DETECTING THE ECOLOGICAL EFFECTS OF ENVIRONMENTAL IMPACTS: A CASE STUDY OF KELP FOREST INVERTEBRATES[1]

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Abstract. Detecting the environmental impacts of human activities on natural communities is a central problem in applied ecology. It is a difficult problem because one must separate human perturbations from the considerable natural temporal variability displayed by most populations. In addition, most human perturbations are generally unique and thus unreplicated. This raises the problem of deciding whether observed local effects are due to human intervention or to the natural differences in temporal patterns that often occur among different sites. These problems can be successfully addressed with the Before–After/Control–Impact (BACI) sampling design, in which Impact and Control sites are sampled contemporaneously and repeatedly in periods Before and After the human perturbation of interest. In the present case, we use this design to examine the ecological effects of the cooling water discharge from a coastal nuclear power plant in southern California.

The results suggest some general lessons about the process of impact assessments that are applicable in many ecological contexts. In systems where plants and animals are long-lived and recruit sporadically, the rates of change in density are often so low that sampling more than a few times per year will introduce serial correlations in the data. As a result, for studies of few years duration, few samples will be taken. A small sample size means that the tests of the assumptions underlying the statistical analyses, e.g., independence and additivity, will have low power. This injects uncertainty into the conclusions. Small sample size also means that the power to detect any but very large effects will be low. In our study, sampling periods of 2–3 yr both Before and After the impact were not long enough to detect a halving or doubling of populations at the impact site. We concluded that there were significant environmental impacts because: (1) the effect size was generally very large ($\approx -75\%$); (2) there was a consistent pattern among species; (3) there were two Impact sites, and effects were larger at the site nearest the discharge; (4) the observed effects accorded with physical changes that could be linked with the source of impact; and (5) a number of alternative mechanisms, unrelated to the source of impact, were examined and rejected.

Relative to control populations, there were statistically significant reductions in density of snails, sea urchins, and sea stars, all of which occurred primarily on rocky substrates. All of the reductions were larger at the Impact station about 0.4 km from the discharge than at a second Impact station 1.4 km away. The most plausible mechanisms for the declines seem to be linked to the turbidity plume created by the power plant and the resultant increase in suspended inorganic and organic materials (+46% at the Impact site nearest the discharge). Any associated flux of fine particles on rocks would have deleterious effects on many of the hard benthos. Populations of two filter-feeding species, a gorgonian coral and a sponge, showed relative increases in density. Although the increase in populations of filter feeders could be related to the ingestion, killing, and discharge of tons of plankton by the cooling system, an alternative natural mechanism was also considered reasonable.

Monitoring studies of relatively long-lived organisms will often have low power to detect ecologically significant changes in density. The present study of kelp forest organisms extended over nearly 6 yr, yet the resulting statistical tests generally had power of <30% to detect a doubling or halving in density at a significance level of .05. In such a community it would be a mistake to conclude that there were no significant ecological effects based on conventional hypothesis tests. Unless there is a willingness to accept the fact that changes in natural populations on the order of 50% will often go undetected, the standards and types of evidence used to demonstrate environmental impacts must be changed.

Key words: BACI statistical analysis; California; effect size; effluent; environmental impact assessment; kelp forest invertebrates; nuclear power plants; open coast; pollution; serial correlation; statistical power; turbidity.

INTRODUCTION

A central problem in applied ecology is the detection of the impacts of human activities on natural communities. Since abundance and other attributes of most natural populations vary greatly in space and time, the detection of anthropogenic perturbations against the background of the naturally occurring variation poses non-trivial methodological and statistical problems (Hurlbert 1984). However, recent work has shown that these problems are potentially tractable (Eberhardt 1976, Skalski and McKenzie 1982, Stewart-Oaten et al. 1986, Carpenter 1989, Carpenter et al. 1989, Underwood 1991, Stewart-Oaten et al. 1992). There is an emerging consensus that in order to detect impacts one should sample repeatedly and contemporaneously at the potential impact site, and at one or more control sites during the periods before and after the impact has begun.

Stewart-Oaten et al. (1986) suggest that to judge whether an impact has occurred one calculate the differences in the variate of interest, generally abundance, between the Impact and Control sites on each survey and compare the averages of these differences in the Before and After periods. The critical elements in this design are that the populations at the Control and Impact sites be sampled at about the same time during each survey and that they vary in about the same way, or track one another, prior to the perturbation being studied. The two populations do not have to have equal densities and their densities do not have to be constant. There may be natural secular trends, cycles, or seemingly non-periodic fluctuations in the populations, but if the populations track one another, the differences between the two sites will vary randomly about some mean value in the Before period. If there is an effect of the perturbation on the mean population at the Impact site, the average difference between it and the Control population will increase or decrease. Provided that certain statistical criteria are satisfied, a statistically significant change in the average difference, or "delta," between the populations after the onset of the perturbation is strong evidence of an ecological effect of the environmental impact. This sampling design is called the Before–After/Control–Impact design (BACI).

From 1980 to 1987 we conducted studies of the ecological effects of the cooling water discharge from two new generating units of the San Onofre Nuclear Generating Station, which is located on the open coast in northern San Diego County, California. Here we present the results of studies of the impacts of the discharge on invertebrates that inhabit forests of giant kelp, *Macrocystis pyrifera*. We used the BACI sampling design, with a few modifications, to detect effects on population densities. We tested for changes from before to after the new generating units began operating, estimated the size of these effects, and calculated the power of the tests. One modification of the BACI design

was the incorporation of a second impact site into the analysis. The intent of having two impact sites located at different distances from the generating station was to provide some information on the size of the area affected.

Other investigators were engaged in assessing the effects of the power plant on the physical environment, and a great deal of oceanographic data were collected during the period of our studies. We have examined these data for physical correlates to the biological changes we observed, which provide clues to the mechanisms underlying the ecological effects. Comparison of oceanographic data from the Control and Impact sites also enables one to test whether large-scale changes, such as the 1982–1984 El Niño, affected the two sites differently.

The organisms we studied are long-lived and recruit infrequently. These characteristics are typical for species in many communities and pose special problems for the environmental biologist. This study has taught us some lessons that we think may be germane in many ecological contexts.

METHODS

San Onofre Nuclear Generating Station

The San Onofre Nuclear Generating Station consists of three units. Unit 1 was commissioned in 1968. Units 2 and 3, the subjects of our study, began operating near their full combined capacity in 1983. Each of the new units contains a pressurized-water nuclear reactor with an electrical output of 1100 MW. The steam used to drive the turbines is generated by heat from the reactor and is then cooled by exchanging heat with ambient sea water.

The once-through cooling system for each unit has a maximum flow rate of 3137 m³/min (1.66 × 10⁶ gal/min) and raises the temperature of the withdrawn sea water 10.7°C (MRC 1988a). The intake structures of both units are located 970 m offshore in 9.1 m of water (Fig. 1) and withdraw water from ≈2.1 m above the sea floor. After passing through the cooling system of the power plant, the heated water is directed offshore where it is discharged through two diffuser pipes. Each diffuser pipe is ≈800 m long and perpendicular to the shoreline. The diffuser structures for Unit 2 lie seaward of the structures for Unit 3, so that together, the diffusers extend from ≈1.0 km to 2.5 km offshore from the power plant. Along each pipe the heated water is discharged through diffuser ports located in 63 evenly spaced outfall riser. The openings of the diffuser ports are ≈2.2 m above the sea floor, are ≈0.6 m in diameter, and are angled upwards and alternately upcoast and downcoast.

The diffuser system was designed to discharge the heated effluent without increasing local sea-surface temperatures above regulatory thermal standards.
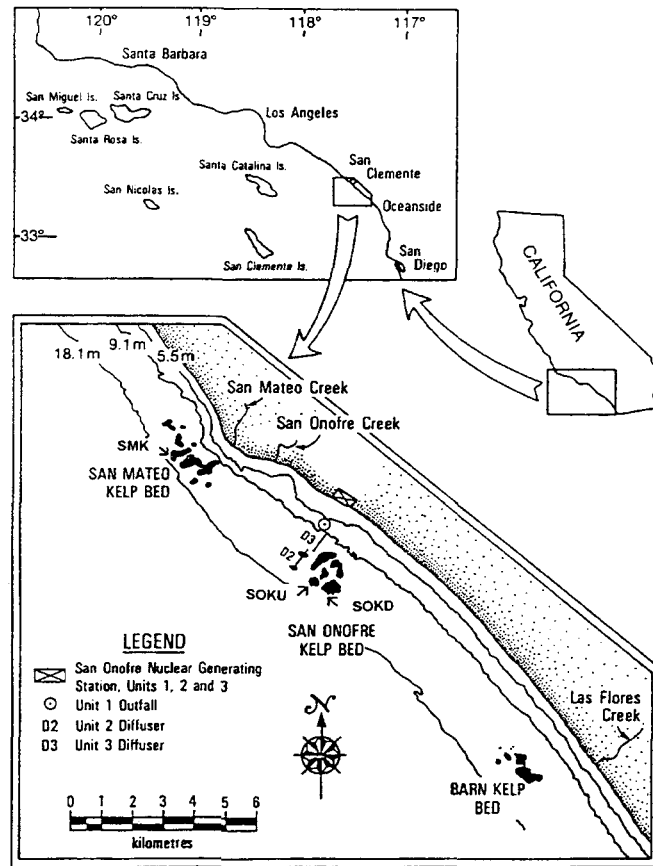
FIG. 1. San Onofre Region. SOKU is the Near Impact site, SOKD is the Far Impact site, and SMK is the Control site.

Rapid cooling is effected because the 63 discharge jets entrain and turbulently mix with ambient water. The volume of entrained water is ≈10 times that of the discharged water. A major consequence of the cooling system design is that the discharge adds a large flux of seaward momentum to local waters (Eco-M 1988). The large and rapid upward and seaward redirection of water and associated suspended inorganic particles and passive organisms appears to be one of the two most significant impacts of Units 2 and 3 on the local physical environment. A second similar impact results from withdrawing turbid nearshore water and discharging it offshore. The cooling water effluent is discharged ≈0.4 km upcoast (northwest) of the San Onofre kelp forest (Fig. 1).

Study sites

Two stations were established in the San Onofre kelp forest, the site of potential impacts on kelp forest or-

ganisms. Both were at a depth of ≈14.5 m. The Near Impact site (Fig. 1: SOKU) was placed as near to the diffusers as possible within the kelp forest, ≈400 m downcoast. The Far Impact site (Fig. 1: SOKD) was placed as far from the diffusers as possible within the kelp forest, ≈1400 m downcoast. This design allowed us to determine whether effects were detectable throughout the kelp forest or were confined to some area closer to the diffusers than the Far Impact station. A third site, the Control (Fig. 1: SMK) was located in the San Mateo kelp forest, 4.5 km to the northwest in ≈12.5 m of water. All of the study sites remained inside of kelp forest boundaries for the duration of the study.

Each site consisted of a metal plate that marked the origin of four 40 m long transects. The transects were oriented in the shape of a cross. Steel rods were driven into the substrate every metre along the transects to help divers find their way during the frequent periods of poor visibility. A permanent 1-m² quadrat was positioned every 4 m along each transect. Thus, at each

study site, there were 40 fixed quadrats within which
plants and animals were periodically censused. All the
sites were located under kelp canopy and placed so that
each of the permanent quadrats was at least 10 m from
the nearest sand patch.

Species studied

The invertebrate species studied were chosen be-
cause they are common members of kelp forest com-
munities in southern California and are easily and re-
liably counted by divers in the field, even under
conditions of poor underwater visibility. Thus, while
a number of larger motile and sessile invertebrate spe-
cies were sampled, most sessile species, including the
smaller species that make up the "fouling" community
on many rocky substrates (e.g., bryozoans, hydroids,
and most sponges), were not. Forty-one species of in-
vertebrates were counted (Table 1). Twenty-three spe-
cies were sampled from the beginning of the study.
Five species of snails were added to the sample list
during the first few surveys, and an additional 13 spe-
cies of snails were added beginning with the penulti-
mate Before sample.

Of the 41 species sampled, 22 were rare throughout
the study. Most of these were absent from two of the
three study sites throughout the After period. Two were
absent at the Control throughout the Before period and
during most of the After period. Data for these species
were not analyzed. Red sea urchins, *Strongylocentrotus
franciscanus*, were sampled, but the data were not an-
alyzed because differential effects of harvesting could
be confounded with a power plant effect. Throughout
the Before period red urchins were commercially har-
vested in both kelp forests. By late 1984 there were so
few red urchins left in the San Onofre kelp forest that
commercial harvesting was no longer feasible. How-
ever, harvesting continued at San Mateo. We've con-
sidered the possibility that reductions of red urchin
populations from harvesting may have indirectly af-
fected the abundances of other species. No experiments
were done to test this hypothesis. However, since har-
vesting tended to bring red urchin populations to sim-
ilar low numbers at our sampling stations at both Con-
trol and Impact sites, we think it unlikely that it would
bias our estimates of a potential power plant effect.

Beginning on the fourth survey in the After period,
a large feeding aggregation, or "front," of red sea ur-
chins moved onto parts of the Control site in the San
Mateo kelp forest. By the end of the study this front
had occupied all of the quadrats on two of the four
transects. There are well-documented cases of such
fronts adversely affecting both algal (Dean et al. 1984)
and invertebrate (Ebert 1977; S. C. Schroeter, J. D.
Dixon, and R. O. Smith, *personal observations*) com-
munities. Therefore, data from the quadrats occupied
by the front were not included in the analyses. As a
result, means at the Control site had sample sizes for

the last five surveys of 39, 34, 31, 27, and 20, rather
than 40.

The data for the remaining 18 species were examined
for effects of the power plant on density (Table 1). The
data for 14 of these species were suitable for the *t* test
using the Near Impact station (Tables 3 and 4), and
10 species passed the more restrictive screen for the
analysis of variance using both impact stations (Table
5).

Plant operating schedule and sampling methods

By May 1983 Units 2 and 3 were circulating water
at rates near the projected long-term operating levels
(Fig. 2). For our analyses, we considered the period
from November 1980 to the end of April 1983 to be
the preoperational or Before period, during which 10
surveys were conducted at 2–4 mo intervals. Since the
species we studied are long-lived and recruit sporadi-
cally, we thought there should be a time lag between
the Before and After periods. Accordingly, a 16-mo
interim period from May 1983 to the beginning of
October 1984 elapsed before operational, or "After,"
samples were taken. During the interim period, surveys
were conducted semiannually. The After period ex-
tended from early October 1984 through December
1986, during which eight quarterly surveys were con-
ducted.

The time and effort required to complete a survey
varied substantially, depending on sea conditions, vis-
ibility, and the abundance of organisms. The time
elapsed from the first to the last sample during a survey
varied from 5 d to 33 d, and sampling effort varied
from 16 to 32 diver-days. Surveys usually included a
training day when all divers would sample the same
quadrats under the supervision of the field leader.

To avoid disturbing sessile species, only those ani-
mals on exposed surfaces were counted. Cracks and
crevices and the sides of rocks were examined, but
boulders and cobbles were not overturned. Species such
as sea urchins, sea stars, and snails, which could quickly
move out of the quadrat, were counted first. Individ-
uals moving into a quadrat after counting began were
not counted.

The distribution of substrate types was also esti-
mated. Within each quadrat, the substrate under each
of 15 uniformly distributed points was noted as sand
and gravel (diameter <1 cm), cobble (1–30 cm), boul-
der (>30 cm), or bedrock reef. The longest dimension
of cobbles and boulders was measured to the nearest
centimetre. Mud was added as a substrate type when
it was first observed in the San Onofre kelp forest in
October 1985.

Temperature, underwater irradiance, and seston flux
were measured near each of our stations by Eco-Sys-
tems Management Associates using underwater instru-
ment systems of their own design (Eco-M 1987). Tem-
perature sensors were deployed at the surface and near

TABLE 1. Species of large kelp forest invertebrates used to test for an effect of the cooling water discharge of the San Onofre (California) nuclear power plant. "Before" and "after" refer to the periods of time before and after full power operation of the plant began.

Species*	Number of surveys		Statistical analyses performed?		
	Before	After	Assump.†	t test	ANOVA
Porifera					
Tethya aurantia	10	8	Yes	Yes	No
Cnidaria					
Lophogorgia chilensis (R)	10	8	No	No	No
Muricea californica	10	8	Yes	Yes	No
Muricea fruticosa (A)	10	8	Yes	No	No
Pachycerianthus fimbriatus (R)	10	8	No	No	No
Annelida					
Diopatra ornata (R)	10	8	No	No	No
Mollusca					
Astraea undosa (T)	7	8	Yes	No	No
Calliostoma spp. (R)	2	5	No	No	No
Conus californicus	6	8	Yes	Yes	Yes
Crassispira semiinflata (T)	5	5	Yes	No	No
Cypraea spadicea	9	8	Yes	Yes	No
Haliotis corrugata (R)	10	8	No	No	No
Haliotis rufescens (R)	10	8	No	No	No
Hesperato vitellina (R)	2	8	No	No	No
Kelletia kelletii	10	8	Yes	Yes	Yes
Latiaxis oldroydi (R)	2	8	No	No	No
Maxwellia gemma	2	8	Yes	Yes	Yes
Mitra idae	6	8	Yes	Yes	Yes
Murexiella santarosana	2	7	Yes	Yes	Yes
Nassarius spp.	2	7	Yes	Yes	No
Ophiodermella inermis (R)	2	5	No	No	No
Pteropurpura festiva	2	8	Yes	Yes	Yes
Pteropurpura vokesae (R)	2	8	No	No	No
Tegula aureotincta	2	5	Yes	Yes	No
Tegula eiseni (R)	2	8	No	No	No
Trivia solandri (R)	2	8	No	No	No
Trivia californica (R)	2	8	No	No	No
Echinodermata					
Sea Urchins					
Centrostephanus coronatus (R)	10	8	No	No	No
Lytechinus anamesus (SC)	10	8	Yes	Yes	Yes
Strongylocentrotus purpuratus	10	8	Yes	Yes	Yes
Strongylocentrotus franciscanus (C)	10	8	No	No	No
Sea Stars					
Asterina (= Patiria) miniata	10	8	Yes	Yes	Yes
Astrometis sertulifera (R)	10	8	No	No	No
Dermasterias imbricata (R)	10	8	No	No	No
Henricia leviuscula (R)	10	8	No	No	No
Linckia columbiae (R)	10	8	No	No	No
Orthasterias koehleri (R)	10	8	No	No	No
Pisaster giganteus (R)	10	8	No	No	No
Pisaster brevispinnus (R)	10	8	No	No	No
Sea Cucumber					
Parastichopus parvimensis (R)	10	8	No	No	No
Urochordata					
Styela montereyensis (SC, T)	10	8	Yes	No	No

  * R = too rare to analyze; A = deltas (differences between population densities at Impact and Control sites on each survey) are non-additive in the Before period; T = linear trend in the deltas in the Before period; SC = deltas are serially correlated in the Before period; C = commercially harvested.
  † Assump. = tests for assumptions.

the bottom. Temperature was recorded every hour in digital loggers (PROM, a Programmable Read Only Memory Semi-conductor chip [Intel Corporation, Santa Clara, California, USA]). Underwater irradiance was measured within the 400–700 nm wavelength range with LI-COR LI-192S Underwater Quantum Sensors. Integrated irradiance values were recorded every hour in digital loggers (PROM). The PROMs were read every
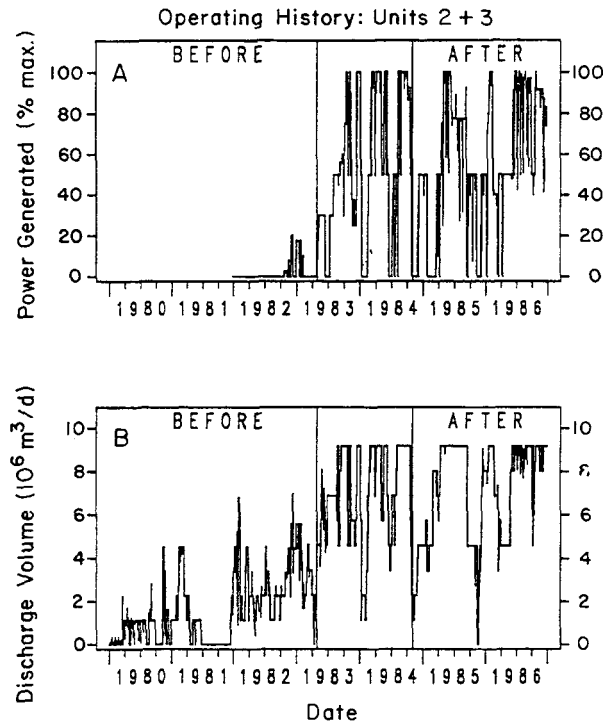
Operating History: Units 2 + 3

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 biweekly 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:

$$X_{ijk} = mS_{i(j)}P_jL_kE\epsilon_{ijk}, \qquad (1)$$

where X is abundance at the ith survey, in the jth operational period, and the kth location; m = the mean value at the Control site during the Before period, $S_{i(j)}$ = 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 = A (After period); E = the effect of the impact: E = e at the Impact site in the After period and 0 otherwise; and ϵ_{ijk} = error.

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

TABLE 2. Expected values for the BACI statistical model. Symbols are explained in *Methods: Statistical design and analysis: t test.*

Survey	Expected value at Control	Expected value at Impact	Expected Impact − Control (delta)
Survey i, during the Before period	$\log(m) + \log(S_{i(j)})$	$\log(m) + \log(S_i) + \log(I)$	$\log(I)$
Survey j, during the After period	$\log(m) + \log(S_j) + \log(A)$	$\log(m) + \log(S_j) + \log(I) + \log(A) + \log(e)$	$\log(I) + \log(e)$

We assume that $\log(\epsilon_{ijk})$ is normal with mean = 0, and log-transformation (with a constant added in the case of zero values) yields the tabled expected values for surveys in the Before and After periods.

and log-transformation (with a constant added in the case of zero values) yields the expected values for surveys in the Before and After periods that are shown in Table 2.

The estimated effect of the power plant is the difference between the mean Before and After deltas, which is an estimate of log(e). e is the proportional change in the average abundance at the Impact site during the After period due to the operation of the power plant, and ($e − 1$) × 100 is the percentage change.

Several assumptions underlie this model:

1) The data are additive. The effects of location, period, and impact are constant and can be added to the underlying mean abundance to get the expected abundances in the different cells in the design. Moreover, the temporal effects associated with individual surveys are the same at the Control and Impact sites.

2) The random errors of the deltas are independent.

3) The random errors are normally distributed with equal variances and means of zero.

Non-additivity can reduce the power to detect an effect or result in a biased estimate of an effect (Stewart-Oaten et al. 1986). If the model underlying the t test is the correct one, log transformation should produce an additive model. We tested this by regressing the Before deltas against the sum of the transformed Control and Impact values. This is Tukey's (1949) one-degree-of-freedom additivity test. A slope significantly different from zero indicates non-additivity.

Not all non-additivity can be dealt with by transformation. Of special concern is the case when the deltas trend positively or negatively with time in the Before period. Such trends could not be caused by the power plant, but if they continued into the After period, would confound the estimates of the effect of the power plant. We tested for trends in the deltas in the Before period by regressing them against time. If we detected a significant trend, the data were excluded from further analysis.

Lack of independence in random errors occurs if differences between replicate deltas vary as a function of time between samples, and results in serial correlations of errors. We expect that when violations of the independence assumption occurs, this will often lead to errors close in time tending to be similar. Such pos-

itive serial correlation has the effect of underestimating the true variance of the deltas and leads to overly sensitive hypothesis tests. Durbin-Watson tests were used to detect serial correlations in the errors. This occurred once, and we replaced the standard t test with a time series intervention (autoregressive) model (Box and Tiao 1965, 1975, Box and Jenkins 1976, McDowall et al. 1980) using the Statistical Analysis System Proc Autoreg (Brocklebank and Dickey 1984).

Finally, the t test of the difference between the Before and After deltas assumes that errors are normally distributed and have equal variances. Unless they are very extreme, violations of normality have little effect on the results of the t test (Stewart-Oaten et al. 1992), and this assumption was not tested. Non-equality of variances can affect the t test when sample sizes differ. When variances between the Before and After periods differed significantly ($P \leq .05$), a Welsh–Aspin test, which corrects for inequality of variances, was used in place of the standard t test.

Since there were sometimes zero values, the log transformation required adding a constant. Our first choice was 0.025, the smallest possible non-zero value for mean abundance at a site (i.e., 1 individual/40 m^2). If the transformation with 0.025 did not produce tractable data, we tried progressively larger constants. We used the smallest constant that produced data that were additive and showed no evidence of trends during the Before period. If the assumption of additivity for the Before period could not be met, we used 0.025 as a constant for purposes of graphical presentation and for calculating relative percentage of change, but no hypothesis testing was done. For five species of snails that were abundant enough to pass the initial screening, data were collected on only two surveys during the Before period, and the additivity test could not be performed.

A separate t test comparing the Near Impact and Control sites was done to estimate the affects on density of the influx of mud at the Near Impact site that began in summer 1985 and buried some of the fixed quadrats. For this analysis we used only those quadrats that were entirely free of mud during every survey. There were 26 quadrats that fulfilled this criterion. We did not

TABLE 3. Back-transformed average densities by Period (Before vs. After the start of full power operation of the San Onofre [California] nuclear power generating plant) for large kelp forest invertebrates at the Near (SOKU) and Far (SOKD) Impact sites (near the plant's cooling-water discharge), and the Control (SMK).

Species	Near Impact		Far Impact		Control	
	Before	After	Before	After	Before	After
	Densities (individuals/m²)					
Porifera						
Tethya aurantia	0.15	0.10	0.05	0.05	0.07	0.03
Cnidaria						
Muricea californica	0.20	1.53	0.24	5.29	5.07	7.17
Mollusca						
Conus californicus	4.43	1.14	2.93	1.69	0.69	1.77
Cypraea spadicea	0.11	0.08	0.06	0.05	0.10	0.21
Kelletia kelletii	2.90	1.02	2.92	1.47	2.52	2.35
Maxwellia gemma	0.78	0.12	0.22	0.14	0.25	0.41
Mitra idae	0.76	0.77	0.34	0.80	0.07	0.22
Murexiella santarosana	0.42	0.11	0.20	0.07	0.42	0.44
Nassarius spp.	0.36	0.26	0.75	0.52	0.22	0.24
Pteropurpura festiva	2.98	0.83	4.29	1.33	0.50	1.08
Tegula aureotincta	0.19	0.04	0.02	0.06	0.02	0.10
Echinodermata						
Sea Urchins						
Lytechinus anamesus	9.35	16.61	8.89	35.90	1.44	13.31
Strongylocentrotus purpuratus	0.16	0.11	0.08	0.08	1.40	1.03
Sea Stars						
Asterina (= *Patiria*) *miniata*	1.14	0.11	0.52	0.29	0.09	0.07

include the last two After surveys because only a few quadrats (12 and 6) were free of mud.

We also did t tests on seston flux and irradiance. One of the most obvious of the physical effects of the operation of the power plant was the frequent creation of a turbidity plume by the discharge from the diffusers. Whenever present, this plume was carried over the San Onofre kelp forest if the long shore currents were flowing to the south, which they did ≈60% of the time (MRC 1989a). We expected this plume to decrease the amount of underwater irradiance and increase the flux of seston near the sea floor in the San Onofre kelp forest relative to the Control, the San Mateo kelp forest. We did not expect water temperature near the bottom to be affected by the power plant. However, temperature was useful for assessing the similarity of the physical environments at the Control and Impact sites, especially during the 1982–1984 El Niño.

Analysis of variance. — The t test was done to test for the effect of the power plant on the Near Impact site. The fact that we also sampled at a Far Impact site allowed us to do an additional analysis to determine whether the significance and size of the impact varied with distance from the power plant's diffuser discharge. Rather than t tests described by Stewart-Oaten et al. (1986), we used an analysis of variance to compare simultaneously the two sets of deltas: Near Impact −

Control and Far Impact − Control. The model for this design is:

$$d_{ijk} = m + P_i + L_j + PL_{ij} + S_{k(i)} + \epsilon_{ijk}, \quad (2)$$

where d_{ijk} = the difference between the Near or Far Impact and the Control values (log-transformed as before) on a given date; m = the underlying mean difference in abundance; P_i = the effect of the ith Period (Before or After); L_j = the effect of the jth Location (Near or Far Impact); PL_{ij} = the Period × Location interaction; $S_{k(i)}$ = the effect of the kth Survey within the ith Period; and ϵ_{ijk} is random error.

Period, Location, and Survey are the main effects in the model. A significant Period effect indicates that the power plant has affected abundances averaged over both of the Impact sites. A significant Period × Location interaction indicates that the power plant affected the two impact sites differently. The Location effect measures differences in the average deltas independent of any power plant effect. Since this doesn't inform us about the plant's effect, we did not report on its significance. The tests are valid even if errors for the Near and Far Impact sites are correlated. The analysis of variance is equivalent to univariate t tests for differences between periods. The Period effect is equivalent to a t test of the difference from Before to After in the average of two deltas: Control − Near Impact, and Control − Far Impact. The Period × Location interaction is equivalent to a t test using the differences

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.

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

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

* Assumption test not done.

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

[ar] 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.
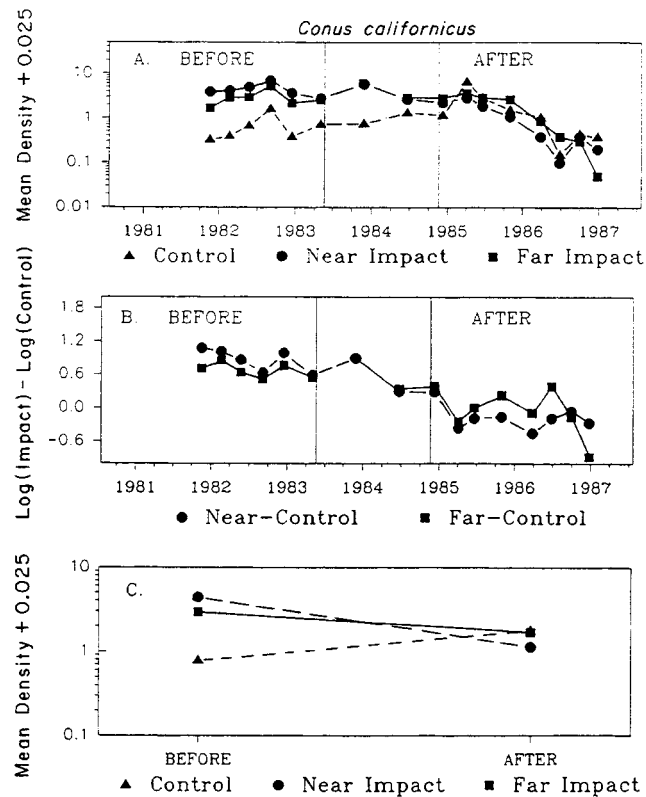
FIG. 3. Changes in the abundance of *Conus californicus* in a kelp forest off the coast of Southern California, in the vicinity of the cooling-water discharge of the San Onofre nuclear power plant. (A) Average density at the Near Impact (SOKU), Far Impact (SOKD), and Control (SMK) sites during the preoperational (Before), interim, and operational (After) periods. Each point is the mean from 40 1-m² 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 si**e 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
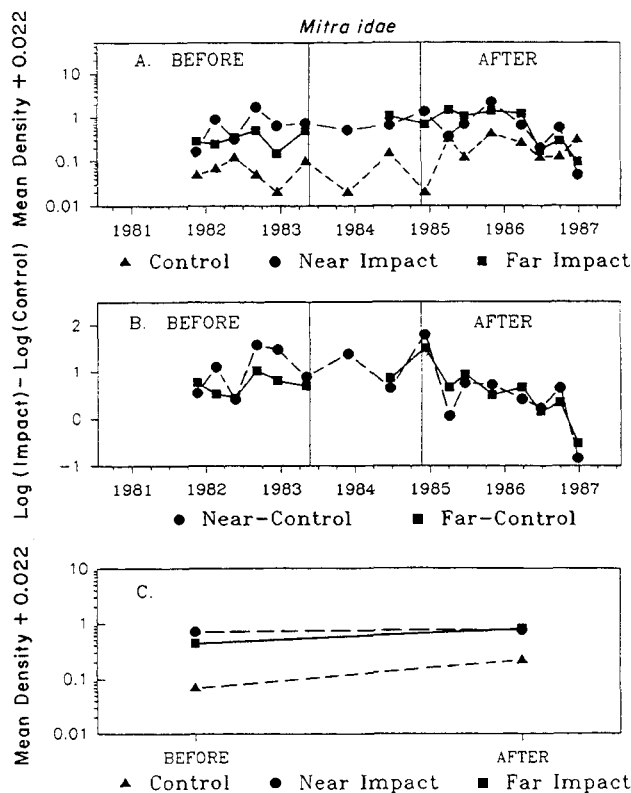
FIG. 4. Changes in the abundance of *Mitra idae* in a kelp forest off the coast of southern California, in the vicinity of the cooling-water discharge of the San Onofre nuclear power plant. See Fig. 3 legend for details.

Before period (Table 3). The patterns of relative change for *L. anamesus* were driven by changes in abundance similar to those seen for *Mitra idae* (Fig. 4). There were substantial increases in density at all the sites during the After period (Table 3). However, the proportional increase was much larger at the Control site, and resulted in relative declines at both of the Impact sites. The relative decline at the Near Impact site was statistically significant and larger than the one at the Far Impact site (Tables 4 and 5). Changes in the abundance of *L. anamesus* were caused by both recruitment and immigration. There was substantial recruitment of recently settled individuals in both the San Onofre and San Mateo kelp forests in the fall and winter of 1981–1982, 1983–1984, and 1984–1985, and immigration of larger animals, especially at the Control site during the last two operational surveys in 1986 (S. C. Schroeter, J. D. Dixon, J. Kastendiek, and R. O. Smith, *unpublished data*). We were concerned that large, site-specific stochastic fluctuations in density due to immigration of adults unrelated to the operation of the power plant might have strongly affected the patterns

we observed. To examine this possibility, we excluded data from the last two surveys and re-ran the t test. This resulted in a somewhat lower effect size (−65% vs. −76%) but a much higher significance level (P = .0008 vs. .018).

The purple urchin, *Strongylocentrotus purpuratus*, is another common grazer in southern California kelp forests. Purple urchins were common at the Control site, but uncommon to rare at both Impact sites during both operational periods (Table 3). There were small declines in average density at the Control and Near Impact sites and a small increase at the Far Impact site in the After period. Neither the t test nor the analysis of variance showed statistically significant effects suggestive of an effect of the power plant (Tables 4 and 5). The significant interaction resulted from the greater relative increase at the more distant impact site, which is not consonant with an effect of the discharge.

The bat star, *Asterina* (= *Patiria*) *miniata*, was the only one of the eight species of sea stars sampled during the study (Table 2) that was abundant enough to test for effects of the generating station. As was the case for
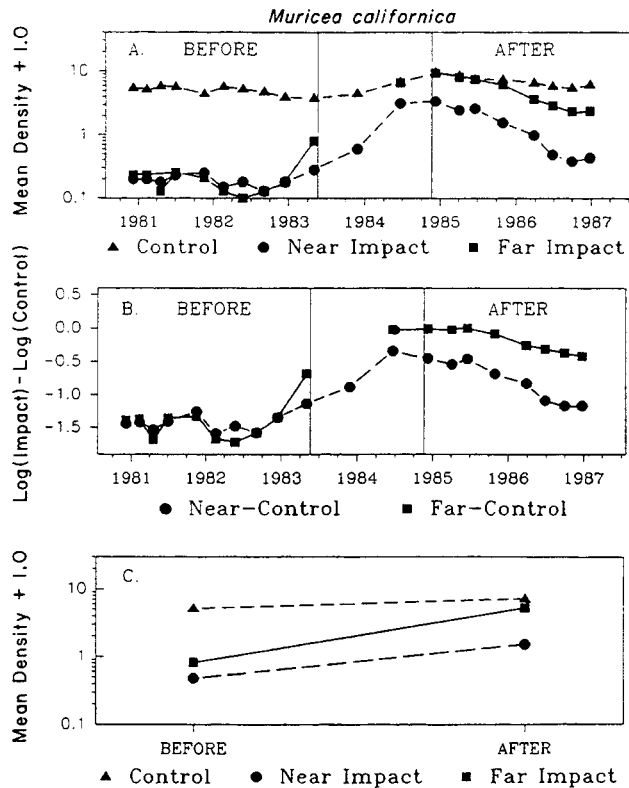
FIG. 5. Changes in the abundance of *Muricea californica* in a kelp forest off the coast of southern California, in the vicinity of the cooling-water discharge of the San Onofre nuclear power plant. See Fig. 3 legend for details.

most of the snails (cf. Fig. 3), patterns of relative change in *A. miniata* were due to declines at the Impact sites (Table 3). In the Before period bat stars were about twice as abundant at the Near Impact site as at the Far Impact site, and densities at the Control site were about 10-fold lower. From 1981 through 1984 subtidal populations of sea stars in southern California were struck with a series of bacterial epizootics that decimated shallow populations (S. C. Schroeter, J. D. Dixon, R. O. Smith and J. E. Hose, *unpublished data*). During the operational period there was some recruitment of small individuals at all sites. The net result was that the average abundance at the Control site did not change from the Before to the After periods, whereas the average abundance was lower at both Impact sites during the After period. The relative decline at the Near Impact site was statistically significant (Table 4) and was greater than at the Far Impact site, where the relative declines were also substantial (Table 5).

Large sessile invertebrates

Data from two species of large sessile invertebrates were suitable for either the *t* test or the analysis of variance. One, the sponge *Tethya aurantia*, was analyzed both with the *t* test and the analysis of variance. Data for the other, the gorgonian coral *Muricea californica*, was analyzed with the *t* test, but failed the assumptions for the analysis of variance (Table 1).

T. aurantia occurred in small numbers at all the sites throughout the study. During the Before period, densities were highest at the Near Impact site and lowest at the Far Impact site. From the Before to the After period, there were modest declines in abundance at the Near Impact and Control sites and no change at the Far Impact site (Table 3). This pattern resulted in a small relative increase at the Near Impact site that was not statistically significant (Table 4). Power for this test was very high. There was a larger relative increase at the Far Impact site resulted in significant Period and Period × Location effects (Table 5). This pattern resulted from changes at the Far Impact station that, if caused by the power plant, require more complicated mechanisms than for cases where effects fall off with distance.

The patterns of relative changes for the gorgonian coral, *Muricea californica*, resulted from large increases

TABLE 6. Results of t test on seston flux near the cooling-water outflow from the San Onofre (California) nuclear power generating plant, using a first-order autoregressive model (AR1) to correct for serial correlations.*

| | Seston flux (mm/day) | | | | | | |
Period	SOKD (Far Impact)	SOKU (Near Impact)	SOKU– SOKD	N	P value	Effect size (%)	Power (%)
Before	7.62	7.65	0.03	31	.001	+45.8	≈100
After	7.47	11.16	3.69	21			

* The Near Impact (SOKU) site is compared to the Far Impact (SOKD) site because no transformations were found that produced additivity for the Control (SMK) vs. Near Impact (SOKU) comparison. Daily seston flux was calculated from bi-weekly accumulations in sediment traps, and transformed as log($x + 0.53$) to produce additivity. N = number of 2-wk periods. Power to detect a 50% change at SOKU was calculated with uncorrelated errors and is therefore somewhat inflated.

at the Impact sites coupled with more modest increases at the Control (Table 3). *M. californica* was an order of magnitude more abundant at the Control site than at the Impact sites during the Before period. There was substantial recruitment in the San Onofre kelp forest during the Interim period, but only modest recruitment at San Mateo. During the After period there was a general decline in density at San Onofre, but little change at the Control site (Table 3). The relative increase at the Near Impact site, due in large measure to the higher recruitment during the Interim period (Fig. 5), was statistically significant (Table 4). The data were not appropriate for an analysis of variance.

Seston flux, irradiance, and substrate changes

The discharge of Units 2 and 3 of the San Onofre Nuclear Generating Station often creates turbid plumes over the San Onofre kelp forest. These plumes are the likely cause of changes in two of the physical variables, seston flux and underwater irradiance, at the Impact sites relative to the Control. Analysis of the data from the seston traps indicates an increase in the flux of seston near the bottom by 46% at the Near compared to the Far Impact site (Table 6; MRC 1989b). The increase in seston flux relative to the Control was probably even higher, since the Far Impact site is also under the plume part of the time. There was, however, no transformation that produced additivity for the Control − Near Impact comparison, so no effect could be estimated. The discharged cooling waters also resulted

in a reduction in underwater irradiance (photon flux density) of ≈0.65 mol·m⁻²·day⁻¹ at the Impact sites relative to the Control when currents were running downcoast and bringing the plume over the San Onofre kelp forest (Table 7) (Reitzel et al., in press). On average, downcoast current days comprise ≈60% of the total.

In contrast to seston flux and irradiance, the operation of the power plant had no effect on water temperature (MRC 1989a). The data are of further interest because they allow us to look for any differential effects of a major oceanographic event, the strong El Niño of 1982–1984, on the Impact and Control sites. This is important since the El Niño occurred just before and during the startup of the power plant. The analysis indicates that temperatures were elevated by an average of ≈2°C during the El Niño, after which they returned to the pre-El Niño values. The changes at the Control and Impact sites were virtually identical (Table 8).

From the Before to the After period at both the Control and Far Impact sites there was a decline in the proportion of the exposed sea floor composed of unconsolidated substrates. In contrast, there was a substantial increase in sediment cover at the Near Impact site (Fig. 6). Sometime between July and October 1985 several of the sampling quadrats were covered with mud. The mud compacted and became armored with coarser materials. This deposit of muddy sand accreted with time (Table 9), resulting in an increase in the

TABLE 7. Comparison of average underwater quantum irradiance (photon flux density levels, using t tests*). Irradiance at SOK is the average of values from three stations spread throughout the San Onofre kelp forest, those at SMK are from one San Mateo station. The P value is for the t test of a difference in the average deltas (SOK − SMK) between the Before and After periods.

| | Average daily irradiance (mol·m⁻²·d⁻¹) | | Reduction due to impact (mol·m⁻²·d⁻¹) | P value |
Period	SOK	SMK		
Before	1.25	1.34	−0.65	<.003
After	1.34	2.08		

* The t tests were done using a first-order autoregressive model (AR1). Results are based on analyses by Reitzel et al., in press.

TABLE 8. Average daily bottom temperature at the Control and the Near and Far Impact sites before, during, and after the 1982–1984 El Niño. The period before El Niño is from October 1981 through September 1982; during El Niño is from October 1982 through September 1984; after El Niño is from October 1984 through September 1986. The table is reproduced from MRC 1989a.

| | Average daily temperature (°C) | |
Period	SMK (Control)	SOK* (Impact)
Before El Niño	14.6	14.8
During El Niño	16.3	16.6
After El Niño	14.6	14.7

* SOK = The average of values from three stations spread throughout the San Onofre kelp forest, off southern California.

TABLE 9. Average percentage of sea floor covered by muddy sediments at the Control (SMK), Near Impact (SOKU), and Far Impact (SOKD) sites from June 1985 to the end of the study.

	% cover of muddy sediments		
Date	SMK (Control)	SOKU (Near Impact)	SOKD (Far Impact)
June 1985	0.0	0.0	0.0
October 1985	0.0	14.7	0.0
March 1986	0.0	29.5	6.8
June 1986	0.0	30.6	6.8
September 1986	0.0	35.0	3.9
December 1986	0.0	44.2	0.2

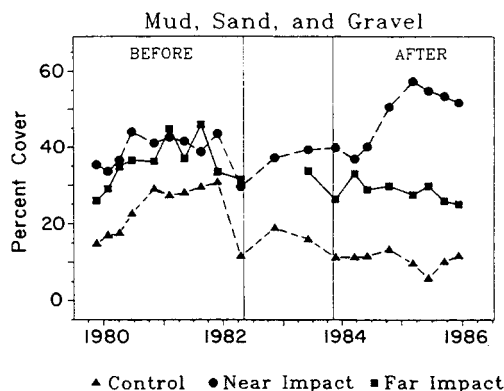Mud, Sand, and Gravel

▲ Control   ● Near Impact   ■ Far Impact

FIG. 6. Average percentage of cover of unconsolidated substrates (mud, sand, and gravel) at the Near Impact (SOKU), Far Impact (SOKD), and Control (SMK) sites in the vicinity of the cooling-water discharge of the San Onofre (California) nuclear power plant, during the preoperational (Before), interim, and operational (After) periods.

percentage of cover of unconsolidated materials at the Near Impact site from ≈40% to between 50 and 60% toward the end of the study (Fig. 6). During the After period mud was frequently observed elsewhere in the San Onofre kelp forest, including the Far Impact site (Table 9), but these deposits were ephemeral.

The results of the *t* tests using only mud-free quadrats at the Near Impact site were essentially the same as the analysis using all the data (Table 10). There were significant relative declines of snails (*Conus californicus, Cypraea spadicea, Kelletia kelletii, Maxwellia*

gemma, Murexiella santarosana, and *Tegula aureotincta*), white sea urchins, *Lytechinus anamesus,* and bat stars, *Asterina miniata.* The gorgonian *Muricea californica* again showed a significant relative increase.

TABLE 10. Results of *t* tests on abundances of large kelp forest invertebrates comparing the Near Impact (SOKU) to the Control (SMK) sites. Only quadrats that were free of mud were used in the analysis.

Species†	Number of surveys		P‡	Effect size (%)	Power (%)
	Before	After			
Porifera					
Tethya aurantia	10	6	.034	+80.6	51.8
Cnidaria					
Muricea californica	10	6	<.001	+393.4	85.7
Muricea fruticosa	10	6	.090	+174.6	2.9
Mollusca					
Astraea undosa (T,*ᵃʳ*)	...	...	...	−85.5	...
Conus californicus	6	6	<.001	−90.5	62.0
Crassispira semiinflata (T)	5	5	...	−82.0	...
Cypraea spadicea	9	6	.039	−59.5	18.2
Kelletia kelletii	10	6	.013	−51.3	69.1
*Maxwellia gemma**	2	6	.006	−91.7	15.5
Mitra idae	6	6	.280	−58.0	11.8
*Murexiella santarosana**	2	6	.002	−87.9	23.8
Nassarius spp.*	2	6	.332	−54.0	8.5
*Pteropurpura festiva**	2	6	.093	−86.1	8.6
*Tegula aureotincta**	2	4	.027	−91.1	19.0
Echinodermata					
Sea Urchins					
*Lytechinus anamesus*ᵃʳ	10	6	.001	**−60.6**	**80.2**
Strongylocentrotus purpuratus	10	6	.406	**−35.3**	**24.2**
Sea Stars					
Asterina (= *Patiria*) *miniata*	10	6	<.001	−86.3	62.7
Urochordata					
Styela montereyensis (T)	10	8	...	−42.9	...

† T = linear trend in the deltas in the Before period; *ᵃʳ* = analysis done with a first-order autoregressive model to correct for serial correlation, but power calculated from ordinary least-squares model and overestimates the true power; * = species for which no assumption tests were done.

‡ *P* values in bold are <.05.

In addition, the sponge *Tethya aurantia* showed a significant relative increase.

DISCUSSION AND CONCLUSIONS

The results of this monitoring study demonstrate two patterns of change in the assemblage of invertebrates in the San Onofre kelp forest that occurred after Units 2 and 3 of the San Onofre Nuclear Generating Station (SONGS) began normal operation. The first was a decline in density, relative to populations at a control site, of a taxonomically diverse group of species. There were statistically significant relative declines in the density of snails (*Conus californicus, Cypraea spadicea, Kelletia kelletii, Maxwellia gemma, Murexiella santarosana,* and *Tegula aureotincta*), a sea urchin, *Lytechinus anamesus,* and a sea star, *Asterina miniata.* The second pattern was an increase in abundance of two species in the San Onofre kelp forest relative to the control populations. These were the gorgonian *Muricea californica* and the sponge *Tethya aurantia.*

How does one judge whether the observed changes in relative density were caused by a human-made perturbation, in this case the cooling-water discharge of a nuclear power plant? The answer depends on confidence in the analyses, consistency of the results, and the weight of the evidence regarding reasonable mechanisms.

Although the BACI design and associated analyses are important tools for assessing environmental impacts, we believe that the case for biological effects of anthropogenic perturbations should not rest solely on the statistical significance of formal hypothesis tests, nor should the results for individual species be evaluated alone. In the absence of a demonstrated causal chain, a convincing case requires that the results for a number of different species tie together and be consistent, that plausible mechanisms for an ecological impact be identified, and that reasonable alternative mechanisms be explored and ruled out.

We believe that the results presented here make such a case. Most species (11 of 14) showed relative declines in density during the After period (i.e., after full-scale operation of the nuclear plant). The average effect size was about −75% at the Near Impact site. Data were appropriate for an analyses of variance for 7 of the 14 species to determine the relative magnitude of the decline at the Near and Far Impact sites. In each case the effect was less at the Far Impact site (average effect size: −52%). This pattern is most convincing for *Conus californicus, Cypraea spadicea, Kelletia kelletii,* and *Mitra idae,* all fairly abundant snails that were sampled 6–10 times in the Before period. However, the pattern of relative decline was very similar for snail species that were only sampled twice in the Before period. Confidence in the pattern was further strengthened by the results for white sea urchins and bat stars, which also showed larger relative declines at the site near the diffusers than at the Far Impact site.

There are plausible mechanisms for the declines. The operation of Units 2 and 3 caused an increase in the flux of fine particles in the water column over the San Onofre kelp forest, especially near the diffusers. There was a 46% increase in seston flux at the Near Impact site relative to the Far Impact site. This undoubtedly resulted in increased flux of fine particles on rocky substrates. The frequent dusting of rocky surfaces with fine inorganic particles and the occasional coating of hard substrates with mud might reduce larval settlement, interfere with egg laying (significant to local populations if larvae are short-lived), induce adult emigration, and cause mortality of encrusting sessile prey. The generating station may also have had other, indirect effects on invertebrates. Generating Units 2 and 3 caused a significant reduction in the size and density of the San Onofre kelp forest relative to the San Mateo kelp forest by reducing recruitment of giant kelp, *Macrocystis pyrifera,* probably by reducing irradiance at the sea floor (MRC 1989*b*). The local reduction in standing stock of giant kelp and the consequent reduction in drift kelp could adversely affect species that utilize it for food, such as white sea urchins (Leighton 1971) and bat stars (Gerard 1976).

Concluding that the power plant has caused the two observed relative increases in density is not as straightforward as for the cases of relative decline. On the one hand, there is a plausible mechanism for the increases. In addition to increasing the local flux of fine inorganic particles, the cooling system takes in, kills, and discharges on the order of thousands of tons of plankton per year (MRC 1988*b*). The resultant organic particles might increase the food available to filter feeders, such as *Muricea californica* and *Tethya aurantia.* On the other hand, the relative increases for both species were greater at the Far than the Near Impact site. Mechanisms involving operation of the power plant could be invoked to account for these patterns, but they are more complicated than mechanisms that account for an effect which falls off with distance. For example, the fine organics may tend to be more concentrated on the bottom at the Far than the Near Impact site because of delays in settlement through the water column. Alternatively, the increased supply of organic particles could have positive effects at both the Near and Far Impact sites, but the increased flux of inorganic particles could have more severe adverse effects (e.g., burial or abrasion) at the Near Impact site.

We have considered three alternative hypotheses unrelated to the operation of the power plant that could potentially explain our results. The first applies to the gorgonian *Muricea californica.* In the case of this species, the differences between the Control and Impact sites in the After period resulted primarily from differences in rates of recruitment from the plankton. Although we did not measure the amount of open space available for settlement, our impression was that there was less substrate available for settlement at the Con-

trol than at either Impact site. This raises the reasonable possibility that the results we observed were a function of space-limited recruitment at the Control site rather than an effect of the power plant.

We considered two other hypotheses that apply to all of the species: (1) the Control and Impact sites were affected differently by oceanographic events, particularly the 1982–1984 El Niño, and (2) a natural increase in sediment cover at the Near Impact site produced the observed declines in relative density.

The oceanographic manifestations of the El Niño occurred just before and shortly after SONGS Units 2 and 3 began operation, and resulted in elevated temperatures, depressed nutrient concentrations, and unusually severe storms in the early spring of 1983 (Simpson 1983, Tegner and Dayton 1987, MRC 1989a). However, the evidence does not suggest that El Niño contributed significantly to the observed relative changes in population density. For example, in each of the El Niño years the correlation coefficient of bottom temperature between the Control and Impact sites was between 0.91 and 0.96 (MRC 1989a). There were no measurable, site-specific changes in physical parameters that parallel and might explain the changes in the invertebrates. Another possibility is that the severe storms in the spring of 1983 interacted with topographical differences between the Impact and Control sites to produce more severe declines at the Impact sites. However, there was more obvious disturbance of the bottom in the San Mateo than in the San Onofre kelp forest during stormy periods (R. O. Smith, S. C. Schroeter, and J. D. Dixon, *personal observations*), and giant kelp mortality was about the same at the two sites during that period (Zabloudil et al. 1989). Therefore it appears that waves associated with the 1983 storms had similar or less destructive effects at San Onofre than at the Control site.

The third alternative hypothesis is that the observed relative changes in population densities resulted from the deposition of mud at the Near Impact site that began in summer 1985. We treat this as an alternative hypothesis because there remains a question as to whether that mud deposition was natural or an effect of the generating station. The deposit of sandy mud that first appeared in October 1985 and that persisted and accreted for the remainder of the study reduced the density of invertebrates in those quadrats that were partially or completely buried. Although this undoubtedly contributed to the decreases in relative density that we observed, it is not a sufficient explanation. This assertion is based on the facts that most species were declining in density at the Impact sites before the mud was deposited, that there were significant, although smaller, relative declines at the Far Impact site in the absence of persistent mud deposits, and that there were relative declines at the Near Impact site in quadrats where there was no mud. Therefore something in addition to a persistent change in substrate composition

was responsible for the biological results. We believe that it was the ephemeral deposition of fine particles discussed above. Although not conclusive, there is also considerable circumstantial evidence that the frequent appearance of mud deposits in the San Onofre kelp forest during the After period was itself an effect of the generating station (MRC 1991). That judgment was based on the following observations: (1) the diffusers created a turbid plume over much of the kelp forest, significantly increasing particle flux; (2) the interactions of the discharge and make-up flow and the discharge and stands of giant kelp created stagnation points where there was little water movement, a condition favorable to particle deposition; (3) there were no observations of mud at kelp forests depths during the Before period, except immediately following those large storms that produced heavy fresh water run off; (4) although the After period coincided with a major drought, mud was frequently observed in the San Onofre kelp forest, especially in the upcoast portion near the diffusers, but was rarely encountered elsewhere at similar depths; (5) mud collected from the San Onofre kelp forest had a higher organic content, corrected for particle size distribution, than mud collected in deeper water where it is the characteristic substrate.

In summary, the results of statistical analyses, coupled with studies of oceanographic parameters, provide strong evidence that the operation of the power plant has affected the densities of many invertebrate species in the San Onofre kelp forest. The analyses also indicate that although the effects of the generating units are detectable throughout the San Onofre kelp bed, they are significantly smaller at a distance of ≈ 1.5 km from the discharges. The evidence for a power plant effect is more convincing for the species that showed relative declines than for the two that showed relative increases. Finally, it is worth noting that only about one third of the species that originally seemed appropriate provided data that were statistically tractable. For most of these, the power to detect a halving or doubling was generally very low. As a result, the only effects that were statistically significant were large (60–90% declines). Therefore, relying only on the statistical analyses would underestimate the number of ecologically significant changes.

As a coda, we would like to summarize the lessons we have learned regarding strategies of environmental impact assessment. The BACI design is a powerful tool to assess whether abundances or other variates of interest have been affected by human perturbations. However, there are limitations to this approach when one is dealing with organisms that live long and recruit infrequently, such as the marine benthic invertebrates in our study. Such characteristics can produce two generic and related problems: serial correlation and low power.

The rates of change of organisms that live many years and recruit sporadically are often so low that sampling

frequencies greater than once, or at most, a few times per year, are likely to introduce serial correlations. In most cases, these serial correlations will be positive because observations close in time are likely to be similar. If we falsely assume independence, we will underestimate the error terms in the analysis and inflate the true Type I error rate (α) relative to the nominal one. It is possible, in theory, to estimate and correct for such serial correlations (e.g., Durbin–Watson test or time-series analyses). However, for long-lived animals of the type considered in our study, the sample sizes for studies shorter than about 10 yr (5 yr of quarterly surveys each for the Before and After periods) are likely to result in low power to detect serial correlation. Even if we decided to correct for serial correlation with no pre-testing, our supposedly "corrected" analyses would still be biased (Park and Mitchell 1980). Thus, serial correlations and their effects on the Type I error of statistical tests will go undetected or under-corrected. This problem (which afflicts most studies, regardless of statistical model) can be cured by increasing the length of the monitoring period—but we suspect that this will be an infrequently applied remedy because of costs and various other practical constraints. We suggest two possible solutions to the problem. First, there are other population attributes, such as settlement, and size-specific individual growth, fecundity, and survivorship, that often can reasonably be estimated frequently and are less likely to be serially correlated (cf. Osenberg et al., in press). Second, field experiments could be conducted with those species that are considered particularly important or that appear to be suffering impacts. The results of such experiments would help identify the mechanisms underlying the density changes, and increase the confidence in the monitoring results. The strongest studies of environmental impacts are those that demonstrate the linkage between physical and chemical perturbations and biological changes. Besides increasing the credibility of the monitoring results, this information could be used by dischargers and regulators to institute physical or operational changes in order to reduce deleterious environmental effects.

The second generic problem is low power of significance tests of impact. Because of the potential problems of serial correlation, increasing sample size usually means increasing the length of the study. This frequently is not an option, both because of increased costs and because the study times required (on the order of 10 or more years) are long relative to regulatory time scales. Two of the possible remedies for serial correlation (use of variates other than abundance, and manipulative experiments) also apply to the problem of low power. At the very least, the magnitude of the problem of low power can be assessed by calculating power and the effect sizes in addition to P values. If one knows both the power of the test and the effect size, one can make informed judgments as to whether the analyses have underestimated the degree of ecologically significant impacts.

The BACI design allows one to test whether there has been a statistically significant change in abundance (or some other variable) at an Impact site relative to one or more Control sites. Most studies of environmental impacts have a single impact site. It has been argued that such a design runs the risk of confusing natural Period × Location interactions with an impact (Hurlbert 1984). Stewart-Oaten et al. (1986) point out that the chances of such misinterpretation are reduced by sampling the paired differences between Control and Impact sites repeatedly in the Before and After periods. Nevertheless, the possibility that natural Period × Location interactions may mimic an environmental impact should be considered. We attempted to address the problem in three ways: by the use of more than one Impact site, by examining a number of potential target species, and by seriously evaluating plausible alternative hypotheses.

Use of either multiple Control (e.g., Carpenter 1989) or multiple Impact sites increases the chances of distinguishing between natural Period × Location interactions and an environmental impact. However, in the present study, the primary value of multiple Impact sites was not to provide replication in a statistical sense, but rather to provide spatial information that was useful in determining the pattern and extent of the impact. Similar patterns of relative change for a number of species clearly strengthen the evidence for an ecological effect of the impact. It seems to us that analyses that deal with individual species lead to stronger inferences than those that use summary statistics that combine data from the different species. There are two reasons for this. First, similar patterns for a number of species tend to corroborate the conclusion of either the presence or absence of an effect. Second, statistics or indices that do not distinguish among species can't adequately describe the diversity of response.

We think it is clear that determining the "significance" of an effect is not something that should be done by rote (cf. Yoccoz 1991). When considering issues of pollution or human health, sole reliance on a statistical significance level of .05 in a hypothesis test to identify impacts is inadequate. The size of the effects, the weight of all of the evidence, and the costs of falsely implicating (Type I error) or falsely exonerating (Type II error) the presumed polluter must be considered.

In conclusion, we think that our study provides some larger lessons about the general process of impact assessments. Although we were able to detect a number of significant effects, this was primarily because many of the effect sizes were substantially larger than 50% changes. The present study extended over nearly 6 yr, yet the resulting statistical tests generally had low power ($<30\%$) to detect 50% reductions (or doublings) in abundance at the conventional test level of .05. We believe that this will often be the case when sampling

populations of relatively long-lived organisms in dynamic natural systems. Many assessment studies are substantially shorter than ours, and we suspect that the design of many impact studies is such that only the grossest effects could be detected. Obviously, it would be a mistake to conclude that there were no, or insignificant, effects based simply on a conventional significance test applied to the results of such a study. Because an increase in effective sample size implies an increased study duration, we cannot generally increase power simply by increasing the resources available for each individual study. The above discussion leads us to conclude that we need to change the standards and types of evidence used to demonstrate an impact, or to accept the fact that effects on the order of 50% changes will often be missed. One solution would be to increase the Type I error rate and thus reduce the Type II error rate; ideally this would be done by balancing the costs of different types of errors. This approach would require some prior idea about the likely size of effects. We believe that intensive studies like ours are generally useful in part because, combined with other relevant information (such as studies of mechanisms), they can provide this type of prior information.

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