

San Onofre Region. SOKU is the Near Impact site, SOKD is the Far Impact site, and SMK is the Control site.

is effected because the 63 discharge jets turbulently mix with ambient water. The cooled water is  $\approx 10$  times that of the ambient. A major consequence of the cooling is that the discharge adds a large flux of

organisms. Both were at a depth of  $\approx 14.5$  m. The Near Impact site (Fig. 1: SOKU) was placed as near to the diffusers as possible within the kelp forest,  $\approx 400$  m downcoast. The Far Impact site (Fig. 1: SOKD) was placed as far from the diffusers as possible within the

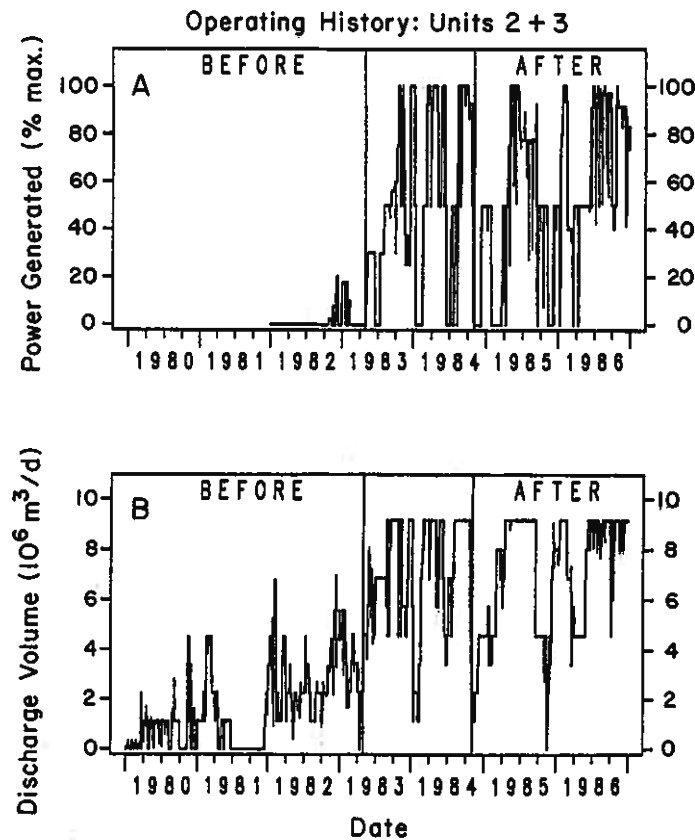


FIG. 2. Combined operating history of Units 2 and 3 of the San Onofre Nuclear Generating Station. The effluent is heated significantly above ambient temperature only when power is being generated. From 1980 to 1983 the new generating units were undergoing testing.

2–3 wk and the data transferred to computer files (Eco-M 1987).

Seston flux was estimated by measuring the accumulation of sediment within sediment traps. The traps were acrylic tubes 2.5 cm in diameter and 30 cm long, closed at the bottom with a rubber stopper. Sets of three tubes were held vertically in the water column on floating racks 2 m above the bottom at each sampling site. The traps were replaced approximately bi-weekly and the height of the accumulated sediment was measured in the laboratory. The mean of the three tubes was used as the variate in the analysis (Eco-M 1987).

#### Statistical design and analysis

We did two types of analyses based on the Before–After/Control–Impact (BACI) sampling design (Stewart-Oaten et al. 1986) to test for the presence of a power plant effect: the *t* test and the analysis of variance. We estimated the density of organisms at about the same time at Control and Impact sites on replicate surveys during ≈2.5-yr periods Before and After the power plant began operation. To test for an effect of the power

plant we first log-transformed the data to achieve additivity (Stewart-Oaten et al. 1986). We then calculated the differences (deltas) between the values at the Impact and Control sites on each survey.

*t* test.—Deltas were averaged over each operational period. The difference between the average Before and After deltas provides an estimate of the effect of the power plant on density. A *t* test was done to determine whether this difference was significantly different ( $P \leq .05$ ) from zero. Before log transformation, the model underlying the *t* test (Table 2) can be represented as:

$$X_{ijk} = mS_{i0}P_jL_kE\epsilon_{ijk}, \quad (1)$$

where  $X$  is abundance at the  $i$ th survey, in the  $j$ th operational period, and the  $k$ th location;  $m$  = the mean value at the Control site during the Before period,  $S_{i0}$  = the effect of Survey  $i$  in Period  $j$ ;  $L_k$  = the effect of Location:  $L_1 = 0$  (Control),  $L_2 = 1$  (Impact);  $P_j$  = the effect of operational period:  $P_1 = 0$  (Before period),  $P_2 = 1$  (After period);  $E$  = the effect of the impact:  $E = e$  at the Impact site in the After period and 0 otherwise; and  $\epsilon_{ijk}$  = error.

We assume that  $\log(\epsilon_{ijk})$  is normal, with mean = 0,

TABLE 4. Results of *t* tests comparing the average difference in density of large kelp forest invertebrates at the Near Impact and Control sites during the periods Before and After the start of full-power operation of the nuclear power plant. *P* values  $\leq .05$  are in bold.

Species	Number of surveys		<i>P</i> value	Effect size (%)	Power (%)
	Before	After			
<b>Porifera</b>					
<i>Tethya aurantia</i>	10	8	.966	+ 16.9	72.5
<b>Cnidaria</b>					
<i>Muricea californica</i>	10	8	<.001	+ 318.0	46.0
<b>Mollusca</b>					
<i>Conus californicus</i>	6	8	<.002	-90.8	64.7
<i>Cypraea spadicea</i>	9	8	.003	-61.9	39.9
<i>Kelletia kelletii</i>	10	8	<.001	-63.5	72.0
<i>Maxwellia gemma</i>	2	8	.019	-88.9	11.9
<i>Mitra idae</i>	6	8	.151	-70.6	11.2
<i>Murexiella santarosana</i>	2	7	.009	-86.3	16.3
<i>Nassarius</i> spp.	2	7	.476	-36.3	10.1
<i>Pteropurpura festiva</i>	2	8	.111	-84.2	8.5
<i>Tegula aureotincta</i>	2	5	.013	-93.2	9.1
<b>Echinodermata</b>					
<b>Sea Urchins</b>					
<i>Lytechinus anamesus</i> <sup>*</sup>	10	8	.018	-76.6	43.2
<i>Strongylocentrotus purpuratus</i>	10	8	.651	+0.7	19.3
<b>Sea Stars</b>					
<i>Asterina (= Patiria) miniata</i>	10	8	<.001	-85.8	38.1

\* = Analysis was done with first-order autoregressive model to correct for serial correlation, but power was calculated from ordinary least-squares model and overestimates true power.

between the Near and Far Impact sites as the variate. Because the  $d_{ijk}$ s are computed by subtracting the same control value from each of the impact values on the same survey, they are likely to be correlated. This does not affect the *F* test provided the correlation does not vary over time (Greenhouse and Geisser 1959).

Tests for additivity, trends, and serial correlations were done on the deltas for both the Near and Far Impact sites in the Before period. The analysis of variance was done only if a common transformation produced additivity and lack of trends for both sets of deltas. In cases where these criteria were not satisfied an analysis of variance was not performed.

**Statistical significance and power.**—In our hypothesis tests, we set the significance level ( $\alpha$ ) of the *t*-test at .05. The value of .05 is a common and arbitrarily set probability of falsely finding a difference between means when there is none (Type I error). One would also like to know the probability of falsely concluding that there is no difference when one exists. This Type II error (usually designated as  $\beta$ ) depends on the variability of the data, the number of samples taken, and the size of the difference in means one wishes to detect. Power =  $1 - \beta$ , and is the probability of finding a difference of a given size if it does in fact exist. In our studies, we have calculated the power to detect a halving or doubling of density with  $\alpha = .05$  for the *t* test, and for the Period effect and the Period  $\times$  Site interaction in the analysis of variance.

## RESULTS

Eighteen species of kelp forest invertebrates were screened for testing for an effect of the power plant (Tables 1 and 3–5). We performed *t* tests for nine species for which the data appeared to be additive and showed no evidence of temporal trends in the Before period, and also on the five species that were sampled only twice in the Before period and for which the data could not be tested for violations of assumptions (Table 4). The data for seven species passed the more restrictive assumption tests for the analysis of variance (Table 5). Analysis of variance was also performed on three species that were only sampled twice in the Before period.

Most of the species studied showed marked declines in population density in the impact area relative to the control area after Units 2 and 3 began operating at their normal, sustainable level. Of these, most declined in absolute numbers at the impact sites, and the declines were most pronounced nearest the diffusers (Table 3). Although not every individual result is statistically significant, the consistency of the overall pattern is notable.

### Snails

The majority of the species of snails that were counted declined in density in the San Onofre kelp forest during the operational, or After, period. At the same time, these species either declined to a lesser degree,

TABLE 5. Results of analysis of variance on the average difference in density of large kelp forest invertebrates at the Near Impact and Far Impact sites during the Before and After periods. The analysis simultaneously compares the Near (SOKU) and Far (SOKD) Impact sites to the Control. *P* values < .05 are in bold.

Species	Effect size (%)		Period			Period × Site			
	SOKU	SOKD	<i>F</i> (df)	<i>P</i>	Power (%)	<i>F</i> (df)	<i>P</i>	Power (%)	
Porifera									
<i>Tethya aurantia</i>	16.9	85.1	5.04 (1,16)	<b>.04</b>	37.9	4.99 (1,16)	<b>.04</b>	39.3	
Cnidaria									
<i>Muricea californica</i>	318.0	590.6 <sup>^</sup>	...	...	...	...	...	...	
Mollusca									
<i>Conus californicus</i>	-90.8	-81.0	46.46 (1,12)	<b>.0001</b>	57.9	4.26 (1,12)	.06	50.1	
<i>Kelletia kelletii</i>	-63.5	-51.8	12.33 (1,16)	<b>.003</b>	77.2	3.12 (1,16)	.096	98.0	
<i>Maxwellia gemma</i> *	-88.9	-61.1	4.00 (1,8)	.08	16.4	6.00 (1,8)	<b>.04</b>	20.6	
<i>Mitra idae</i>	-70.6	-35.0	1.55 (1,12)	.24	17.8	3.47 (1,12)	.087	28.9	
<i>Murexiella santarosana</i> *	-86.3	-62.8	3.42 (1,8)	.10	25.7	1.00 (1,8)	.35	9.1	
<i>Pteropurpura festiva</i> *	-84.2	-73.6	2.87 (1,8)	.13	8.7	1.11 (1,8)	.32	5.2	
Echinodermata									
Sea Urchins									
<i>Lytechinus anamesus</i> <sup>^</sup>	-76.6	-40.4	3.14 (1,15)	.08	99.8	6.29 (1,15)	<b>.02</b>	68.7	
<i>Strongylocentrotus purpuratus</i>	+0.7	+47.6	0.35 (1,16)	.56	23.5	4.43 (1,16)	<b>.05</b>	49.7	
Sea Stars									
<i>Asterina (= Patiria) miniata</i>	-85.8	+0.1	81.11 (1,16)	<b>.0001</b>	60.9	81.1 (1,16)	<b>.0001</b>	82.1	

\* Assumption test not done.

<sup>^</sup> = Deltas (differences between population densities at Impact and Control sites on each survey) are non-additive in the Before period.

<sup>^</sup> Analysis was done with first-order autoregressive model to correct for serial correlation, but power was calculated from ordinary least-squares model and overestimates true power.

or increased in abundance at the San Mateo kelp forest (Table 3). This resulted in large relative declines at the Impact sites. At the Near Impact site, all 11 species of snails for which an effect size was calculated declined in density relative to the Control. All but one of these relative declines exceeded 50% (Table 4). At the Far Impact site, all snail species for which an effect size could be calculated also showed relative declines in density (Table 5). However, in every case, the relative declines were less than those seen at the Near Impact site.

We performed *t* tests on the data for nine species of snails. Six showed statistically significant declines at the Near Impact site relative to the Control (Table 4). Analysis of variance was appropriate for six of the species. For two of these, the change averaged over the Near and Far Impact sites was statistically significant (Table 5: Period effect). For one, the decline was significantly greater at the Near than at the Far Impact site (Table 5: Period × Site). Below are the results for individual taxa.

*Snails sampled on most pre-operational surveys.*—Four species of snails were counted on most pre-operational surveys (*Conus californicus*, *Cypraea spadicea*, *Kelletia kelletii*, and *Mitra idae*). All are benthic predators (Morris et al. 1980) that are ubiquitous in southern California kelp forests (J. D. Dixon, J. Kastendiek, R. O. Smith, and S. C. Schroeter, *personal observations*). The abundances of all four declined at

the Near Impact site relative to the Control. The declines were statistically significant for all but *Mitra idae* (Table 4).

These relative declines were brought about by two different patterns of change in abundance. One, illustrated by *Conus californicus*, was a decline in abundance at the Impact sites accompanied by an increase at the Control (Fig. 3). The other, illustrated by *Mitra idae*, was an increase at the Control, accompanied by little or no change at the Impact sites (Fig. 4).

*C. californicus* and *K. kelletii* were both more abundant at the Impact sites than at the Control site during the Before period. Their average abundance declined at both the Near and Far Impact sites during the After period. The decline was greater at the Near Impact site for both species, but there was not a significant Period × Location interaction (Table 5), indicating power plant effects of similar magnitude at both sites.

Although *M. idae* changed in relative abundance similarly to the other three species, neither the effects of Period (Tables 4 and 5) nor the Period × Location interaction were statistically significant (Table 5). However, the power for all tests was very low (Tables 4 and 5).

*Snails sampled on only two pre-operational surveys.*—Five snail taxa were analyzed separately because they were only sampled near the end of the Before period. As a consequence, the assumptions underlying the hypothesis tests could not be adequately tested.

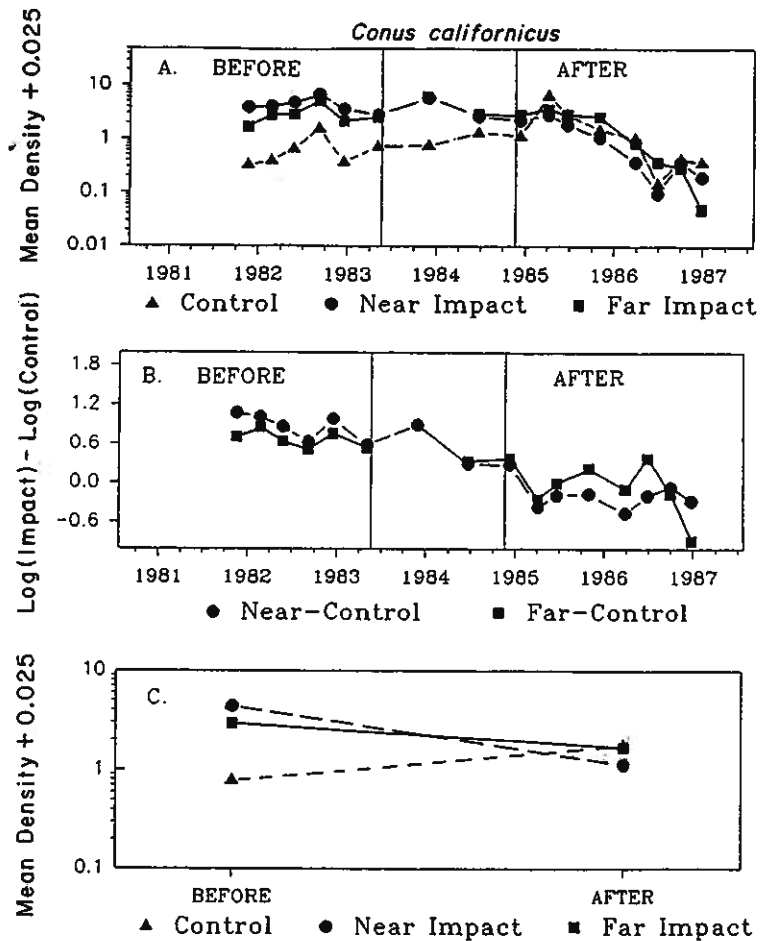


FIG. 3. Changes in the abundance of *Conus californicus* in a kelp forest off the coast of Southern California, in the vicinity of the cooling-water discharge of the San Onofre nuclear power plant. (A) Average density at the Near Impact (SOKU), Far Impact (SOKD), and Control (SMK) sites during the preoperational (Before), interim, and operational (After) periods. Each point is the mean from 40 1-m<sup>2</sup> quadrats plus the constant, *C*, specified in the ordinate labels of graphs A and C. (B) Delta plot. Difference in the logs of the average density (mean + *C*) at the Impact and Control sites. These are the data used in the *t* test and the analysis of variance. (C) Interaction plot. Overall average density in the Before and After periods at the Impact and Control sites.

Standing alone, these results are less convincing evidence for an effect of the generating station than the results from species sampled more often and over a longer time period. However, the patterns are similar to those for the species sampled on many pre-operational surveys and thus tend to corroborate the hypothesis of a power plant effect.

*Maxwellia gemma*, *Murexiella santarosana*, and *Pteropurpura festiva* are benthic predators; *Nassarius* spp. are scavengers; and *Tegula aureotincta* is an herbivore (Morris et al. 1980). The abundance of all five taxa declined at the Impact sites relative to the Control (Tables 4 and 5). Relative declines were brought about by changes in abundance similar to those seen for *C. californicus*, namely a decrease at the Impact site and an increase or no change at the Control during the After period (Table 3). Relative declines exceeded 80% at the Near Impact site for four of the species (*M. gemma*, *M. santarosana*, *P. festiva*, and *T. aureotincta*), and were statistically significant for all but *P. festiva* (Table

4). Anovas were performed on data for *M. gemma*, *M. santarosana*, and *P. festiva*. The declines were larger at the Near Impact site but the Period × Location interaction was only significant for *M. gemma* (Table 5). The power to detect a Period × Location interaction was low for the remaining two species (Table 5).

#### Echinoderms

Data for the two sea urchins and a sea star passed the assumptions for the *t* test and the analysis of variance. All three are common inhabitants in southern California kelp forests. White sea urchins, *Lytechinus anamesus*, are abundant in the San Onofre region, particularly along the outer edges of the kelp forests (Schroeter et al. 1983). They often move about a great deal and graze on both drifting and attached algae (Leighton 1971, Dean et al. 1984, 1988), and prey on other urchin species (Coyer et al. 1987). White sea urchins were most abundant at the Impact sites in the