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Coastal Power Plant Discharge Enhances Nitrogen Content of Kelp (*Macrocystis pyrifera*)

Andrew E. Jahn†, Wheeler J. North‡, John B. Palmer§, and Robert S. Grove*

† ENTRIX, Inc.
590 Ygnacio Valley Road
Walnut Creek, CA 94596,
U.S.A.

‡ California Institute of Technology
Pasadena, CA 91125, U.S.A.

§ 2544 Robruce Lane
Hacienda Heights, CA 91745,
U.S.A.

* Southern California Edison
2244 Walnut Grove Avenue
Rosemead, CA 91770, U.S.A.

ABSTRACT

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Heated water from the San Onofre Nuclear Generating Station (SONGS) is discharged through a multiport diffuser system, which secondarily entrains about 10 times its volume of ambient water, principally from below the thermocline. On average, this rising and spreading plume should be enriched in inorganic nutrients, including nitrogen, compared to ambient surface waters. Effects from the plume on kelp were investigated by sampling kelp canopy tissues and analyzing for nitrogen content. In seven samplings from August 1991 to March 1994, the area of the San Onofre kelp bed (SOK) nearest the offshore diffuser consistently yielded higher than average nitrogen on a percent dry weight basis, and there was an overall pattern of decreasing enrichment with distance from the diffusers (χ^2 probability < 0.005).

The presumed SONGS-induced nutrient upwelling is therefore considered to exist. The portions of SOK that benefit from the artificially upwelled nutrients would be more likely to survive a period of generally poor conditions such as an El Niño, and then serve as a source of spores for repopulating the kelp bed.

ADDITIONAL INDEX WORDS: *Macrocystis, upwelling, nitrogen content, nutrients.*

INTRODUCTION

Giant kelp (*Macrocystis pyrifera*) is both an important habitat former and organic carbon source for the nearshore environment in southern California. Standing stocks of fish and invertebrates can be substantially higher in kelp beds (FOSTER and SCHIEL, 1985; DEMARTINI and ROBERTS, 1990). With an average canopy area of approximately 70 ha (Southern California Edison Company, unpublished data) and yearly net production of 500 g C m^{-2} (MANN, 1973; JACKSON, 1987), the San Onofre kelp bed (SOK) should contribute some 350 metric tons of carbon per year to the coastal food web. The San Onofre Nuclear Generating Station (SONGS) stirs the water near SOK, as described below. Because of the very large amounts of water moved through the plant as well as horizontally and vertically in the nearshore ocean, the potential environmental effects of SONGS have received a great deal of attention. Most of this attention has been on potential problems, including the effects of increased turbidity (MRC, 1980, 1989; SCHROETER *et al.*, 1993), but it is possible that some aspects of power-plant operations may benefit the ecosystem (MRC, 1980).

We hypothesize that the diffuser discharge of SONGS enhances tissue nitrogen in nearby canopies of giant kelp. The hypothesis, based partially on our observations of "healthy" appearances of canopy kelp downcurrent of the diffuser line, is that artificially upwelled bottom water, naturally rich in nutrients relative to surface water, produces nitrogen enrichment in exposed kelp tissues.

SONGS consists of three generating units, all having once-through cooling systems discharging to the Pacific Ocean near the Orange–San Diego County (California) line (33°23′N, 117°32′W). Unit 1, with a maximum cooling-water flow of 1,211 m^3 per min. discharged through a vertical structure 750 m offshore, does not figure significantly in the phenomenon under investigation. The ecologically significant movers of water are Units 2&3, each with 1,100 MW generating capacity and 3100 m^3 per min. pump rating. Units 2&3 intakes are located 970 m offshore, temperature rise over the condensers is about 10.7 °C, and discharge is through horizontal diffuser structures, each 750 m long with 63 ports set 2.2 m above the bottom. The Unit 2 diffuser spans from 1,795 to 2,545 m offshore, at depths of 11.9 to 14.9 m. The Unit 3 diffuser extends from about 1085 to 1835 m offshore, in depths of 9.8 to 11.6 m (SCE, 1981; SCHROETER *et al.*, 1993).

Based on a hydraulic model (KOH *et al.*, 1974) and on actual field experiments (REITZEL *et al.*, 1987), it is estimated that the diffusers secondarily entrain into a rising and spreading plume approximately 10 times the volume of water discharged. A compensating onshore flow, to replace the water forced offshore in the plume, is also thought to consist largely of relatively clear, cool, nutrient-rich water of offshore origin.

A thin layer of nitrate-enriched water can often be detected

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encroaching on the shelf to about the depths of the SONGS diffusers (BARNETT and JAHN, 1987). This near-bottom nutrient pool is generally out of reach of the kelp canopy and most phytoplankton. However, with the SONGS diffusers operating, a localized mechanism exists whereby near-surface waters can be enriched by these waters of deeper origin secondarily entrained in the discharge plume.

The alongshore current flows toward the southeast ("downcoast") about 60% of the time, causing part of the diffuser plume to enter the San Onofre kelp bed (SOK) (MRC, 1989). The work described here was designed to test whether there is a detectable pattern of nitrogen enrichment in kelp tissues exposed to the plume. We expected to see elevated levels of tissue nitrogen in those portions of SOK nearest the diffusers. Moreover, because the nitrate concentration in bottom water will on average be greater along the deeper, offshore section of the diffusers than inshore, and because the average diffuser plume heads obliquely offshore (MRC, 1989), we expected greatest enrichment to occur in the offshore half of SOK. A pattern of upcoast enrichment, decreasing in a downcoast direction, would be interpreted as a positive SONGS effect, because we know of no natural mechanism for such a pattern. If prevailing currents enriched the upcoast end more than the rest of the kelp bed (as conjectured, though not demonstrated, by JACKSON, 1977), then the downcoast end, which is the "leading" edge during the 40% of time the currents flow upcoast, should also be enriched with respect to the center of the kelp bed.

A pilot study conducted in August 1991 indicated the investigation was feasible, with a number of repetitions of the sampling being necessary to test for a pattern of enrichment above a rather variable background. This report summarizes data from the pilot study and six standard surveys (December 1991, January, March and April 1992, and January and March 1994) of a project to monitor the nitrogen content of giant kelp in the vicinity of SONGS.

METHODS

Sampling

Sampling was conducted in two temporally disjunct periods. The first period spanned August 1991 to April 1992, during which five samplings were completed. The second period occurred in January and March 1994 (two samplings). The minimum time separation between samplings (5 weeks) should have been long enough for the processes of uptake and utilization to produce independence (R. ZIMMERMAN, *personal communication*). Sampling was done on four transects in SOK, each transect consisting of inshore and offshore blocks. Initial plans to use a nearby kelp bed (San Mateo Pt., 5 km northwest) as a reference were abandoned when canopy kelp could not be found there in 1994.

Navigation was by a range-range microwave (MiniRanger) system for the 1991 and 1992 samplings. During later samplings, navigation was done by Global Positioning System (GPS) with differential correction. The range-range data were transformed to a rectangular coordinate system (MRC coordinates) having its X-axis approximately parallel to shore and origin at the SONGS Unit 1 discharge. Latitude and longitude from GPS readings were also plotted in the MRC coordinate system.

The basic plan involved sampling 10 blades from each station (pilot study) or block. In the pilot study in August 1991, and in the December 1991 survey, kelp blades were sampled haphazardly at each station, selection criteria being only that the blade appear to be mature or nearly mature, and not senescent (see ARNOLD and MANLEY, 1985). Beginning in January 1992, a strong effort was made to sample several (3–5) plants equally within each block. This was done because it was suspected and then shown that there were significant differences in nitrogen content among plants within blocks (2-way ANOVA). Kelp was difficult to find in some blocks on several surveys, leaving gaps in the sampling grid for these events.

Processing

On each survey, kelp blades were labeled in the field and kept cold until laboratory processing began, either the same afternoon or the next morning. Preparation for [N] analysis followed WHEELER and NORTH (1980). The blades were scraped free of fouling organisms, rolled, and placed in open, labeled 4-ounce jars. The samples were dried for at least 24 hrs. at 50 °C, milled to a coarse powder, and sealed in vials and labeled with random digits. Duplicate vials were prepared for approximately 20 randomly chosen blades.

Chemical analysis was by a Leeman Laboratories CE440 automated CHN analyzer. On each survey, duplicate analyses differed by only about 4–7%. These differences were consistent with the nominal levels of precision and accuracy for the weight of the samples analyzed. Duplicates were used only for quality assurance, not in the statistical summaries.

Data Analysis

To tabulate the data, sampling blocks were designated as to transect number and cross-shelf postiion, *e.g.,* 1.1 (transect 1, inshore), 4.2 (transect 4, offshore). Each block is represented by the mean percent dry weight N (hereafter, %N or [N]) of all blades within the block.

Although the basic sampling design was that of a three-way ANOVA (plant × block × sampling event), difficulties involving replication and balance made this standard approach intractable. In particular: (1) in the first two samplings, the individual blades could not be assigned to a particular plant; (2) on the fourth sampling, only one plant was located in block 1.2; and (3) on several dates, no plants at all could be found in several of the blocks.

To simplify the analysis of spatial pattern, and to display the data from all seven surveys on the same scale, the problem was reduced to a consideration of the number of samplings in which each block had above- or below-average nitrogen content for a sampling event. That is, for each sampling, the mean of all the blades analyzed in a block was obtained, and the mean of these block means was computed. Each block was then scored (+ or −) as to whether or not it was above the event mean. To avoid bias due to a possible cross-shelf gradient in nutrient supply, inshore and offshore scores were calculated separately.

Table 1. *Unweighted mean [N] % dry wt. in SOK by sampling period and block.*

Stratum	Block	Aug-91	Dec-91	Jan-92	Mar-92	Apr-92	Jan-94	Mar-94
Inshore	1.1	na	1.41	0.84	1.06	0.83	na	0.75
Inshore	2.1	0.90	1.43	1.03	0.95	0.68	0.75	0.74
Inshore	3.1	1.06	1.25	0.87	na	0.69	0.71	0.85
Inshore	4.1	0.90	1.14	1.10	0.95	0.90	0.57	0.53
Inshore Mean		0.95	1.31	0.96	0.99	0.78	0.68	0.72
Offshore	1.2	1.48	1.47	1.16	1.11	1.02	0.82	1.06
Offshore	2.2	1.02	1.42	1.05	1.14	0.89	0.69	0.84
Offshore	3.2	1.26	na	0.84	1.11	0.84	0.75	0.63
Offshore	4.2	na	1.05	0.91	1.01	0.74	0.71	0.71
Offshore Mean		1.25	1.31	0.99	1.09	0.87	0.74	0.81
Grand Mean		1.10	1.31	0.98	1.05	0.82	0.71	0.76

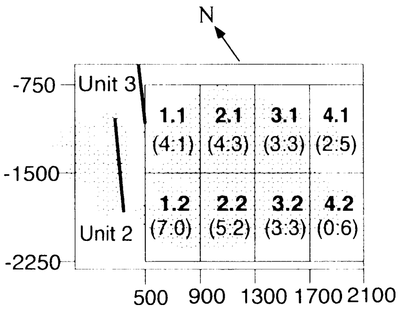

Figure 1. Map of SOK showing the extent of hard substrate and the relationship of the kelp bed to the SONGS diffusers (diagonal lines). Bold numerals are sampling block numbers. Values in parenthesis are the ratio of positive:negative [N] scores. The grid is a Cartesian coordinate system that uses the Unit 1 discharge structure for reference (distance unit = meters).

The binary data set so obtained was then further compressed into a 2 × 4 contingency table (above or below average × alongshore block number, 1–4) and analyzed by χ^2 (Snedecor and Cochran, 1967). Combining the inshore and offshore blocks was done to maintain expected cell frequencies above 5 (Cochran, 1952).

RESULTS

There were substantial differences among the surveys as to the general level of nitrogen content (Table 1). The means of the blocks ranged from 1.3% dry weight nitrogen in December 1991 to 0.7% in January 1994 (Table 1). Offshore nitrogen content was slightly greater than inshore (differences of 0.03% to 0.30%) in all samplings except December 1991, when inshore and offshore means were the same.

The differences in mean [N] among surveys and between inshore and offshore were eliminated by recoding the data as described above. The ratio of positive to negative scores is shown for each sampling block in Figure 1, where the geographical relation of the blocks to the diffuser lines is also diagrammed.

As described in the introduction, because of the prevailing currents and known nitrate distribution in near-bottom waters, we expected greatest enrichment to be seen in the upcoast, offshore portion of SOK. This was exactly the case. The offshore block nearest the Unit 2 diffuser (block 1.2) had positive scores in all seven samplings. Moreover, there was a regular pattern of decreasing ratios of positive:negative scores with increasing distance from the diffuser lines. Combining the (+:−) ratios in the four colums of the grid in Figure 1 gives 11:1, 9:5, 6:6, 2:11 for $\chi^2 = 15.4$ with 3 degrees of freedom; $p < 0.005$.

We therefore reject the null hypothesis of no pattern. A very reasonable alternative hypothesis is the one stated *a priori, i.e.*, that the SONGS diffuser plume enriches canopy tissues in SOK, with the strongest effect nearest the diffusers.

DISCUSSION

The spatial extent of the enhancement cannot be determined from our study. That is, without experimentally turning the power plant on and off repeatedly for several-week periods, one could not tell the difference between the diffuser-enhanced condition and natural background. In this study the downcoast quarter of the kelp bed was generally below average for SOK in tissue nitrogen. Assuming the downcoast condition is no worse than natural background, we can infer that at least three quarters of the area that can be occupied by kelp at SOK is enriched by the artificial upwelling.

The variations in nitrogen content reported here are considered physiologically significant. Gerard (1982) found that a well-nourished kelp plant grew at a rate of over 3% of its biomass per day, but that this rate fell to around 1% over the course of a month as the plant was deprived of nutrients and blade nitrogen content fell to about 1%. Dean and Jacobsen (1986) found that juvenile kelp growth rates varied significantly with tissue nitrogen in the range 0.7% to 1%. This is the range seen in the present study in April 1992 (Table 1), the high end attributed to the enriching effect of SONGS.

While kelp bed decline due to winter storm damage is common, low nutrient conditions can also cause mortality of adult plants (Gerard, 1984; Foster and Shiel, 1985; Tegner and Dayton, 1987). It is conceivable that the portion of SOK that benefits from the artificially upwelled nutrients might survive a period of generally poor conditions such as an El Niño. Apparently, anthropogenic nutrient inputs sustained a kelp bed in Los Angeles County during the 1982–84 El Niño (Dayton and Tegner, 1990). Best survival at SOK during that same El Niño in fact occurred in the offshore portions of the bed (Petersen, 1985).

Recovery periods can last several years, so plants sustained by the SONGS upwelling might serve as a source of spores and, conceivably, significantly decrease the length of time SOK is without much kelp following a devastating period of low nutrient. Over time, this effect might counterbalance the effects of reduced kelp recruitment (MRC, 1989) correlated with the turbidity of the plume.

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