

NITRATE-RICH GROUNDWATER INPUTS TO DISCOVERY BAY, JAMAICA: A SIGNIFICANT SOURCE OF N TO LOCAL CORAL REEFS?

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ABSTRACT

The freshwater aquifer at Discovery Bay, Jamaica, produces subterranean springs and seeps near the reef at the mouth and along the southern and western shorelines of the bay. A strong inverse correlation exists between salinity and N concentration. Undiluted spring-water typically contains 80 μg at N per liter or more, primarily as nitrate, but is essentially devoid of P. Input from the springs is enough to reduce the salinity by one to several parts per thousand near these sites and appears to produce a significant enrichment of nitrogen to the bay.

Much attention has been paid to the relationship between nutrient dynamics and productivity in tropical shallow water communities. The impetus for this attention is the contrast between the characteristically high productivities and standing stocks of these communities and the surface waters bathing them, which are typically clear, unproductive, and low in dissolved and particulate nutrient content (Lewis, 1977).

Interisland coral reefs on a Pacific atoll, remote from substantial influence of terrestrial nutrient inputs, were among the first of these communities to be studied intensively (Odum and Odum, 1955). These reefs appear to derive much of the N they require from *in situ* N-fixation (Wiebe et al., 1975), while their P requirements appear reduced by tight phosphorus retention and recycling (Pomeroy and Kuenzler, 1969; Pilson and Betzer, 1973). Other factors that appear to support high levels of gross productivity in such coral reefs include vigorous water circulation and flow (Smith and Jokiel, 1975; Jokiel, 1978) and adaptive, polytrophic mechanisms of reef organisms to acquire N and P efficiently from seawater impinging on them (D'Elia and Webb, 1977; Muscatine and Porter, 1977).

Recently, the focus of attention in nutrient-productivity studies has expanded from low island, atoll reefs to include reefs in the vicinity of high islands where terrestrial factors may be important. Although nutrients derived from man's activity are undoubtedly of local importance (Smith et al., 1978), the question has been raised whether nutrients naturally present in groundwater and runoff are potentially significant on a larger scale (Marsh, 1977).

Our observations of high NO_3^- levels near the sites of underground springs and seeps in Discovery Bay, Jamaica, prompted us to determine that groundwater is the source of this NO_3^- and may represent a significant input of nitrogen to the bay and nearby coral reefs.

MATERIALS AND METHODS

Research Site

Discovery Bay is located on the central north coast of Jamaica, West Indies. The bay is a semi-enclosed basin about 1.4 km^2 in area and 1.2 km across at the mouth; its central depression is about 50 m deep (Fig. 1). The seaward mouth is protected from the open ocean by a fringing reef, emergent at low spring tides, that extends roughly two-thirds of the way across the bay, dissected midway by a 20 m deep channel for bauxite ships that is periodically dredged at its center. The mean tidal range is less than 1 m. The land form of the drainage basin is relatively porous allowing phreatic flow

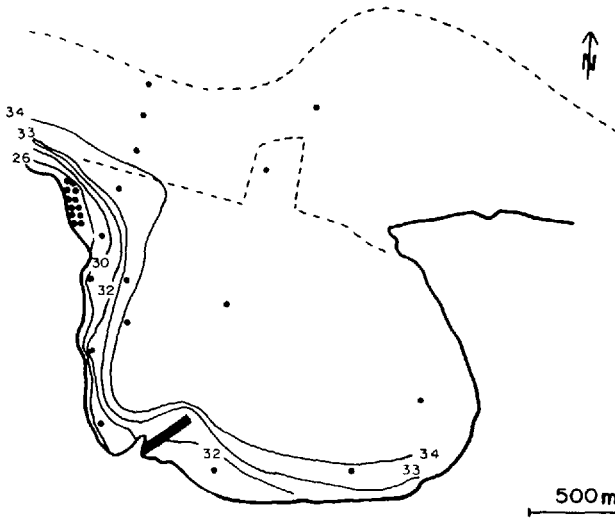


Figure 1. Chart of Discovery Bay, Jamaica, showing surface salinity isopleths on August 18, 1979. Sampling sites are indicated by filled circles.

through limestone bedrock (Land, 1973); there are no permanent rivers that empty into the bay, but surface run-off during rains occurs via several rivulets along the central and western end of the bay where the land slopes up rapidly to the 100 m high limestone terraces of the Hope Gate geological formation (Land, 1973). The limestone terraces, cliffs, and near-shore platforms are perforated by subterranean cracks, crevices, and caves such as the nearby Green Grotto Caverns. These basement rock fissures act as natural channels conducting water from inland to the coast.

Sampling

Surface water samples were taken at a number of sites (Fig. 1) in the bay during August 1979, and January, February, and March 1980. Once, in March 1980, we took vertical temperature profiles at these sites using a Beckman salinometer whose temperature but not salinity capability was reliable. Subsurface water samples to 2 m depth were taken in the vicinity of the laboratory in areas where springs occurred. Once in February 1980, we took samples from rivers and streams between Discovery Bay and Ocho Rios, from freshwater springs on the beach at Dunn's River Falls, and from well water in Stewarttown, a small town in the hills above Discovery Bay. Samples from the laboratory seawater system and from the Discovery Bay freshwater system (well water) were also taken frequently. All glass and plasticware used for sampling and storage were rinsed with dilute acid (10% HCl), distilled water, and an aliquot of sample. Samples were filtered (GF/C) either immediately after being taken or upon return to the laboratory. Aliquots for total dissolved nitrogen (TDN) and phosphorus (TDP) were frozen for storage for later analysis, but all other nutrient determinations were made within hours on the freshly collected samples.

Analytical Determinations

Salinity was determined using a Bausch and Lomb refractometer. NO_3^- , NO_2^- , NH_4^+ , and PO_4^{3-} determinations were performed on either a Scientific Instruments CFA 200 or a Technicon AAI automated chemistry system using standard methods (USEPA Methods 353.2, 351.1, 365.1, Kopp and McKee, 1979) or slight modifications thereof (Keefe et al., in prep.); TDN and TDP were determined using an alkaline persulfate digestion (D'Elia et al., 1977); urea was determined using the method of DeManche et al. (1973). Internal standards and frequent standard curves were run.

RESULTS

Nutrient-Salinity Relationships

Although freshwater sources undoubtedly charge the submarine springs entering Discovery Bay, a great deal of subterranean mixing of fresh and seawater

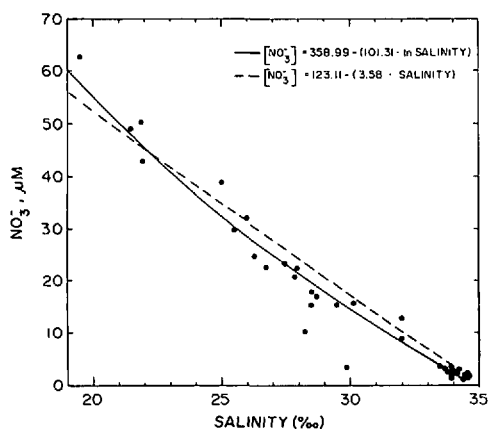


Figure 2. (Left) Salinity vs. nitrate mixing diagram for August 18, 1979.

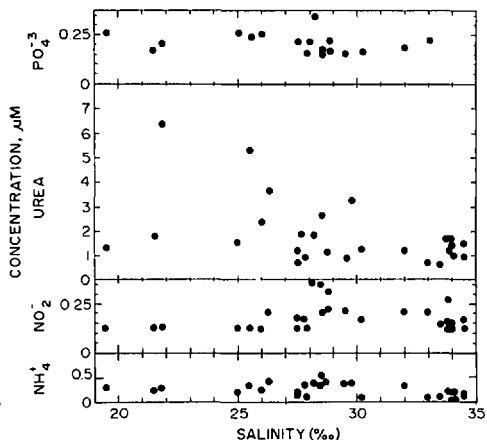


Figure 3. (Right) Salinity vs. nitrite, ammonia, phosphate and urea mixing diagram for August 18, 1979.

apparently occurs before the springs discharge into the bay, for we were unable to obtain water samples of less than 20‰ salt content even in the spring mouths. The most striking feature of the nutrient data of samples from the bay during August 1979, was a highly significant negative correlation between nitrate concentration and salinity (Fig. 2). Although simple linear regression ($y = a + bx$, where $a = 123.11$ and $b = -3.58$) gave an excellent fit to the data ($r = -0.97$; F ratio = 545.1), a logarithmic relationship ($y = a + b \ln x$, where $a = 358.99$ and $b = -101.31$) proved slightly better ($r = -0.98$; F ratio = 814.0). This indicates some curvilinearity exists in the dilution curve: had all of the data points fallen on a straight line, a conservative mixing relationship would have explained the dilution of NO_3^- rich freshwater by NO_3^- free seawater. During January and February 1980 (original data not shown), we again saw linear or nearly linear relationship between salinity and NO_3^- concentrations. The bends in the fitted curves did not consistently fall substantially above or below the rectilinear conservative mixing relationship. These slight deviations from linearity probably indicate a variation with time in the groundwater NO_3^- concentration (Loder and Reichard, in press), although alternatives are possible such as benthic nutrient sinks or sources, or the mixing of multiple sources of freshwater with different NO_3^- content (Boyle et al., 1974).

We base our belief that there is variation with time in the NO_3^- concentration of the groundwater on evidence presented in Table 1, which gives the results of linear regressions of NO_3^- concentration against salinity on six different sampling occasions. Although estimates of NO_3^- concentration in undiluted groundwater are only roughly determined as the ordinal intercepts obtained from such regressions, they represent statistically different values as the precision of the intercept estimates, as indicated by their standard errors, is considerably smaller than the differences between intercept values. Further evidence of temporal variation in groundwater NO_3^- content comes from analyses of laboratory tapwater whose source is a local well (Table 2). These measured values in freshwater agree reasonably well with values predicted from dilution curve intercepts, although the latter tend to be somewhat higher and more variable. Also given in Table 2 are analyses of various freshwater sources along Jamaica's north shore that reveal spatial differences also exist.

Table 1. The regression statistics for nitrate concentration and salinity described as a linear relationship, $y = a + bx$, where y = nitrate concentration (μM), b = slope, a = y intercept (predicted NO_3^- content, μM , of freshwater), n = number of samples, r = correlation coefficient, and % range is the salinity range of the samples (\pm values are standard errors)

Date	n	a	b	r	% range
16 Aug. 1979	11	111.6 \pm 3.4	-3.20 \pm 0.11	0.99	22.0-34.5
18 Aug. 1979	29	130.0 \pm 9.7	-3.80 \pm 0.33	0.91	19.5-34.5
31 Jan. 1980	20	88.0 \pm 7.9	-2.47 \pm 0.24	0.92	26.0-36.0
12 Feb. 1980	19	171.0 \pm 9.4	-4.74 \pm 0.29	0.97	25.0-36.0
26 Feb. 1980	26	250.0 \pm 13.2	-7.06 \pm 0.42	0.96	26.0-36.0
28 Feb. 1980	5	214.0 \pm 8.02	-6.13 \pm 0.30	0.99	18.0-31.0

Neither PO_4^{3-} , nor NO_2^- , nor NH_4^+ , nor urea concentrations showed significant positive or negative linear correlation with salinity, suggesting that groundwater did not supply these nutrients to the bay (Fig. 3). Our sample at a salinity of 19.5‰ contained an atomic NO_3^- -N: PO_4^{3-} -P ratio of >298:1, clearly indicating a nutrient source relatively deficient in P to N. At higher salinities, of course, since PO_4^{3-} concentrations remain similar and NO_3^- concentrations decrease, lower ratios were obtained.

Total Dissolved Nitrogen and Phosphorus

Total dissolved nitrogen (TDN) concentration correlated positively and strongly ($r = 0.93$) in a 1:1 ($b = 1.07 \pm 0.1$) linear fashion with NO_3^- concentration (not shown). The organic nitrogen fraction (in effect, TDN less NO_3^-) remained constant at all NO_3^- concentrations, and hence at all salinities observed. The ordinal intercept (21.4 ± 3.0) determined by linear regression represents the approximate dissolved organic nitrogen content of all samples. Total dissolved phosphorus values (TDP—not shown) were similar to and not statistically distinguishable from DIP values. Thus, dissolved organic phosphorus concentration was low, and it is apparent that freshwater inputs supply trivial amounts of P relative to N in the estuary.

Table 2. Nitrate content of various freshwater sources, at various times, on Jamaica's North Coast

Date	Source	$[\text{NO}_3^-]$, μM
16 Aug. 1979	Lab tap	87
26 Jan. 1980	Lab tap	85
28 Jan. 1980	Lab tap	67
31 Jan. 1980	Lab tap	61
8 Feb. 1980	Lab tap	109
12 Feb. 1980	Lab tap	118
23 Feb. 1980	Spring near beach at Dunn's River	93
23 Feb. 1980	Dunn's River Falls	125
23 Feb. 1980	Pear Tree Creek	103
23 Feb. 1980	Laughlin's Little River	157
23 Feb. 1980	Pear Tree River	136
23 Feb. 1980	Creek near St. Ann's Bay	147
24 Feb. 1980	Lab tap	87
26 Feb. 1980	Lab tap	120
3 Mar. 1980	Lab tap	73
3 Mar. 1980	Well at Stewartown	87
6 Mar. 1980	Lab tap	87
6 Mar. 1980	Rain at lab	2.8

DISCUSSION

Geochemical processes resulting from the movement of meteoric water through the Hope Gate and Falmouth formations of the Discovery Bay area and its mixing with seawater have been considered by geologists (Land, 1973). We have found that meteoric water in this area presently contains much nitrogen in the form of nitrate and thus may be expected to have significant effects on biological processes after its discharge into the bay. Our discovery is reminiscent of that of Marsh (1977) who found high nitrate input from terrigenous sources in Guam. In agreement with Marsh, we consider that phreatic nutrient inputs, especially for high island ecosystems, need to be evaluated on a pantropical basis. We also concur with others (Kohout, 1966; Manheim, 1967) who advocate more intensive study of the general importance of submarine springs.

We can presently say little about the sources of N-enrichment to the groundwater, although we believe that they are naturally and not anthropogenically derived. Water entering groundwater pools in Jamaica is probably exposed to both leguminous and non-leguminous terrestrial nitrogen fixing organisms and to plant litter decomposers. These organisms may leach NH_4^+ which is subsequently oxidized to NO_3^- by nitrifiers before the water enters the aquifer. Another major source of NO_3^- could be rainwater. Several analyses of rainwater during January–March 1980, gave NO_3^- concentrations from 2–10 μM , far below concentrations we observed in the groundwater. However, rainfall has been reported to be extremely variable in nitrate concentrations in other areas (Valiella et al., 1978) and thus may at times contain more NO_3^- than we found in our samples. In addition, the evaporation and transpiration of rainwater after it has fallen may concentrate NO_3^- before it enters the groundwater. Although sewage is a potential source of N as well, we regard it to be of little consequence in the rural Discovery Bay area.

We did not have available the resources and equipment in this preliminary study to make detailed quantitative measurements of hydrographic or hydrologic processes. However, some of our general observations have given us some qualitative information about these processes. From our surface salinity sampling it was apparent that most of the phreatic freshwater input into the bay occurred on the western shore near the marine laboratory (Fig. 1). When we temperature-profiled the central portion of the bay, we saw no evidence of temperature stratification. During northeasterly trade winds, which prevail during the day, and at high tide, seawater is certainly transported into the bay along the entire reef crest which traverses the bay mouth. Return flow to the sea may occur through the ship channel where J. Woodley (pers. comm.) has observed strong currents at depth. However, under calm conditions (typically dusk through early morning) and at low slack tide, we have frequently observed visually slicks of surface water transported across the reef seaward in the northwest corner of the bay: when we sampled water from the center of one of these slicks we found it contained water ranging from 33 to 35‰, lower than full strength seawater (36‰). Thus, there appears to be a hydrographic mechanism for transporting NO_3^- rich water from inside the Bay to the shallow reef.

We lack direct measurements of the groundwater discharge rate to the bay, and hence the N-enrichment rate. Indirect hydrographic measurements such as water residence time in the bay could be used with our dilution curve data to make such an estimate.

Significant phreatic P inputs to the bay seem unlikely on the basis of our data. Similarly, Marsh (1977) believed that uncontaminated groundwater constituted a significant source of N but not P for the rural Tumon Bay ecosystem. The N:P

atomic ratio of the groundwater in the Discovery Bay aquifer is about 625 (125 μg at NO_3^- -N: 0.2 μg at PO_4^{-3} -P). The explanation for the high N:P ratios in the groundwater is uncertain, however, it is well known that PO_4^{-3} tends to sorb to many soil types, forming calcium, aluminum and iron complexes (Suess, 1970; 1973; Logan and McLean, 1973). Soils in the Discovery Bay watershed are rich in bauxite and calcium carbonate and may strongly retain what PO_4^{-3} , if any, is present. Unlike PO_4^{-3} , NO_3^- is highly mobile in soils and undergoes little sorption; thus, high NO_3^- concentrations are characteristic of groundwaters from many localities, tropical and temperate (Loeb and Goldman, 1979; Valiella et al., 1978).

The high N:P ratios of the groundwater source and the extremely low phosphate concentration of Caribbean water in general (Johnson and Pilson, 1972) suggest that environments such as Discovery Bay are very poor in P. Considering this, the work of Reid (1966) showing higher P levels in the Pacific than in the Atlantic, and the work of Kinsey and Davies (1979) who attributed depression in reef calcification to experimental P enrichment, one wonders if phosphorus levels relate to observations of Adey (1978) that "geographically and morphologically spectacular Indo-Pacific atoll reefs have been growing slowly with little recent increase in thickness, while less extensive systems in the Caribbean are growing rapidly and have achieved greater vertical accumulation."

Our considerable experience with low island reef communities in the Pacific (Johannes et al., 1972; Webb et al., 1975; Webb and Wiebe, 1975; Wiebe et al., 1975; LIMER 1975 Expedition Team, 1976) suggests to us that low island, Pacific reef communities rely more heavily on nitrogen fixation for N acquisition than would be expected for reefs in the vicinity of Discovery Bay which receive a subsidy of N as NO_3^- from terrigenous sources. This subsidy might be expected to reduce the need for N-fixation in such systems. Likewise, nitrification might be expected to be a less important process in the Discovery Bay area than at Pacific reefs where one of us (KLW) has found that process to be an important feature of reef N metabolism. Indeed, unpublished studies (J. Baker and T. J. Goreau) indicate that nitrification rates in Discovery Bay are extremely low.

Two final considerations seem warranted. First, we speculate that even modest enrichment of Discovery Bay or similar environments with domestic sewage, which is typically rich in P, would initiate eutrophication problems, given the existence of N-rich groundwater inputs. Second, we caution researchers at Discovery Bay Marine Laboratory to take into account in their experimental designs and interpretations, the effects of N-enrichment of the seawater system (where we found concentrations of NO_3^- as high as 33.5 μM), and of the nearshore enrichment of the western part of the bay, not to mention the reduction in salinity that accompanies this enrichment.

ACKNOWLEDGMENTS

This is Contribution No. 1021 of the University of Maryland's Center for Environmental and Estuarine Studies, No. 964 of Virginia Institute of Marine Science, and No. 214 of the Discovery Bay Marine Laboratory. This material is based on research supported in part by the National Science Foundation under Grants No. OCE78-08415 (CFD), OCE78-20433 (KLW), and OCE77-26781 (JWP). We thank J. D. Woodley, T. J. Goreau, S. V. Smith, L. Pastor, C. Keefe, K. Wood, L. Lubbers, and S. Lynch for helping with various aspects of this study and the preparation of this manuscript.

LITERATURE CITED

- Adey, W. H. 1978. Coral reef morphogenesis: a multidimensional model. *Science* 202: 831-837.
Boyle, E., R. Collier, A. Dengler, J. Edward, A. Ng, and R. Stallard. 1974. On the chemical mass balance in estuaries. *Geochim. Cosmochim. Acta* 38: 1719-1728.

- D'Elia, C. F., and K. L. Webb. 1977. The dissolved nitrogen flux of reef corals. Pages 325–330 *in* D. L. Taylor, ed. Proc. Third Int. Coral Reef Symp. 1. Biology. Univ. of Miami, Miami, Florida.
- , P. A. Steudler, and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. *Limnol. Oceanogr.* 22: 760–764.
- DeManche, J. M., H. Curl, Jr., and D. D. Coughenower. 1973. An automated analysis for urea in seawater. *Limnol. Oceanogr.* 18: 686–689.
- Johannes, R. E. et al. 1972. The metabolism of some coral reef communities: A team study of nutrient and energy flux at Eniwetok. *BioScience* 22: 541–543.
- Johnson, D. L., and M. E. Q. Pilson. 1972. Arsenate in the Western North Atlantic and adjacent regions. *J. Mar. Res.* 30: 140–149.
- Jokiel, P. L. 1978. Effects of water motion on reef corals. *J. Exp. Mar. Biol. Ecol.* 35: 87–97.
- Kinsey, D. W., and P. J. Davies. 1979. Effects of elevated nitrogen and phosphorus on coral reef growth. *Limnol. Oceanogr.* 25: 939–940.
- Kohout, F. A. 1966. Submarine springs: A neglected phenomenon of coastal hydrology. Central Treaty Organization, Symp. Hydrology and Wat. Res. U.S. Dept. Interior: 391–413.
- Kopp, J. F., and G. D. McKee. 1979. Methods for chemical analysis of water and waste. U.S.E.P.A. Publication EPA-600/4-79-020. 460 pp.
- Land, L. S. 1973. Contemporaneous dolomitization of middle Pleistocene reefs by meteoric water, north Jamaica. *Bull. Mar. Sci.* 23: 64–92.
- Lewis, J. B. 1977. Processes of organic production on coral reefs. *Biol. Rev.* 52: 305–347.
- LIMER 1975 Expedition Team. 1976. Metabolic processes of coral reef communities of Lizard Island, Queensland. *Search* 7: 463–468.
- Loder, T. C., and R. P. Reichard. In press. The dynamics of conservative mixing in estuaries. *Estuaries*.
- Loeb, S. L., and C. R. Goldman. 1979. Water nutrient transport via groundwater from Ward Valley into Lake Tahoe. *Limnol. Oceanogr.* 24: 1146–1154.
- Logan, T. E., and E. O. McLean. 1973. Nature of phosphorus retention and absorption with depth in soil columns. *Soil Sci. Am. Proc.* 37: 351–355.
- Manheim, F. T. 1967. Evidence for submarine discharge of water on the Atlantic Continental Slope of the southern United States, and suggestions for further research. *Trans. N.Y. Acad. Sci.* 29: 839–853.
- Marsh, J. A. 1977. Terrestrial inputs on nitrogen and phosphorus on fringing reefs of Guam. Pages 331–336 *in* D. L. Taylor, ed. Proc. Third Int. Coral Reef Symp. 1. Biology. Univ. of Miami, Miami, Florida.
- Muscatine, L., and J. W. Porter. 1977. Reef corals: mutualistic symbioses adapted to nutrient-poor environments. *BioScience* 27: 454–460.
- Odum, H. T., and E. P. Odum. 1955. Trophic structure and productivity of a windward coral reef community on Eniwetok Atoll. *Ecol. Monogr.* 25: 291–320.
- Pilson, M. E. Q., and S. B. Betzer. 1973. Phosphorus flux across a coral reef. *Ecology* 54: 581–588.
- Pomeroy, L. R., and E. J. Kuenzler. 1969. Phosphorus turnover by coral reef animals. Pages 474–482 *in* 2nd Proc. Conf. Radioecol. AEC Conf.-67053.
- Reid, J. L., Jr. 1962. On the circulation, the phosphate-phosphorus content, and the zooplankton volumes in the upper part of the Pacific Ocean. *Limnol. Oceanogr.* 7: 287–306.
- Smith, S. V., and P. L. Jokiel. 1975. Water composition and biogeochemical gradients in the Canton Atoll lagoon: 2. Budgets of phosphorus, nitrogen, carbon dioxide, and particulate materials. *Mar. Sci. Communications* 1: 165–207.
- , R. E. Brock, J. T. Harrison, J. Hirota, P. L. Jokiel, W. Kimmerer, D. W. Kinsey, E. A. Laws, D. G. Redalje, S. Taguchi, and T. W. Walsh. 1978. Kaneohe Bay sewage relaxation experiment: pre-diversion report. USEPA Report, Hawaii Institute of Marine Biology, Kaneohe, Hawaii. 166 pp.
- Suess, E. 1970. Interaction of organic compounds with calcium carbonate—I. Association phenomena and geochemical implications. *Geochim. Cosmochim. Acta* 34: 157–168.
- . 1973. Interaction of organic compounds with calcium carbonate—II. Organo-carbonate association in recent sediments. *Geochim. Cosmochim. Acta* 37: 2435–2447.
- Valiella, I., J. M. Teal, S. Volkmann, D. Shafer, and E. J. Carpenter. 1978. Nutrient and particulate fluxes in a salt marsh ecosystem: Tidal exchanges and inputs by precipitation and groundwater. *Limnol. Oceanogr.* 23: 798–812.
- Webb, K. L., and W. J. Wiebe. 1975. Nitrification on a coral reef. *Can. J. Microbiol.* 21: 1427–1431.
- , W. D. DuPaul, W. Wiebe, W. Sottile, and R. E. Johannes. 1975. Eniwetak (Eniwetok) Atoll: aspects of the nitrogen cycle on a coral reef. *Limnol. Oceanogr.* 20: 198–210.
- Wiebe, W. J., R. E. Johannes, and K. L. Webb. 1975. Nitrogen fixation in a coral reef community. *Science* 188: 257–259.

DATE ACCEPTED: August 26, 1980.

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