

THE EFFECTS OF OIL FROM THE T/V PUERTO RICAN
ON RECRUITMENT AND RECOVERY OF BARNACLE POPULATIONS

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Introduction and Background

Oil that spilled from the T/V Puerto Rican during October and November of 1984 covered stretches of both rocky and sandy shoreline, and left residues which persisted for at least several months after initial contact. Populations of intertidal organisms were exposed to the physical and chemical effects of the oil, and an example of the impact was clearly visible on a section of rocky shore on southern Bodega Head at the northern boundary of the Point Reyes/Farallon Islands National Marine Sanctuary. Essentially all barnacles (Balanus glandula and Chthamalus dalli) died within a 10-meter length of the south jetty at the entrance to Bodega Harbor during the first month after the tanker accident. Further barnacle mortality was observed inside Bodega Harbor (Figure 1). In these areas, oil residues stained the substrata and remaining, empty barnacle tests, and other associated invertebrate species also died or moved away.

The continuing presence of oil in marine environments is a potential long-term source of alterations for shore populations of plants and animals. The persistence of oil in barnacle habitats for several months beyond the initial spill could potentially have produced additional mortality to adult barnacles in nearby areas. Moreover, oil residues, even if not clearly visible, could have had detrimental effects on the recruitment of planktonic larvae to adult populations on the shore. Larvae often play a critical role in selecting appropriate adult habitats (see review by Newell 1979) and are particularly sensitive to alterations in environmental conditions. Even in affected areas where the initial oilspill did not produce heavy adult mortality, population densities would have been expected to decline eventually if larval recruitment was adversely altered by persistent oil residues. In areas where oil actually killed adult invertebrates, recovery would be delayed.

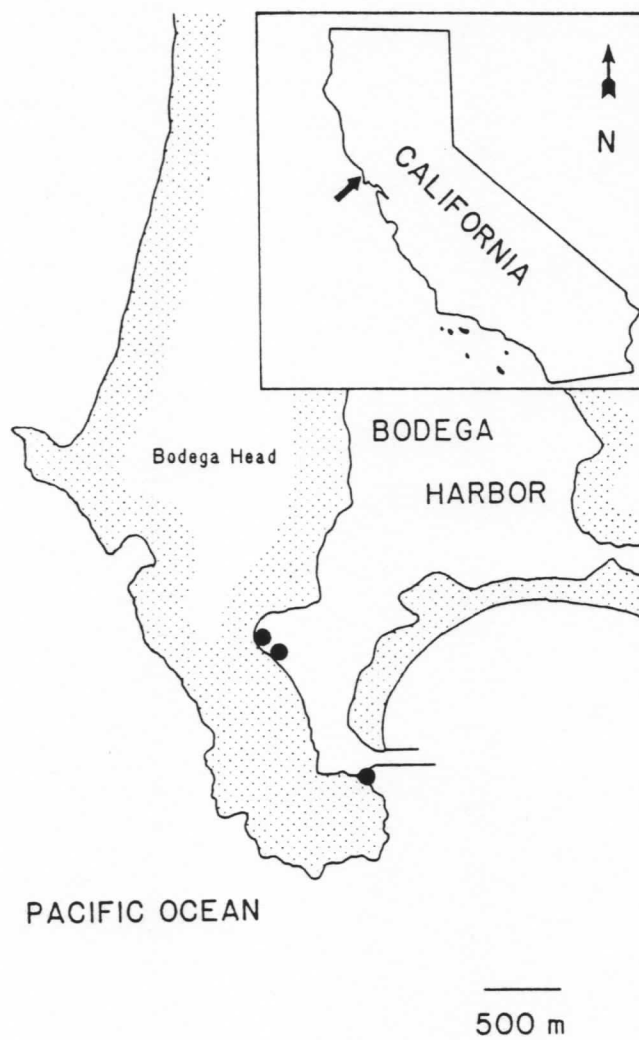


Figure 1: Sites of barnacle mortality on Bodega Head
and in Bodega Harbor ●

In this study, we measure some of the effects of the Puerto Rican oilspill on the mortality, recruitment, and recovery of impacted barnacle communities. In particular, we examine the possibility of continued adult barnacle mortality as a result of residual oil and cumulative toxic effects. We also quantify rates of barnacle recruitment to oil-impacted areas and describe patterns of recovery for some populations of algae and gastropods associated with barnacle beds. Laboratory studies on the toxicity of oil to barnacle larvae were conducted as well.

I. Adult Barnacle Mortality (Reciprocal Transplants)

Materials and Methods

Continuing impacts of the oilspill on adult barnacles were evaluated by measuring mortality in field populations of Balanus glandula. An experimental design using reciprocal transplants of barnacles from oil-affected and unaffected sites was used to compensate for geographical differences in barnacle populations and inter-habitat differences in mortality rates before attributing any mortality to oil contact.

On 3 December 1985, 24 days after initial oil contact at Bodega Head, collections of Balanus glandula were taken from three sites subjectively determined as differing in exposure to oil (Figure 2). Site 1 was adjacent to Westside Park on the protected shores within Bodega Harbor, and was free of visible contamination. Site 2 was between Gaffney Point and Campbell's Cove, also within protected Bodega Harbor, and was heavily impacted by oil (with a coating of oil persisting on rocks and barnacle tests). Extensive barnacle mortality was observed at this site in the weeks following the oilspill. Site 3 was on the wave-exposed rocky intertidal shore of the open coast, approximately 200 m north of Horseshoe Cove; the rocky intertidal zone in this region was covered by a thin but visible coating of light oil

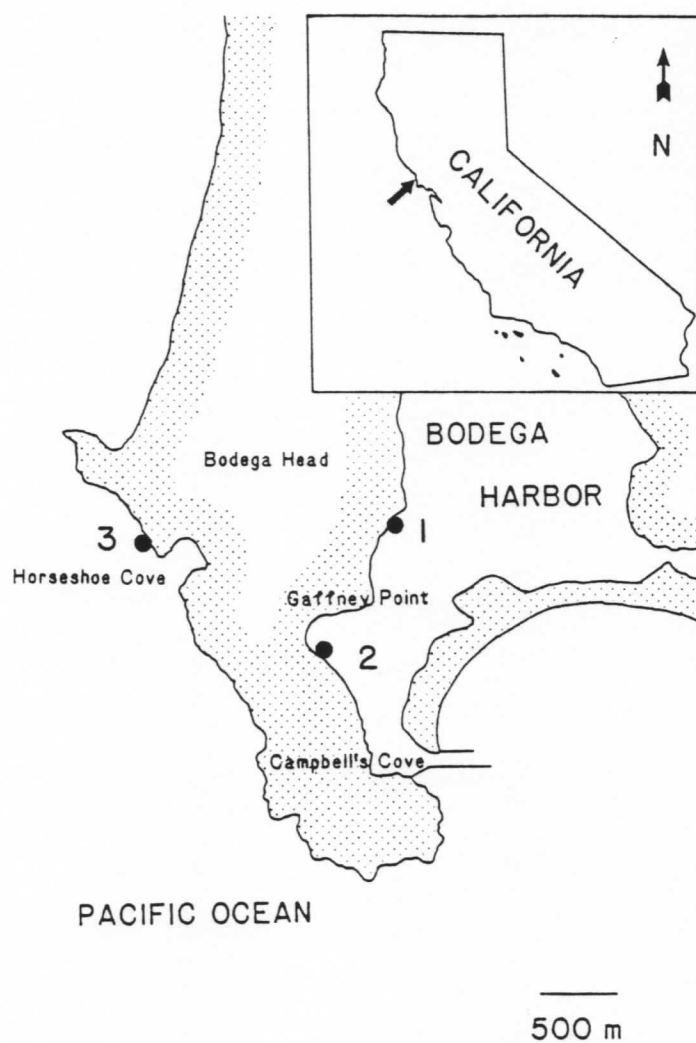


Figure 2: Collection and transplant locations of adult Balanus glandula

Site 1 (Westside Park: no oil contamination)

Site 2 (Between Campbell's Cove and Gaffney Point: heavy contamination)

Site 3 (Outer coast near Bodega Marine Laboratory: light contamination)

during the peak of the oilspill event. Fragments of rock containing barnacles were removed from each of these sites with a rock hammer and chisel, and brought to the Bodega Marine Laboratory where they were placed in running seawater. The following day (4 December), 12 rock fragments from each site were marked with colored plastic bee tags using cyanoacrylate adhesive. Photographs were then taken and used to determine the number of living and dead barnacles on a designated section of each rock fragment (presence of opercular plates = live, absence = dead); each designated section contained between 19 and 285 barnacles. Rocks from each site were randomly divided into three equivalent groups of four rocks each; these groups of four from each site were pooled into three groups of twelve, each composed of four rocks from each of the three sites. The groups of twelve were returned to the original sites using a marine cement (Waterplug, Thoro System Products). The experimental design is summarized in Table 1.

After six weeks, all remaining rock fragments were recovered from the field sites; three rock fragments were lost during the experimental field period. The number of adult Balanus glandula surviving were tabulated and compared to initial counts. Barnacle mortality rates for reciprocal transplants were then compared statistically using one-tailed Mann-Whitney U-tests (Sokal and Rohlf 1981) to evaluate whether rates were higher at sites exposed to oil.

Results and Conclusions

Mortality rates of transplanted adult barnacles appeared to be related to both habitat changes and to exposure to persistent oil residues. Figure 3 shows mean mortality rates of reciprocal transplants for the two protected harbor sites (Sites 1 and 2) and the one exposed coast site (Site 3) for the six week period starting in early December. All Balanus glandula positioned at Site 1 near Westside Park (no visible oil) survived very well regardless of their site of origin. Mortality was generally less than 10% among barnacles on all transplanted rock fragments. The low mortality rates indicate that the experimental

Table 1

Mortality Rates of Adult Balanus glandula Transplanted
to Sites With Three Levels of Oil Contamination

This table lists the number of samples remaining (rock fragments) at the conclusion of the experiment by original sample location and transplanted destination.

Source of Sample	Final Transplant Site		
	Site 1	Site 2	Site 3
Site 1	4	3	3
Site 2	4	4	3
Site 3	4	4	4

Site 1 (Westside Park: no oil contamination)
 Site 2 (Between Campbell's Cove and Gaffney Point: heavy contamination)
 Site 3 (Outer coast near Bodega Marine Laboratory: light contamination)

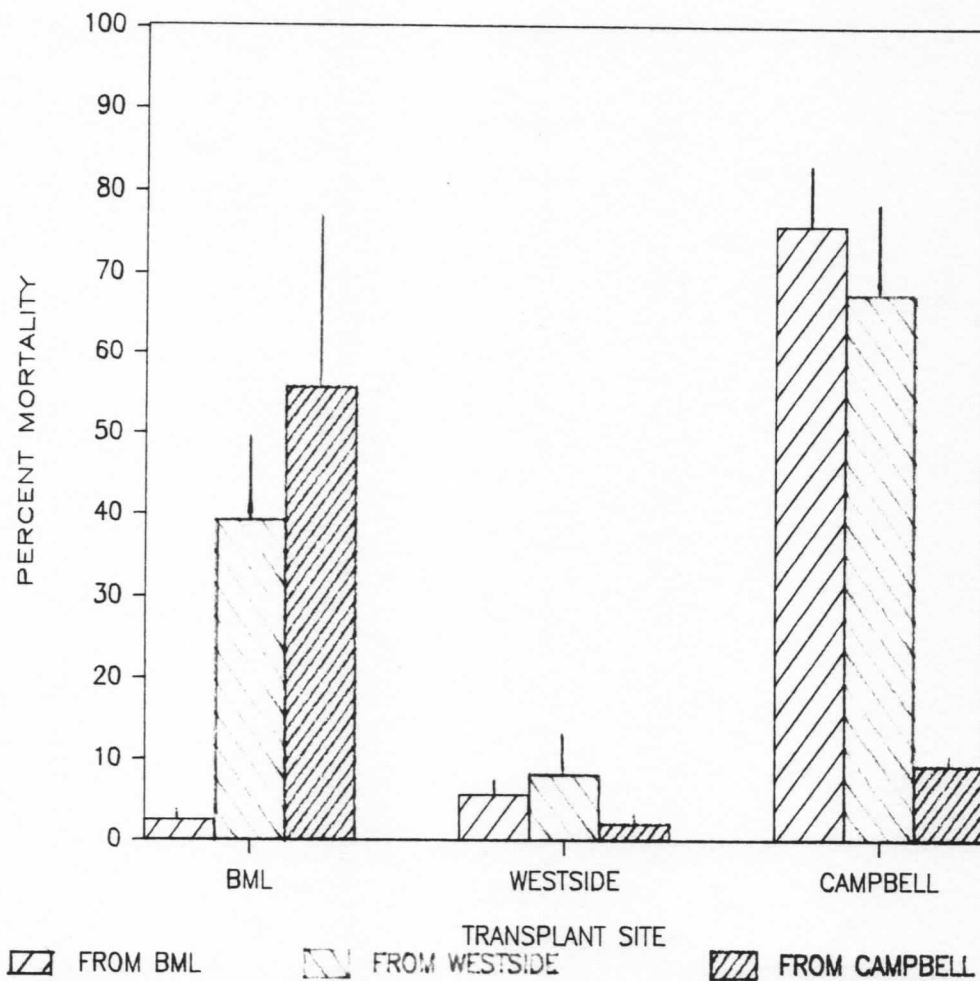


Figure 3: Mean mortality rates (with standard errors) of reciprocal transplants of adult Balanus glandula at the three study sites

Site 1 (Westside Park: no oil contamination)

Site 2 (Between Campbell's Cove and Gaffney Point: heavy contamination)

Site 3 (Outer coast near Bodega Marine Laboratory: light contamination)

transplanting technique itself had no obvious detrimental impact on the barnacles and that barnacles from both the harbor and the open coast tolerate environmental conditions of wave-protected habitats when oil residues are absent.

When barnacles from harbor sites were transplanted to the open coast site near Horseshoe Cove (Site 3), mortality rates increased significantly (Mann-Whitney U-tests: $P < 0.05$) relative to the low mortality rates of all barnacles at Site 1 (Westside Park), reaching average levels of approximately 40-55%. However, barnacles transplanted from the open coast survived well on the open coast, and had significantly lower mortality rates than animals transplanted from protected habitats (Mann-Whitney U-tests: $P < 0.05$).

The high mortality of barnacles transferred from the harbor sites to the open coast was probably not related to the presence of oil, since oil contamination at the open coast site during the period of the oilspill did not persist and did not induce observable mortality in the native open coast population. Moreover, there is no reason to believe that the barnacles transplanted from the open coast which survived well during the field experiment were necessarily more tolerant of oil. It seems more likely that Balanus glandula from the harbor populations lacked suitable morphological and physiological adaptations for existence at the exposed coast site. Environmental characteristics of the open coast (e.g., temperature, desiccation, wave shock) may have stressed barnacles newly transplanted to that habitat. In contrast, the transfer of open coast barnacles to benign environmental conditions within Bodega Harbor did not increase mortality.

However, average mortality rates reached their highest levels (67-78%) when barnacles from uncontaminated (Site 1: Westside Park) or lightly-contaminated (Site 3: open coast) habitats were transplanted to the highly oil-contaminated study site between Gaffney Point and Campbell's Cove (Site 2). At this site, mortality rates of barnacles transplanted from the open coast were significantly higher than similar barnacles repositioned on the open coast or transplanted to Westside Park (Mann-Whitney U-tests: $P < 0.05$). Likewise, barnacles from Westside Park suffered significantly higher mortality at Site 2 than comparable

animals repositioned at Westside Park or even those transplanted to the open coast (Mann-Whitney U-tests: $P < 0.05$). Such results suggest that the toxic effect of oil residues remained for at least one month after the initial oilspill and subsequent clean-up.

Yet, barnacles from contaminated Site 2 that were re-positioned at Site 2 had a relatively low average mortality rate (approximately 9%). Although this mortality at Site 2 was significantly higher than for comparable barnacles at Westside Park, the rate was significantly less than for barnacles transplanted to Site 2 from either Westside Park or the open coast (Mann-Whitney U-tests: $P < 0.05$); i.e., barnacles from the contaminated site survived well at the contaminated site during the field experiment and resisted any further mortality after the initial month of exposure to oil. We believe the explanation can be found in prior mortality of contaminated barnacles: the most susceptible barnacles may have died quickly after exposure to oil and only more resistant individuals remained to be used in this transplant experiment. Numbers of dead barnacles and of recent barnacle scars were much higher on rocks at Site 2 than at Sites 1 and 3. This result suggests that the greatest impact of oil residues on resident Balanus glandula populations is likely to occur soon after first contact, even though the toxicity of the oil persists for a considerable length of time.

II. Recruitment of Barnacle Larvae and Recovery of the Associated Community

Materials and Methods

Recruitment rates of larval barnacles (Balanus glandula and Chthamalus dalli) were determined experimentally in the field on oil-affected and unaffected (control) substrata during spring and early summer of 1985. Experimental substrata were established on the open side of the south jetty at the entrance to Bodega Harbor in an area exposed to the open ocean but protected from severe wave exposure by

Bodega Head. Combinations of several test substrata were placed within and adjacent to the site of severe adult barnacle mortality (Figure 4).

Twenty replicates were established within the study area in positions typically dominated spatially by Balanus glandula at tidal levels between 1.2 m and 1.8 m above mean lower low water. Ten replicates were located within the oil-impacted area (severe adult barnacle mortality) and 10 replicates were located in control areas (no unusual barnacle mortality) within 10 m of the impacted area. Each replicate consisted of five 7.5 cm X 7.5 cm experimental substrata as follows:

- 1) An unaltered portion of the native rock surface with existing flora and fauna. These substrata were marked with small dabs of paint at the corners and they provided information on possible recruitment effects of residual oil, on the natural recovery of oil-impacted surfaces, and on seasonal changes of control surfaces.
- 2) A rock surface cleared of macro-flora and fauna with a wire brush (basal plates of barnacles were not removed). These substrata measured possible effects of oil on barnacle recruitment after removing variation due to resident attached organisms. Textural conditions were thus more uniform on oil-affected and control substrata at the beginning of the experiment. (Other studies have shown that patterns of barnacle recruitment can be influenced by substratum texture and by previously established organisms (e.g., Crisp and Barnes 1954, Luckens 1970, 1975a)).
- 3) A rock surface cleared and then outlined with sticky resins (Tree Tanglefoot) to exclude mobile herbivores, such as limpets (Collisella) and periwinkles (Littorina), and barnacle predators, such as whelks (Nucella). Measures of barnacle recruitment were made on these substrata while controlling for the abundances and activities of gastropod species which have been shown to disrupt settlement of barnacles (e.g., Connell 1961a, 1970, Luckens 1975b).
- 4) An artificial plate which was positioned using an epoxy-based marine cement (Custom Plug hydraulic patching mortar). The artificial plates were ceramic tiles which had been soaked in running seawater for one week before being cemented at the study area. These substrata were

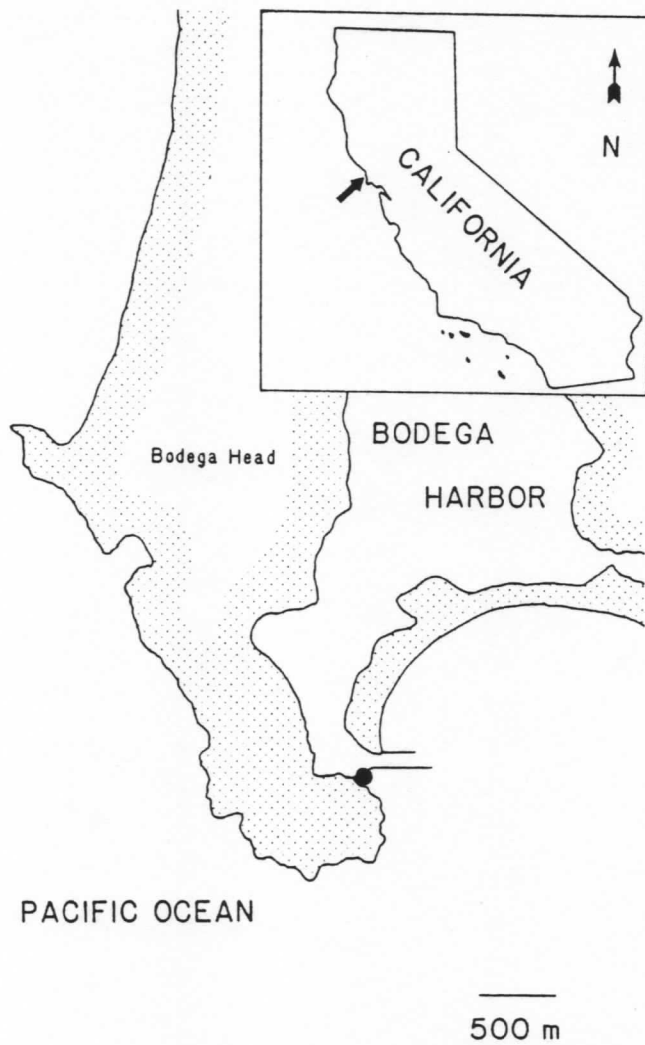


Figure 4: Site of experimental plots for measurements of barnacle community recruitment and recovery ●

designed to measure barnacle recruitment onto surfaces uncontaminated by oil in both oil-affected and control areas.

5) A removable, artificial plate which was attached at the study areas using bolts cemented to the rock surfaces. Again, the ceramic plates were soaked in running seawater for one week before use. These substrata were replaced every two weeks and were designed to measure temporal variation in recruitment rates. However, barnacles never settled on these plates in any significant number and results were not analyzed.

The unaltered substrata, the cleared substrata with herbivores present, and the artificial plates were established between April 1-3; the cleared substrata with herbivores excluded were established on April 30. All substrata were censused April 24-26 and every four weeks thereafter until July 21-23. For each census period, counts were taken of adult and newly-recruited (1985) Balanus glandula and Chthamalus dalli. Grazing gastropods (Collisella digitalis and Littorina plena) were counted as well. During the first two censuses (April and May), a quantitative estimate of algal abundance was also made; the combined cover of Enteromorpha, Porphyra, and Endocladia was determined for each replicate from a grid of 225 points. In later censuses, only presence or absence of algae was noted.

Two-tailed Mann-Whitney U-tests (Sokal and Rohlf 1981) were utilized to test statistical significance of differences between oil-affected and control surfaces.

Results and Conclusions

Patterns of barnacle recruitment and recovery varied markedly on the different experimental substrata. Disturbances due to oil contamination and persistence apparently had complex direct and indirect influences on the successional events that occurred following the initial mortality of adult barnacles in November, 1984.

Tremendous densities of barnacle cypris larvae and newly-

metamorphosed individuals (Balanus glandula) were observed at the study site and on nearby shores on 19-20 March, 1985, before the field experiment was established. Abundant planktonic larvae were also observed in surge channels on the outer coast, suggesting that larvae were widely available for colonization of open surfaces. Yet, oil-impacted areas at the study site had notably fewer cypris larvae attached to rock surfaces than control areas; no newly-metamorphosed barnacles were observed on these surfaces either.

The large settlements of Balanus cypris larvae were no longer present when the field experiment was started in early April.

Unaltered Experimental Substrata

Algal cover was greatly enhanced on unaltered substrata located in oil-impacted areas compared to control areas where oil did not cause observable changes. Algal mats that consisted primarily of Enteromorpha and Porphyra spatially dominated zones which had supported extensive populations of Balanus glandula previous to the oilspill. Figure 5 shows the statistically significant differences (Mann-Whitney U-tests: $P < 0.05$) in algal cover between oil-impacted and control substrata during April and May. In oil-impacted areas, algae typically covered more than 25% of the surface, while mean algal cover in control areas was only approximately 1%.

The increase in algal cover on oil-impacted substrata was probably due to a decrease in gastropod herbivore abundance. Figure 6 shows the mean densities of periwinkles (Littorina plena) and limpets (Collisella digitalis) on unaltered experimental substrata from April through July. Littorina were 3-14 times more abundant in control areas than in oil-impacted areas during all censuses (Mann-Whitney U-tests: $P < 0.05$); Collisella were rarely observed in oil-impacted areas and were significantly more abundant in control areas during the May and July censuses (Mann-Whitney U-tests: $P < 0.05$). Many studies (e.g., Castenholz 1961, Cubit 1975, Chow 1983) have shown that these herbivores usually occur at population densities sufficiently high to keep algal

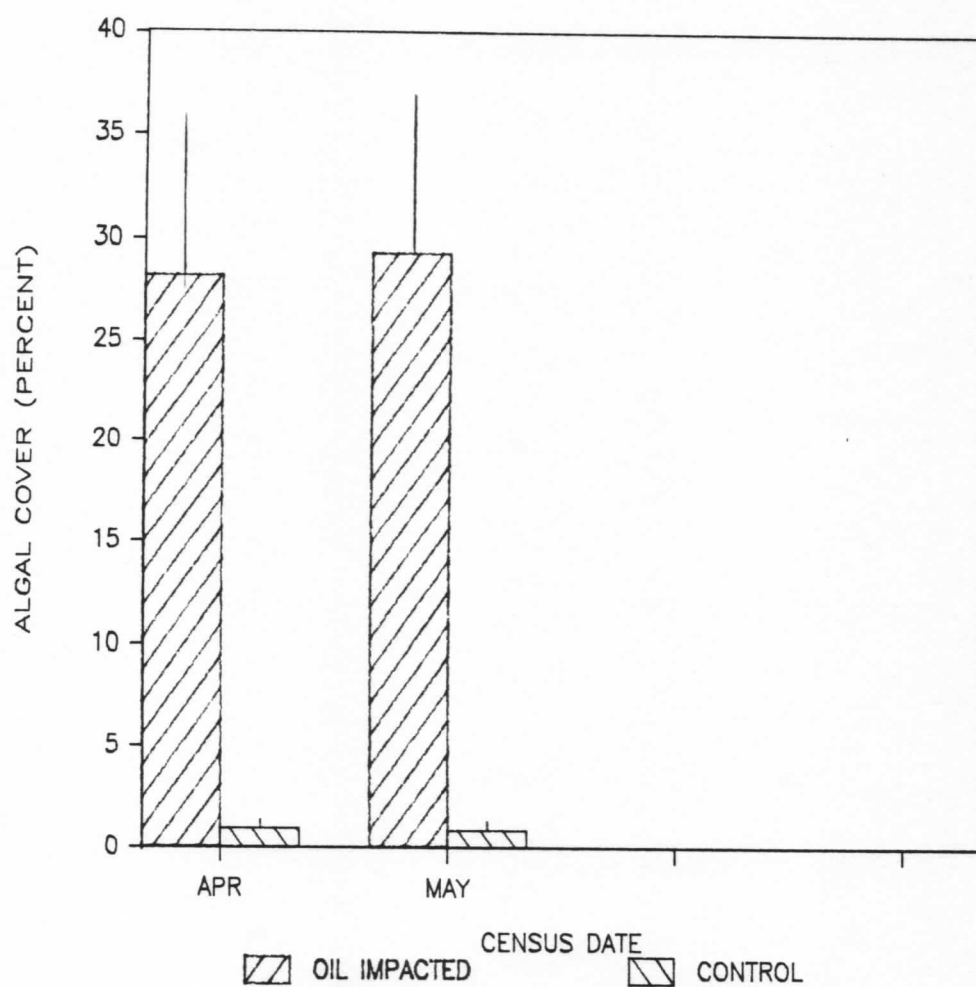


Figure 5: Mean percentages (with standard errors) of algal cover on unaltered experimental substrata in oil-impacted and control areas during April and May censuses

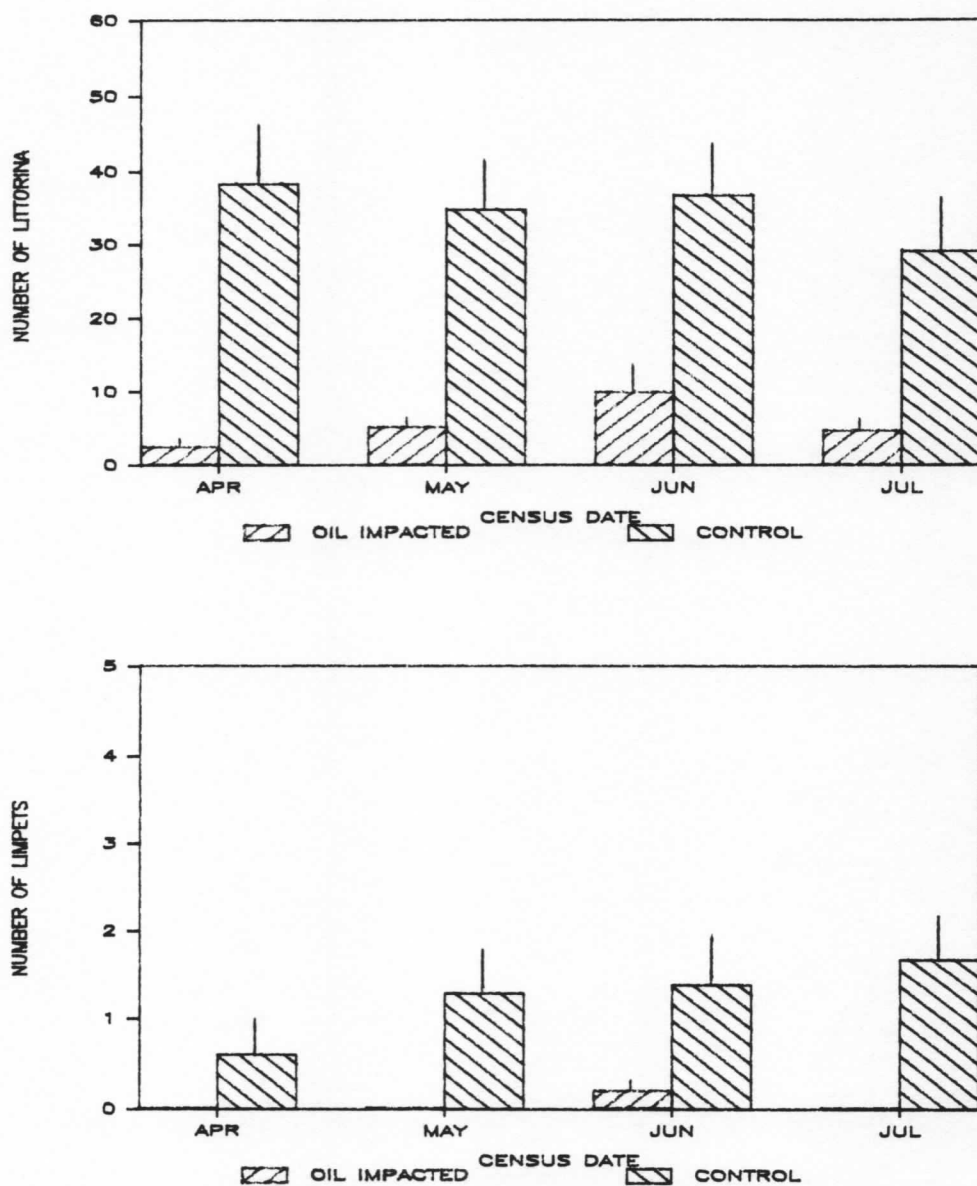


Figure 6: Numbers of gastropod herbivores (with standard errors) on unaltered experimental substrata in oil-impacted and control areas

- A Littorina plena (Periwinkles)
- B Collisella digitalis (Limpets)

standing biomass at very low levels. In oil-impacted areas, however, most herbivores apparently died or migrated to other locations. The oil itself may have been toxic, or herbivores may have been responding to the indirect habitat changes that resulted from the loss of barnacles (e.g., barnacle tests provide physical relief which serves as shelter for some gastropods (Chow 1975, Choat 1977, Creese 1982, Underwood and McFadyen 1983)).

Recruitment and recovery rates of Balanus glandula populations themselves were not significantly different in oil-impacted areas compared to control areas (Mann-Whitney U-tests: $P > 0.05$). Figure 7 shows that the numbers of new Balanus recruits may actually have been slightly greater in areas that were contaminated with oil. It was not possible to separate seasonal recruitment rates from mortality rates as the number of surviving recruits decreased during the experimental period. Yet, even though large numbers of recruits did settle on oil-impacted substrata, care must be exercised before drawing conclusions from these results. Unaltered control substrata began the experiment with approximately 30-300 well-established adult B. glandula present, and the adults themselves may have inhibited larval recruitment. Uninhabited surfaces, which are often in short supply for settling barnacles (see Connell 1961a, b, Luckens 1975a, Carefoot 1977), were less available in control areas so that the number of B. glandula recruits may have been reduced. Presumably, the experimentally cleared substrata provided a more direct measure of the oil impact on larval recruitment rates (see next section).

In contrast, even with reduced substratum availability, Chthamalus dalli recruits were significantly more successful in control areas than in oil-impacted areas for all censuses (Mann-Whitney U-tests: $P < 0.05$) (Figure 8). However, several processes may have contributed to the observed differences in recruitment rates; larval C. dalli may have been responding to the oil persistence or may have been affected by competition for space with Balanus glandula. Luckens (1970, 1975a) has reported that preclusion of open space by algae can inhibit barnacle recruitment, so the enhanced algal cover on oil-contaminated substrata may have contributed to the lower recruitment rates. (However, this

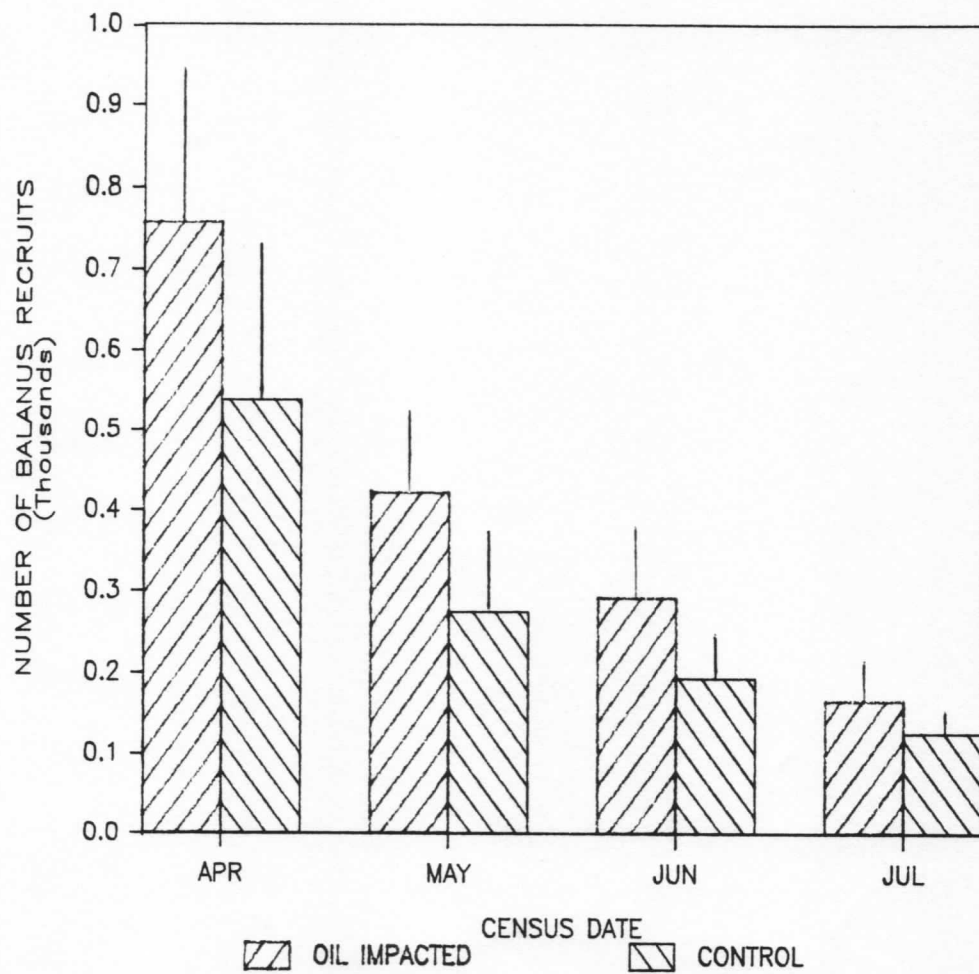


Figure 7: Numbers of *Balanus glandula* recruits (with standard errors) on unaltered experimental substrata in oil-impacted and control areas

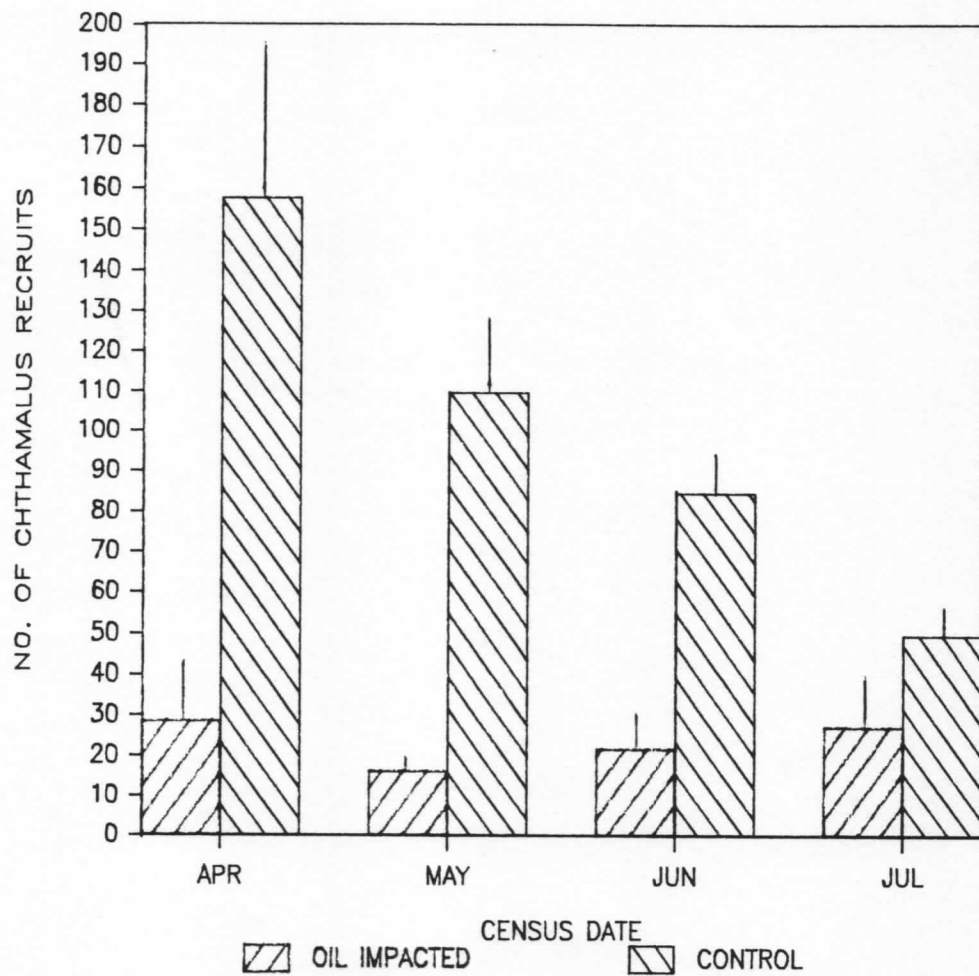


Figure 8: Numbers of Chthamalus dalli recruits (with standard errors) on unaltered experimental substrata in oil-impacted and control areas

interaction did not obviously affect Balanus recruitment adversely.)

Experimentally Cleared Substrata

On substrata cleared of fauna and flora in control areas, recruitment rates of Balanus glandula were comparable to rates on unaltered substrata (compare Figures 7 and 9). In oil-impacted areas, however, recruitment of B. glandula was greatly reduced by clearing the substrata, and the mean number of new recruits in oil-impacted areas was significantly lower than the mean found in control areas during the April census (Mann-Whitney U-test: $P < 0.05$) (Figure 9). Thus, oil contamination seemed to affect B. glandula recruitment rates negatively after experimentally controlling for algal and adult barnacle abundance.

A similar pattern is revealed for Chthamalus dalli. On cleared substrata, recruitment of C. dalli was higher in control areas than in oil-impacted areas (Figure 10), though the differences are not statistically significant (Mann-Whitney U-tests: $P > 0.05$). In addition, recruitment was very much lower than on unaltered experimental substrata (compare Figures 8 and 10). No algal cover developed on any cleared substrata during the period of this experiment (until the end of July), so competition for space with algae was not likely an important factor in population recovery. However, competition with other newly-settled barnacles was still a possibility. The absolute amount of open space decreased rapidly during the experiment as successful B. glandula and C. dalli recruits quickly grew. The absence of C. dalli on all cleared surfaces in May (Figure 10) indicates that larval settlement prior to 22 May 1985 was completely unsuccessful.

Not surprisingly, gastropod herbivores more quickly recolonized cleared control substrata than oil-impacted substrata (Figure 11); although any oil residues may have inhibited immigration, herbivores also had much longer distances to migrate in order to re-inhabit oil-impacted sites. However, the numbers of periwinkles (Littorina) were still significantly lower on oil-impacted substrata during the June censuses (Mann-Whitney U-test: $P < 0.05$), and the numbers of limpets

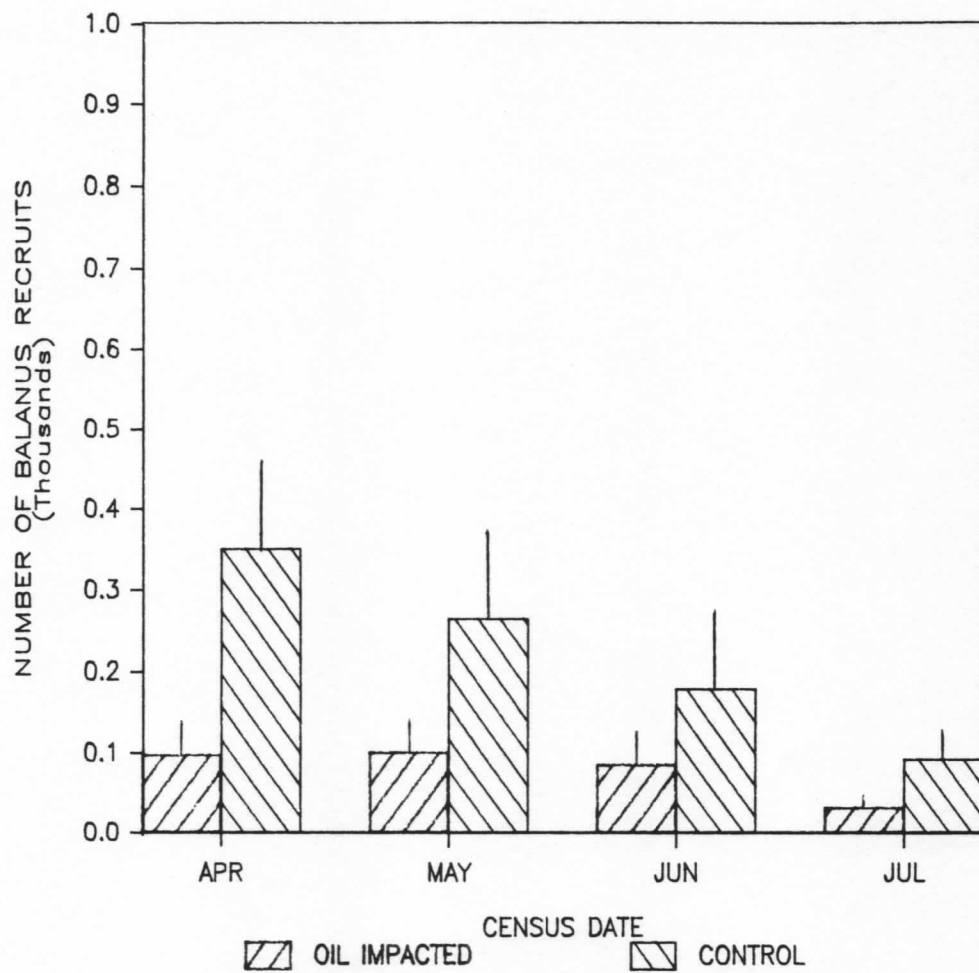


Figure 9: Numbers of *Balanus glandula* recruits (with standard errors) on experimentally cleared substrata in oil-impacted and control areas

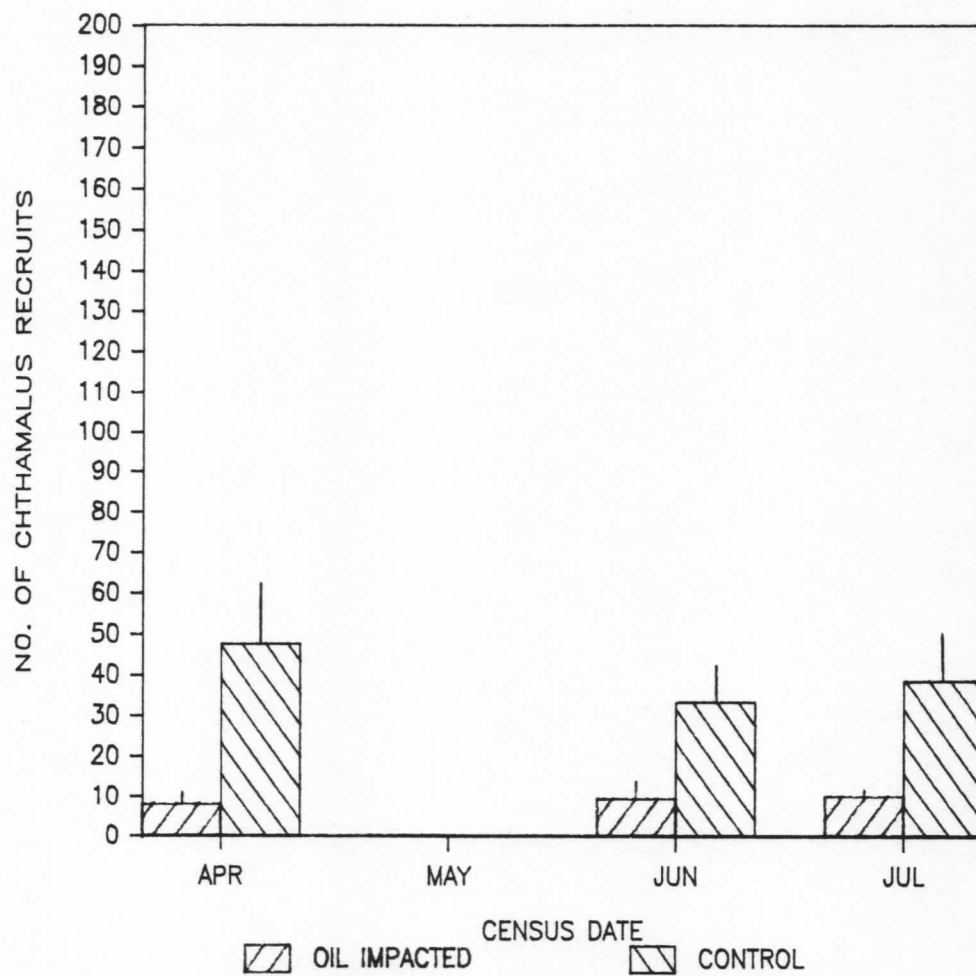


Figure 10: Numbers of Chthamalus dalli recruits (with standard errors) on experimentally cleared substrata in oil-impacted and control areas

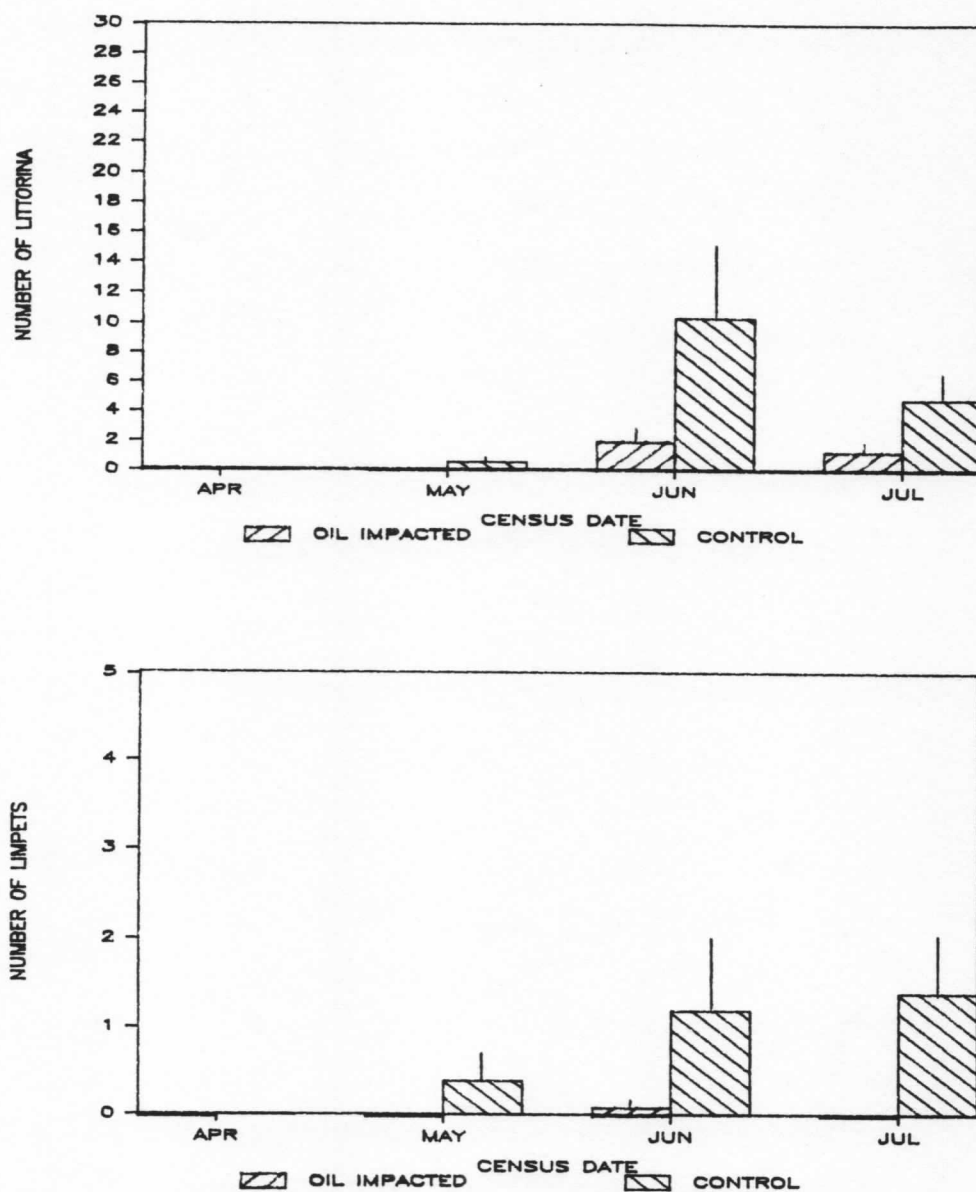


Figure 11: Numbers of gastropod herbivores (with standard errors) on experimentally cleared substrata in oil-impacted and control areas

A *Littorina plena* (Periwinkles)

B *Collisella digitalis* (Limpets)

were significantly lower on oil-impacted substrata during the July census. If gastropod herbivores had any negative effects on barnacle recruitment (as has been shown to be a possibility by Connell 1961a, 1970, and Luckens 1975b), then the effects would be expected to have been greater on the control substrata.

Experimentally Cleared Substrata: Herbivores Excluded

Balanus glandula recruits were slow to colonize cleared substrata from which gastropod herbivores were excluded. These substrata were not directly comparable to cleared substrata with herbivores present since they were established four weeks later; a significant period of larval settlement may have been missed. Low barnacle recruitment rates may also have been a result of a larval aversion to the substances used to exclude the herbivores.

In spite of the relatively low recruitment, the numbers of Balanus glandula colonizing oil-impacted areas were significantly lower than those colonizing control areas as measured during the June and July censuses (Mann-Whitney U-tests: $P < 0.05$) (Figure 12). These results further suggest that persistent oil residues actually inhibited barnacle recruitment and recovery in oil-impacted areas after eliminating algal cover, adult barnacle abundance, and gastropod abundance as possible confounding factors.

Very few Chthamalus dalli recruits were observed on cleared substrata from which herbivores were excluded, and no attempt was made to analyze the data. Again, the late starting date of the experiment and larval reactions to the herbivore exclusion treatment itself may have reduced barnacle recruitment.

No algal cover developed on any cleared substrata with herbivores excluded during the period of this experiment (until the end of July).

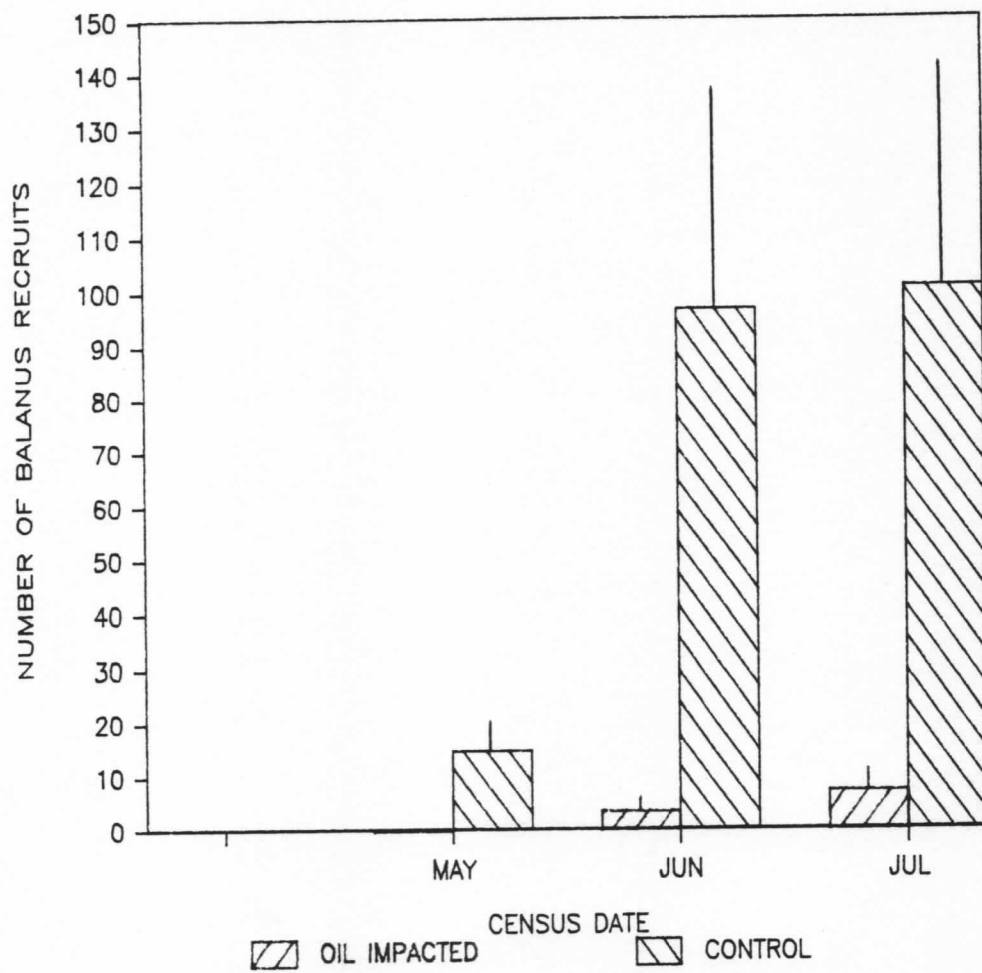


Figure 12: Numbers of *Balanus glandula* recruits (with standard errors) on experimentally cleared substrata in oil-impacted and control areas when gastropod herbivores were excluded

Artificial Substrata

The numbers of barnacles colonizing ceramic plates were low. Figure 13 shows the numbers of Balanus glandula and Chthamalus dalli combined which recruited to the artificial substrata. No barnacles were ever observed on substrata located in the oil-impacted area. Significantly greater numbers of barnacles were observed in control areas during the April census (Mann-Whitney U-test: $P < 0.05$).

Cypris larvae settling from the plankton may have been less abundant (and less available to colonize the ceramic plates) in oil-impacted areas than in control areas, though the proximity and the physical similarities of the two areas makes this possibility seem unlikely. Larvae may otherwise have avoided settling in general areas impacted by oil if residues still remained, or may have preferentially settled in areas adjacent to thriving adult populations (control areas). The details and scale of larval settling behavior are not known with enough confidence to distinguish between these alternatives based on the available results.

Summary

Between November 1984 and March 1985, there was no recovery of barnacle populations at sites where adult mortality had been severe as a result of the Puerto Rican oilspill. The persistence of barely discernible oil residues apparently prevented successful larval recruitment in these areas although heavy widespread recruitment was apparent in surrounding habitats. Surveys of organisms in oil-impacted areas indicated that large faunal changes had accompanied the loss of barnacles. This study showed that gastropod herbivores, in particular, either died or emigrated at affected sites, and that altered community interactions were probably the cause of algal blooms on substrata devoid of pre-spill populations of barnacles and invertebrate herbivores.

Evidence from field experiments conducted between April and July 1985 indicated that larval recruitment of barnacles was inhibited at

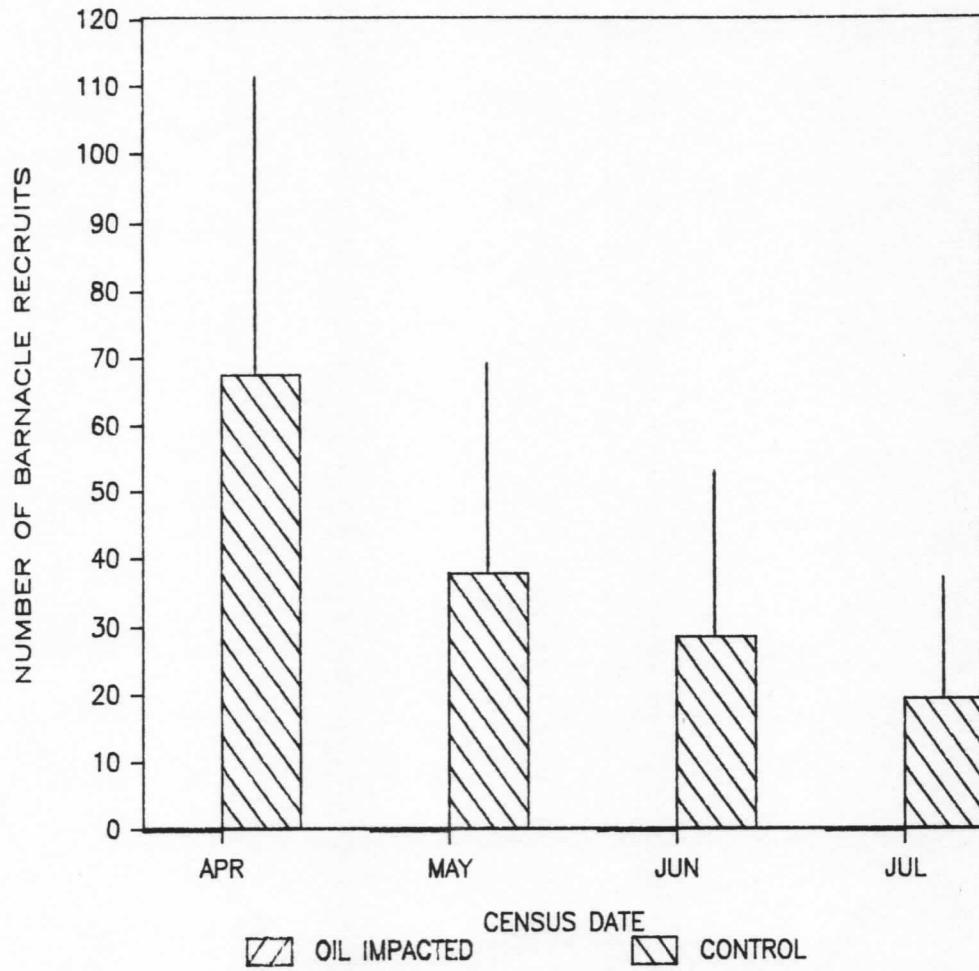


Figure 13: Numbers of Balanus glandula and Chthamalus dalli recruits combined (with standard errors) on artificial substrata in oil-impacted and control areas

oil-impacted sites for at least 8 months after the initial oilspill. The results from cleared experimental plots with and without herbivores and from artificial substrata suggest that persistent oil residues contributed to the slow recovery of barnacle populations. However, new barnacle recruits did settle and survive on unaltered substrata in oil-impacted areas suggesting that the spatially dominant pre-spill populations of Balanus glandula will recover if no further disturbances occur.

III. Toxicity of Oil to Balanus glandula Larvae

Materials and Methods

We conducted controlled laboratory studies intended to determine the levels of oil which are toxic to swimming barnacle larvae. During late August, 1985, adult Balanus glandula were collected on small rocks from Bodega Harbor near Westside Park (Figure 14). The two egg lamellae were dissected from brooding adult barnacles after the barnacles were removed from the rocks. One egg lamella from each barnacle was examined under a light microscope to determine the developmental stage of the eggs. If the eggs were in the final stages of development (i.e., transparent, unhatched larva with prominent nauplius eye and active appendages), the second egg lamella was placed in a 500 ml beaker with unfiltered seawater and aerated continuously. Temperatures were maintained at approximately 16° C for the duration of the experiment.

After six hours, emerging nauplius larvae were transferred to separate 1000-ml beakers containing 600 ml of filtered (1 um mesh and UV-irradiated) seawater and 225 ml of a diatom mixture (Thalassiosira and Chaetoceros) which provided food for the larvae. Forty-eight hours later, 450 surviving nauplii from each brood were distributed among nine 400-ml beakers containing 200 ml of filtered seawater and 75 ml of the diatom mixture. After another 24 hours, the nauplii in each beaker were re-counted. All beakers were aerated continuously until this time.

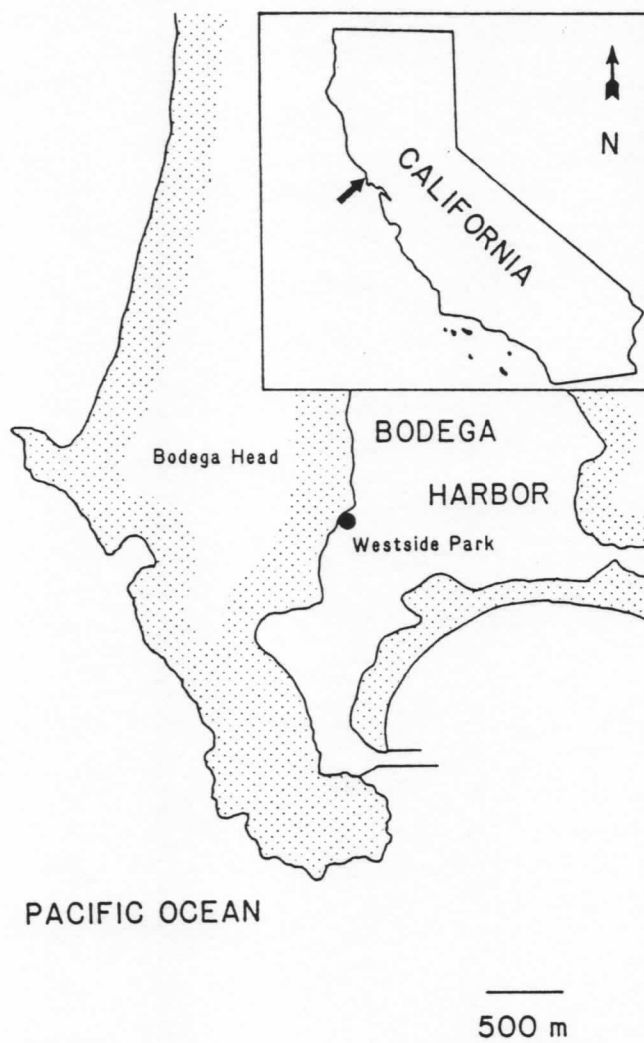


Figure 14: Site of adult barnacle collections (Balanus glandula) used to obtain larvae for laboratory studies of oil toxicity

Seventy-two hours after the barnacle larvae hatched from their eggs, two concentrations of Alkane-60 (a refined petroleum component of the spilled oil) were added to some of the beakers containing larvae. Three beakers each received 1.0 ml (high concentrations) of Alkane-60, and three beakers each received 0.2 ml (low concentrations) of Alkane-60. Three beakers were left oil-free to serve as experimental controls. All beakers were immediately stirred vigorously for 30 seconds, and again twice each day for the duration of the experiment.

Surviving nauplii were counted every 24 hours for a period of 17 days. The effects of the different concentrations of Alkane-60 on the survivorship of nauplii were compared statistically using one-tailed Mann-Whitney U-tests (Sokal and Rohlf 1981) to determine if mortality rates were significantly higher in oil-contaminated treatments.

Results and Conclusions

Increasing concentrations of Alkane-60 had a detrimental effect on the larval survival of Balanus glandula in a laboratory situation. Figure 15 shows patterns of mortality for barnacle nauplii exposed to high and low concentrations of the compound and in non-oiled controls over a 16-day period. Although nine days after initial exposure to oil, large numbers of larvae had died in all treatments, survivorship was significantly decreased with any additions of oil (Mann-Whitney U-tests: $P < 0.05$). Twelve days after initial exposure, not only was mortality increased at low oil concentrations compared to nauplii maintained with no oil present, but mortality for larvae maintained in high oil concentrations was also significantly greater than for nauplii maintained with low oil concentrations (Mann-Whitney U-tests: $P < 0.05$).

Water-soluble oil fractions appear likely to have had a toxic impact on barnacle nauplii since mortality directly increased with increasing concentrations of Alkane-60. However, during the experiment, oil tended to form water-insoluble droplets at the water surface. Mortality of barnacle larvae may have occurred in part as a result of direct physical contact with these droplets. Toxic and mechanical

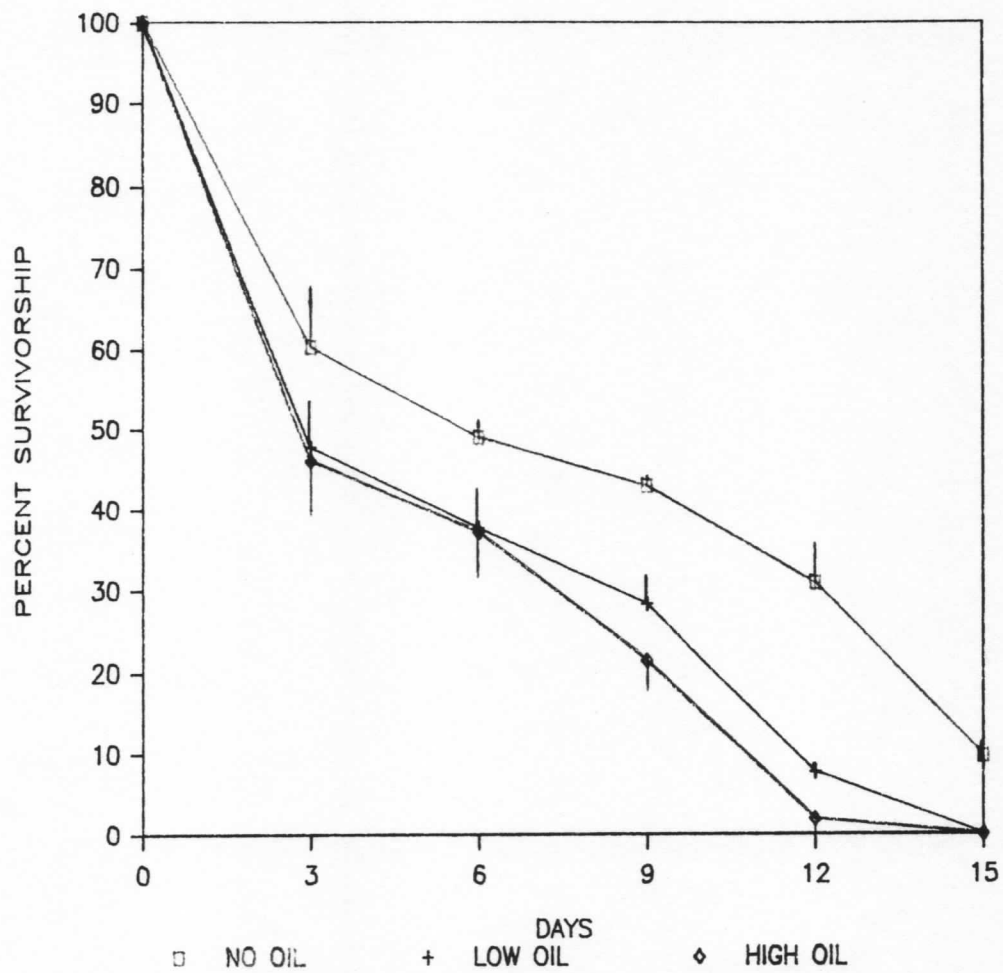


Figure 15: Survivorship of Balanus glandula larvae (with standard errors) exposed to three concentrations of oil (Alkane-60)

effects of relatively insoluble oil fractions would presumably be significant only if larvae made contact with the droplets, although, alternatively, the oil at the surface may have reduced oxygen exchange and, under laboratory conditions, produced physiological stress for the larvae beyond any toxic effects of the oil itself.

The applicability of laboratory results to pelagic populations of barnacle larvae and other planktonic organisms is difficult to estimate. Components of the spill from the Puerto Rican show some demonstrable toxicity, but the actual impact on natural populations would have depended upon the extent and dispersal of oil, the micro-diffusion and persistence of toxic components, the length of time that individual organisms were exposed to toxic concentrations, and the abundances of the organisms themselves.

General Discussion and Conclusions

Both adult and larval barnacles were susceptible to the direct toxic effects of oil spilled from the damaged T/V Puerto Rican. It was not possible to determine the extent of the impact on natural populations of planktonic larvae. Although the potential spatial scale of impact was enormous, there were no obvious indications that larval populations were seriously impaired; larval recruits were extremely abundant locally several months after the oilspill. The initial severity of adult mortality was apparently confined to limited stretches of shoreline in and near Bodega Harbor.

However, affected sites retained visible traces of oil for at least several months even though mechanical means were used to remove most of the oil within days after initial contamination. Concentrations of residues seemed to be high enough to cause mortality in newly-exposed barnacles and to deter recovery of barnacle populations by retarding recruitment of barnacle cypris larvae. Some level of continuing barnacle mortality may have resulted from the direct chronic toxicity of

oil traces, although this study did not attempt to determine how great that mortality might have been nor for what length of time oil toxicity may have lasted.

However, there were clearly additional changes in barnacle habitats that were indirectly related to the presence of oil. As this study shows, large faunal and floral alterations occurred in the months following the oilspill. Adult gastropod herbivores, in particular, decreased in number as a result either of mortality or of emigration from impacted areas. The suitability of the habitat was impaired perhaps because of the toxic effects of oil or of reduced availability of necessary resources following contamination by oil. The loss of herbivores presumably facilitated the bloom of algae on oil-affected substrata. So, not only did the oilspill cause severe barnacle mortality, but habitat quality, population dynamics, trophic relationships, and community composition and structure were also disturbed.

At the field sites examined in this study, dense populations of Balanus glandula dominate the natural substrata. A return of the typical biological community associated with B. glandula is presumably dependent upon the recovery of these barnacles. However, recruiting barnacle larvae appeared to prefer or to survive better in areas not impacted by oil.

Other researchers (e.g., Luckens 1970) have indicated that barnacle recruitment can be enhanced if open space (a resource typically in limited supply for sessile intertidal organisms) is provided. During this study, however, the experimental provision of open space by clearing of algal cover failed to accelerate B. glandula recruitment in oil-impacted areas and, in fact, appeared to inhibit recovery of barnacle populations. Even though recovery of the barnacle community may have been slowed by oil residues, further actions which may have removed or reduced the concentrations of oil were unsuccessful in promoting new recruitment.

The effects of the oilspill on the organisms studied in this investigation are presumed to be representative of the impact to the great diversity of species that inhabit shore environments. On a very

local scale, some populations were devastated, and a considerable amount of time may pass before typical population densities and dynamics of all species are restored at all sites. However, species which dominated the community before the oilspill are, in fact, capable of recruiting to impacted areas and are expected to re-establish adult populations eventually, assuming that there are no further environmental disturbances.

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