fauna with and without *Mediomastus* in $1/25 \text{ m}^2$, station 5.

in the next month, they began to recolonize this station. Thereafter live animals were more numerous than dead. The pattern was very similar at station 10 (Fig. 43). Shortly after the spill the living outnumbered the dead, but from October, 1969, through August, 1970, more ampeliscids were dead than alive. Living animals arrived at this station in September, 1970, and were more numerous than dead ones until August, 1971, when less-degraded #2 fuel oil reinvaded this site. In that month, amphipods, as well as many other kinds of animals, died. Within four months pollution lessened, and amphipods again re-established themselves at station 10.

Shortly after the spill, amphipods at station 20 were little affected by the already markedly modified oil in the sediments (Fig. 44). By October, however, less-degraded oil arrived at this site and killed most of the amphipods. From November, 1969, through June, 1970, ampeliscids, both living and dead, were generally few. The amphipods quickly recolonized this site in the summer of 1970, and living animals

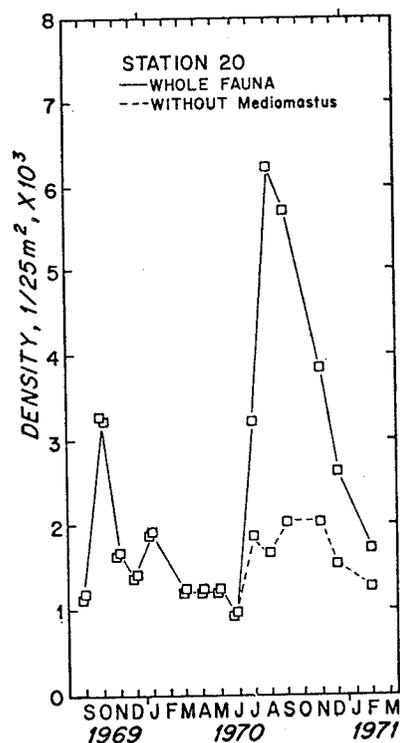


Figure 28. Density of fauna with and without *Mediomastus* in 1/25 m², station 20.

considerably outnumbered the dead. Ampeliscids continued to live at this station for the rest of the sampling period.

At station 35 ampeliscids suffered only slightly from the oil (Fig. 45). After October, 1969, living animals were abundant, dead ones rare or absent. At offshore station 36, ampeliscids flourished between November, 1969, and February, 1971. The number of ampeliscids seems to have been normal in November, 1969, at station 37, where fuel oil was absent from the sediments. In the winter and early spring following the spill, fuel oil invaded this site and the ampeliscids died.

Coefficient of variation

The curves (Fig. 46) representing coefficients of variation of all species having a mean density of three or more at each station form three groups: that of stations 20 and 35, that of stations 9 and 10, and that of station 31, in order of increasing coefficient. Forty-two percent of these species at stations 20 and 35 have coefficients lower than the least value at station 9; 69% of the species at station 20 and 55% of those at station 35 have coefficients lower than the lowest value of station 31. Only 28% of the species at station 10 and 30% of those at station 9 have coefficients

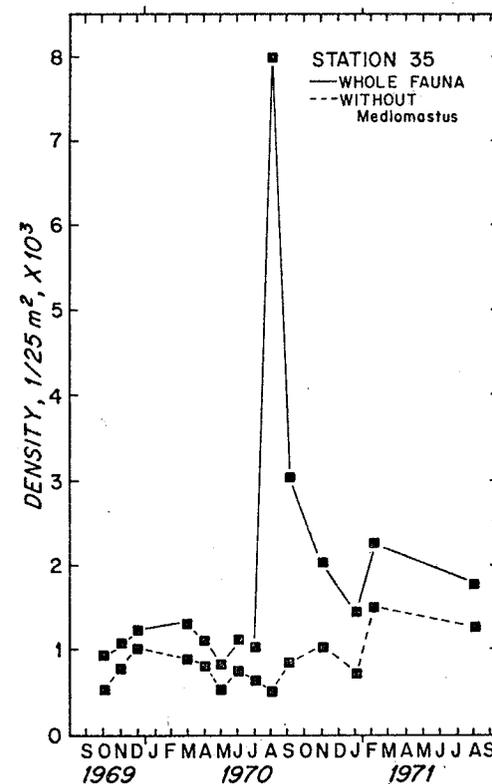


Figure 29. Density of fauna with and without *Mediomastus* in 1/25 m², station 35.

lower than the least value at station 31. The greatest value at station 35 is considerably lower than the highest values of the other stations.

Many of the species numerous at stations 9, 10, and 31 were quite variable in abundance (Fig. 47). Species abundant at stations 20 and 35 were only slightly variable. At all stations, minor species were variable in abundance, more so at stations 9, 10, and 31. We have excluded from this analysis (Fig. 47) six species: *Mediomastus ambiseta*, *Glycinde solitaria*, *Minuspio cirrifera* and *Odostomia winkleyi*—that were so much more abundant in the second year at stations 9, 10, 20 and 35 that their high coefficients overshadow those coefficients of other species—and the abundant but transient *Pholoe minuta* and *Pectinaria gouldii*. Also omitted are epifaunal species (amphipods, and gastropods other than naticids) because they tend to respond to surficial features and are, therefore, more patchily distributed (more variable from sample to sample) than are infaunal species.

We ranked the stations according to increasing coefficient of variation within each of several density intervals (Table 5) and used Kendall's Coefficient of Concordance (Siegel, 1956) to test whether the ranks of a station in all density intervals are simi-

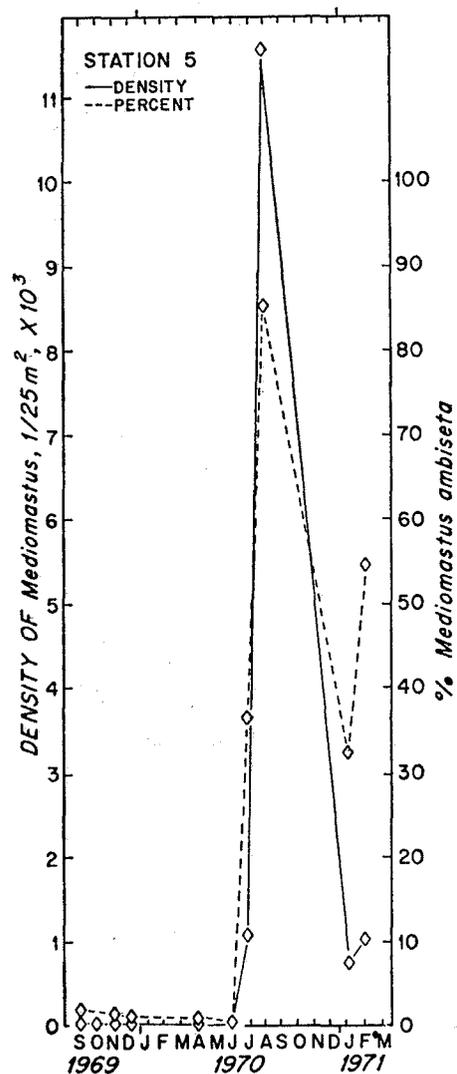


Figure 30. Density of *Mediomastus* in $1/25 \text{ m}^2$, at station 5, and percent of whole fauna comprised by the polychaete.

lar among themselves. For these five stations and the four density intervals of mean density greater than five containing values for every station, the observed sum of squares, 128, exceeds the critical value, 109.3, at the 0.01 level of significance. We therefore rejected the null hypothesis that the rank of a station according to coefficient of variation is independent of density at the 99% confidence limit. Lack of representation of station 9 forced us to omit mean density interval J from the calculations. Stations 20 and 35 have the lowest mean ranks in most intervals, includ-

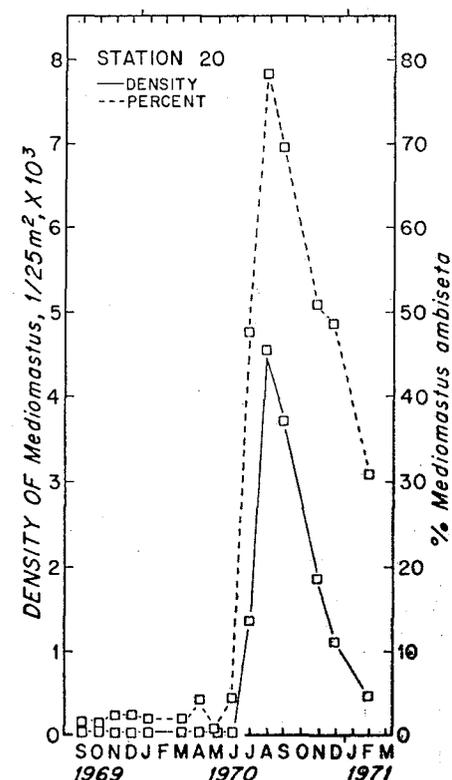


Figure 31. Density of *Mediomastus* in $1/25 \text{ m}^2$, at station 20, and percent of whole fauna comprised by this polychaete.

Table 5. Ranks of Stations 20, 35, 10, 9, and 31 by increasing coefficients of variation at the mean density intervals. Ranks in brackets omitted from analysis.

Density interval	Mean density	Stations				
		20	35	10	9	31
K	1000	1	2	4	5	3
J	100	(1)	(2)	(3)	—	(4)
I	50	2	1	4	3	5
H	20	2	1	4	3	5
G	10	1	2	4	3	5
F	5.0	1	4	3	2	5
E	2.5	3	2	5	4	1
D	1.0	1	3	2	4	5
C	0.2	3	1	2	4	5
B	0.1	2	1	3	4	5
Sum		16	17	31	42	39
Av. Rank		1.78	1.89	3.44	3.56	4.33

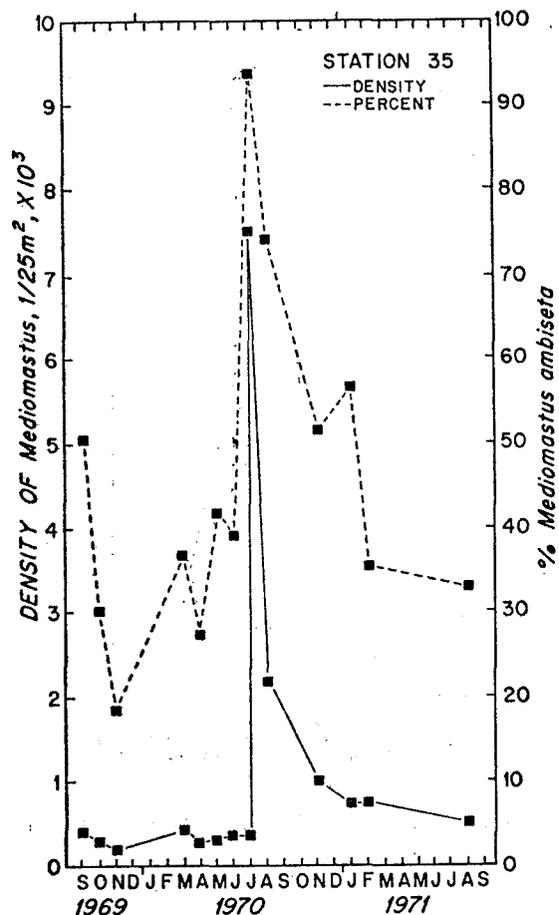


Figure 32. Density of *Mediomastus* in $1/25 \text{ m}^2$, at station 35, and percent of whole fauna comprised by this polychaete.

ing interval J. The values for stations 9 and 10 are similar, and higher than those for stations 20 and 35, indicating that the faunas at the nearer-shore stations fluctuated much more than those of stations 20 and 35. Kendall's Coefficient of Concordance over the intervals of lower mean density, B-F, for the five stations yields a χ^2 of 6.80; the probability that the ranks are independent of density is between 0.20 and 0.10. Even at these low mean densities, the faunas at stations 20 and 35 clearly tended to be less variable than those at stations 9, 10, and 31.

In seven of the nine intervals, station 31 ranks fifth, most variable. In interval J, omitted from the calculations, this station also ranks last. It ranks first in interval E, and third in interval K. In interval E, however, only *Syllides verrilli* is present. The high average rank, 4.33, indicates that changes in density and faunal composition at this station were sudden and rapid for at least three years after the spill.

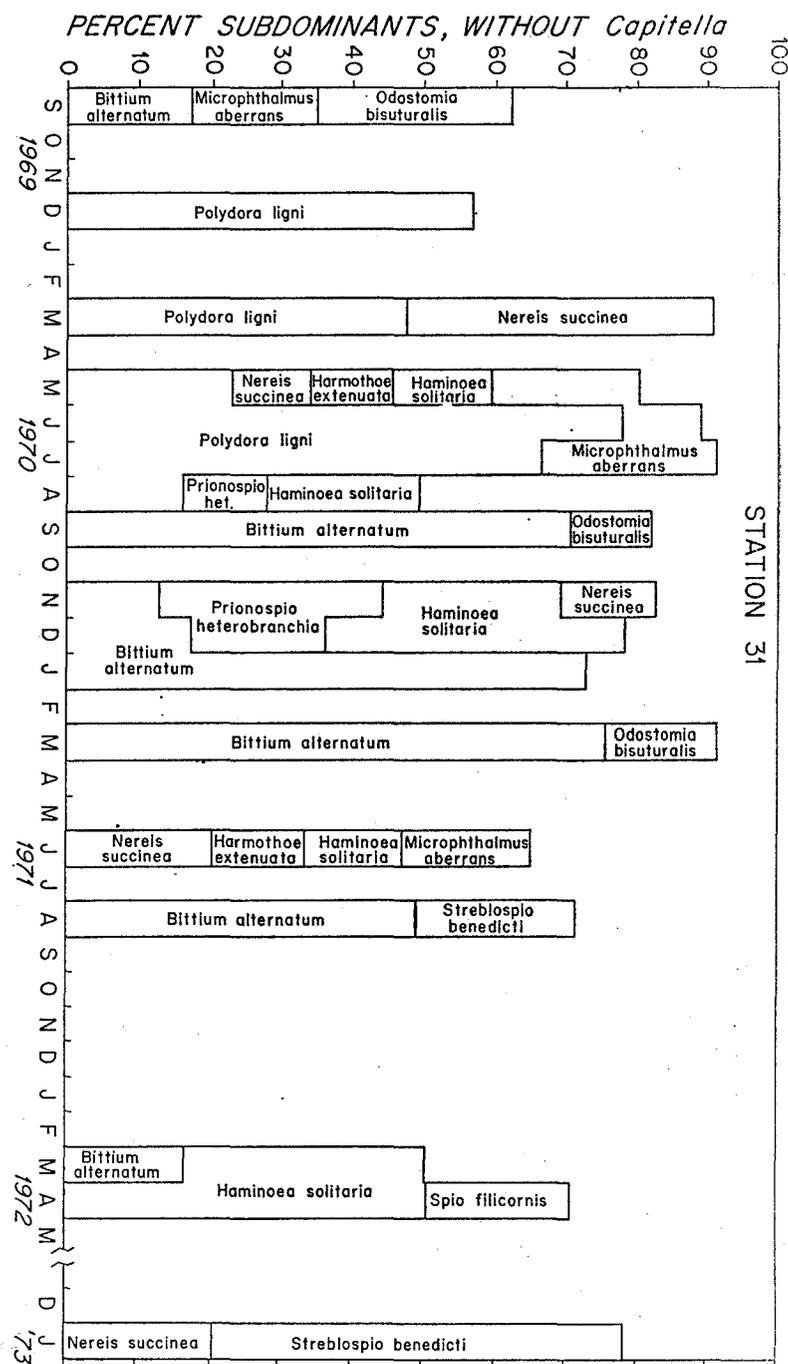


Figure 33. Subdominants at station 31.

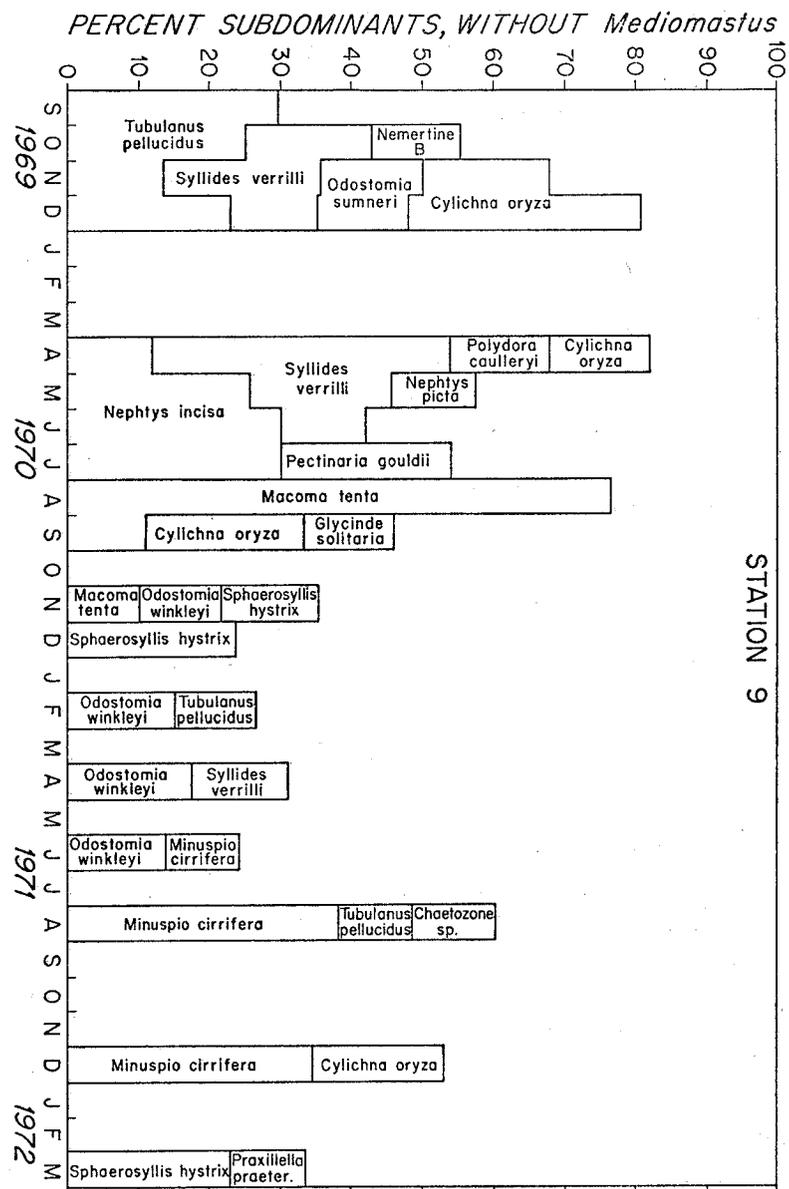


Figure 34. Subdominants at station 9. *Praxillella praeter*. = *Praxillella praetermissa*.

We used the Mann-Whitney U Test to test the null hypothesis that the mean coefficient of variation for a suite of species each having a given minimal mean density (here, 3 individuals in 1/25 m²) at one station is not significantly different at the 90% level from the mean coefficient of variation for the corresponding suite of

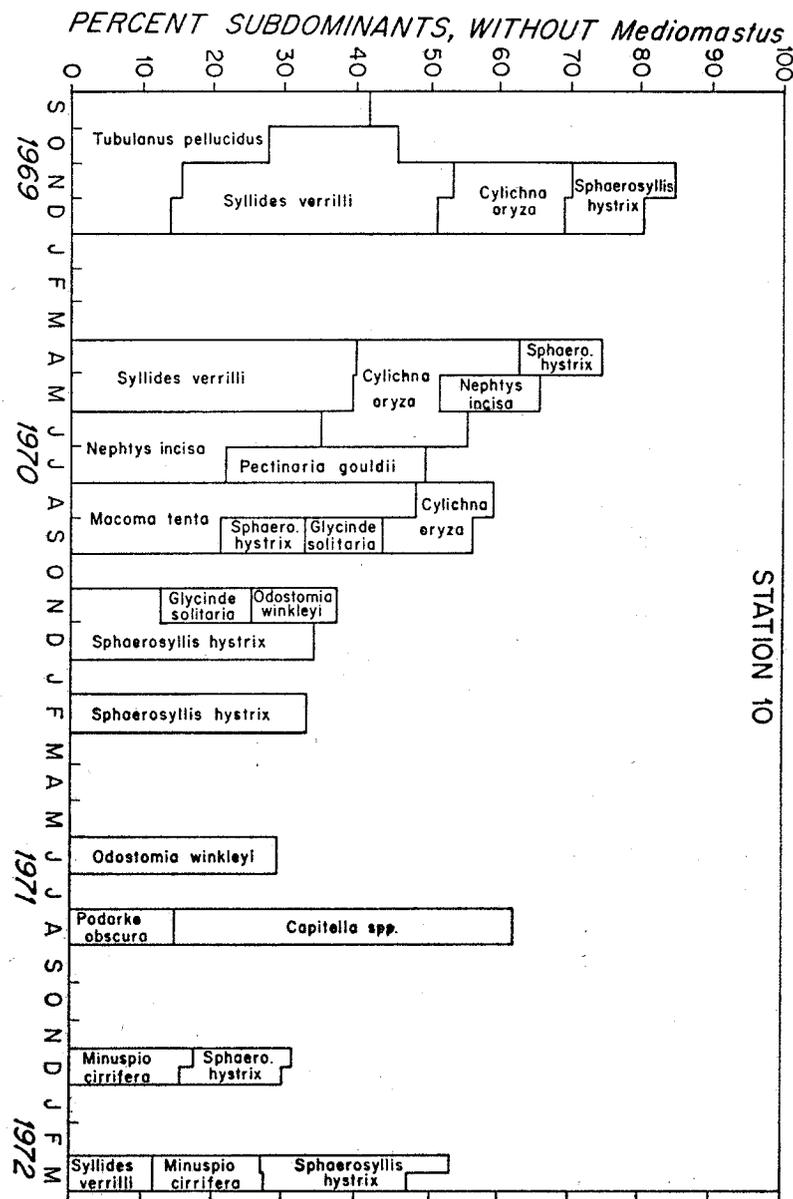


Figure 35. Subdominants at station 10. Replicate samples taken in December, 1971, and March, 1972, were analyzed.

species from another station. Because mode of life and temporal constancy are of no import to these calculations, all species of requisite mean density are included. This test shows (Table 6) that only two pairs of stations, 20 and 35, and 9 and 10,

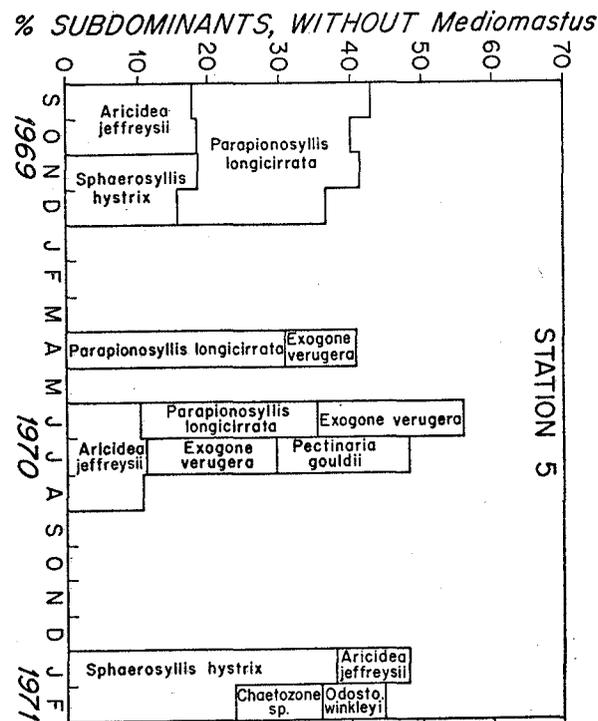


Figure 36. Subdominants at station 5. *Odosto. winkleyi* = *Odostomia winkleyi*.

have mean coefficients of variation not significantly different. Station 31 is significantly different from each of the other stations in this regard.

The mean coefficients of stations 20 and 35 are not significantly different, and the arithmetic difference between them is slight (Table 6). The overlap of the ranges of coefficients is fairly great (Fig. 48). Amphipods were less variable in abundance at station 35 than at station 20, whereas *Parapionosyllis longicirrata*, *Brania wellfleetensis*, and *Ampharete arctica* were more variable at station 35. These differences lessened the similarity of the mean coefficients of these two stations.

Table 6. Probability values associated with the Mann-Whitney U test of coefficients of variation comparisons between any two stations. Difference between mean coefficients of variation of any two stations.

Station	20	35	10	9	31	Mean C. V.
20	X	0.090	0.663	0.514	0.933	1.263
35	0.4716	X	0.573	0.424	0.843	1.353
10	0.00006	0.0006	X	0.149	0.270	1.926
9	0.001	0.008	0.4778	X	0.419	1.777
31	0.00006	0.00046	0.0672	0.0524	X	2.196
No. species	36	40	36	23	14	

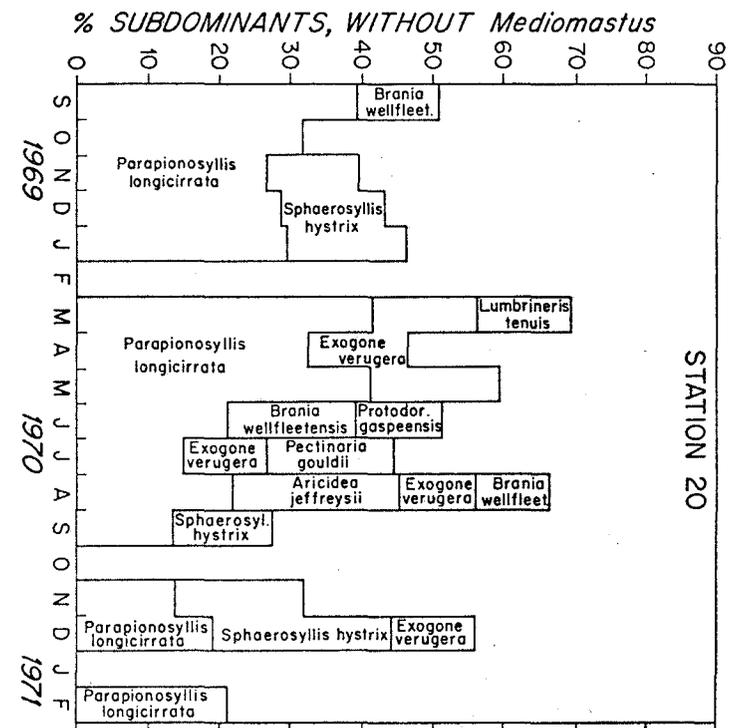


Figure 37. Subdominants at station 20. *Protodor. gaspeensis* = *Protodorvillea gaspeensis*.

fleetensis, and *Ampharete arctica* were more variable at station 35. These differences lessened the similarity of the mean coefficients of these two stations.

The mean coefficients of stations 9 and 10 are statistically and arithmetically similar. The overlap of the ranges of coefficients is considerable (Fig. 49). *Mediomastus ambiseta* was much less variable at station 9, *Sphaerosyllis hystrix*, *Glycera americana*, and *Phascolion strombi* were less variable at station 10.

The mean coefficient of variation of station 31 is significantly different from those of the other stations; the arithmetic differences are considerable. The range of coefficients of this station and those of stations 9 and 10, respectively, overlap to a moderate or considerable extent (Figs. 50, 51). The range of coefficients of station 31 and those of stations 20 and 35, respectively, overlap little or not at all (Figs. 52, 53). The one species common to stations 31 and 35, *Mitrella lunata*, was more variable at station 35. The mean coefficients of stations 31 and 10 differ to a lesser extent than the *p* value of 0.0672 might suggest. This anomaly may be due in part to the fact that five of the coefficients of station 10 are greater than 3.0, whereas only one coefficient at station 31 is of this magnitude.

The mean coefficients of variation of the four remaining pairs of stations (Figs.

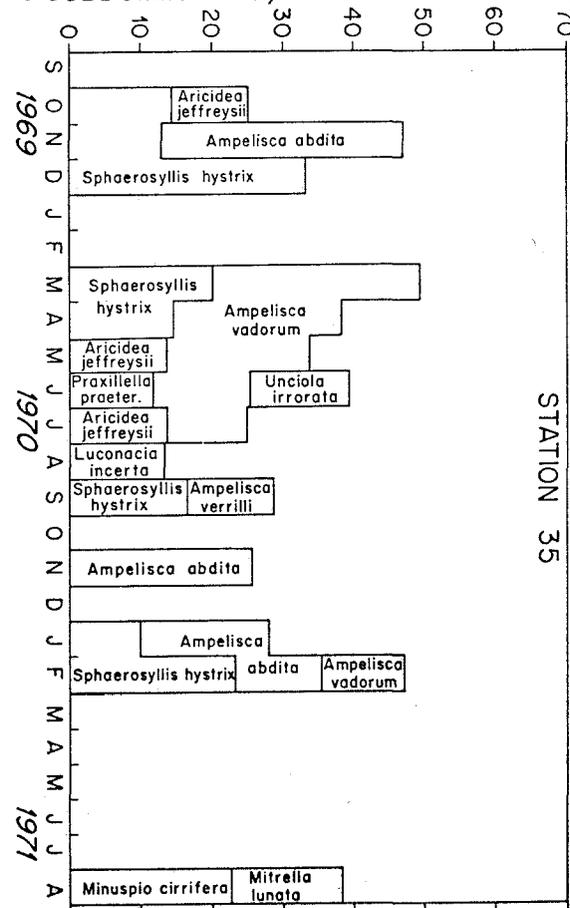
% SUBDOMINANTS, WITHOUT *Mediomastus*

Figure 38. Subdominants at station 35. *Praxillella praeter.* = *Praxillella praetermissa*.

54-57) are also significantly different. In each case, the station nearer shore has a mean coefficient greater than that of the station farther from shore. The majority of species shared by two stations have higher coefficients at the station closer to shore. Overlaps of ranges of coefficients are slight to moderate.

Some may argue that those species occurring at only the more heavily oiled stations owe their presence there solely to the oil, and are by nature more variable than those species at lightly oiled stations, and further that these variable species at the more heavily oiled sites may unduly influence the patterns of the coefficients of variation. To answer this objection, we include in another analysis only those species shared by any two stations at mean densities of three or more. Because only four species at station 31 occurred at any of the other four stations in densities suffi-

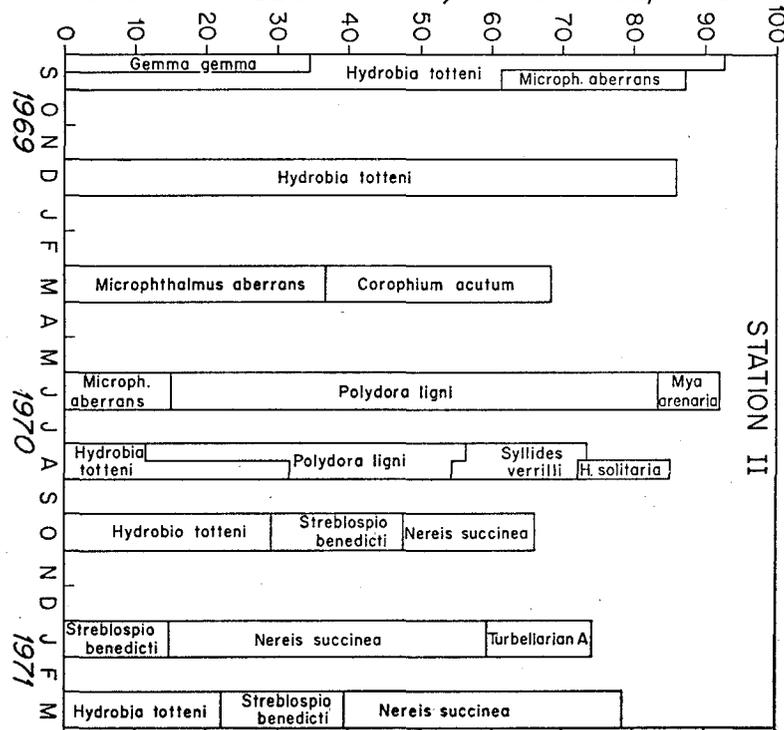
PERCENT SUBDOMINANTS, WITHOUT *Capitella*

Figure 39. Subdominants at station II. Two samples were taken in September, 1969: one on the 19th and another on the 26th. Replicate samples taken in August, 1970, were analyzed. *H. solitaria* = *Haminoea solitaria*.

cient for valid testing, we omitted station 31 from the analysis.

The null hypothesis states:

$$p(X_A > X_B) = p(X_A < X_B) = 1/2$$

in which X_A are coefficients of variation at station A , and X_B are coefficients of variation at station B . The null hypothesis is proven when half of the species common to the two stations have higher coefficients at one of the stations. The greater the departure from parity, the lower the probability, p , that the coefficients of variation at the two stations are not significantly different.

The large values of p for pairs of stations 20 and 35, 9 and 20, and 9 and 10 show that the coefficients for species shared here are not significantly different (Table 7). The results for stations 20 and 35 and stations 9 and 10 agree with the results of the test in which every species present at a mean density of three or more is included regardless of its absence from a station. The high p value of 0.754 for stations 9 and 20 differs greatly from the earlier value of less than 0.001. As in the

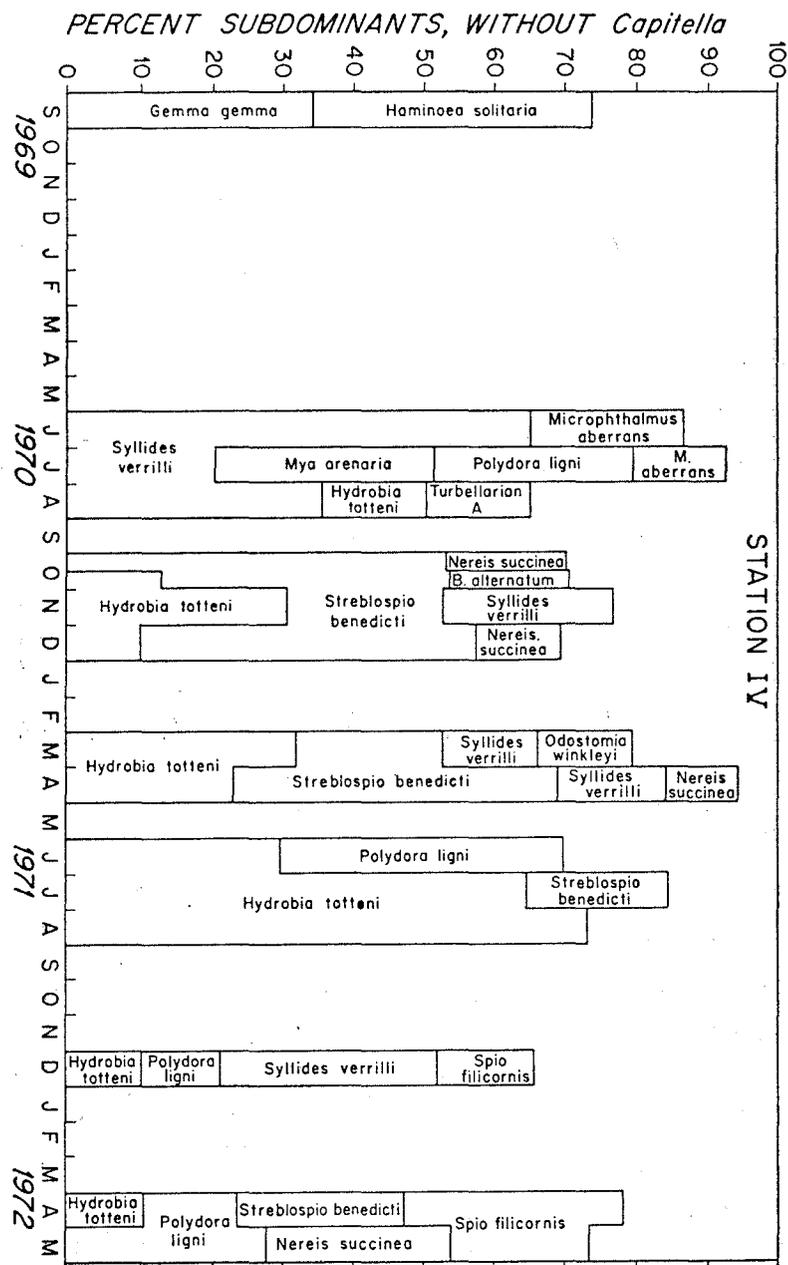


Figure 40. Subdominants at station IV. Replicate samples taken in October, 1970, were analyzed. *B. alternatum* = *Bittium alternatum*.

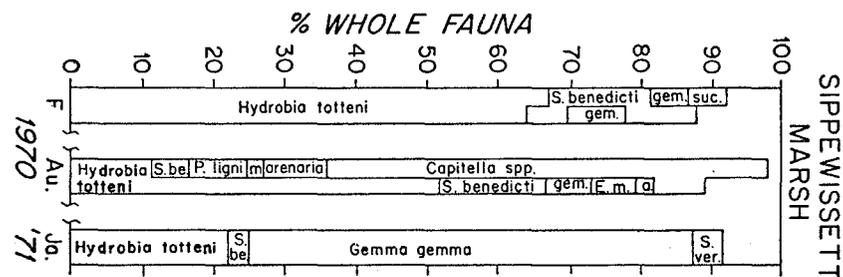


Figure 41. Abundant species at control station in Sippewissett Marsh. *S. be.* = *S. benedicti* = *Streptosio benedicti*. *gem.* = *Gemma gemma*. *suc.* = *Nereis succinea*. *P. ligni* = *Polydora ligni*. *m.* = *E. m.* = *Edotea montosa*. *a.* = *arenaria* = *Mya arenaria*. *S. ver.* = *Syllides verrilli*.

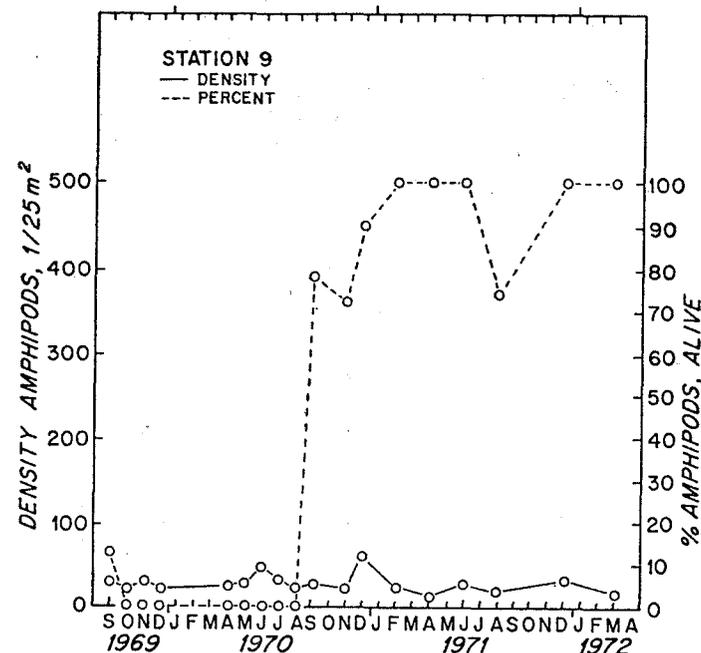


Figure 42. Density of ampeliscid amphipods in 1/25 m² at station 9, and the proportion found alive.

earlier test, the *p* values of the remaining pairs of stations demonstrate that the coefficients of variation of the shared species are significantly different.

To reduce noise, we removed *Glycinde solitaria*, *Minuspio cirrifera*, *Mediomastus ambiseta*, and *Odostomia winkleyi*, which were much more abundant in the second year after the spill than in the first, and *Pectinaria gouldii*, which was present at very low constancy. This test (Table 8) also yields *p* values greater than 0.5 for pairs of

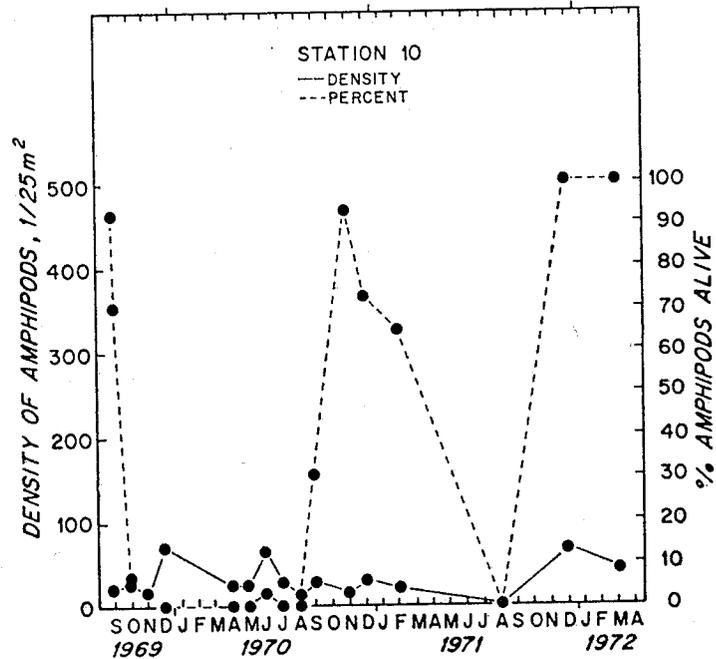


Figure 43. Density of ampelisid amphipods in $1/25 \text{ m}^2$ at station 10, and the proportion found alive.

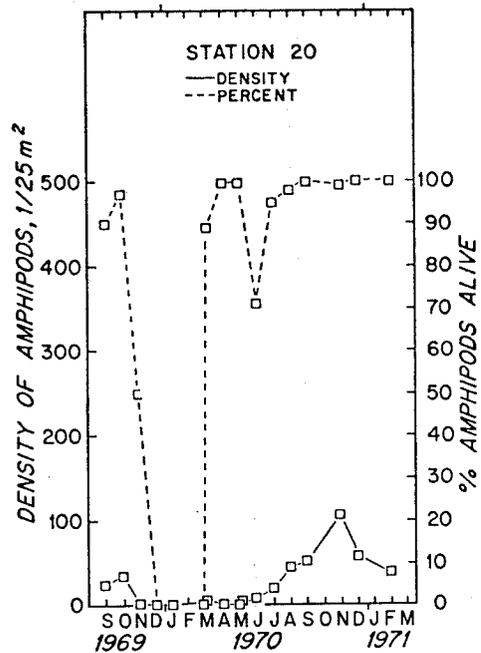


Figure 44. Density of ampelisid amphipods in $1/25 \text{ m}^2$ at station 20, and the proportion found alive.

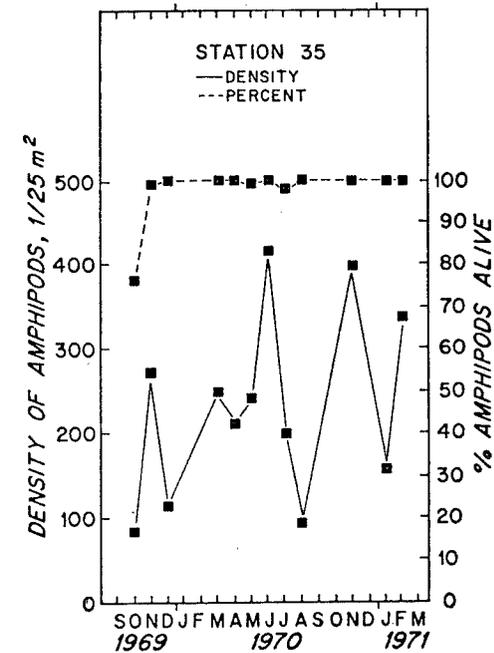


Figure 45. Density of ampelisid amphipods in $1/25 \text{ m}^2$ at station 35, and the proportion found alive.

Table 7. Number of species present at mean densities ≥ 3.0 in $1/25 \text{ M}^2$ common to each pair of stations; probability that coefficients of variation for species shared by two stations are not different.

Station	20	35	10	9	31
20	X	0.832	0.076	0.754	—
35	22	X	0.004	0.030	—
10	16	22	X	0.524	—
9	10	18	22	X	—
31	1	1	4	0	X

Table 8. Number of species present at mean densities ≥ 3.0 in $1/25 \text{ M}^2$ common to each pair of stations. The probability that the coefficients of variation of species shared by two stations are not different, omitting four species much more abundant at all four stations in the second year than in the first, and a fifth species of low constancy.

Station	20	35	10	9
20	X	1.000	0.022	0.124
35	19	X	0.012	0.022
10	13	17	X	0.630
9	7	13	17	X

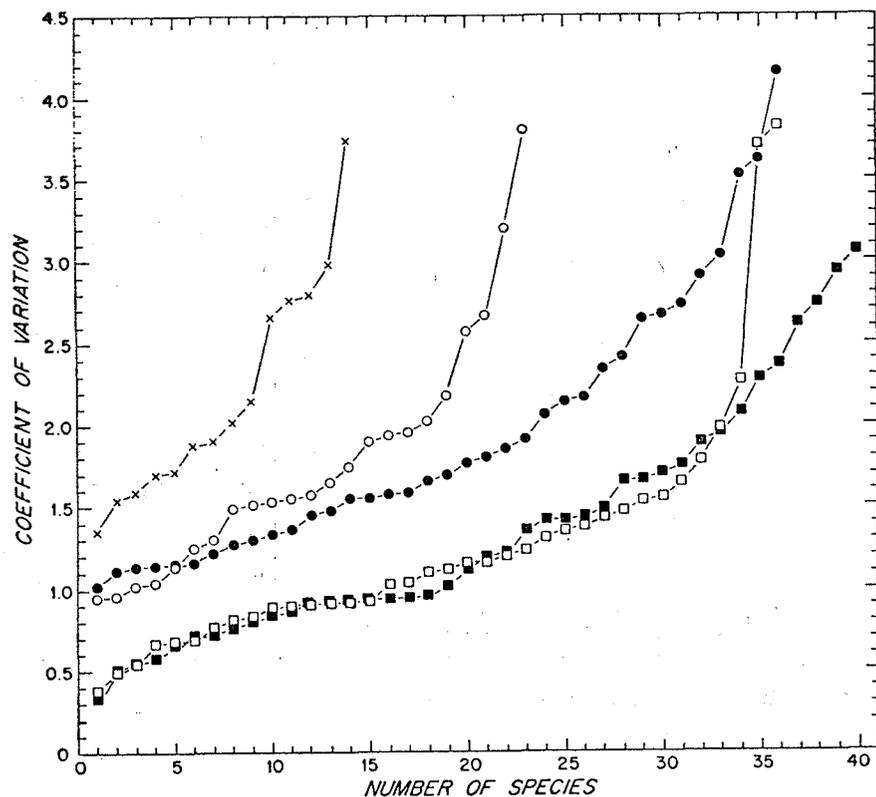


Figure 46. Coefficients of variation of species having mean densities of 3 or more at stations 31 (X), 9 (O), 10 (●), 20 (□), and 35 (■).

stations 20 and 35, and 9 and 10. The p value for the pair 9 and 20 is much lower in this test than that in which all abundant species in common are included. The number of species shared by stations 9 and 20 is seven, marginally low. Although six of these seven species have higher coefficients at station 9, the p value is only 0.124, just barely not significant ($p = 0.100$).

Constancy

Both absolute and relative numbers of species present in more than 45% of the samples from a station was greatest at stations farthest from shore and least at stations 31, II, and IV (Table 9).

Almost all species constant at station 31 were infrequent at the offshore stations. Almost all the highly constant species of stations 9 and 10 were as constant or much more constant at the stations farther offshore. Only a very few species were most constant at stations 9 and 10. Several species were highly constant at one or more of stations 5, 20, and 35. The proportion of highly constant species was greatest at

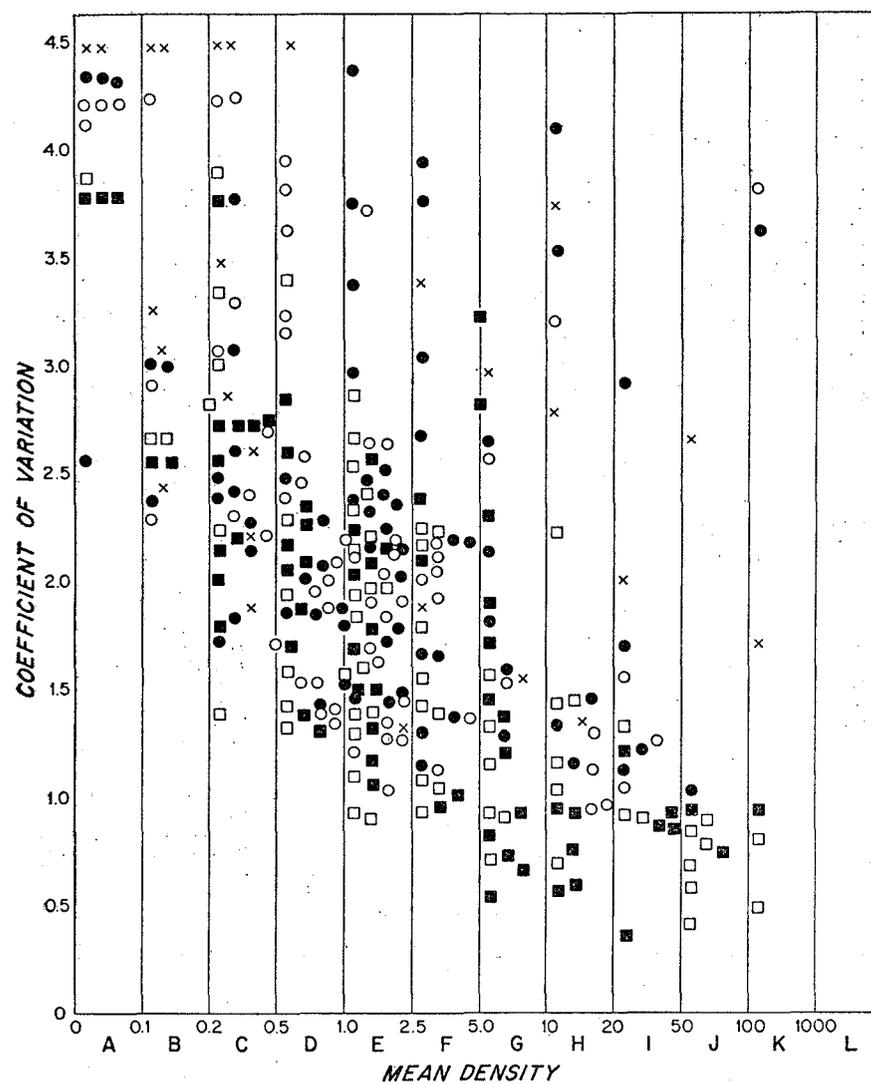


Figure 47. Relationship between coefficient of variation and mean density of species at stations 31 (X), 9 (O), 10 (●), 20 (□), and 35 (■). Epifaunal species, species much more abundant in the second year than in the first, and transient species omitted.

the three stations farthest from shore, and least at nearshore station 31 (Fig. 58).

More species and a greater proportion of species were constant at the control station in Sippewissett Marsh than at stations II and IV in the intertidal zone of Wild River (Table 9, Fig. 59). Most of the constant species common to Sippewissett and either of the other stations were more constant at the control station. *Hydrobia totteni*, *Streblospio benedicti*, and *Edotea montosa* occurred in every sample from

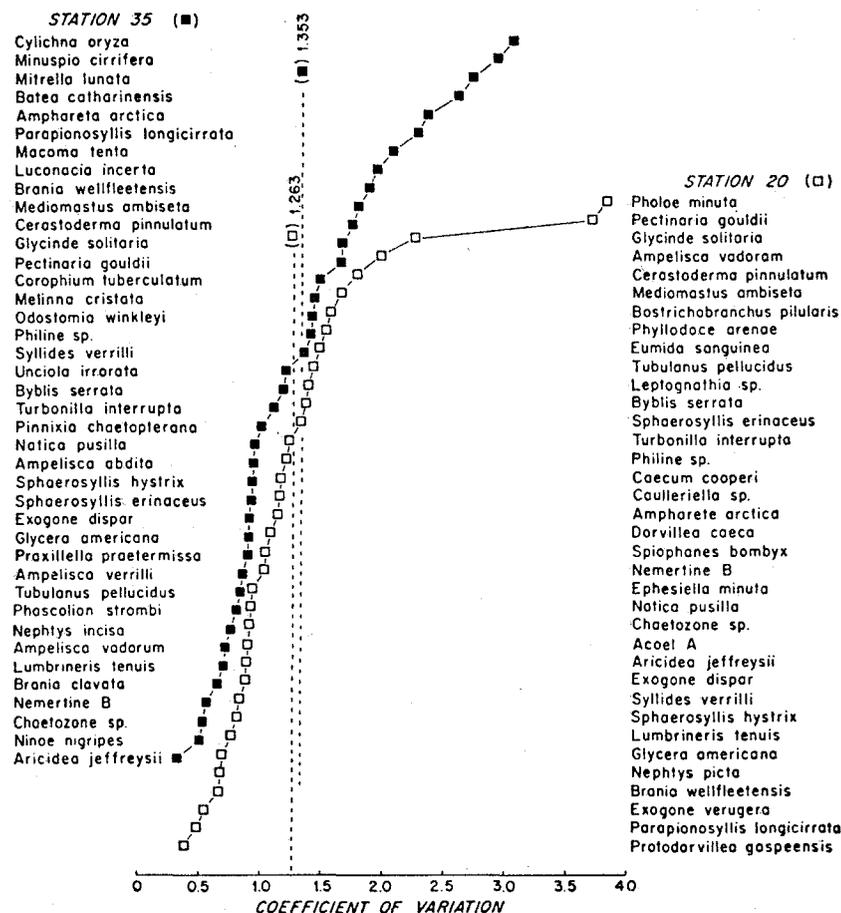


Figure 48. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 35 (■), and 20 (□).

Sippewissett. Only *Capitella* occurred in every sample from station IV; the constancies of the species in the *Capitella capitata* group were lower (Grassle and Grassle, 1977). The most constant species at station II, *Hydrobia totteni*, was not in every sample. The sudden increase in numbers of *Capitella* in Sippewissett Marsh probably reflects invasion by this polychaete from a nearby test plot. *Gemma gemma* occurred in most samples from Sippewissett; in Wild Harbor River, however, this bivalve died soon after the spill, did not reappear for a year, and was thereafter infrequent and sparse. *Gemma gemma* broods its young, the young settle near the mother, and dispersal is relatively slow. Members of four major taxa were constant in Sippewissett Marsh; those of only two major taxa were constant in Wild Harbor River.

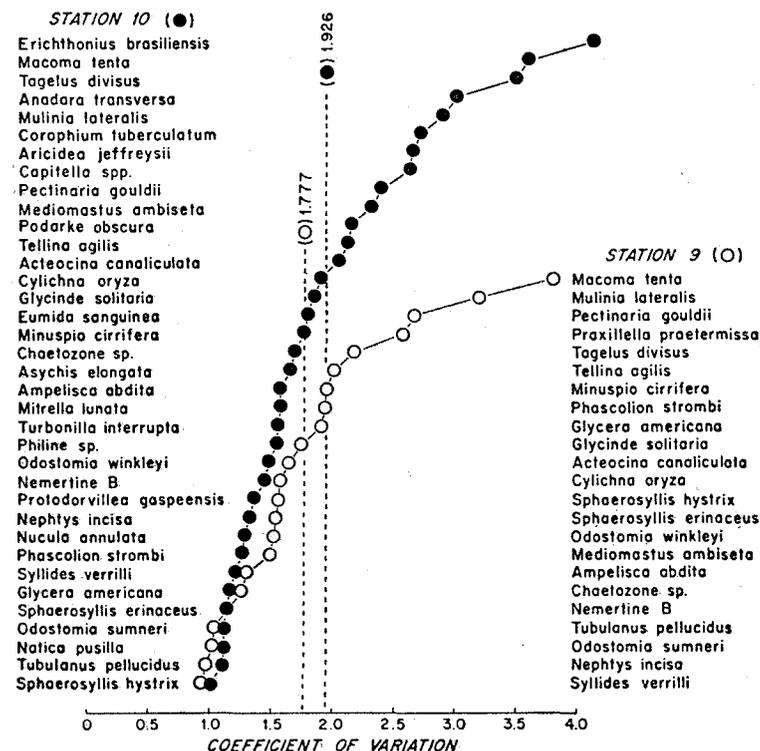


Figure 49. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 9 (○) and 10 (●).

Discrepancy index

Values of the discrepancy index for the whole fauna at stations 31, 9, 10, 20, and 35 between the first and second years concur with the gradient of oil-induced stress

Table 9. Absolute and relative numbers of species present in more than 45% of samples.

Station	Total species	No. species with constancy >.45	% Species with constancy >.45
31	123	6	4.9
II	41	5	12.2
IV	51	7	13.7
9	148	29	19.6
10	182	34	18.7
5	149	44	29.5
20	147	47	32.0
35	145	47	32.4
Sipp.	30	10	33.3

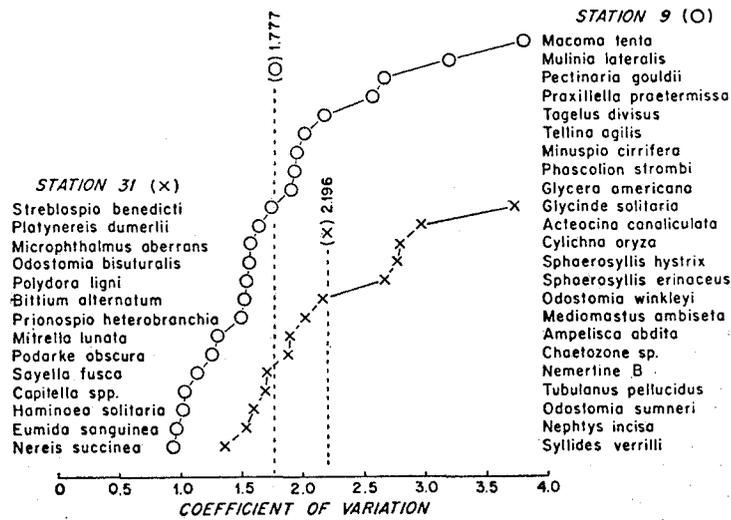


Figure 50. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 31 (X) and 9 (O).

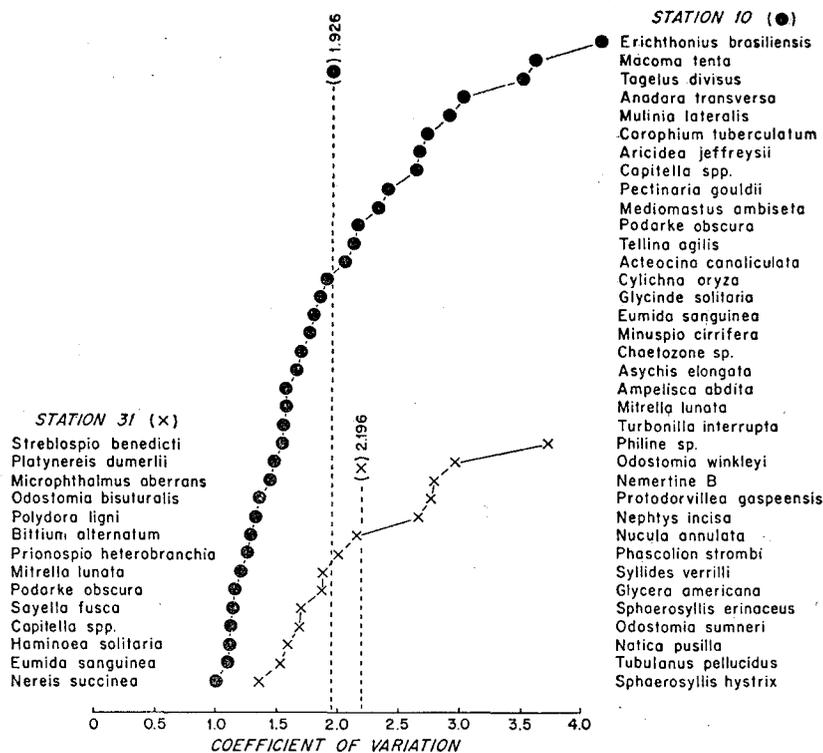


Figure 51. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 31 (X) and 10 (●).

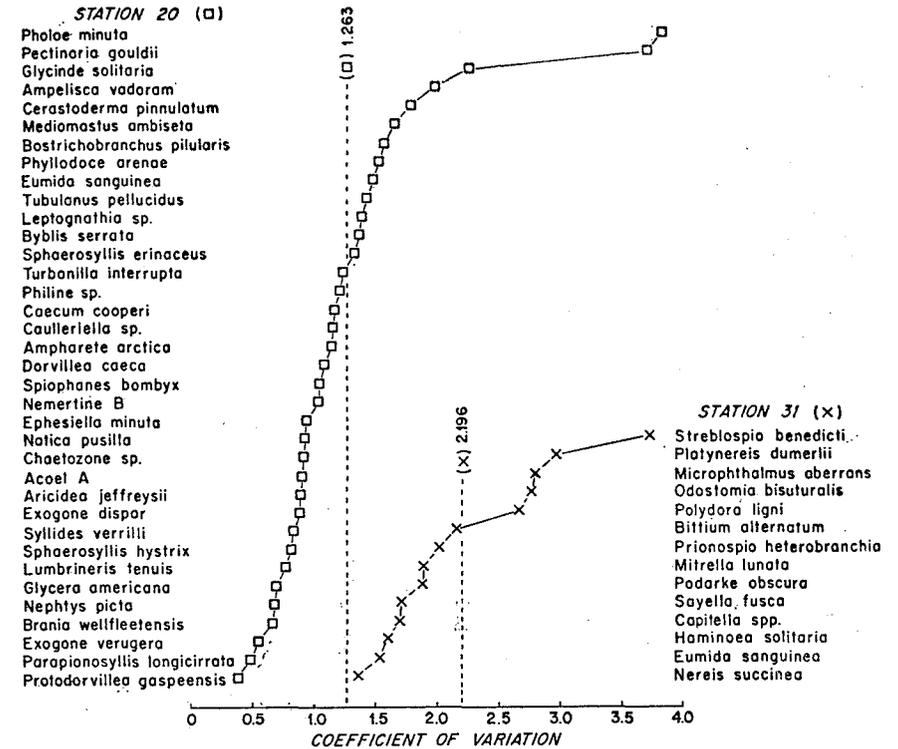


Figure 52. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 31 (X) and 20 (□).

(Fig. 60). Values were least at the two stations farthest offshore, where concentrations of oil were lowest. Discrepancy was greater at intermediately oiled stations 9 and 10, and greatest at most heavily oiled station 31. Such pronounced differences reflect the large disparities not merely of the few very common species, but also of the numerous less common species.

The number of very discrepant species which together account for ninety percent of the total discrepancy is small at stations 31 and 9, but considerably larger at the other three stations (Fig. 61). Amphipods, demonstrated to be sensitive to oil, were among the discrepant species at stations 20 and 35, but were absent from stations nearer shore. The discrepant species at station 31 were not those at the other four stations, which shared a suite of species, chief among which were *Mediomastus ambiseta*, *Glycinde solitaria*, *Minuspio cirrifera*, and *Odostomia winkleyi*.

The influx of juveniles in August, 1970, lowered values of the discrepancy index for the first two years, greatly at all of the more heavily oiled stations, but only slightly at the minimally oiled sites (Fig. 62). The effect of the August, 1970, samples can be measured by placing, by station, each species for which the sum of the

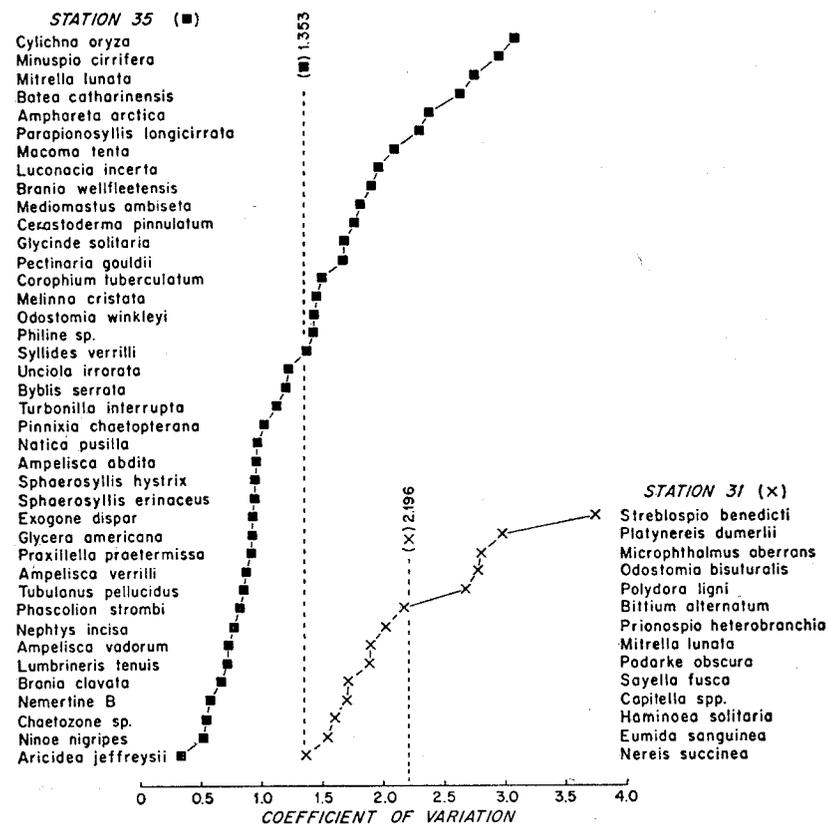


Figure 53. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 31 (X) and 35 (■).

mean densities of the first two years was ten or more into one of seven categories of disparity. Wherever exclusion of the August, 1970, sample results in a change of category, an arrow shows the direction and magnitude of that change.

The majority of species at minimally oiled stations 20 and 35 (Figs. 63, 64) are in the category of least disparity, A, some in the category of next smallest disparity, B, and only about one-sixth in categories of higher disparity. Most species at stations 9, 10, and 31, however, are in categories of intermediate or high disparity (Figs. 65-67). Without the August, 1970, samples, disparity considerably increased at stations 9, 10, and 31, but increased only slightly at stations 20 and 35. The proportion of change which was to higher disparity was greatest at stations 31 and 9, somewhat less at stations 10 and 20, and least at station 35 (Table 10).

The very heavy settlement of the young of many species at intermediately oiled stations 9 and 10 in August, 1970, initiated the next phase of colonization, although other species also more abundant in the second year had not yet settled in great

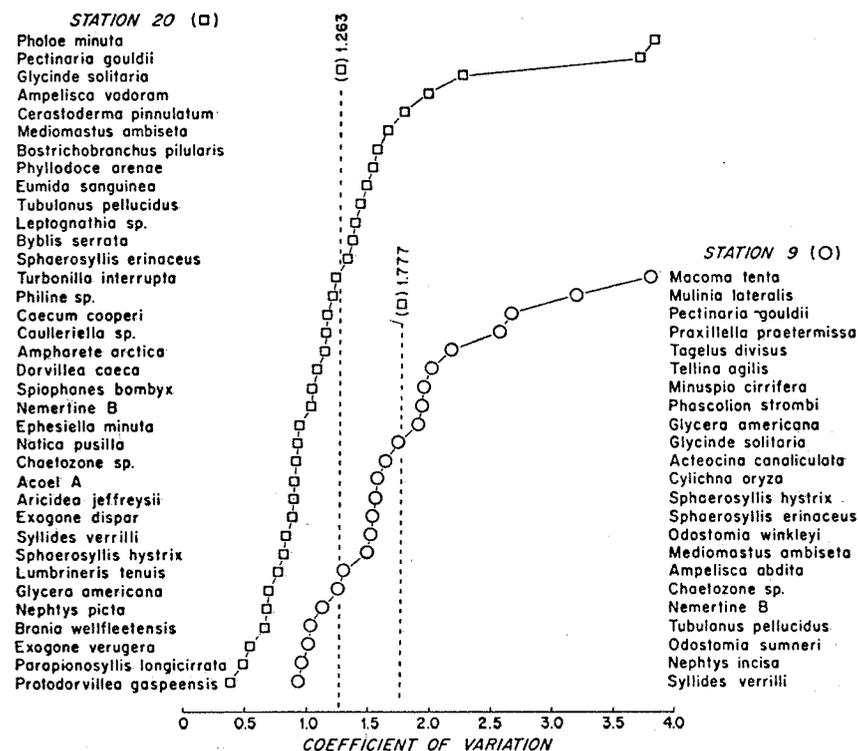


Figure 54. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 9 (O) and 20 (□).

numbers. As these juveniles grew during the second year, they became crowded, and some species failed while others rapidly declined in numbers. At minimally oiled stations 20 and 35 juveniles of only one species, *Mediomastus ambiseta*, were numerous in August, 1970. The small differences in disparity with and without the August, 1970, sample indicate that the fauna at these two stations changed relatively

Table 10. Mean disparity with and without the August, 1970, sample; the direction and extent of change in category of disparity upon omission of August, 1970 sample.

Station	No. species of requisite density	Mean rank all samples	% Species changing rank	Total change in rank	% Change to greater disparity	Net mean rank without Aug. 1970 sample
31	14	3.26	50	1.14	100	4.40
9	20	3.25	45	1.00	95	4.15
10	23	2.74	74	1.83	81	3.87
20	30	1.70	17	0.20	85	1.84
35	32	1.78	19	0.19	68	1.85

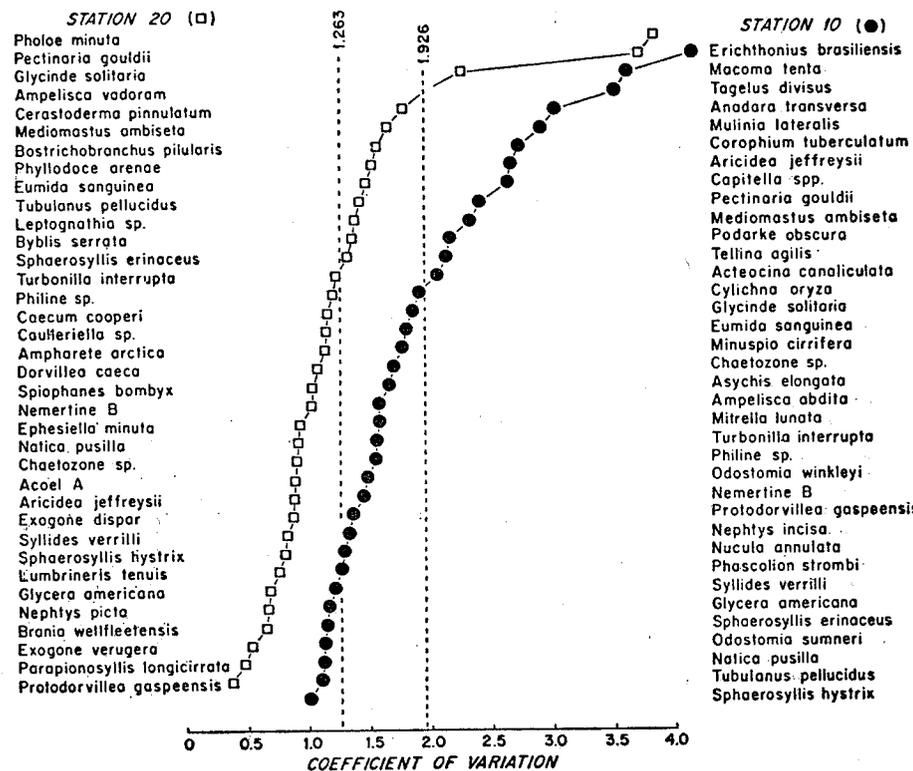


Figure 55. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 10 (●) and 20 (□).

little from the first year to the second. In August, 1970, the fauna at these two offshore stations was similar in composition to that of both preceding and succeeding months. The proportion of the discrepancy index contributed by the four species common to stations 9, 10, 20, and 35 increased greatly at station 10, but only slightly at the other three stations (Fig. 68). The number of very discrepant species was low at stations 9, 10, and 20, but fairly high at station 35.

At severely oiled station 31 density and faunal composition fluctuated rapidly and widely. These surges in species and numbers usually lasted from three to five months, although some were as brief as one month and others as long as nine months. In August, 1970, there was a major faunal shift from the dominants of the first year to some of those of the second. Although temporally adjacent samples differed in faunal composition, that of August, 1970, more closely resembled the succeeding samples.

Enough samples taken in the third year at stations 31 and 10 were analyzed to warrant discussion. At station 31, discrepancies were quite high and indicative of considerable faunal variation during the three years (Fig. 69). Like the uncommon

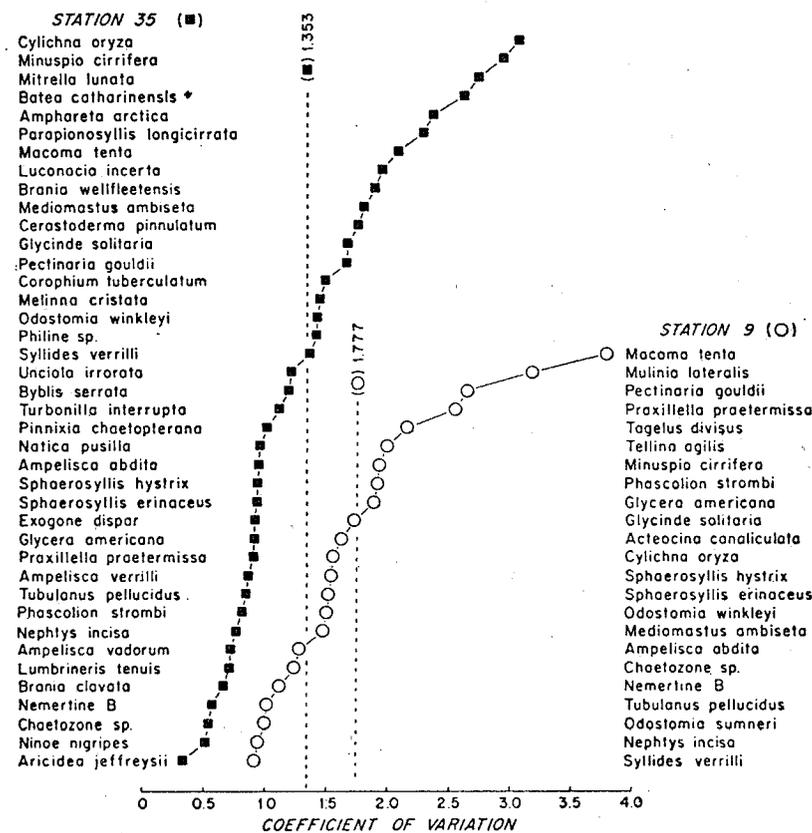


Figure 56. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 9 (○) and 35 (■).

species, the dominants came to a brief climax in only one of the three years, and the suite of dominants changed from one year to the next. At both stations 31 and 10, the number of very discrepant species did not change very much with the passage of time (Figs. 70, 71). After three years the fauna at station 31 had only slightly recovered. Mean densities at intermediately oiled station 10 (Fig. 72) for the three years were fairly similar to one another, and the values of the index were generally much lower there than at station 31. Almost all the specimens of *Mediomastus ambiseta* found in later months arrived as juveniles during the very heavy settlement in August, 1970. The abundance of this polychaete was almost the sole cause of the low discrepancy between the first two years. The discrepancy was less, although in some cases only slightly so, between the second and third years at all densities greater than 500. The faunas of the first and third years were the least similar. The fact that the fauna of the second year resembled that of the third year indicates that the fauna was recovering. This discrepancy between the second and

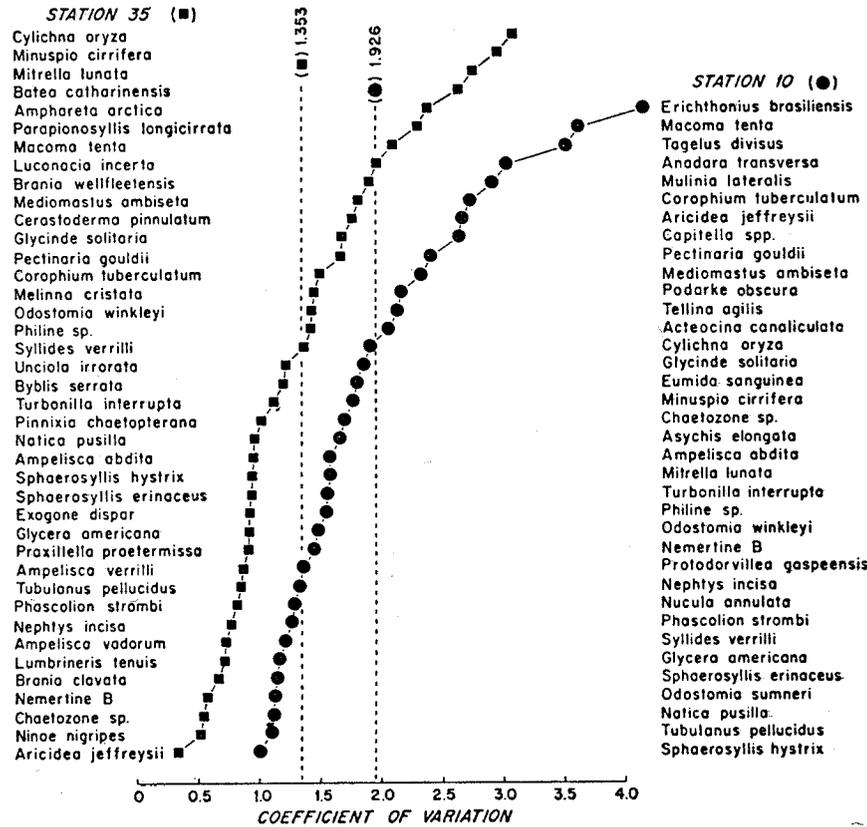


Figure 57. Coefficients of variation of all species having mean densities of 3 or more in $1/25$ m^2 at stations 10 (●) and 35 (■).

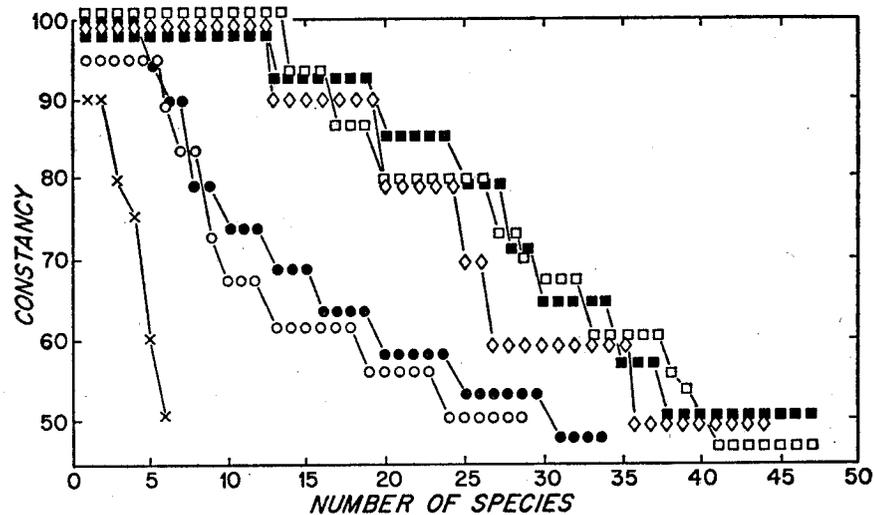


Figure 58. Constancies of species at stations 35 (■), 20 (□), 5 (◇), 10 (●), 9 (○), and 31 (X).

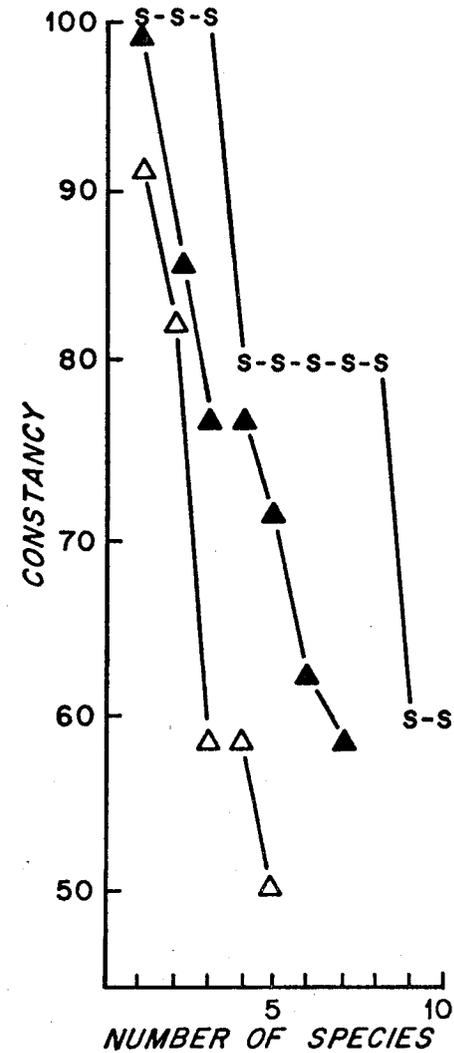


Figure 59. Constancies of species at stations II (△) and IV (▲) and the control station in Sipewissett Marsh (S).

third years at station 10 is markedly greater at all cumulative densities save the very smallest than the discrepancy between the first and second years at minimally oiled stations 20 and 35. The fauna at station 10, therefore, showed only slight recovery three years after the spill.

Diversity

We describe diversity in terms of the Hurlbert rarefaction curves, and note dif-

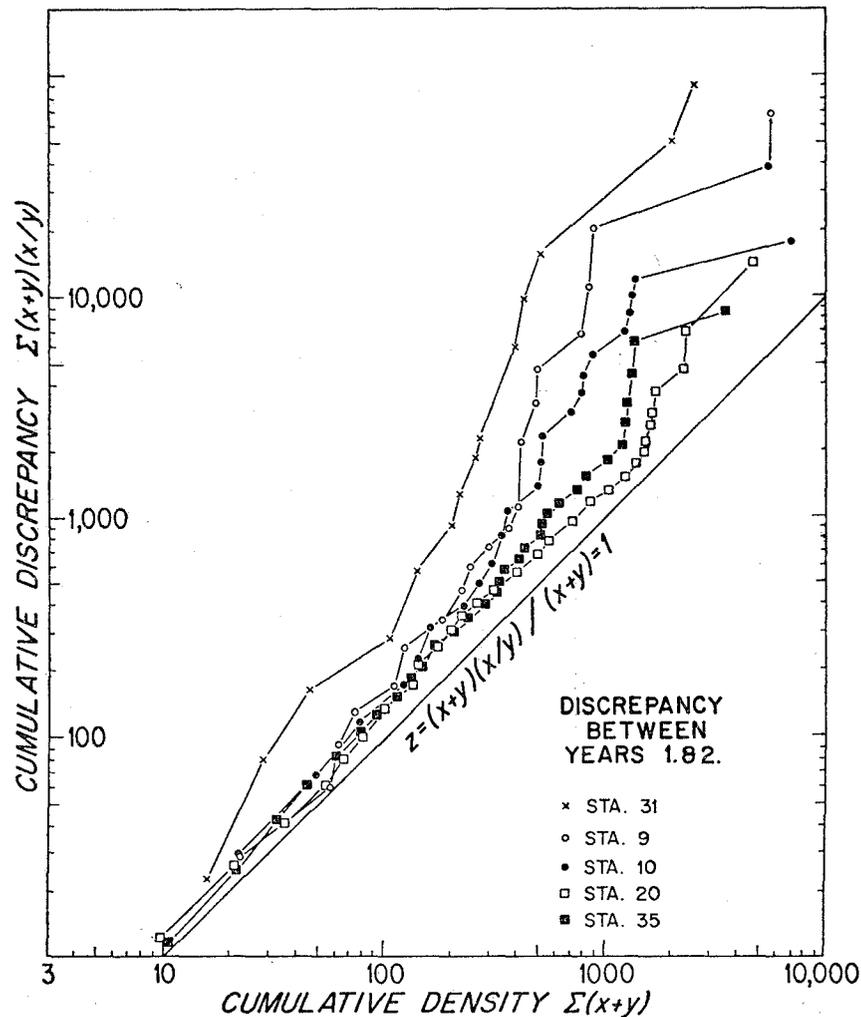


Figure 60. Discrepancy between the mean densities of the first and second years for species at stations 31 (X), 9 (O), 10 (●), 20 (□), and 35 (■).

ferences between the results of this index and those yielded by the Shannon-Wiener information function.

On September 25, 1969, ten days after the spill, diversity at station 31 was very low (Figs. 73, 74), and continued to decline through the winter of 1969-70, when *Capitella* and five other species were abundant. Evenness (Fig. 75) was artificially high in September and October, 1969, when density was too low to allow expression of possible dominance. During the autumn and winter of 1969-70, evenness fell to its lowest value. After March, 1970, diversity slowly rose, although it was still very

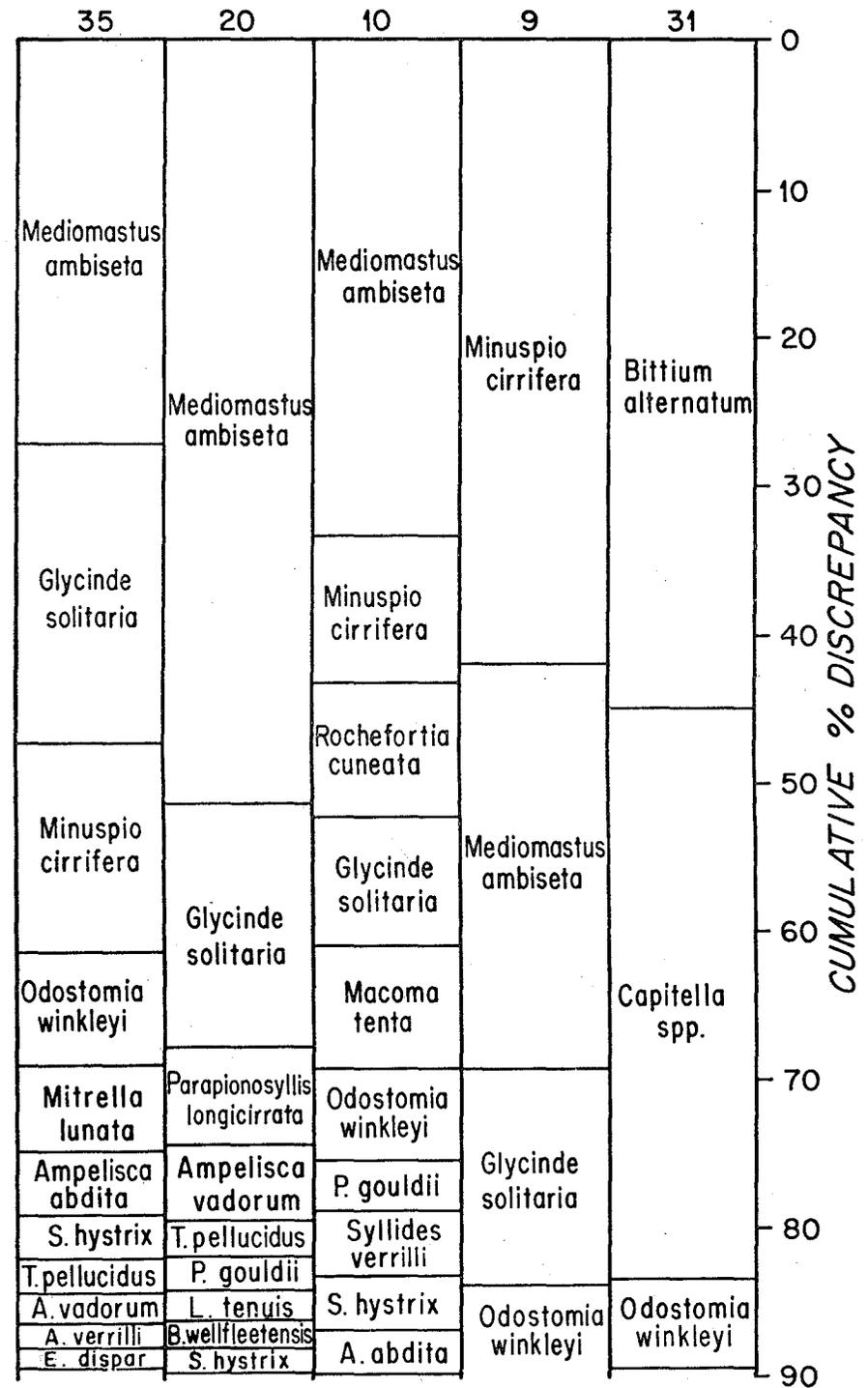


Figure 61. Species which together contributed almost 90% of discrepancy in mean densities of the first and second years at stations 31, 9, 10, 20, and 35.

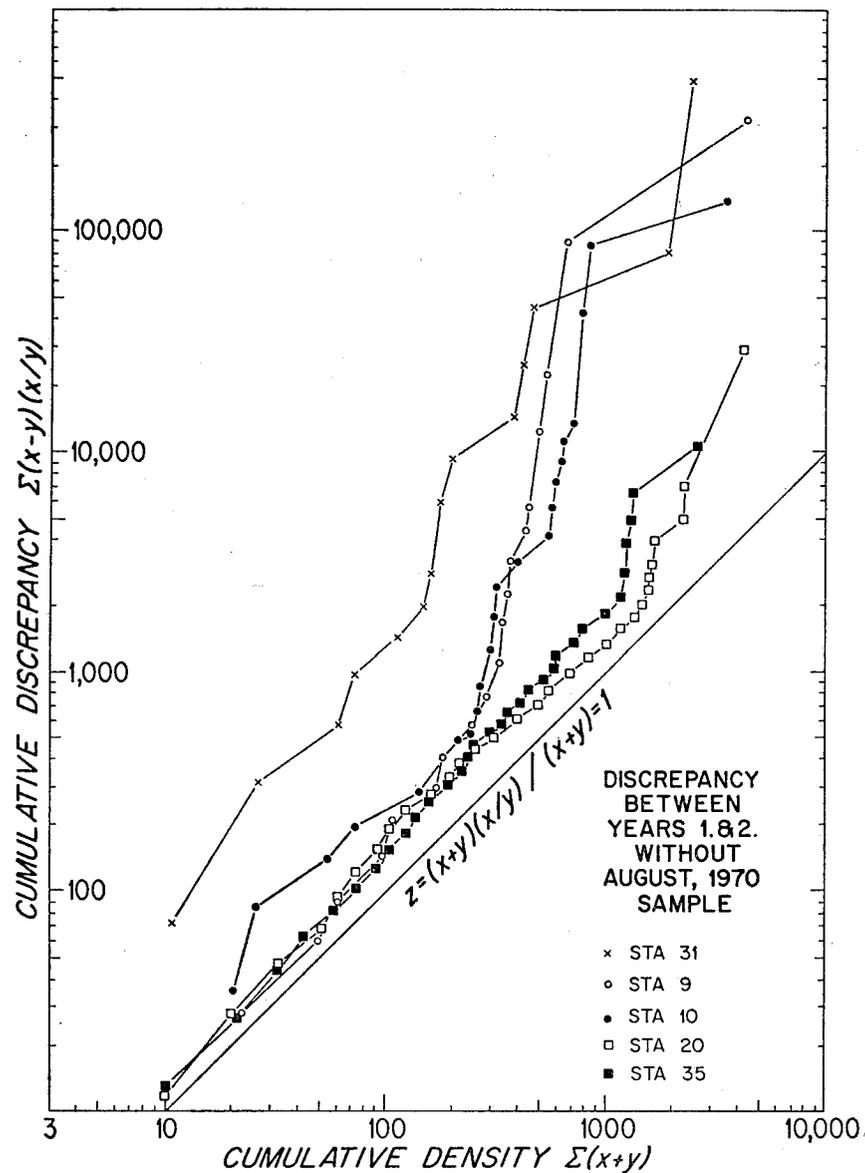


Figure 62. Discrepancy between the mean densities of the first and second years, without the August, 1970, samples, for species at stations 31, 9, 10, 20, and 35.

STATION 20

Glycinde solitaria
 Pectinaria gouldii
 Ampelisca vadorum
 Tubulanus pellucidus
 Sphaerosyllis erinaceus
 Mediomastus ambiseta
 Lumbrineris tenuis
 Acoel B
 Ephesiella minuta
 Chaetozone sp.
 Byblis serrata
 Turbonilla interrupta
 Parapionosyllis longicirrata
 Sphaerosyllis hystrix
 Brania wellfleetensis
 Protodorvillea gaspeensis
 Aricidea jeffreysi
 Syllides verrilli
 Exogone dispar
 Caecum pulchellum
 Nemertine B
 Archeannelid
 Nephtys picta
 Cauleriella sp.
 Glycera americana
 Bostrichobranthus pilularis
 Philline sp.
 Natica pusilla
 Exogone verugera
 Eumida sanguinea

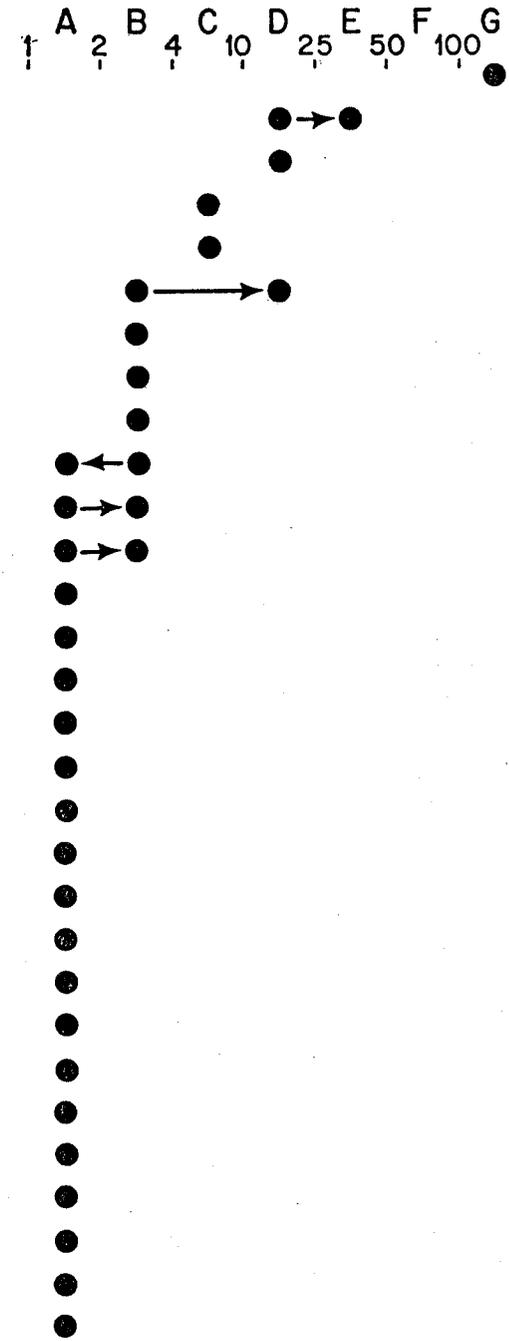


Figure 63. Changes in disparity (greater mean density divided by lesser mean density) between first and second year for species at station 20, upon omission of August, 1970, sample.

STATION 35

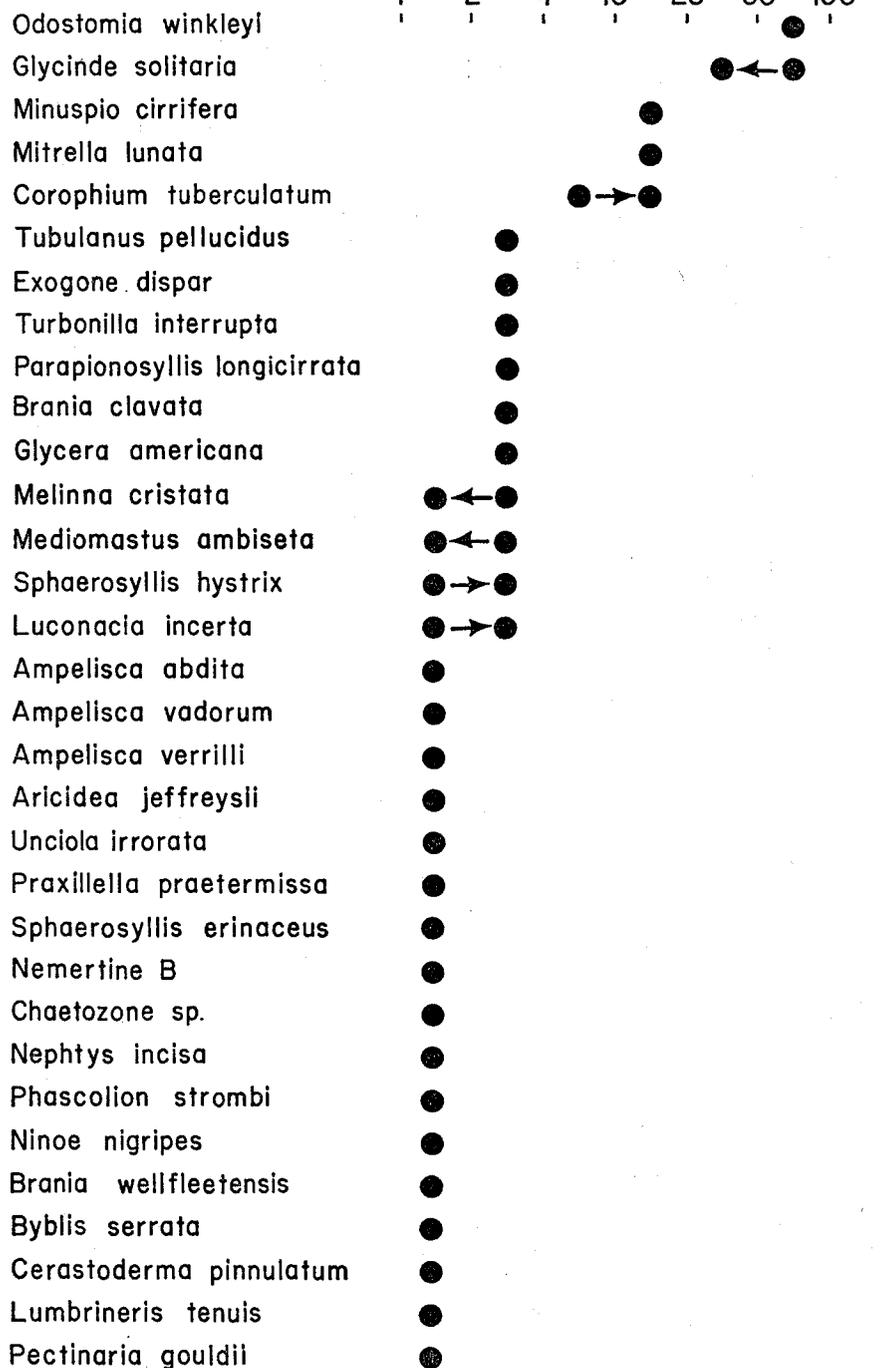


Figure 64. Changes in disparity (greater mean density divided by lesser mean density) between first and second year for species at station 35, upon omission of August, 1970, sample.

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STATION 9

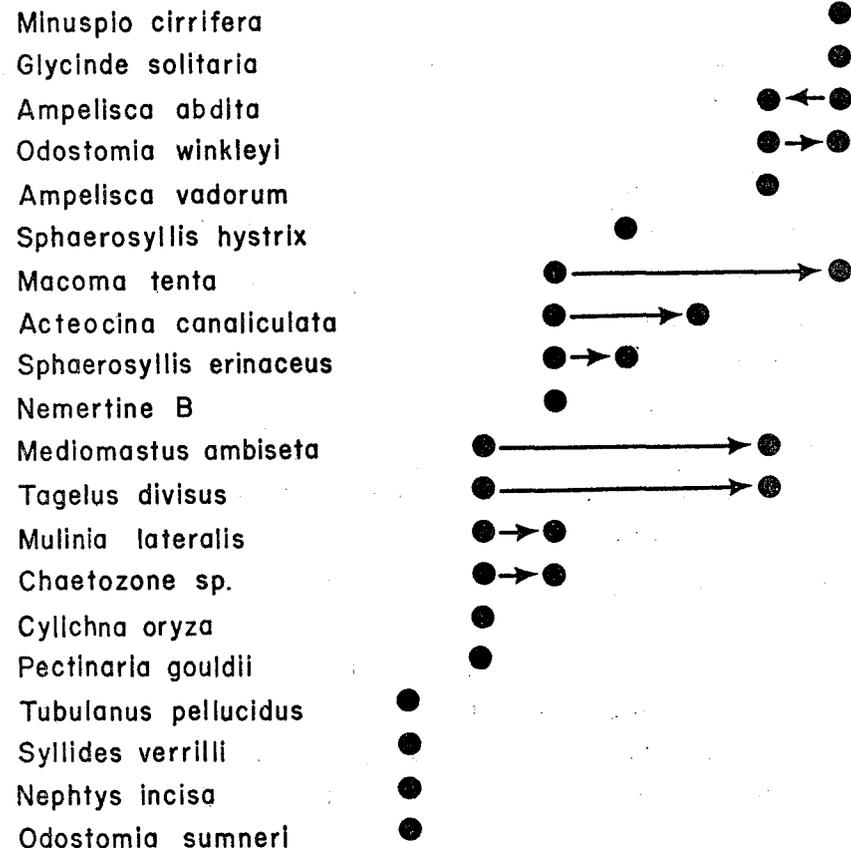


Figure 65. Changes in disparity (greater mean density divided by lesser than density) between first and second year for species at station 9, upon omission of August, 1970, sample.

low. During the first year diversity was fairly variable, especially in the early months. Evenness fluctuated and slowly increased during the latter half of the first year. In August, 1970, diversity and evenness increased considerably with the settlement of juveniles of many species. In the second year diversity and evenness were lowest in winter, when four species of gastropods were subdominant and density was low. During the second year, evenness and diversity fluctuated widely and rapidly, and slowly increased. In the season of recruitment of 1971, three species were subdominant; evenness was moderate and diversity fairly high. Thereafter, density was so low that values of the information function and evenness index based on 1/25 m² samples were invalid. After three and one-half years, evenness and diversity measured by rarefaction still remained low. Diversity measured by the less sensitive in-

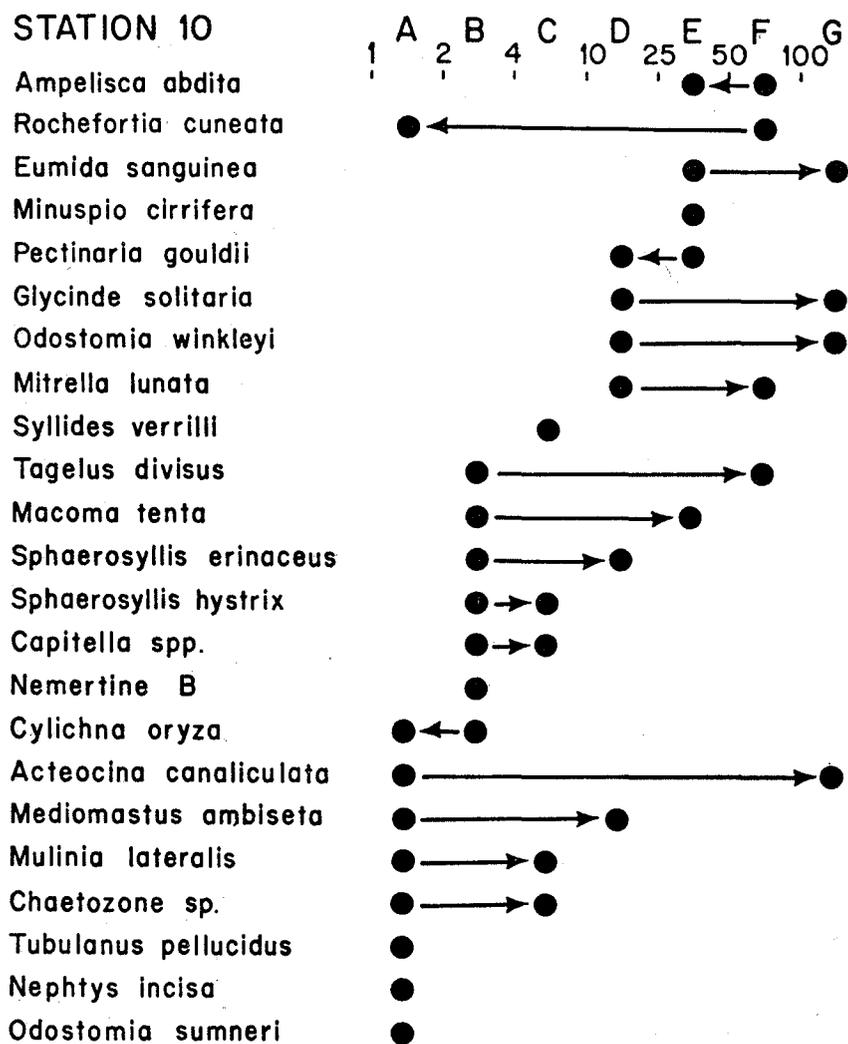


Figure 66. Changes in disparity (greater mean density divided by lesser mean density) between first and second year for species at station 10, upon omission of August, 1970, sample.

formation function would suggest a degree of recovery greater than that indicated by rarefaction curves.

During the first year the abundance of *Capitella* at station 31 depressed diversity and evenness. The fauna without this polychaete was apparently diverse (Fig. 76), but density was very low. Only in June, July, and August, 1970, was the fauna without *Capitella* dense enough to ensure statistical validity. For the first year as a whole, evenness decreased and diversity, after the initial drop, slowly increased. Both fluctuated widely. Evenness and diversity of the fauna without *Capitella* rose in August,

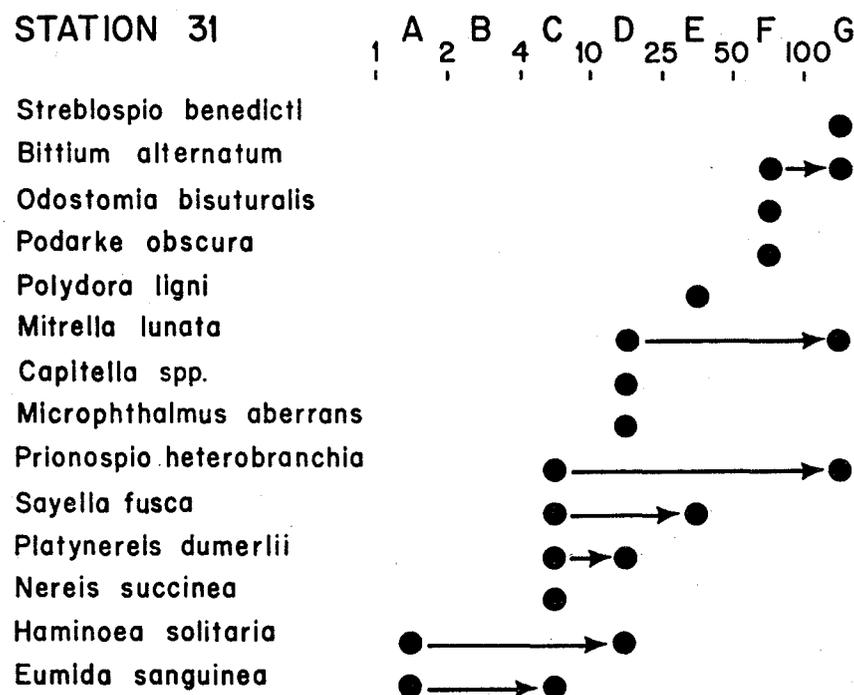


Figure 67. Changes in disparity (greater mean density divided by lesser mean density) between the first and second year for species at station 31, upon omission of August, 1970, sample.

1970. *Capitella* soon crashed; the curves of the rest of the fauna are thereafter essentially those of the whole fauna.

Values of evenness and diversity for the first nine months at station 9 were deceptively high, regardless of index (Figs. 77-79), because density was very low. According to the information function, diversity decreased in the winter of 1969-70. The low value of the information function for April, 1970, partly reflects the increased dominance of *Mediomastus*. In June, 1970, diversity and evenness fell rapidly, but not to the very low values prevalent at station 31. Owing to the dominance of *Mediomastus* diversity according to the information function was least in the following month. Diversity was very variable in the first year. Diversity remained low for about nine months, then rose fairly rapidly in the spring and summer of 1971, and reached moderate values in the winter of 1971-72. Neither diversity nor evenness rose to values prevalent shortly after the spill. Diversity was quite variable in the second year.

Without *Mediomastus*, densities at station 9 were extremely low in the first year, and diversity and evenness were artificially high (Fig. 80). In August, 1970, the rest of the species were fairly evenly represented. During the second year diversity and evenness of the fauna without *Mediomastus* quickly recovered from the depres-

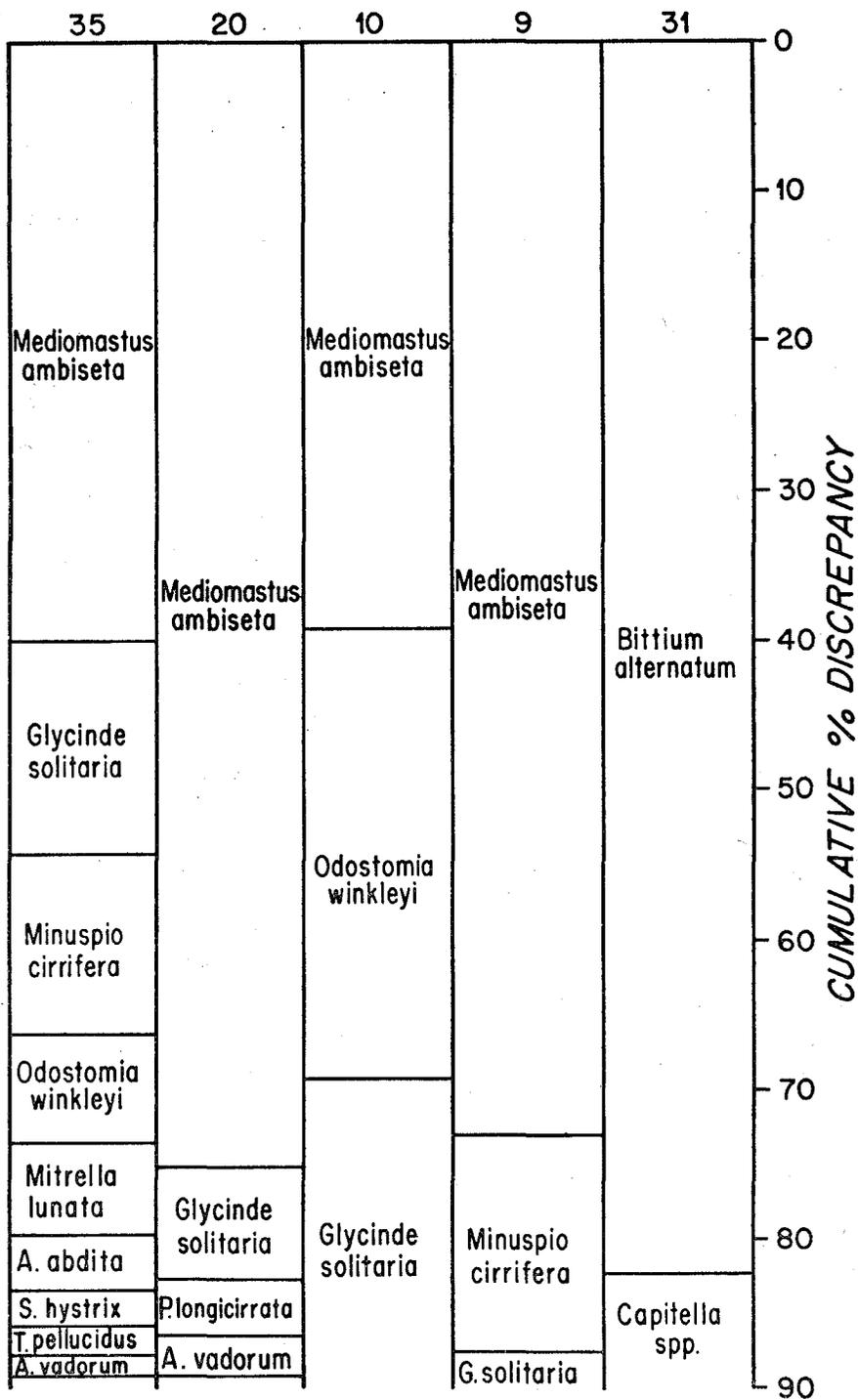


Figure 68. Species which together contributed almost 90% to the discrepancy in mean densities of the first and second years, without August, 1970, samples, at stations 31, 9, 10, 20, and 35.

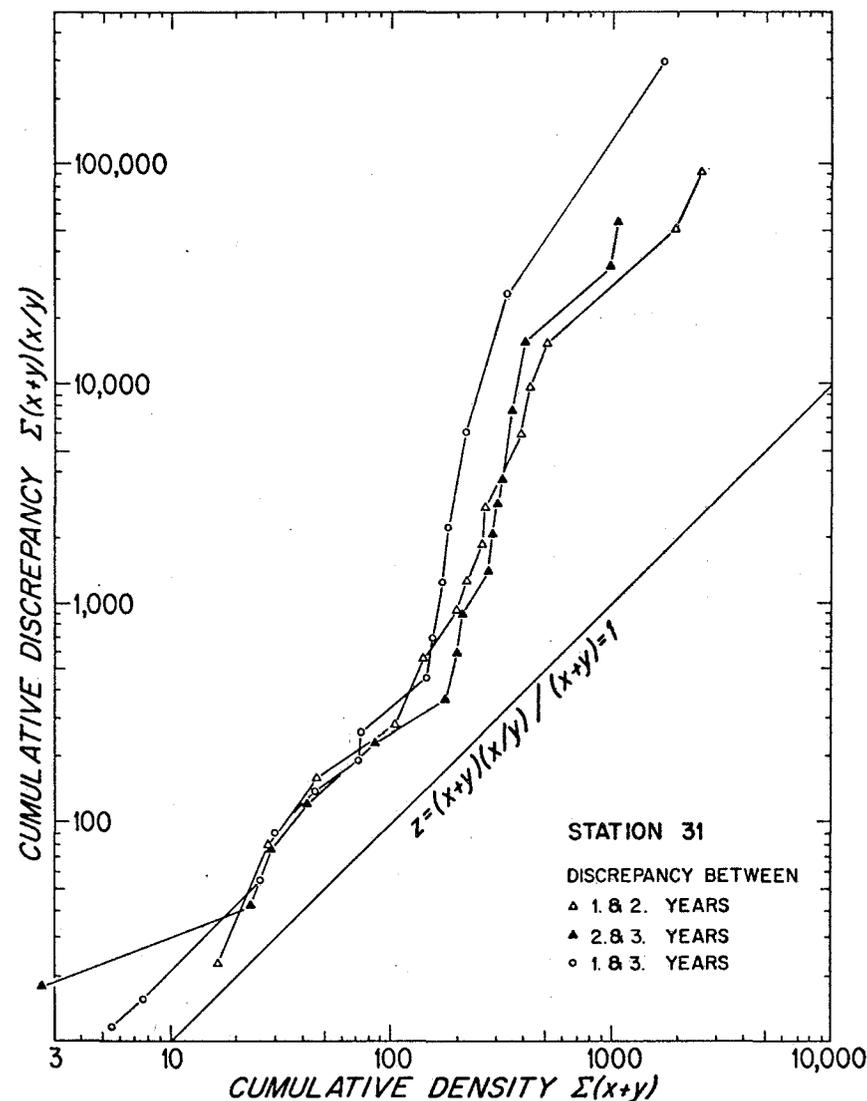


Figure 69. Discrepancies between mean densities of species of first and second, second and third, and first and third years at station 31.

sion of August, 1970, and thereafter were fairly high and rapidly fluctuating. Diversity and evenness fell in the late summer and autumn of 1971, rather than in the winter.

At station 10, density was very low in the first ten months; both evenness and diversity were artificially high (Figs. 81-83). In July, 1970, diversity and evenness decreased abruptly and remained low until August, 1971. Diversity according to

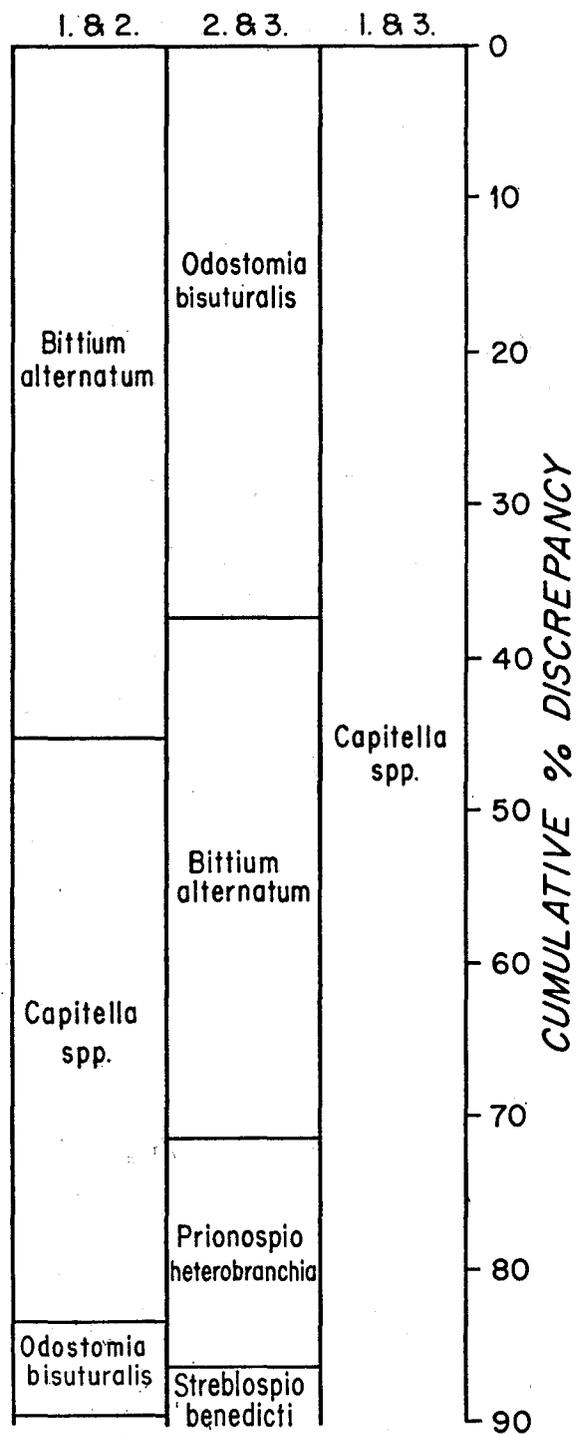


Figure 70. Species which together contributed almost 90% to discrepancy in mean densities of the first and second, second and third, and first and third years at station 31.

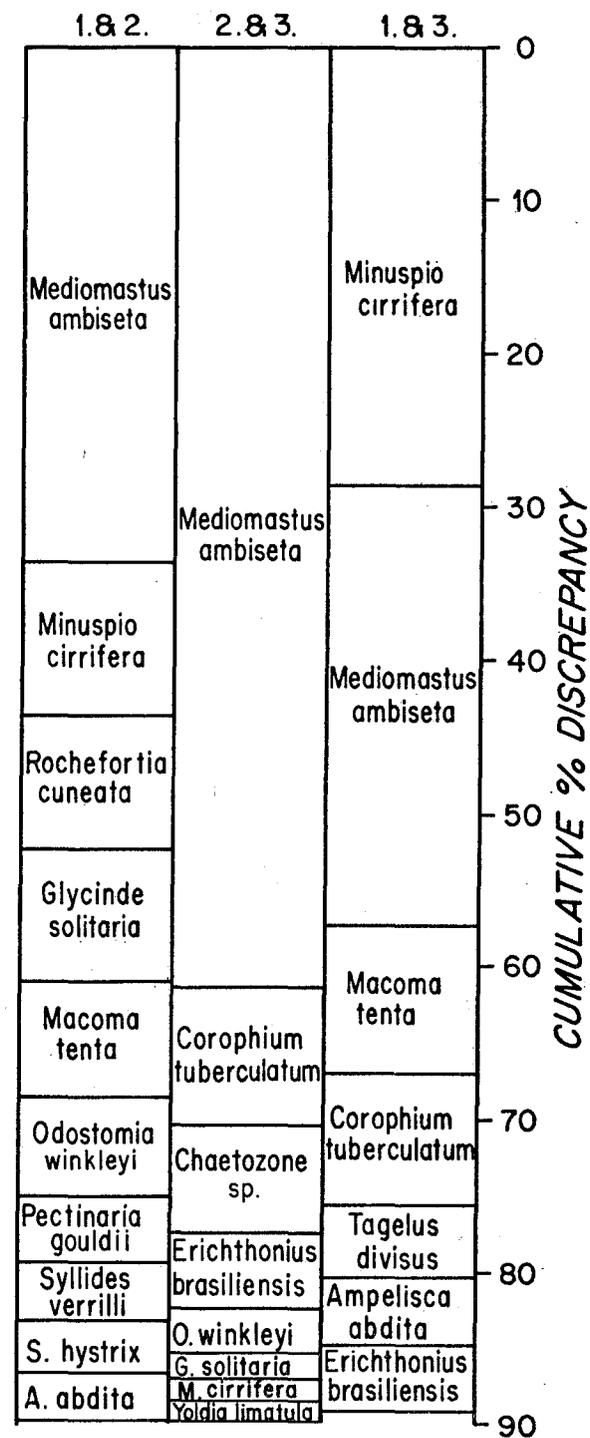


Figure 71. Species which together contributed about 90% to discrepancy in mean densities of the first and second, second and third, and first and third years at station 10.

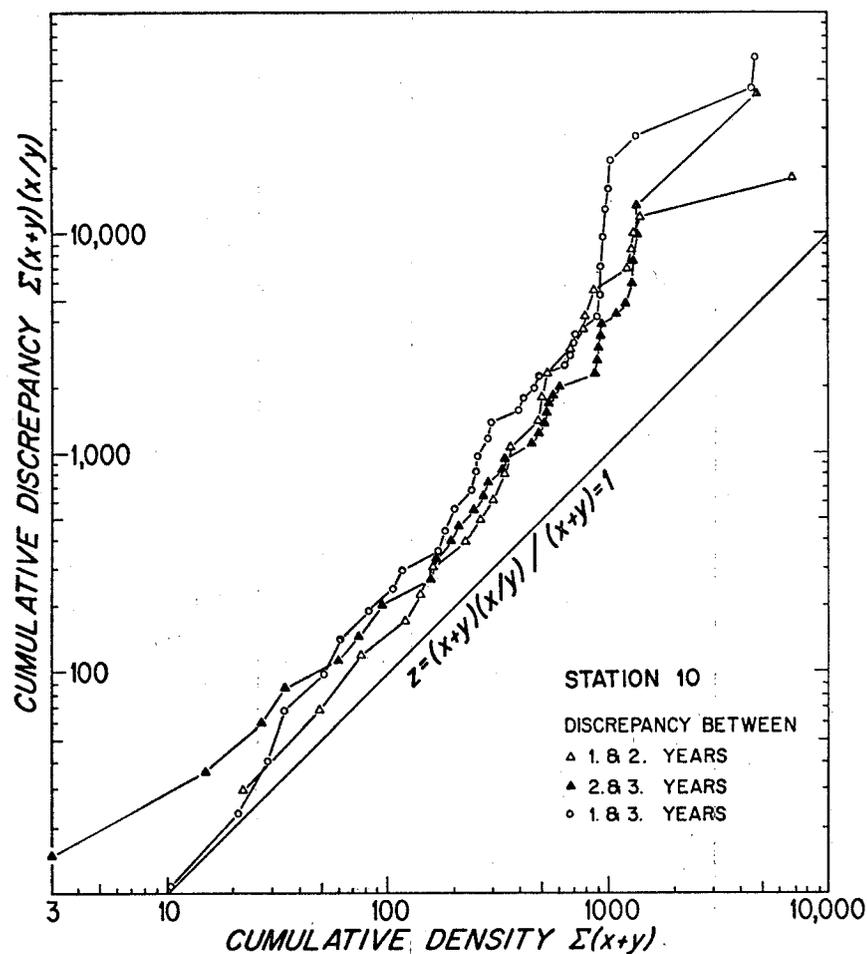


Figure 72. Discrepancies between mean densities of species of first and second, second and third, and first and third years at station 10.

rarefaction fluctuated more here in the first year than at station 9, although the information function suggests lesser fluctuations at station 10. Diversity and evenness perhaps began to recover slightly sooner than at station 9. Fluctuations of diversity and evenness in the second year were of greater magnitude here than at station 9.

Without *Mediomastus* the drop in diversity (Fig. 84) and evenness at station 10 in the autumn and winter of 1969-70 was somewhat more evident. For the next fourteen months diversity of the fauna without this polychaete slowly rose with some fluctuation to fairly high values in June, 1971. Evenness and diversity decreased in August, 1971, but soon rose to fairly high levels. During these fourteen months, fluctuations of diversity and evenness were rapid, but less broad than those of the

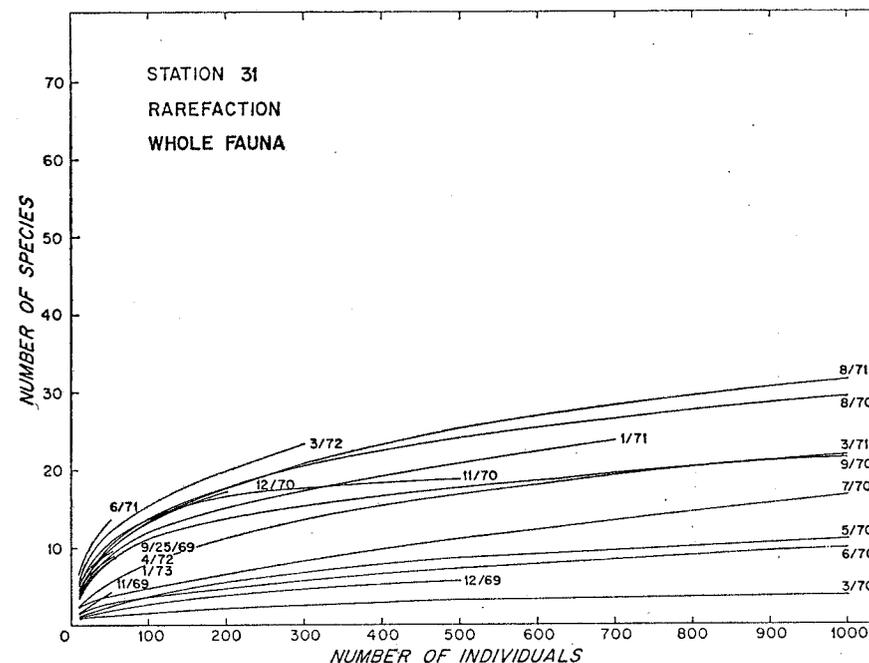


Figure 73. Diversity of the whole fauna at station 31, according to the Hurlbert rarefaction method.

whole fauna. After two and one-half years, values of diversity and evenness had risen above initial levels, but were still fluctuating.

At station 35 diversity was at first fairly high and evenness moderate (Figs. 85-87). Both fluctuated slightly in the earlier months of the first year, but little thereafter. In early and mid-summer of 1970, both diversity and evenness decreased, but soon recovered. According to rarefaction this recovery was complete in little more than a month; the information function suggests that this recovery took six months. In August, 1971, diversity increased.

Without *Mediomastus* diversity at station 35 was higher, especially in the second year (Fig. 88). The autumnal-hibernal decrease in diversity was very slight in the first year, and not clearly evident in the second. Diversity was high in August, 1971. Variations in diversity and evenness were moderate to slight, and seemingly diminished in amplitude with the passage of time.

At station 20 diversity was about as high as that at station 35, but much less variable (Figs. 89, 90). In the first year there was only a slight hibernal-vernal decline in diversity. The decline in August, 1970, was modest. Within a month, according to rarefaction, diversity not only had recovered, but had increased above former levels. According to the information function, recovery of diversity took

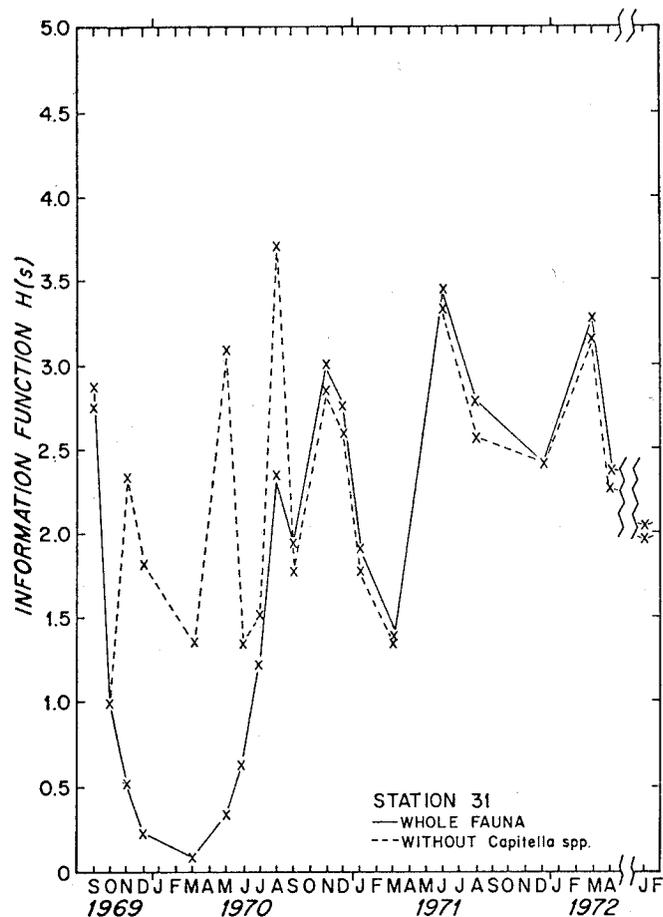


Figure 74. Diversity of the fauna with and without *Capitella* at station 31, according to the Shannon-Wiener information function.

about three months. Evenness (Fig. 91), which also decreased in August, 1970, recovered in about six months.

According to the rarefaction curves (Fig. 92), diversity of the fauna without *Mediomastus* was somewhat more variable than that of the whole fauna at station 20. Diversity and evenness were lowest in the late winter and early spring of 1970, and rose during the following summer and autumn, a year after the spill, to levels higher than those prevalent in the first month.

Relative contributions of species richness and evenness to diversity

Species richness was so low at severely oiled station 31 that only 7 of the 20 samples contained the requisite 20 or more species. Samples that did not qualify included those taken previous to July 1970 when *Capitella* comprised almost the entire

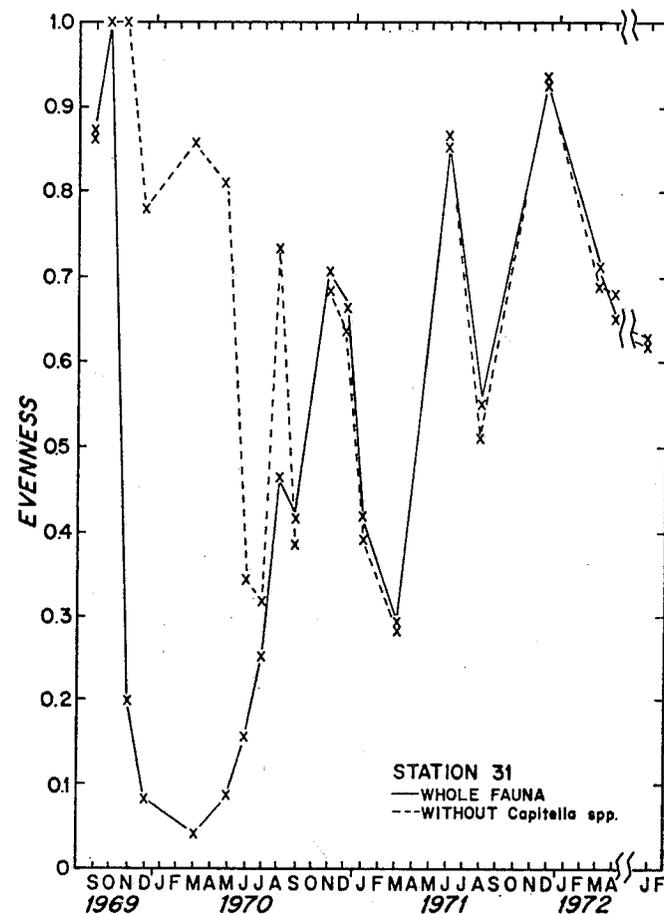


Figure 75. Evenness of the fauna with and without *Capitella* at station 31.

fauna for many months to yield the least equitable samples obtained throughout the study. The seven samples that did qualify were uniformly very low (Figs. 93 and 94) and thus species richness and equitability were also very low. Yet, equitability was the positive constituent raising and, alternatively, species richness was the negative component lowering these diversity rankings. At the opposite end of the spectrum, when highest mean rank diversities were achieved, species richness, with one exception was the enhancing factor and equitability the diminishing component of diversity (Figs. 95, 96, 97, 98, 99, 100, 101 and 102). This one exception was for the ten-month period following the oil spill at intermediately oiled station 9. Benthic densities were at that time sufficiently reduced in the samples that the degree of dominance inherently present could not be realized yielding an artificially high equitability value that, in turn, was the agent for high mean diversity rank for this interval at station 9 (Fig. 95). This feature was also true to a lesser degree for inter-

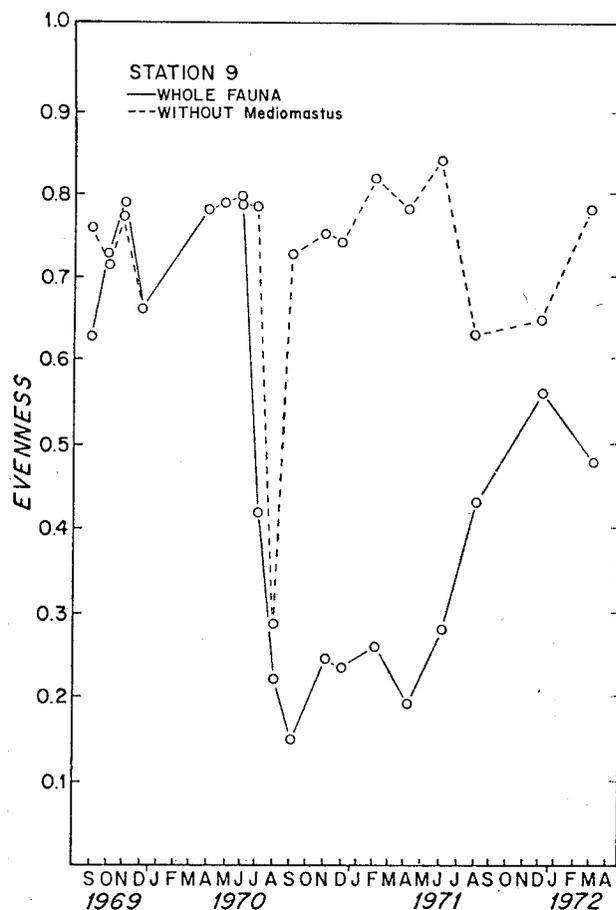


Figure 79. Evenness of the fauna with and without *Mediomastus* at station 9.

of reducing or lowering the mean rank diversity. It persistently comprised most of the fauna at stations 9 and 10 so that the mean diversity ranks for this period were low (Figs. 95 and 97), many ranks below the mean diversity ranks when *Mediomastus* was excluded (Figs. 96 and 98). Thus the overwhelming dominance of *Mediomastus* at this time masked the considerably higher equitability and species richness values in its absence. At stations 20 and 35, *Mediomastus* formed the majority of the fauna only for one or two months. Thus, there was less difference in the mean rank diversities with and without *Mediomastus* (Figs. 99, 100, 101 and 102). If the August 1970 samples were excluded, the rank position for total faunal diversity would be raised by 4.4 ranks at station 20 and 7.5 ranks at station 35.

This analysis indicates that species richness is more important than evenness, the other component of diversity, in the faunal recovery after pollution and is a less variable, more conservative, and more reliable index of recovery.

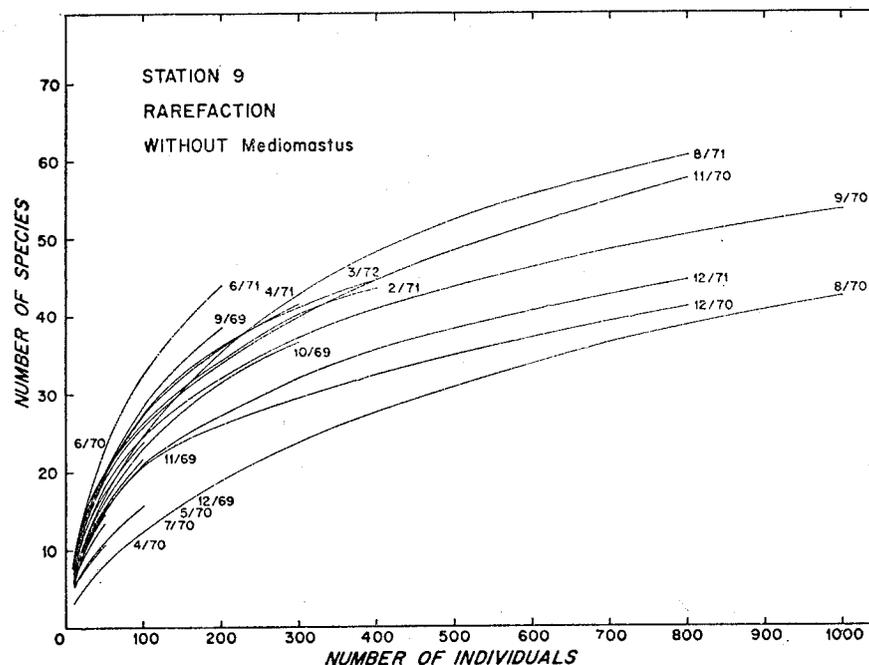


Figure 80. Diversity of the fauna without *Mediomastus* at station 9, according to the Hurlbert rarefaction method.

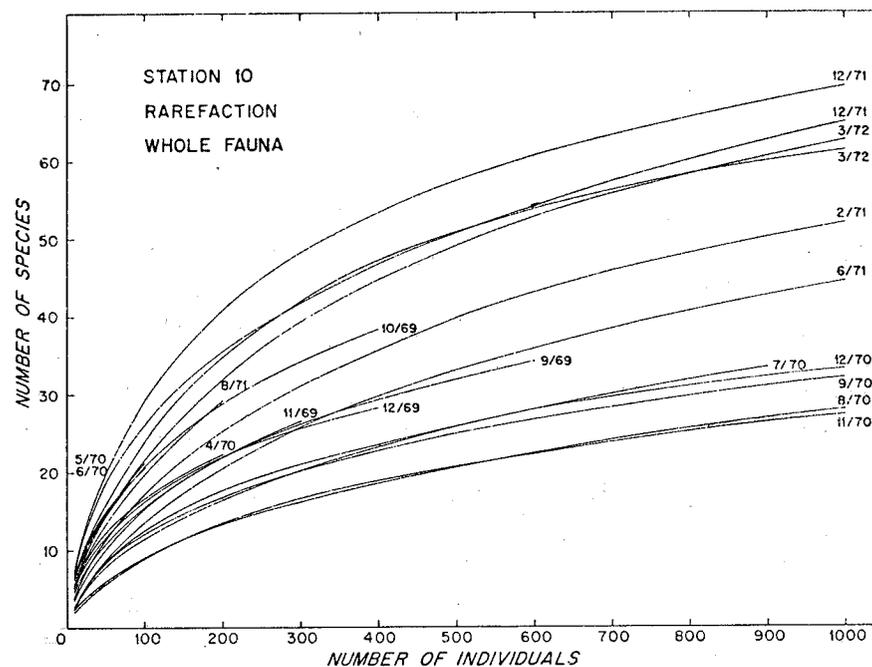


Figure 81. Diversity of the whole fauna at station 10, according to the Hurlbert rarefaction method. Replicate samples taken December, 1971, and March, 1972, were analyzed.

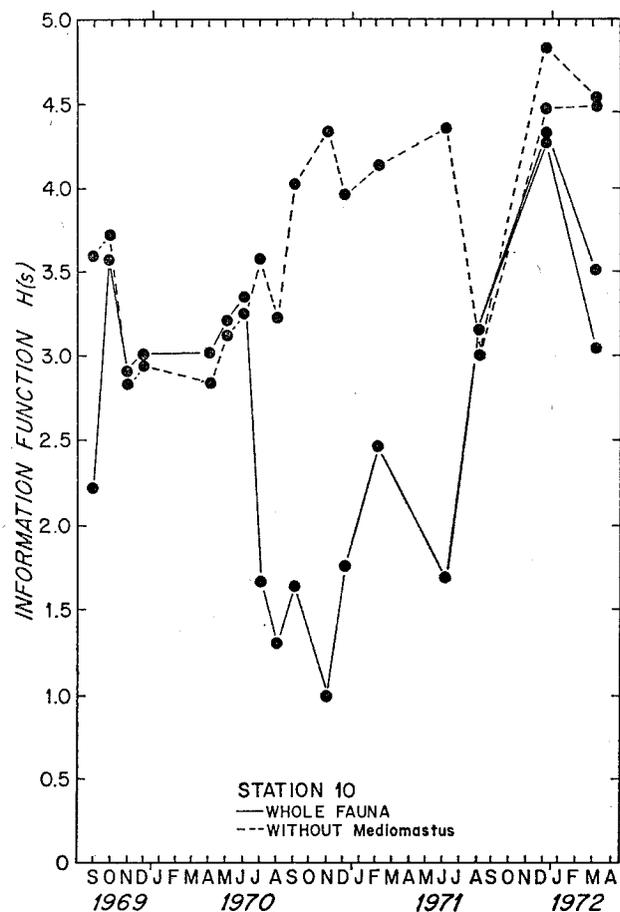


Figure 82. Diversity of the fauna with and without *Mediomastus* at station 10, according to the Shannon-Wiener information function. Bifurcation of lines indicates replicate samples.

Cluster analysis

Samples of the whole fauna at farthest offshore, lightly oiled station 35 were fairly similar among themselves, and unlike samples from other stations. The amphipod fauna here remained normal. Samples cluster by month and season (Fig. 103, cluster C; Fig. 104, cluster D). Samples taken in the winter after the spatfall of August, 1970, however, cluster with those taken in the months just before the bloom of *Mediomastus*, rather than with other winter samples. Without *Mediomastus*, these winter samples cluster with other winter samples (Fig. 105, cluster C; Fig. 105, cluster D). Samples taken during the bloom of *Mediomastus*, in August and September, 1970, aggregate with samples from station 10 (Fig. 103, cluster B; Fig. 104, clusters B, C). Without *Mediomastus*, these samples cluster with those

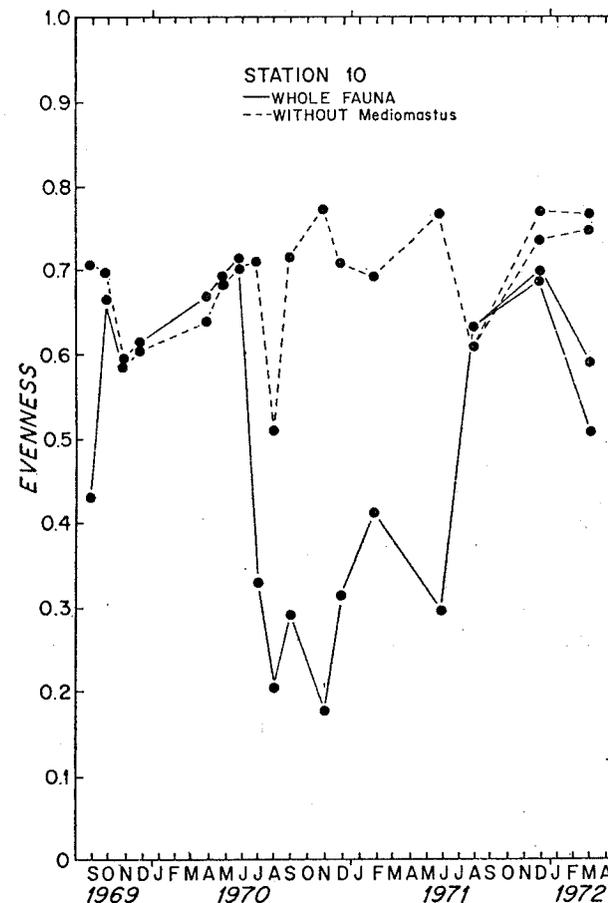


Figure 83. Evenness of the fauna with and without *Mediomastus* at station 10. Bifurcation of lines indicates replicate samples.

of the same or adjacent months of other years at station 35. In these summer months recruitment to the whole fauna is maximal. The fauna at this lightly oiled station underwent normal, modest seasonal changes, and, except for the brief bloom of *Mediomastus*, varied only slightly from year to year.

Offshore stations 5 and 20 were lightly oiled; effects were not patent until a month after the spill. The faunas of these two stations were essentially identical. When compared with those of stations 10 and 35, samples of the fauna with and without *Mediomastus* from station 20 cluster tightly together (Fig. 103, cluster D; Fig. 105, cluster D). The samples do not cluster in any obvious seasonal or successional pattern, except for those of the months of faunal recruitment, which tend to cluster. Without *Mediomastus*, groups of samples from the autumn and winter of

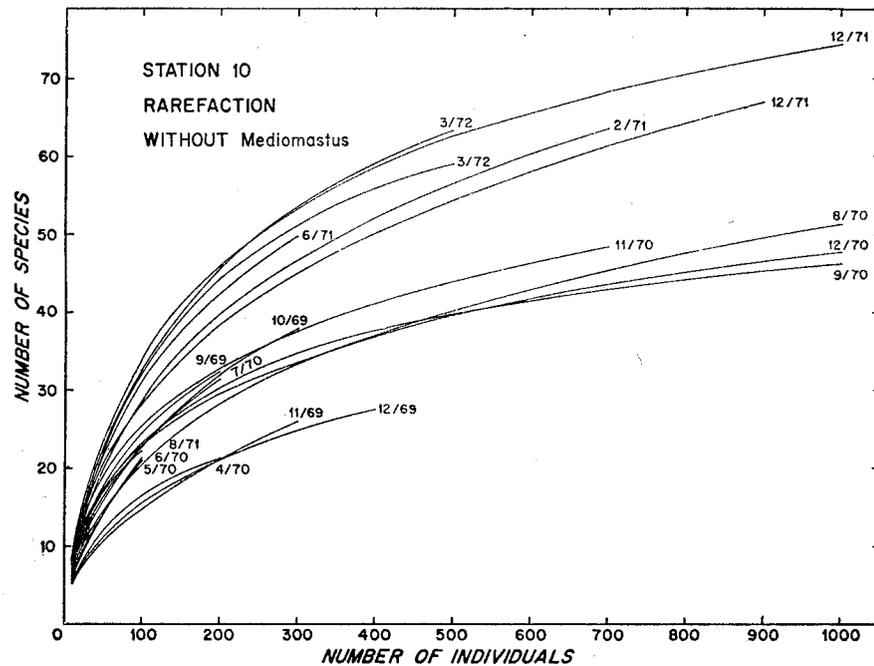


Figure 84. Diversity of the fauna without *Mediomastus* at station 10, according to the Hurlbert rarefaction method. Replicate samples taken December, 1971, and March, 1972, were analyzed.

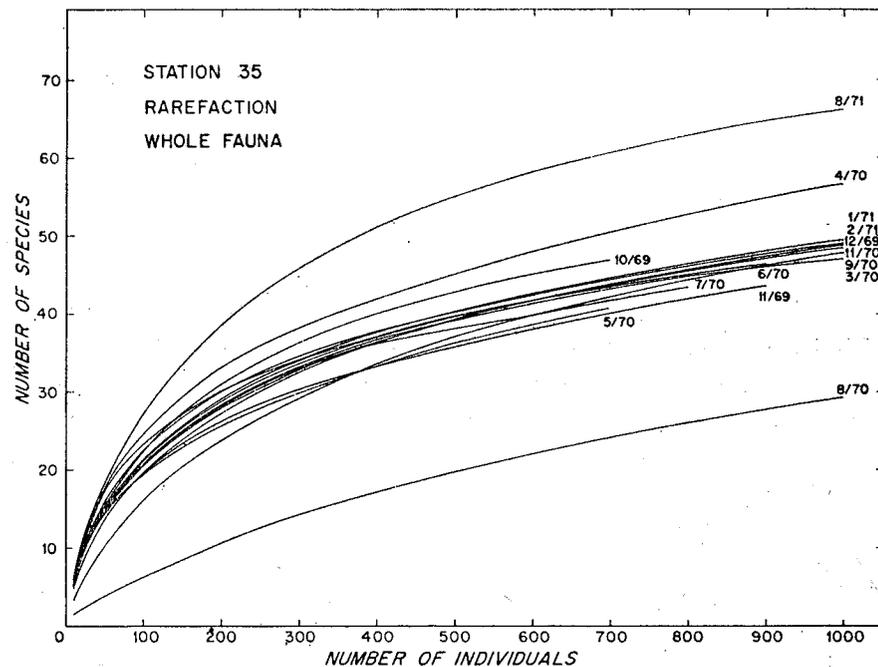


Figure 85. Diversity of the whole fauna at station 35, according to the Hurlbert rarefaction method.

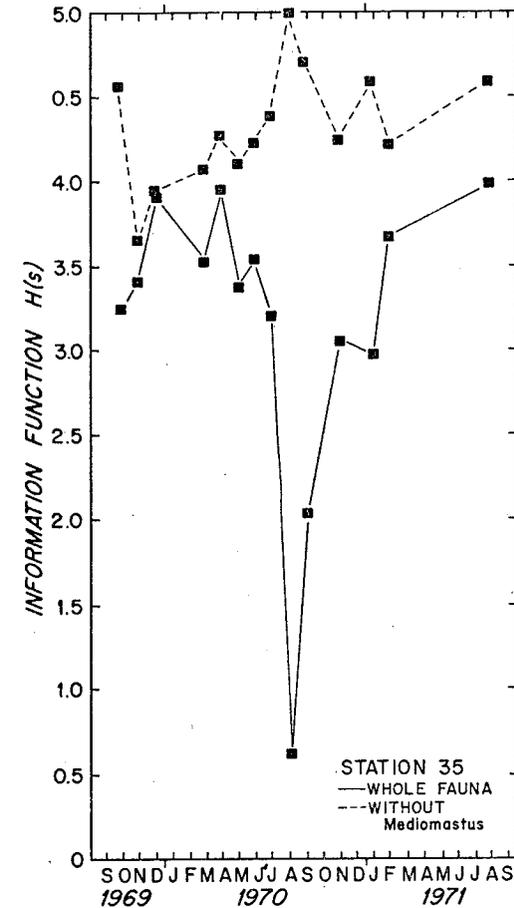


Figure 86. Diversity of the fauna with and without *Mediomastus* at station 35, according to the Shannon-Wiener information function.

successive years differ from each other. When samples from stations 20, 5, 9, and 30 are compared, those of stations 5 and 20 behave as replicates (Fig. 107, cluster C; Fig. 108, cluster C). The clustering of the whole fauna is not obviously by time or station; without *Mediomastus*, however, clusters tend to be tighter and seasonal.

Without *Mediomastus*, the two samples from station 5 with anomalous sediments aggregate with samples from station 9, to which they are similar in fauna and granulometry (Fig. 107, clusters A, B; Fig. 108, cluster A). The whole fauna at station 20 in August, 1970, was similar to summer samples of the same year from stations 9 and 30. Without *Mediomastus*, this August sample was similar to the others from station 20, although seasonal recruitment rendered this sample the least similar of the cluster (Fig. 107, cluster B; Fig. 108, cluster C). At stations 5 and 20 the

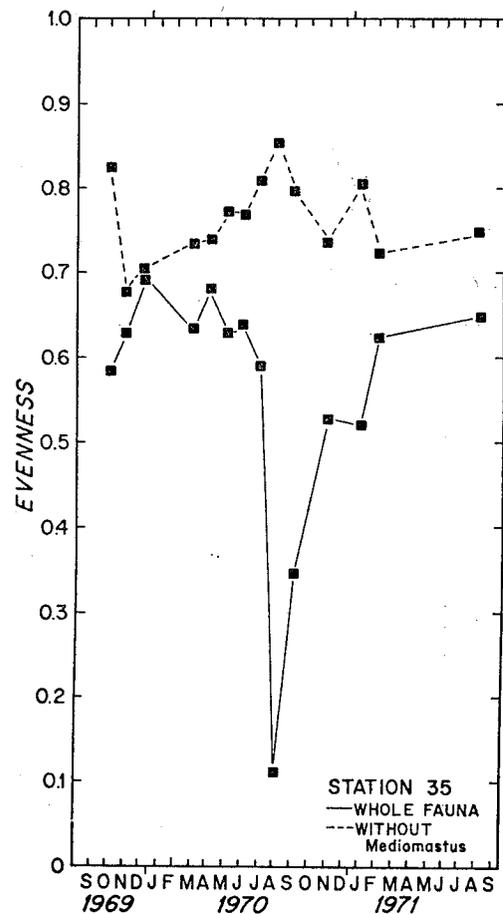


Figure 87. Evenness of the fauna with and without *Mediomastus* at station 35.

fauna was fairly stable in the first ten months, before *Mediomastus* became common. The July, 1970, samples were quite distinct, and marked the transition from the cluster of the initial period to the cluster of the following autumn and winter.

When compared with those of stations 20 and 35, samples from intermediately oiled station 10 form two annual clusters (Fig. 103, clusters A, B). Without *Mediomastus*, samples from this station cluster slightly closer (Fig. 105, cluster A, B). Replicate samples cluster together, with and without *Mediomastus*. The whole fauna of the third year, when diversity was high, was somewhat similar to that of the first year; without *Mediomastus*, the samples of the third year cluster with those of the second. The sample taken in August, 1971, when less-degraded #2 fuel oil reinvaded this station and disrupted the fauna, clusters with those of the first seven post-spill months. Samples of the whole fauna of the second year were all dominated by *Mediomastus*.

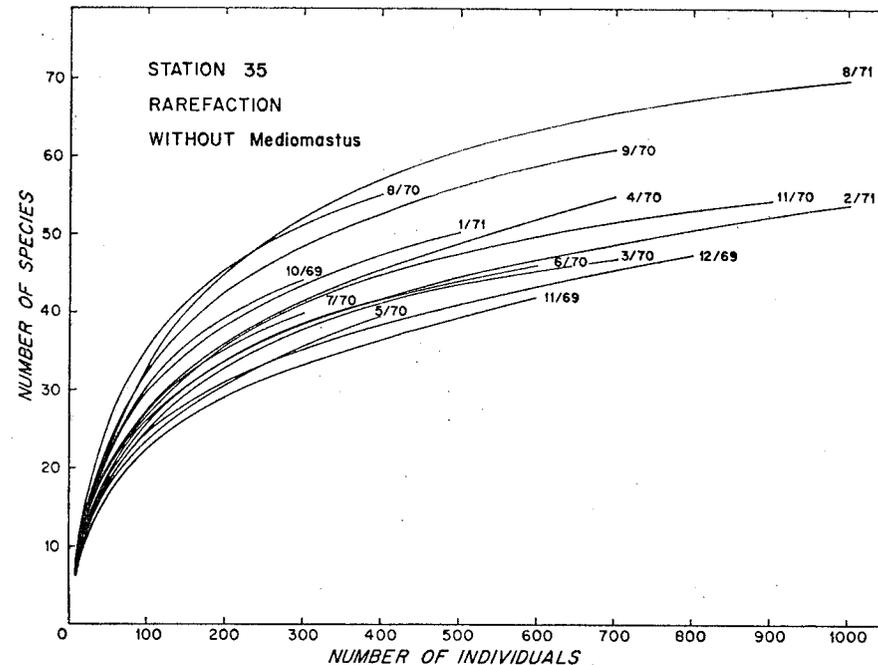


Figure 88. Diversity of the fauna without *Mediomastus* at station 35, according to the Hurlbert rarefaction method.

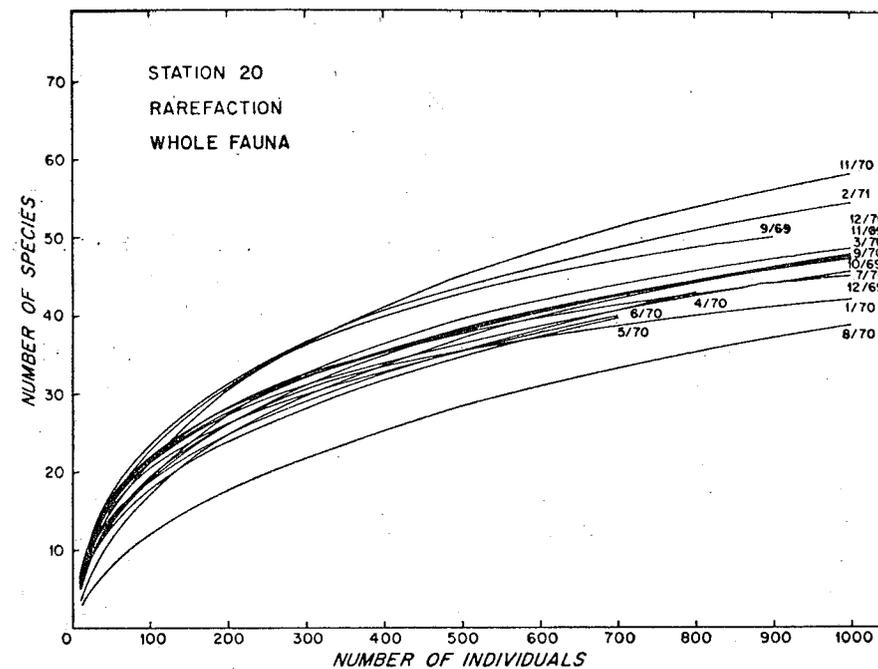


Figure 89. Diversity of the whole fauna at station 20, according to the Hurlbert rarefaction method.

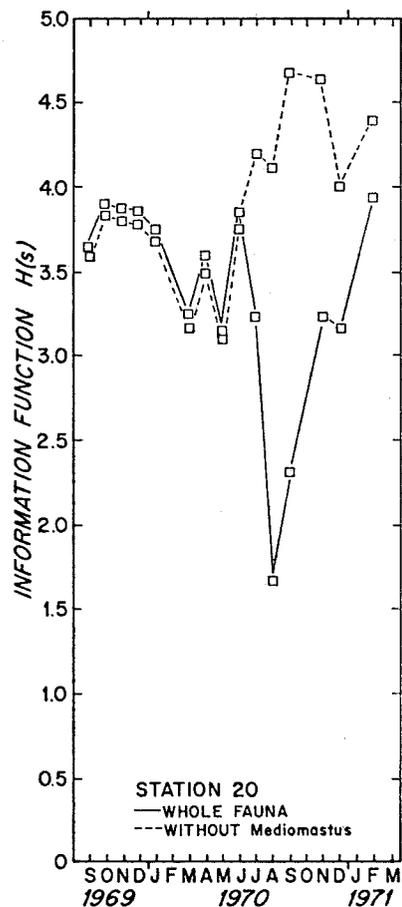


Figure 90. Diversity of the fauna with and without *Mediomastus* at station 20, according to the Shannon-Wiener information function.

When compared with those of stations 5, 20, and 30, samples from intermediately oiled station 9 aggregate rather loosely and temporally in annual clusters (Fig. 107, clusters A, B; Figure 108, clusters A, B). The fauna was scanty in the first ten months after the spill. The abundance of various species, including *Mediomastus ambiseta*, caused the samples from the summer of 1970 to cluster, not with other samples from this station, but with summer samples from other stations. Without *Mediomastus*, the temporal sequence is clearer.

Despite some differences in sediments, faunal samples from stations 9 and 10 cluster together as replicates and in temporal array (Fig. 104, clusters A-D; Fig. 108, clusters G-I). Samples richest in *Mediomastus* cluster, regardless of year. Throughout the three years after the spill, faunal changes at these two stations were

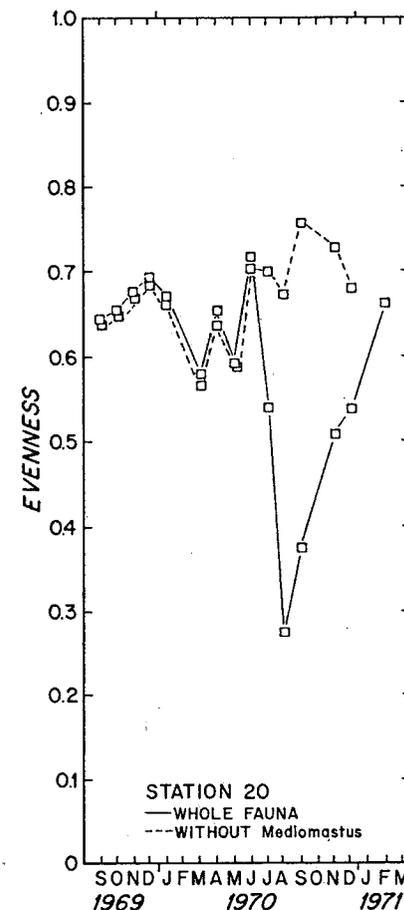


Figure 91. Evenness of the fauna with and without *Mediomastus* at station 20.

large, rapid, synchronous, and successional. When station 10 was re-oiled in August, 1971, the fauna reverted to the condition prevalent in the first seven months following the spill.

Concentrations of oil at station 30 were intermediate, similar to those at stations 9 and 10. The general character of the fauna at station 30 was strongly influenced by grain size; most samples from this nearshore station cluster loosely with those of stations 5 and 20 (Fig. 107, cluster G; Fig. 108, cluster C). Without *Mediomastus*, they cluster more closely with these granulometrically similar stations. The fauna was scanty for ten months after the spill, and underwent large, rapid successional changes. The sample of September, 1970, clusters with samples from the season of recruitment at stations 5 and 20, and with a sample from station 10 taken after the reinvasion of fuel oil (Fig. 109, cluster I).

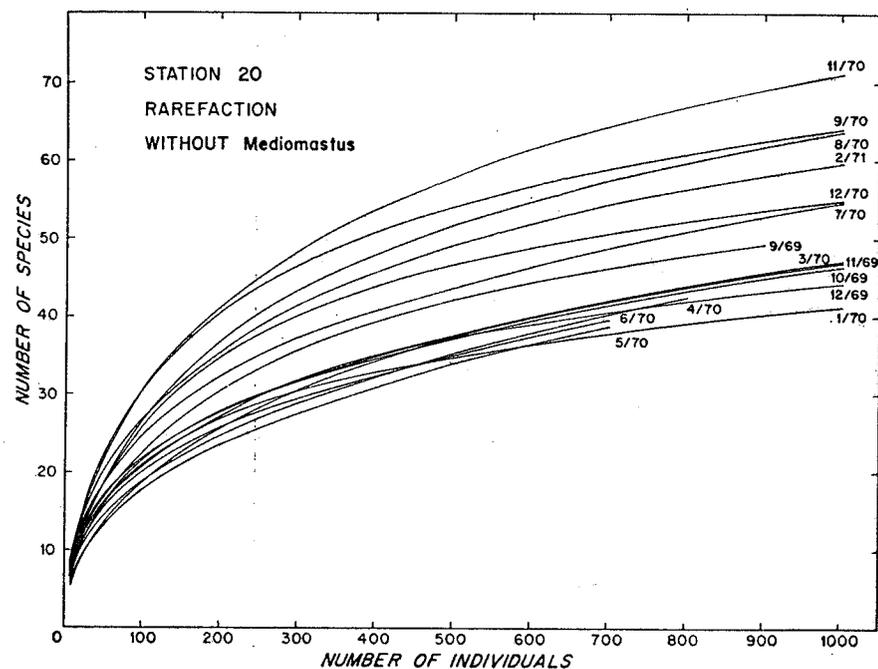
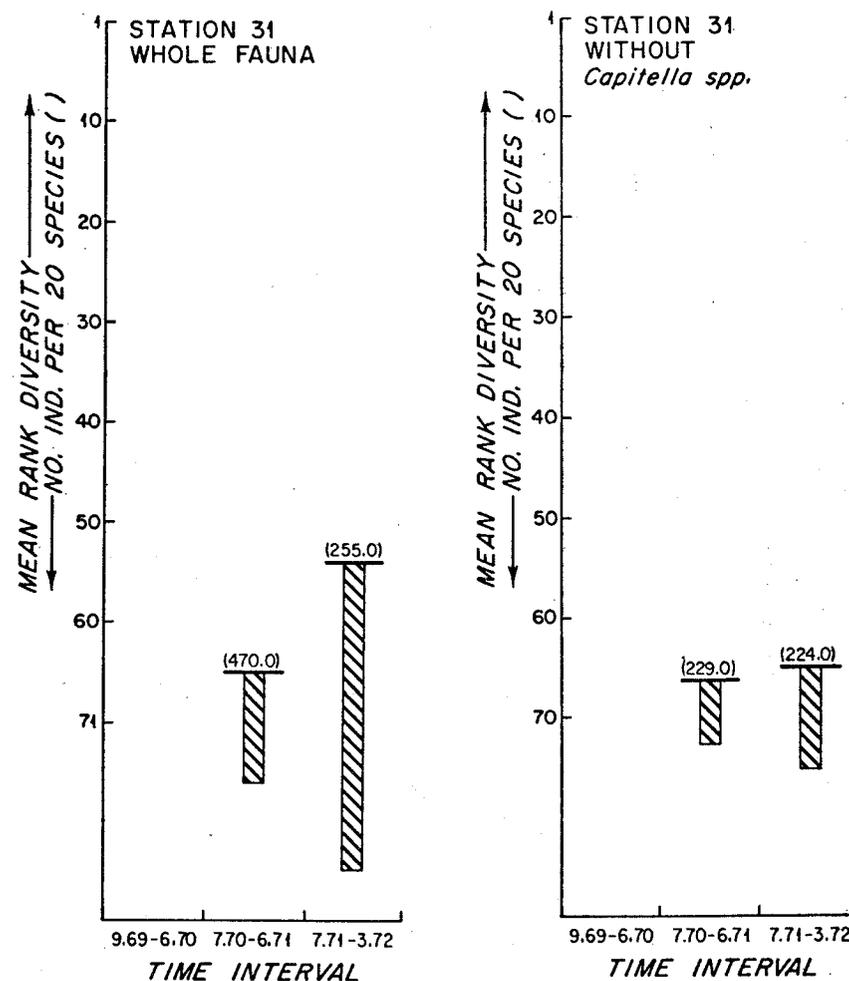
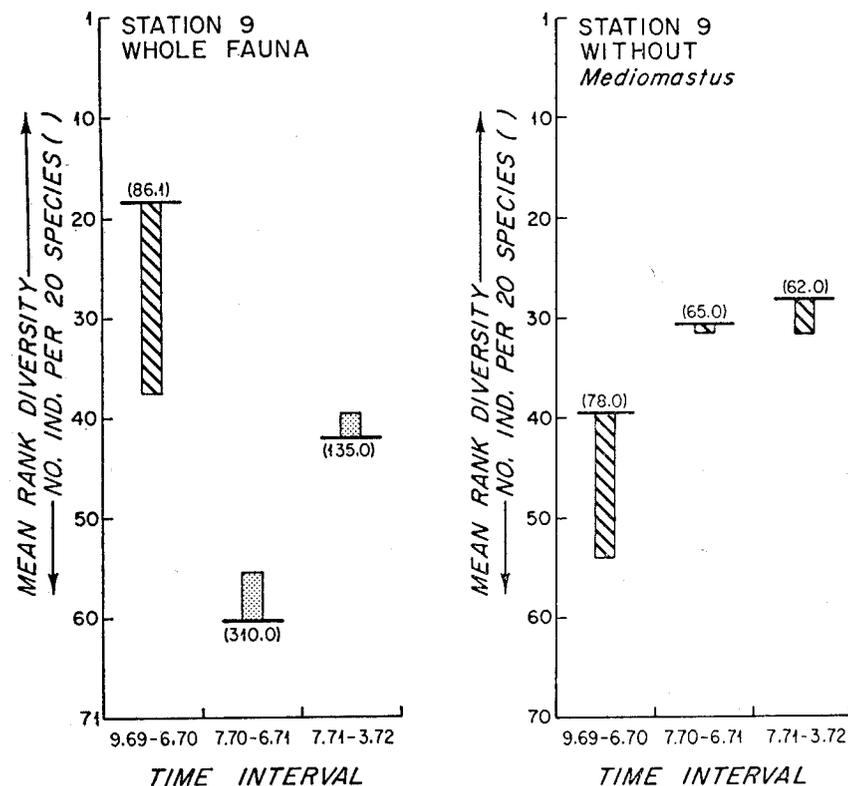


Figure 92. Diversity of the fauna without *Mediomastus* at station 20, according to the Hurlbert rarefaction method.

The difference in water depth and granulometry between subtidal station 31 and intertidal stations II and IV ordinarily would be attended by differences in fauna. The features characteristic of these three stations were the high concentrations of #2 fuel oil, and the opportunistic fauna dominated by *Capitella* spp., *Polydora ligni*, and *Microphthalmus aberrans* during the first year (Grassle & Grassle, 1974, 1976, 1977). Samples from these three stations are scattered among several clusters. Almost all samples taken in the first eleven months, when the fauna was very sparse, cluster by date, although the samples of June and July, 1970, cluster by station (Fig. 109, cluster A). Many samples of the second year cluster together, and tend to cluster by station (Fig. 109, clusters B, E). Replicate samples taken at station IV resemble each other (Fig. 109, cluster E). Samples of the season of recruitment, some of those of the second year, and those of the third year resemble one another (Fig. 108, cluster B). Within this cluster the samples aggregate by station. The sample taken at station II on September 19, 1969, before the populations of *Gemma gemma* had been killed, is not like the other samples taken at any of these three stations, but is somewhat similar to samples from unpolluted Sippewissett Marsh (Fig. 109, clusters C, D). After the heavy settlement of juveniles in the summer of 1970, the fauna underwent successional changes, and by the end of the second year



Figures 93 & 94. The horizontal bars give the mean rank diversity of the total fauna and with the exclusion of the numerically dominant *Capitella* spp. at station 31 for the time intervals shown. Above or below the horizontal bars and in brackets are the corresponding density of animals per 20 species for the mean rank diversity value. The vertical stippled bars extending upward from the horizontal bars mean that species richness is the enhancing component increasing diversity and equitability is the depressing component diminishing diversity. The longer becomes the upward extension the greater is the elevating force of species richness and, correspondingly, the more pronounced is the depressing force of the evenness component to the diversity value. Alternatively, vertical diagonally-lined bars extending downward from the horizontal bars signify that equitability is enhancing constituent and species richness is the reduction or depressive constituent of diversity. The more the downward departure, the greater become the elevating force of equitability and the depressing force of species richness.



Figures 95 & 96. The horizontal bars give the mean rank diversity of the fauna at station 9 with and without *Mediomastus ambiseta* for the time intervals shown. (For rest of legend, see Figures 93 and 94.)

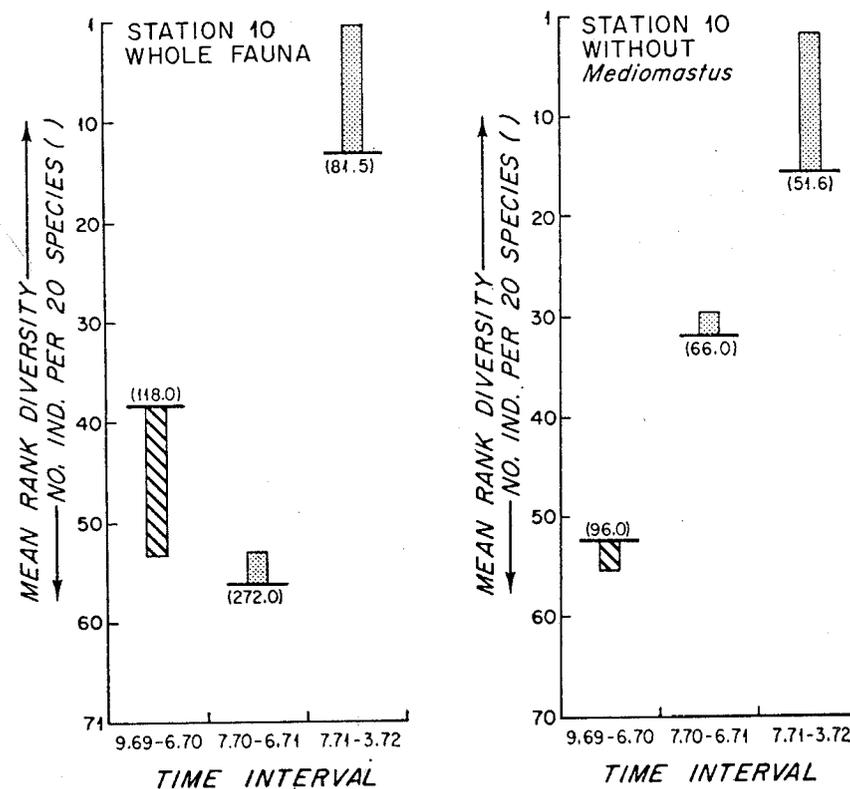
and beginning of the third year after the spill it had not yet attained the level of stability prevalent at lightly oiled station 35. The fauna at these severely oiled stations had not recovered.

Samples from the unoiled control station in Sippewissett Marsh cluster tightly together, and show little resemblance to samples from Wild Harbor River (Fig. 108, cluster D). Replicate samples cluster together, and, as usual, samples taken in the summer are not closely similar to those taken in other seasons. Faunal changes were modest and seasonal.

3. Discussion

Oil pollution

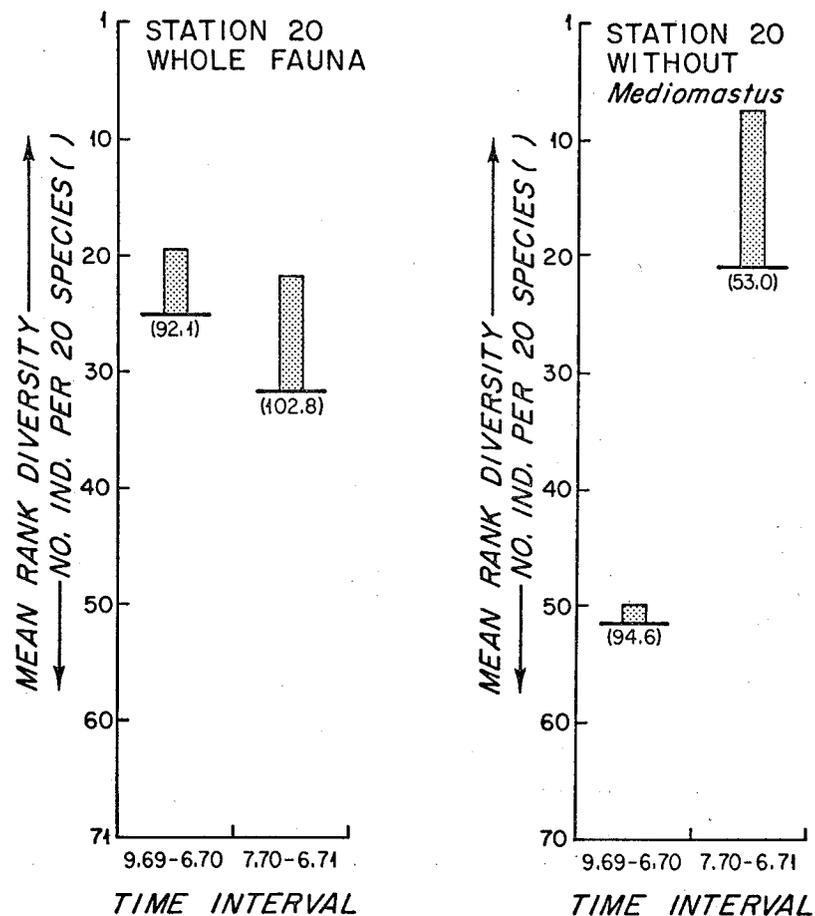
Analyses of hydrocarbons in the sediments showed that #2 fuel oil spilled by the *Florida* invaded Wild Harbor River and nearby offshore areas, and established a gradient in severity of pollution from most severe in the river to least severe at the



Figures 97 & 98. The horizontal bars give the mean rank diversity of the fauna at station 10 with and without *Mediomastus ambiseta* for the time intervals shown. (For rest of legend, see Figures 93 & 94.)

most distant offshore stations. Severity of pollution was manifest in the original concentrations of oil and in the rates of degradation of the various components of the oil. Almost every sample contained hydrocarbons identified by the ratio of adjacent homologues as the #2 fuel oil spilled by the *Florida*. Concentrations of hydrocarbons were high for at least five years in the peat and mud of the intertidal and subtidal zones of Wild Harbor River, less at nearshore stations, and least and ephemeral at the more distant offshore stations. After the spill, oil spread seaward in pulses from the heavily oiled inshore areas; one of these waves reached station 10 in August, 1971.

Biodegradation and dissolution were the chief modes of degradation of the oil. Bacterial action was delayed for several months at the most heavily oiled station. Biodegradation began sooner at intermediately oiled stations. The fact that readily degraded *n*-alkanes persisted at all stations for at least two years suggests that bacterial seeding may not be effective in reducing oil residues in polluted sediments.



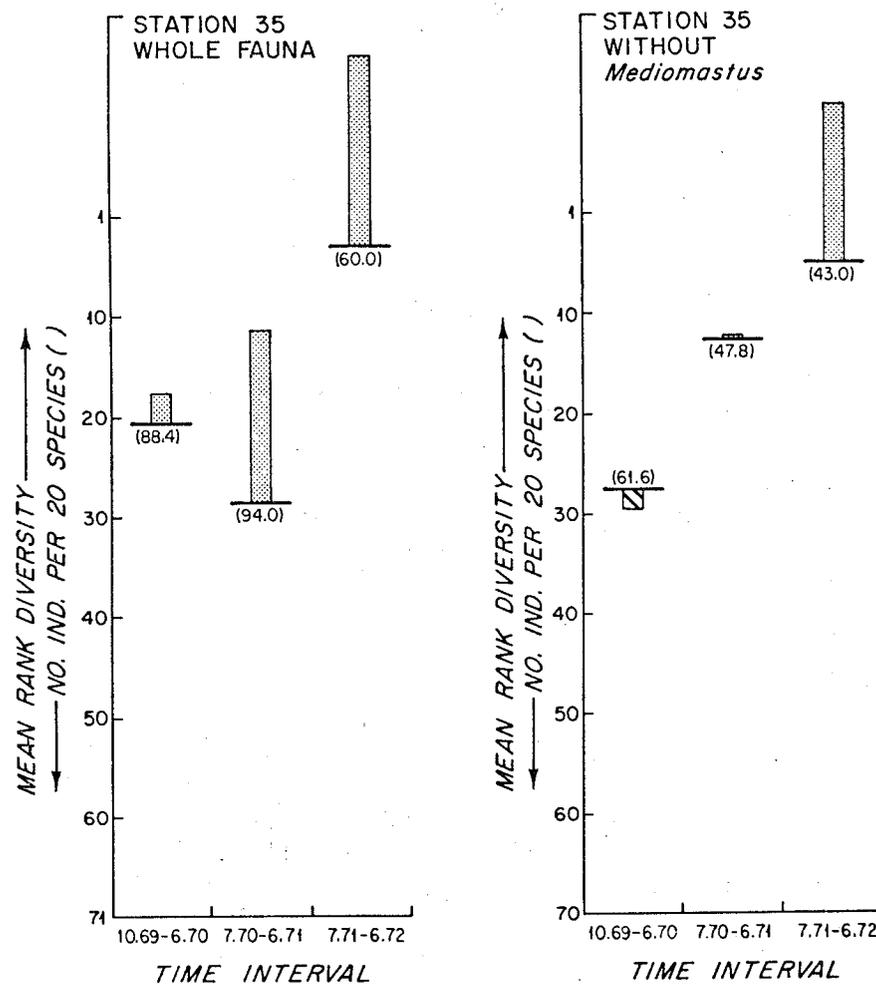
Figures 99 & 100. The horizontal bars give the mean rank diversity of the fauna at station 20 with and without *Mediomastus ambiseta* for the time intervals shown. (For rest of legend, see Figures 93 & 94.)

Constituents of low boiling point attenuated slowly at the heavily oiled sites and were still detectable after two years at intermediately and lightly oiled stations.

Mortality

Mass mortality of many kinds of animals supervened within hours after the spill. The extent and rate of mortality was highest at the most severely oiled stations, and least at the lightly oiled stations.

Amphipod crustaceans of the family Ampeliscidae are very common members of the shallow water infauna of New England (Mills, 1963, 1964, 1965, 1967a, b; Sanders, 1956, 1958). *Ampelisca vadorum*, *A. abdita*, *A. verrilli*, and *Byblis serrata* were found alive in the sandy substratum of Buzzards Bay. Recruits ordinarily swim



Figures 101 & 102. The horizontal bars give the mean rank diversity of the fauna at station 35 with and without *Mediomastus ambiseta* for the time intervals shown. (For rest of legend, see Figures 93 & 94.)

into an area from elsewhere and, in favorable conditions, build tubes in the sediment and persist. In the presence of pollutant fuel oil, however, these amphipods die. After the *Esso Essen* spill of crude oil in South Africa in 1968, amphipods in the intertidal and subtidal zones suffered severe mortality, whereas other members of the megafauna survived (Stander and Venter, 1968). Oil spilled by the *Amoco Cadiz* off Brittany in 1978 (Fig. 110) penetrated the bottom sediments and killed immense numbers of the trophically important ampeliscid amphipods (Cabioc, Davin, and Gentil, 1978). In West Falmouth, amphipod mortality was greatest and

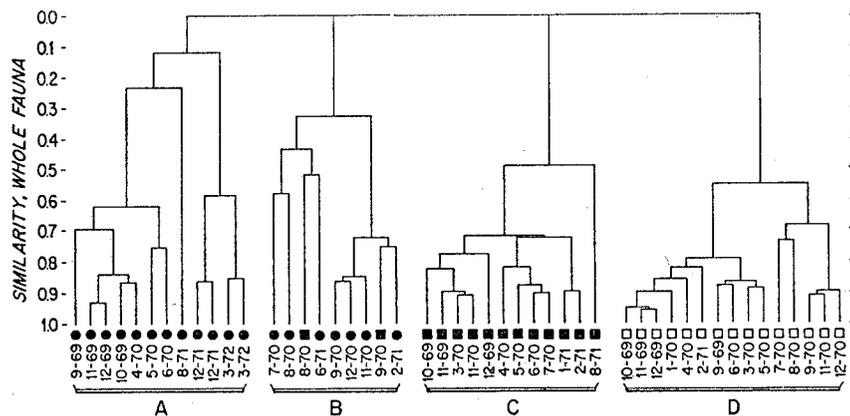


Figure 103. Samples of the whole fauna from stations 10 (●), 35 (■), and 20 (□) clustered by normalized expected species shared.

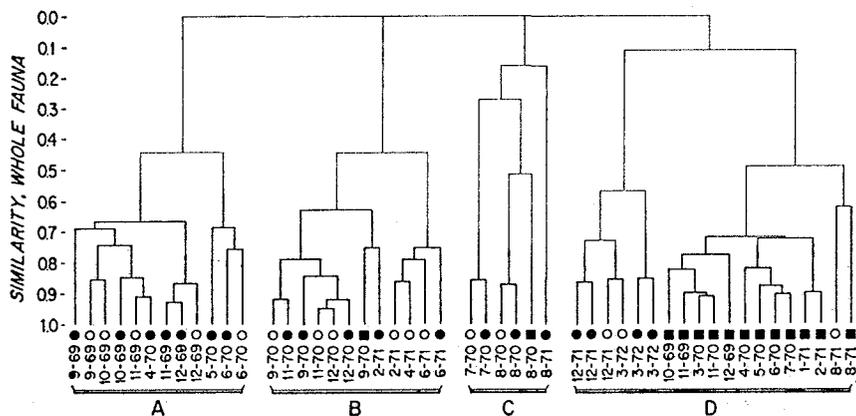


Figure 104. Samples of the whole fauna from stations 9 (○), 10 (●), and 35 (■) clustered by normalized expected species shared.

of longest duration at the most heavily oiled stations, and successively less severe and of shorter duration at less heavily oiled stations.

The Falmouth shellfish warden reported the mortality in 1970 of 769 bushels of soft-shelled clams, 1135 bushels of native seed clams, and all seed and parent stocks of clams transplanted in that year in Wild Harbor River (Souza, 1970). He set the value of these animals at \$27,573. A few of the shellfishing areas closed after the Florida spill were opened in 1973, but the catch was below former levels (Souza, 1973).

Analysis of variance and covariance of faunal densities at stations 9, 10, 20, and 35 showed that in the ten months following the first season of recruitment after the

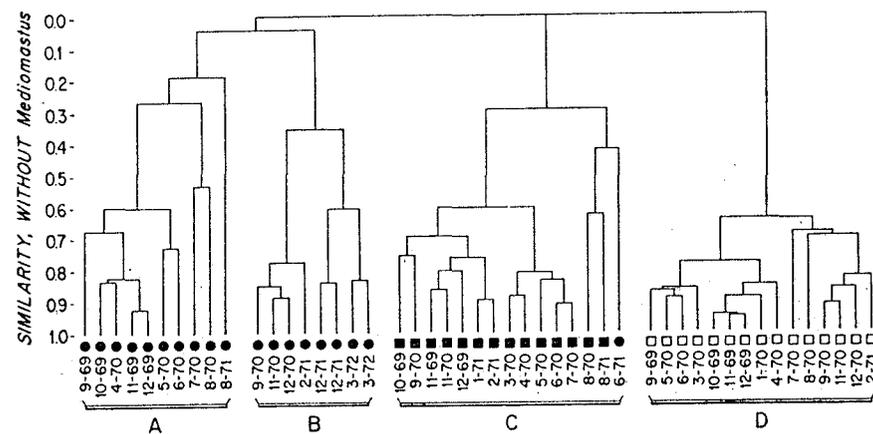


Figure 105. Samples of the fauna without *Mediomastus* from stations 10 (●), 35 (■), and 20 (□) clustered by normalized expected species shared.

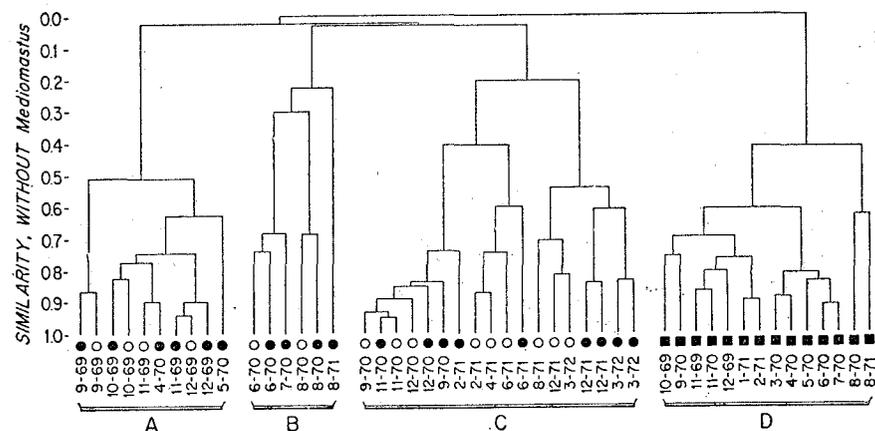


Figure 106. Samples of the fauna without *Mediomastus* from stations 9 (○), 10 (●), and 35 (■) clustered by normalized expected species shared.

spill the decline of the fauna without the extremely abundant *Mediomastus ambiseta* was moderate at the intermediately oiled stations 9 (-199) and 10 (-343), slight at lightly oiled station 20 (-54). At station 35, also lightly oiled, faunal density increased (+83). Mortality of *Mediomastus* was very high at station 10 in this same period, and less but still great at the other three stations.

The high mortality in Wild Harbor River in all probability had adverse effects on the habitability of the substratum. Infauna, especially deposit feeders, and prowling predators modify the substratum by plowing, burrowing, feeding, excreting, and binding grains together (Rhoads, 1963, 1967). Their activities loosen the sediment,

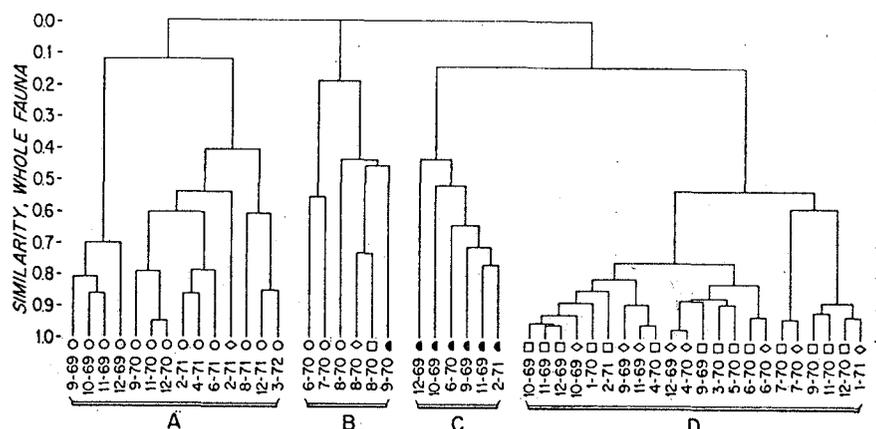


Figure 107. Samples of the whole fauna from stations 9 (○), 30 (▲), 20 (□), and 5 (◇) clustered by normalized expected species shared.

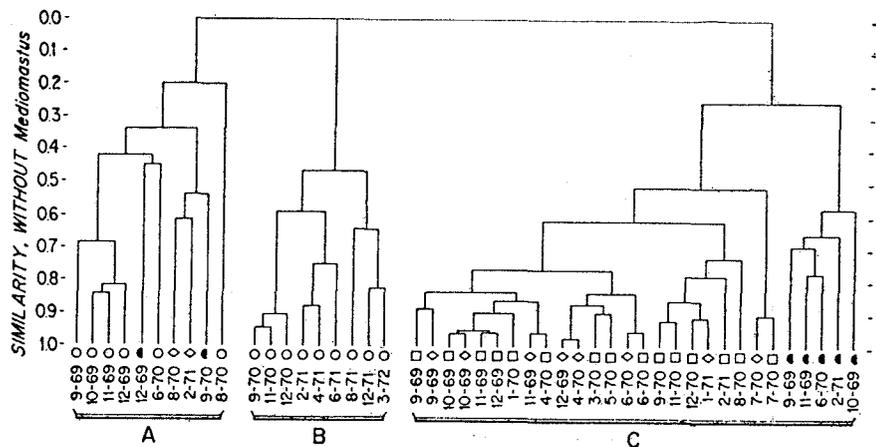


Figure 108. Samples of the fauna without *Mediomastus* from stations 9 (○), 30 (▲), 20 (□), and 5 (◇) clustered by normalized expected species shared.

allowing penetration of oxygenated water to depths of six centimeters (Rhoads and Young, 1970). The mass mortality of the benthic biota brought bioturbation and oxygenation to an end. For several weeks after the spill, the sediments at stations 31 and 30 were black and anoxic. At Station 31 hydrogen sulfide was obviously present. Throughout the study, anaerobic conditions prevailed at station 31, while the sand at offshore station 35 was light in color, apparently well oxygenated.

Faunal stability

When the physical and biological parameters vary slightly and predictably from year to year, the fauna is diverse and relatively stable in numbers and composition.

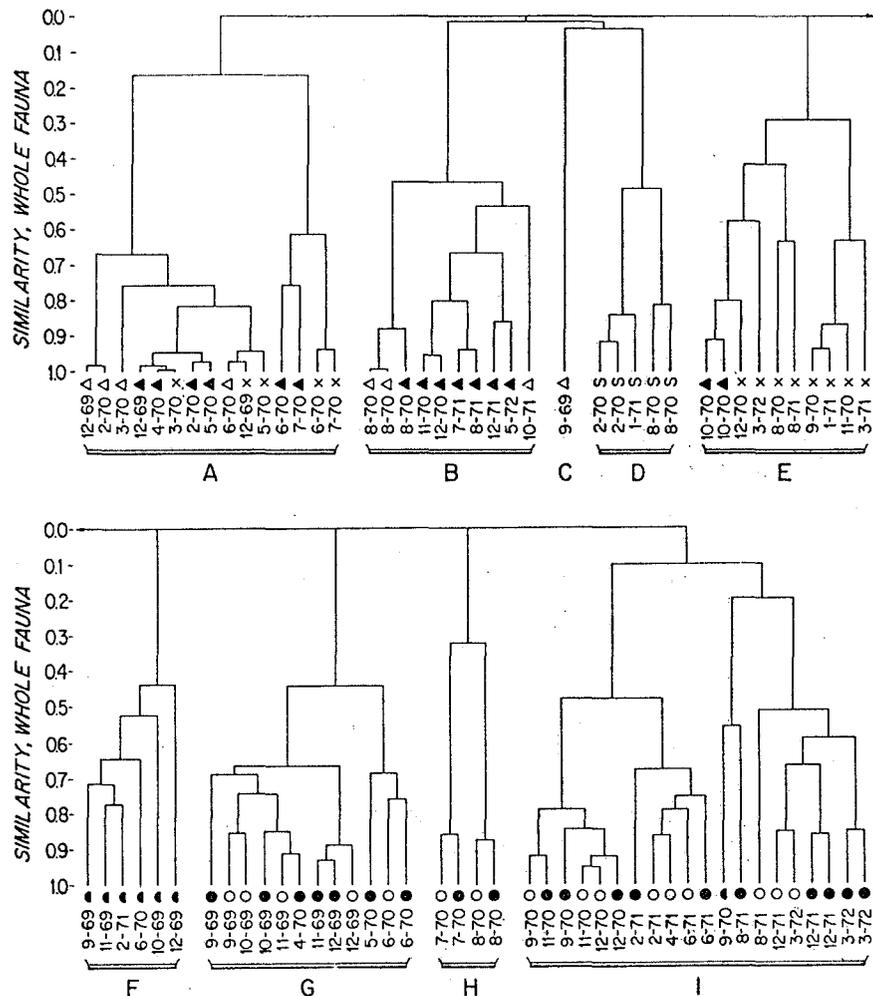


Figure 109. Samples of the whole fauna from stations II (△), IV (▲), 31 (X), 9 (○), and 10 (●), and Sippewissett Marsh (S) clustered by normalized expected species shared.

Whenever some environmental parameter, or exotic influence, exceeds the normal range of variation or rate of change, the fauna suffers dislocation or stress or severe mortality. As a result of this stress, the fauna is less diverse and undergoes successional changes. In the first stage of succession, opportunists dominate the fauna, and density is quite variable. As succession progresses, density and faunal composition become more stable. During succession there may be an ephemeral phase of high diversity when the environment is still undersaturated (the non-interactive phase of Simberloff and Wilson, 1969). This short-lived diversity is not the diversity that develops on an evolutionary time scale. In a stable shallow water environment,

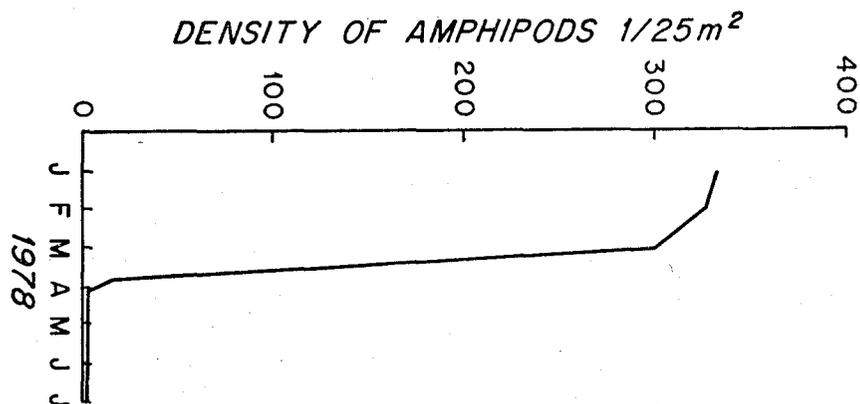


Figure 110. Reduction in density of ampeliscid amphipods in the aftermath of the AMOCO CADIZ oil spill off Brittany, France in 1978 (modified from Cabioch, Dauvin, and Gentil, 1978).

a characteristic community becomes established (Grassle and Sanders, 1973). Such is the *Nephtys-Nucula* community in the muds of south-central Buzzards Bay, which has changed little in almost two decades. Pearson and Rosenberg (1978) have reviewed the manifold changes of faunas in response to abruptly changed levels of organic matter, including petroleum.

Faunal changes which resulted from the *Florida* oil spill are considered under three headings: first, changes in density, number of species, diversity, and evenness; second, changes in faunal composition; and third, the seasonal or successional character of these compositional changes. The analyses concur in showing that faunal changes were most severe in degree and character at the most heavily oiled stations, and least severe at the lightly oiled stations.

At stations II, IV, and 31, density and numbers of species showed broad and rapid changes. Average density of the fauna without *Capitella* was lowest and most variable at these stations throughout the three-year sampling period. This variability decreased with the passage of time. Opportunistic *Capitella* increased explosively to occupy the denuded substratum in vast numbers, then within a few months crashed. By the end of the sampling period, densities and numbers of species had not risen to the initial levels. The fauna at station 31 underwent sharp, frequent fluctuations in diversity for at least three years. The very low diversity at this station was due to the small number of species and low evenness.

At intermediately oiled nearshore subtidal stations 9 and 10, nearly synchronous fluctuations in density and number of species were rapid and initially almost as broad as those at the more heavily oiled stations. Fluctuations began to lessen in amplitude during the second year, but still had not stabilized by the end of two and one-half years. At these stations *Mediomastus ambiseta* monopolized the bottom in

the second year, and declined in later years. Reinvasion of station 10 by fuel oil in August, 1971, prevented the surge of numbers that can occur on biologically unsaturated substrata during the season of recruitment. Density of the fauna without *Mediomastus* at these stations was low and only slightly variable in the first eleven months, more variable in the second year, and higher and less variable thereafter. At these two nearshore stations changes in diversity were also nearly synchronous. During the first ten months after the spill, density was so low that diversity and evenness were deceptively high. In the second year diversity and evenness were low. After early to mid-summer of 1971 diversity and evenness were high. Diversity and evenness of the fauna without *Mediomastus* were low in the first year and less variable than those of the whole fauna. After the first year, species richness raised diversity at stations 9 and 10, but recovery of evenness and diversity was slow at these two stations, slower at station 9.

At lightly oiled stations 20 and 35 variability in density and numbers of species was relatively slight, with and without *Mediomastus*. After a brief surge of *Mediomastus* in August, 1970, density and numbers of species increased, and soon stabilized. At station 35 diversity and evenness were generally high and fairly uniform. Values decreased in the summer of 1970, when *Mediomastus* was dominant, but increased soon thereafter, and became stable. At station 20 diversity and evenness of the fauna with and without *Mediomastus* were usually fairly high and uniform. The whole fauna here was slightly more diverse than that at station 35, but the fauna without *Mediomastus* at station 20 was usually less diverse. Diversity and evenness decreased during the season of recruitment of 1970. At station 20 *Mediomastus* declined soon after August, 1970, and diversity and evenness recovered. Species richness raised diversity after the first year at stations 20 and 35.

At many stations, density, number of species, diversity, and evenness declined slightly in the winter or early spring. This decline was perhaps due to the death of short-lived animals during the colder months. During the breeding season, the few remaining animals propagated, and contributed to the rise in density and diversity during the spring and summer.

Michael, Van Raalte, and Brown (1975) extended analysis of the benthic fauna at stations II, IV, V, 31, 9, 10, 20, and 35 into the fourth and fifth years after the spill. Species were fewer and more opportunistic at the intertidal stations in Wild Harbor River than in Sippewissett Marsh. The fact that densities remained very low in Wild Harbor River indicates considerable inhibition of secondary production there. At station 31 species were usually few, turnover of faunal composition was rapid, and most individuals were juveniles which died before attaining maturity. Although the average number of species increased somewhat in 1974 at stations 9 and 10, species at these two intermediately oiled stations were fewer and more opportunistic than those at minimally oiled stations 20 and 35.

Indices of discrepancy and constancy show that changes in faunal composition

were greater at the heavily oiled stations and least at the lightly oiled stations. The number of species of constancy greater than 0.45 was least at stations in Wild Harbor River, somewhat greater at the nearshore subtidal stations, and greatest at the more distant subtidal stations. Faunal turnover was greatest at stations II, IV, and 31, least at stations 5, 20, and 35. The fauna at station 31 was still unstable in composition after three years. At stations 9 and 10 faunal composition was still unstable, but showed slight recovery after two years. At lightly oiled stations 20 and 35 faunal composition was fairly stable and recovered rapidly.

Analysis by discrepancy index also suggests that species near the limit of their ranges were most heavily affected and showed the poorest recovery. Thirty-two species principally affected the values of the index at station 10. Some species had the highest mean density in the first year. *Tubulanus pellucidus*, *Nephtys incisa*, and *Syllides verrilli* varied little in density, even in August, 1970. *Rocheportia cuneata*, *Mulinia lateralis*, *Tagelus divisus*, *Macoma tenta*, and *Cylichna oryza*, all mollusks, were abundant only in August, 1970. *Mulina lateralis* and *Cylichna oryza* occur northward to Maine, but the others extend only as far north as Cape Cod. *Pectinaria gouldii* was common in both July and August of 1970. Cape Cod seems to be the northern limit of this species. Other species were densest in the second year. *Mediomastus ambiseta*, *Acteocina canaliculata*, and *Chaetozone* sp. were abundant in August, 1970, as well as in the second year. *Glycinde solitaria*, *Podarke obscura*, *Glyceria americana*, *Mitrella lunata*, and *Odostomia winkleyi* were densest in the autumn of 1970, although a few animals of these species had settled as early as August, 1970. All five of these species have their northern limits in southern Massachusetts. *Odostomia sumneri*, known to occur only in the Woods Hole area, was most abundant in the autumn and early winter of 1970-71. *Capitella* spp. were densest in August, 1971, when less-degraded #2 fuel oil re-invaded station 10, *Sphaerosyllis hystrix* was nearly equally dense in the second and third years, and much more abundant than in the first year. Yet other species were densest in the third year. *Minuspio cirrifera*, *Protodorvillea gaspeensis*, *Phascolion strombi*, *Ampelisca abdita*, and Nemertine B all increased gradually in density in the three years. Most of these species also occur as far north as the Gulf of Maine or the Canadian Arctic Archipelago. *Eumida sanguinea* and *Sphaerosyllis erinaceus* were uncommon in the first year, abundant in the second year and slightly more abundant in the third year. These species extend from Iceland to the Caribbean Sea, and from the Arctic Ocean to Virginia. *Corophium tuberculatum*, *Yoldia limatula*, and *Asychis elongata* were much more abundant in the third year than in the earlier two years. The first two species extend to the north of Cape Cod, but the other species does not. Many species in the North Atlantic, especially those of the Virginian Marine Province, require high summer temperatures for survival of larvae, but can withstand the commonly very low winter temperatures in the intertidal and shallow subtidal zones. In general, it appears that those species whose northern limit is southern

New England were least stable, but those which extend farther northward showed better recovery. Boesch, Wass, and Virnstein (1976) noted that species which were not opportunistic and were near the limits of their ranges declined in abundance after the fauna was disturbed by a tropical storm.

Cluster analysis of the fauna with and without the dominant polychaete and graphic analysis of subdominants showed that changes in faunal composition were successional at the heavily oiled stations. At intermediately oiled stations faunal changes were predominantly successional, but at lightly oiled stations these changes were seasonal. Changes in faunal composition were independent of the character of the substratum.

The initial samples from stations II, IV and 31 clustered together in temporal sequence despite differences in sediments; samples taken after the first year showed a slight tendency to cluster by station. One suite of subdominants replaced another every six to ten months; none of the suites recurred once it disappeared. Although many subdominants were common to these three stations, their proportions varied from station to station. Most species tended to be subdominant in the same sequence at these stations, but *Streblospio benedicti* and *Nereis succinea*, which occurred together at stations II and IV in late 1970 and early 1971, tended to occur separately at station 31 until early 1973.

Samples from intermediately oiled stations 30, 9, and 10 clustered by temporal sequence for many months after the spill. Samples taken more than one and one-half years tended to cluster by season. The sequence of subdominants at station 9 was similar to that at station 10. Only *Sphaerosyllis hystrix* seasonally recurred. Few species at stations 9 and 10 were in common with stations 31, II, or IV, or with stations 5, 20, or 35.

Samples from lightly oiled stations 5, 20, and 35, and from the control station in Sippewissett Marsh clustered by station and season. Only those samples from station 5 with anomalously fine sediments clustered with samples from stations more heavily oiled. Stations 5, 20, and 35 shared most members of a small suite of subdominants, which recurred seasonally. Particularly evident was the alternation of *Sphaerosyllis hystrix* with *Exogone verugera*, and of *Ampelisca abdita* with *A. vadorum*. In unoiled Sippewissett Marsh, the suite of abundant species varied little from one sample to another.

Comparison of results obtained by Sumner, Osburn, and Cole (1913), Hough (1940), and Moore (1963) shows that the boundaries between coarser sands, finer sands, and mud remained stable for about fifty years. Analyses of sediments collected in this study showed only slight temporal trends in median grain size and sorting. The effects of sedimentary texture on faunal composition is suggested by the abundance of *Odostomia winkleyi* and *Chaetozone* sp. in the fine sediments of station 9 and in the similarly fine sands at station 5 in February, 1971. At station IV the increase in the amount of mud may have resulted from an early removal of fines

by waves impinging on the bottom, or from the later influx of fine sediment from the marsh. The general trend toward finer grain size may also reflect the recolonization of the bottom, after about sixteen months, by organisms capable of binding mud. A cluster analysis performed on some of the granulometric data showed that samples clustered first by median grain size, then by sorting or skewness; and that there were not any clearly defined temporal trends in these characters. The successional and seasonal changes in the fauna were not, therefore, related to the granulometry of the sediments.

Physiological and behavioral disturbances

The fact that diversity and density may have increased and stabilized does not mean that damage was at an end. Further studies of the fauna in the area affected by the *Florida* spill have shown that oil pollution forces animals to turn from the most economical biochemical pathways to others physiologically more costly, and that fuel oil distorts behavioral responses to inadapative or even lethal modes.

Krebs and Burns (1977) measured the effect of the *Florida* spill on populations of the fiddler crab, *Uca pugnax*, in Wild Harbor Marsh over a span of seven years. They found that lightly weathered #2 fuel oil with more than 20% aromatics and in concentrations greater than 1000 ppm at the sediment-water interface, killed adult crabs. Residues of the same oil in concentrations of 100 to 200 ppm killed overwintering juveniles, and were cumulatively sublethal at lower concentrations. With increasing concentrations of oil residues the crabs suffered impaired activity, loss of equilibrium, and death. The higher the concentration, the shorter the life of the crab. Concentrations which were sublethal for the moment, immobilized and killed if persistent. According to survival rates for the first two year-classes after the spill, densities of *Uca* were lower at all stations at which sediments contained more than 200 ppm of petroleum hydrocarbons. The higher the concentration of oil, the lower the density of crabs. During the first four years following the oil spill, Burns and Teal (1979) observed no significant reduction in the amount of petroleum hydrocarbons in the tissues of *Uca*; 242 ± 47.0 ppm or 24.2 ± 4.7 mg/100 g body tissue. "This amount probably represented the maximum concentrations they could accumulate and still survive . . ." Density remained low in Wild Harbor Marsh for at least seven years before recovery began. Immediately after the spill, many surviving adult crabs molted and showed breeding coloration out of season. Because of their loss of equilibrium and impaired escape response, the crabs were very vulnerable. This locomotory impairment, which was manifest at least four years after the spill, was most evident at temperatures near the lower limit of the crab's range of activity, 13°C, in May and September, when coming out of or going into winter dormancy. Crabs in moderately and heavily oiled sediments dug burrows too shallow to protect them from freezing in winter. The death of juveniles, and the locomotory and behavioral impairment and ensuing death of adults indicate that oil caused the

reduction of fiddler crab populations in Wild Harbor Marsh for at least seven years after the spill.

Chronically exposed *Fundulus heteroclitus*, a small estuarine fish, from Wild Harbor Marsh contained in its tissues as much as 75 ppm petroleum hydrocarbons from the 1969 *Florida* oil (Burns, 1976). The fish from the control area in unpolluted Sippewissett Marsh did not have residues of #2 fuel oil in their tissues. Unlike the fiddler crab *Uca*, *Fundulus* showed dramatic reduction in the concentrations of petroleum hydrocarbons in the body tissues; 75 ppm in 1970 to a mean of 6.67 ± 2.40 ppm in 1974 (Burns and Teal, 1979). By 1974 *Fundulus* developed high levels of hydrocarbon metabolizing enzymes relative to controls as probable adaptations to the oil residues (Burns, 1976).

Biochemical differences between *Fundulus* populations from the two marshes were obvious. Tissues of the fish from contaminated Wild Harbor showed a lower net rate of hepatic lipogenesis than did those fish in uncontaminated Sippewissett Marsh. Incorporation of acetate-1-¹⁴C in the gill, muscle, and brain tissues was 40-50% lower in the Wild Harbor *Fundulus* than in fish from Sippewissett Marsh. The pronounced decrease in the rate of hepatic phospholipid synthesis suggests that the oil affected the cell membranes on the cytoplasmic or intracellular surface, for phospholipids and cholesterol are the major constituents of most membranes (Sabo and Stegeman, 1977). The rate of synthesis of triglyceride was also much lower. Serum of oil-contaminated Wild Harbor *Fundulus* contained less nitrogen as urea, glucose, triglycerides, and cholesterol than did serum of the Sippewissett controls. Oil-induced physiological stress draws heavily on several stores of energy (Sabo, Heineke, and Stegeman, 1977).

Studies on polluted animals from other areas show that physiological stress is also manifested in higher energy demand. *Mya arenaria* and two species of mussels living in sediments contaminated with petroleum hydrocarbons showed changed carbon flux (Gilfillan, 1975; Gilfillan, et al., 1976). The higher the concentrations of petroleum hydrocarbons, particularly of aromatics, the higher the metabolic demand, the lower the rate of assimilation, the slower the growth, and the lower the fertility. It is clear that increasing environmental stress so elevates metabolism and reduces assimilation as to leave too little energy for growth and reproduction. As a result, most species disappear from such an environment, leaving only those few tolerant species typical of chronically polluted habitats.

4. Conclusions

1. The petroleum hydrocarbons in the sediments of Wild Harbor River and adjacent areas offshore came from the #2 fuel oil spilled by the *Florida* on September 16, 1969. Concentrations were highest and degradation slowest in the intertidal and subtidal zones of the river. Concentrations were lowest at stations farthest from shore.

2. Oil spread seaward from the areas of highest concentration for at least five years. After this span of time, fuel oil which was only somewhat degraded was still detectable in the peat and sediments of the river.
3. Within twelve hours after the spill, marine animals began to die in great numbers. Mortality was most severe and longest lasting in the river, less at nearshore subtidal stations, and least and of shortest duration at the more distant offshore stations. This trend in mortality was especially evident among ampeliscid amphipods.
4. The opportunistic polychaete, *Capitella*, monopolized the biologically denuded substrata at the heavily oiled stations for the first eleven months after the spill, then crashed. At the offshore stations, *Mediomastus ambiseta*, another capitellid polychaete, became common nearly a year after the spill, and remained so during the second year at intermediately oiled stations, but soon declined in numbers at lightly oiled stations.
5. Faunal changes matched in intensity and duration the gradient of pollution by #2 fuel oil from the *Florida*, but were only occasionally related to granulometry of the sediments.

The fauna in Wild Harbor River was unstable in density, diversity, and composition. Fluctuations in composition were successional. After more than five years the fauna there had only slightly recovered.

At the nearshore subtidal stations, faunal fluctuations were rapid and very broad in the first year, and successively less in later years. After the first year, changes in composition began to alter in character from successional to seasonal. Recovery had begun, but was not very far advanced by the end of two and one-half years.

Faunal changes at stations farthest from shore were relatively slight and seasonal in nature. The fauna recovered in density, number of species, and diversity after about a year.

At unoiled stations, faunal changes were slight and seasonal.

6. Increased species richness usually contributed more to recovery of diversity than did increase in the evenness with which individuals were distributed among species.
7. Even if the fauna began to recover in diversity and density, the animals continued to suffer the ill effects of the oil. Physiological and behavioral disorders caused by the oil resulted in impairment of growth and reproduction, and in death.
8. Bacterial seeding in areas heavily polluted by oil is probably inadequate to hasten the degradation of petroleum hydrocarbons.
9. Faunal surveys undertaken more than a week after an incident of oil pollution probably will not find any of the larger soft-bodied animals killed by the oil.
10. Most necessary are carefully conducted, quantitative, long-term studies, especially those designed to detect physiological and behavioral damage, of the effects of oil spills on all levels of the marine trophic structure, the apical member of which is often man. Mathematical techniques, particularly diversity indices, must be used with comprehension and care. Only through such studies can society appreciate the

true price paid for the undramatic, pervasive, ever-spreading, chronic pollution which disrupts and alters increasingly great reaches of natural habitats.

Acknowledgments. We wish to thank Mary S. Dale, Virginia Goodrich-Mahoney, Ron Rahn, Robert Andrews, Isabelle Williams, and Ruth Swanson, who processed samples and collated data, and Kent Colbath, who performed the preliminary granulometric analyses. We are grateful for the valuable help of Captain Arthur D. Colburn, Jr., skipper of R.V. *Asterias*. To Dr. Woollcott Smith and Margie Moffatt, computer experts, we express our gratitude. The Department of Graphic Arts, particularly Betsey Pratt, prepared the many figures. We extend our thanks especially to Margaret Dimmock and Jane Peterson, who with cheer and skill typed the various drafts of this paper. Finally, we are indebted to Donald Rhoads, Donald Boesch, Paul Dayton and two anonymous reviewers for their constructive comments, helpful suggestions and selfless dedication. Our study was partially supported by the Federal Water Pollution Control Contract 15080, the Environmental Protection Agency Grant No. R80100102 and Massachusetts Division of Water Pollution Control primarily during the initial three years and by the Woods Hole Oceanographic Institution at specific key periods. Contribution No. 4519 from the Woods Hole Oceanographic Institution.

REFERENCES

- Adam, N. K. 1936. The pollution of the sea and shore by oil: a report submitted to the Council of the Royal Society. Royal Society, London, 27 pp.
- Blumer, M., H. L. Sanders, J. F. Grassle, and G. R. Hampson. 1971. A small oil spill. *Environment*, 13, 2-12.
- Blumer, M., and J. Sass. 1972a. The West Falmouth Oil Spill. Data available in November, 1971. II. Chemistry. Woods Hole Oceanographic Institution, Tech. Rept. WHOI-72-19, 60 pp.
- 1972b. Oil pollution: persistence and degradation of spilled fuel oil. *Science*, 176, 1120-1122.
- 1972c. Indigenous and petroleum-derived hydrocarbons in a polluted sediment. *Mar. Poll. Bull.*, 3, 92-94.
- Blumer, M., J. Sass, G. Souza, H. Sanders, F. Grassle, and G. Hampson. 1970. The West Falmouth Oil Spill. Woods Hole Oceanographic Institution, Tech. Rept. WHOI-70-44, 32 pp.
- Blumer, M., G. Souza, and J. Sass. 1970a. Hydrocarbon pollution of edible shellfish by an oil spill. Woods Hole Oceanographic Institution, Tech. Rept. WHOI-70-1, 13 pp.
- 1970b. Hydrocarbon pollution of edible shellfish by an oil spill. *Mar. Biol.*, 5, 195-202.
- Boesch, D. F., M. L. Wass, and R. W. Virnstein. 1976. The dynamics of estuarine benthic communities, in *Estuarine Processes*, 1, M. Wiley, Editor. Academic Press, New York.
- Burns, K. A. 1976. Microsomal mixed function oxidases in an estuarine fish, *Fundulus heteroclitus*, and their induction as a result of environmental contamination. *Comp. Biochem. Physiol.*, 53B, 443-446.
- Burns, K. A., and J. M. Teal. 1971. Hydrocarbon incorporation into the salt marsh ecosystem from the West Falmouth oil spill. Woods Hole Oceanographic Institution, Tech. Rept. WHOI-71-69, 24 pp.
- 1979. The West Falmouth Oil Spill: Hydrocarbons in the Salt Marsh Ecosystem, *Estuarine and Coastal Mar. Sci.*, 8, 349-360.
- Cabioch, L., J. -C. Dauvin, and F. Gentil. 1978. Preliminary observations on pollution of the sea bed and disturbance of sub-littoral communities in Northern Brittany by oil from the *AMOCO CADIZ*. *Mar. Poll. Bull.*, 9, 303-307.
- Clark, R. C., Jr., and M. Blumer. 1967. Distribution of *n*-paraffins in marine organisms and sediment. *Limnol. Oceanogr.*, 12, 79-87.

- Crocker, R. A. 1969. Post Oil-Spill Intertidal Survey, Great Bay, N. H., June 3-7, 1969. Report to the Executive Committee of the Jackson Estuarine Laboratory, unpublished manuscript, 18 pp.
- Dixon, W. J. 1973. BMD, Biomedical Computer Programs. University of California Press, Los Angeles, 772 pp.
- Fisher, R. A., A. S. Corbet, and C. B. Williams. 1943. The relation between the number of species and the numbers of individuals in a random sample of an animal population. *J. Anim. Ecol.*, 12, 42-58.
- Folk, R. L. 1974. Petrology of Sedimentary Rocks. Hemphill, Austin, Texas, 182 pp.
- Gilfillan, E. S. 1975. Decrease of net carbon flux in two species of mussels caused by extracts of crude oil. *Mar. Biol.*, 29, 53-57.
- Gilfillan, E. S., D. Mayo, S. Hanson, D. Donovan, and L. C. Jiang. 1976. Reduction in carbon flux in *Mya arenaria* caused by a spill of #6 fuel oil. *Mar. Biol.*, 37, 115-123.
- Gooding, R. M. 1971. Oil pollution on Wake Island from the tanker *R.C. Stoner*. U.S. Dept. Commerce, N.O.A.A., Natl. Mar. Fish. Serv., Spec. Sci. Rept., Fish. No. 636, 12 pp.
- Grassle, J. F., and J. P. Grassle. 1974. Opportunistic life histories and genetic systems in marine benthic polychaetes. *J. Mar. Res.*, 32, 253-284.
- 1976. Sibling species in the marine pollution indicator *Capitella* (Polychaeta). *Science*, 192, 567-569.
- 1977. Temporal adaptations in sibling species of *Capitella*, in *Ecology of Marine Benthos*, pp. 177-189, B. C. Coull, Editor. University of South Carolina Press, Columbia, South Carolina.
- Grassle, J. F., and H. L. Sanders. 1973. Life histories and the role of disturbance. *Deep-Sea Res.*, 20, 643-659.
- Grassle, J. F., and W. Smith. 1976. A similarity measure sensitive to the contribution of rare species and its use in investigation of variation in marine benthic communities. *Oecologia*, 25, 13-22.
- Hough, J. L. 1940. Sediments of Buzzards Bay, Massachusetts. *J. Sedim. Petrol.*, 10, 19-32.
- Hurlbert, S. H. 1971. The nonconcept of species diversity: a critique and alternative parameters. *Ecology*, 52, 577-586.
- Krebs, C. T., and K. A. Burns. 1977. Long-term effects of an oil spill on populations of the salt-marsh crab *Uca pugnax*. *Science*, 197, 484-487.
- Krumbein, W. C. 1939. Graphic presentation and statistical analysis of sedimentary data, in *Recent Marine Sediments*, P. D. Trask, Editor. American Association of Petroleum Geologists, 558-592.
- MacArthur, R. H. 1957. On the relative abundance of bird species. *Proc. Nat. Acad. Sci.*, 43, 293-295.
- Margalef, R. 1957. La teoria de la informacion en ecologia. *Memorias de la Real Academia de Ciencias y Artes de Barcelona*, 23, 373-449.
- Michael, A. D., C. R. Van Raalte, and L. S. Brown. 1975. Long-term effects of an oil spill at West Falmouth, Massachusetts, in 1975 Conference on Prevention and Control of Oil Pollution, Proceedings, March 25-27, 1975, San Francisco. American Petroleum Institute, Washington, D.C., 573-582.
- Mills, E. L. 1963. A new species of *Ampelisca* (Crustacea: Amphipoda) from eastern North America, with notes on other species of the genus. *Can. J. Zool.*, 41, 971-989.
- 1964. *Ampelisca abdita*, a new amphipod crustacean from eastern North America. *Can. J. Zool.*, 42, 559-575.
- 1965. The zoogeography of North Atlantic and North Pacific ampeliscid amphipod crustaceans. *Syst. Zool.*, 14, 119-130.
- 1967a. A reexamination of some species of *Ampelisca* (Crustacea: Amphipoda) from the east coast of North America. *Can. J. Zool.*, 45, 635-652.
- 1967b. The biology of an ampeliscid amphipod crustacean sibling species pair. *J. Fish. Res. Bd. Canada*, 24, 303-355.
- Moore, J. R., III. 1963. Bottom sediment studies, Buzzards Bay, Massachusetts. *J. Sedim. Petrol.*, 33, 511-558.
- Murphy, T. A. 1970. Environmental effects of oil pollution. Paper presented at session on oil pollution control, Amer. Soc. Civil Engineers, Boston, Mass. Federal Water Quality Administration, unpublished manuscript, 27 pp.
- North, W. J., M. Neushul, Jr., and K. A. Clendenning. 1965. Successive biological changes observed in a marine cove exposed to a large spillage of mineral oil, in *Comm. Int. Explor. Sci. Mer. Medit., Pollutions marines par les microorganismes et les produits petroliers, Symposium de Monaco (Avril, 1964)*, 335-354.
- Pearson, T. H., and R. Rosenberg. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol. Ann. Rev.*, 16, 229-311.
- Preston, F. W. 1948. The commonness, and rarity, of species. *Ecology*, 29, 254-283.
- Rhoads, D. C. 1963. Rates of sediment reworking by *Yoldia limatula* in Buzzards Bay, Massachusetts, and Long Island Sound. *J. Sedim. Petrol.*, 33, 723-727.
- 1967. Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts. *J. Geol.*, 75, 461-467.
- Rhoads, D. C., and D. K. Young. 1970. The influence of deposit-feeding organisms on sediment stability and community trophic structure. *J. Mar. Res.*, 28, 150-178.
- Sabo, D. J., E. Heineke, and J. J. Stegeman. 1977. Environmental stress and blood chemistry in marine fish. *Fed. Proc.*, 36, 1146.
- Sabo, D. J., and J. J. Stegeman. 1977. Some metabolic effects of petroleum hydrocarbons in marine fish, in *Physiological Responses of Marine Biota to Pollutants*, F. J. Vernberg, A. Calabrese, F. P. Thurberg, and W. Vernberg, Editors. Academic Press, New York, 279-287.
- Sanders, H. L. 1956. Oceanography of Long Island Sound, 1952-1954. X. The Biology of Marine Bottom Communities. *Bull. Bingham Oceanogr. Collection*, 15, 345-414.
- 1958. Benthic studies in Buzzards Bay. I. Animal-sediment relationships. *Limnol. Oceanogr.*, 3, 245-258.
- 1968. Marine benthic diversity: a comparative study. *Amer. Nat.*, 102, 243-282.
- 1974. The West Falmouth Saga. *New Engineer*, 3, 32-35, 38, 40-41.
- 1978. Florida Oil Impact on the Buzzards Bay Benthic Fauna: West Falmouth. *J. Fish. Res. Bd. Canada*, 35, 717-730.
- Sanders, H. L., J. F. Grassle, and G. R. Hampson. 1972. The West Falmouth Oil Spill. I. Biology. Woods Hole Oceanographic Institution, Tech. Rept. WHOI-72-20, 23 pp.
- Schlee, J. 1966. A Modified Woods Hole Rapid Sediment Analyzer. *J. Sedim. Petrol.*, 36, 404-413.
- Shannon, C. E., and W. Weaver. 1963. *The Mathematical Theory of Communication*. University of Illinois Press, Urbana, Illinois.
- Siegel, S. 1956. *Nonparametric Statistics for the Behavioral Sciences*. McGraw-Hill, New York.
- Simberloff, D. S., and E. O. Wilson. 1969. Experimental zoogeography of islands: the colonization of empty islands. *Ecology*, 50, 278-295.
- Simpson, E. H. 1949. Measurement of Diversity. *Nature*, 163, 688.

- Smith, W., and J. F. Grassle. 1977. Sampling properties of a family of diversity measures. *Biometrics*, 33, 283-292.
- Smith, W., J. F. Grassle, and D. Kravitz. 1979. Measures of diversity with unbiased estimators, in *Ecological Diversity in Theory and Practice*, Statistical Ecology Volume S6. International Cooperative Publishing House, Fairland, Maryland.
- Souza, G. 1969. Report of the Shellfish Warden, in *Annual Report of the Finances of the Town of Falmouth for the year ending December 31, 1969*, 125-128.
- 1970. Report of the Shellfish Warden, in *Annual Report of the Finances of the Town of Falmouth for the year ending December 31, 1970*, 161-165.
- 1973. Report of the Shellfish Officer, in *Annual Report of the Finances of the Town of Falmouth for the year ending December 31, 1973*, 174-177.
- Stander, G. H., and J. A. V. Venter. 1968. Oil pollution in South Africa, in *International Conference on Oil Pollution of the Sea*, 7-9 October 1968 at Rome, Report of Proceedings, 251-259.
- Stevens, N. P., E. E. Bray, and E. D. Evans. 1956. Hydrocarbons in Sediments of Gulf of Mexico. *Bull. Amer. Assoc. Petrol. Geol.*, 40, 975-983.
- Sumner, F. B., R. C. Osburn, and L. J. Cole. 1913. A biological survey of the waters of Woods Hole and vicinity. Section 1.—Physical and Zoological. U.S. Fish Wildl. Serv., *Bull. Bur. Fish.*, 31, 11-442.
- Tegelberg, H. 1964. Washington's Razor Clam Fisheries in 1964. *State of Washington Dept. Fish.* 74th Ann. Rept., 53-56.
- Whittaker, R. H. 1965. Dominance and Diversity in Land Plant Communities. *Science*, 147, 250-260.
- Williams, W. T. 1971. Principles of Clustering. *Ann. Rev. Ecol. Syst.*, 2, 303-326.
- Wilson, E. O., and W. H. Bossert. 1971. *A Primer of Population Biology*. Sinauer Associates, Stamford, Conn.

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