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Author: Barile, Peter J.

Source: Journal of Coastal Research, 2004(204) : 1237-1245

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/04-0212.1

Journal of Coastal Research	20	4	1237–1245	West Palm Beach, Florida	Fall 2004

Evidence of Anthropogenic Nitrogen Enrichment of the Littoral Waters of East Central Florida

Peter J. Barile

Division of Marine Science
Harbor Branch Oceanographic Institution
5600 US 1 Ft. Pierce, FL 34946, U.S.A
pbarile@hboi.edu

ABSTRACT

BARILE, P.J., 2004. Evidence of anthropogenic nitrogen enrichment of the littoral waters of east central Florida. *Journal of Coastal Research,* 20(4), 1237–1245. West Palm Beach (Florida). ISSN 0749-0208.

Excessive human-derived nutrient availability has been implicated as a primary driver in the decline of the water quality and biota of coastal ecosystems. In 2003, seven sites along an urbanized section (~100 km) of the Atlantic littoral coastline in east-central Florida were assessed for the bio-availability of the primary nutrients nitrogen and phosphorus. Ratios of dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonium) to soluble reactive phosphorus (SRP) in 74 beach water samples averaged 8:1, indicating strong water column nitrogen-limitation. DIN concentrations ranged from 0.69 to 8.11 μM with a grand mean of 2.10 μM, a value two-fold above the reported threshold value of ~1 μM that saturates growth of Florida red tide, *Karenia brevis* and macroalgae species utilized in this study, such as *Ulva lactuca.* The majority (mean = 56%) of this DIN was in the form of ammonium, even during a peak upwelling event in June and August, suggesting the importance of anthropogenic land-based nitrogen as the primary N source. Macroalgae from subtidal sabellariid worm reefs were assessed for $\delta^{15}N$. At all study sites, macroalgal tissue mean $\delta^{15}N$ values ranged from +8.7 to +9.9‰, values similar to those in macroalgae from sewage-polluted coastal areas, such as Boston Harbor. Many of the abundant macroalgae collected on these reefs, including *Ulva lactuca, Chaetomorpha linum, Gracilaria tikvihae,* and *Caulerpa prolifera,* are known sewage indicator species in other eutrophic coastal water bodies receiving excessive anthropogenic nutrient loads. These results suggest the need for improved nutrient removal in wastewater treatment facilities that discharge nearly 100 million liters of secondary-treated sewage effluent/ day into the highly transmissive silica-sand barrier island of Brevard and Indian River Counties in east-central Florida..

ADDITIONAL INDEX WORDS: *Eutrophication, macroalgae, sabellariid reefs, water quality, sewage.*

INTRODUCTION

The mobilization of fixed nitrogen by humans into the biosphere, particularly the coastal zone, may be the most drastic and recognizable symptom of human-induced global scale environmental alteration of earth to date (VITOUSEK *et al.,* 1997). The consensus policy document of the National Academy of Sciences NATIONAL RESEARCH COUNCIL (2000) entitled: "Clean Coastal Waters: Understanding the consequences of nutrient enrichment" states:

> "Over the last twenty years, there has been a growing awareness that coastal ecosystems have been experiencing a number of environmental problems that can be attributed to the introduction of excess nutrients. At first glance, many of the diverse problems seem unrelated and their causes are often not readily apparent. However, there is a growing body of evidence that events such as the deaths of unusually large numbers of sea lions and manatees, unusual patterns of coral reef destruction, widespread fish kills, outbreaks of certain shellfish poisonings, disappearance of seagrasses, and the occurrence of the so called "dead-zone" in the Gulf of Mexico actually have much more in common than originally thought. All of these events reflect both subtle and not-so-subtle changes in the relative and absolute abundance of certain organisms near the very base of the food web. The abundance of these organisms is related, sometimes directly and at other times indirectly, to nutrients flowing into the system from upstream watersheds."

On the east-central coast of Florida, many of these symptoms, including: intense red-tides, novel dinoflagellate blooms and biotoxin production (*e.g.* saxitoxin, okadaic acid), macroalgal blooms, fish kills, bird and marine mammal deaths and skin diseases, a high incidence of fibropapilloma tumors in sea turtles, elevated human fecal bacteria counts, in addition to purported marine fungal-related sores on humans following beach-bathing, have been recently reported.

The barrier island in Brevard and Indian River County, FL is an important residential and commercial corridor, with 19 wastewater treatment facilities (WWTP's, see Table 1, Figure 1) in addition to nearly 3000 Onsite Sewage Disposal Systems (OSDS's, or septic tanks) in the lower portion of Brevard County, and nearly 300 residences with septic tanks in northern Indian River County. Two of the WWTP's on the barrier islands in Brevard County utilize deep-injection discharge of secondarily effluent to 1000m depth below the barrier island (see Figure 1). The south beaches central wastewater treat-

04-0212 received and accepted in revision 06 May 2004.

Table 1. *Wastewater treatment methods, effluent discharge, and loadings for the barrier island study area.*

Wastewater Treatment Method[1]	No. of Facilities	Effluent Discharge (million liters/day)	TN Load (tonnes/d)	TP Load (tonnes/d)
Percolation ponds, subsurface drainfields (secondary treatment)	17[1]	35.7[1]	0.74[4]	0.25[4]
Deep-well injection (secondary treatment)	2[1]	56.8[1]	1.14[4]	0.40[4]
Septic tanks (OSDS)				
Brevard Co.	3,000[2]	1.1[5]	0.05[5]	0.02[5]
Indian River Co.	300[3]	0.1[5]	0.01[5]	<0.01[5]
Total	3,319	93.7	1.94	0.68

[1] Florida Department of Environmental Protection; [2] Brevard County—Office of the Property Appraiser; [3] Indian River County—Department of Health; [4] from Clark, J.W. *et al.* 1977; [5] from USEPA (1980) Design Manual for Onsite Wastewater Treatment and Disposal Systems, EPA #625/1-80-012.

ment facility, with a permitted capacity of 36 million liters/day has been identified in a recent USEPA risk assessment as a facility with "the potential for significant vertical migration of effluent into the overlying drinking water aquifer" (USEPA 2003). Overall, the magnitude of permitted wastewater treatment (almost exclusively secondary treatment) on the barrier island is nearly 100 million liters/ day (Table 1, FDEP, 2004). The majority (17 of 19 WWTP's located on the barrier island) of these wastewater treatment facilities utilize either "percolation ponds" or "subsurface drainfields" to dispose of the soluble wastewater fraction into the quartz sand barrier island. Some of these facilities also have USEPA discharge permits to discharge secondarily treated wastewater into adjacent surface waters during "wet-weather" events. The loading of total nitrogen (TN) and phosphorus (TP) from permitted sewage wastewater facilities into the barrier island system is 1.94 (TN) and 0.68 (TP) metric tonnes/day, or 708 (TN) and 248 (TP) metric tonnes/year (see Table 1).

Despite the significant magnitude of wastewater disposal on the barrier island system, and a general recognition of the previously mentioned ecological problems in adjacent littoral waters, no previous attempt has been made to characterize the general water quality on the littoral Atlantic coast of east-central Florida. According to NOAA (1996), concentrations of primary nutrients (nitrogen, phosphorus) are the most common measure and indicator of environmental stress in coastal areas. Here, I provide the first annual record of inorganic nitrogen and phosphorus concentrations in this system. Also, stable isotope tracer techniques were utilized to discriminate and characterize the importance of natural and anthropogenic sources (*e.g.* upwelling, nitrogen fixation, human sewage, fertilizer) of the primary limiting nutrient, nitrogen, to benthic macrophyte producers in this system.

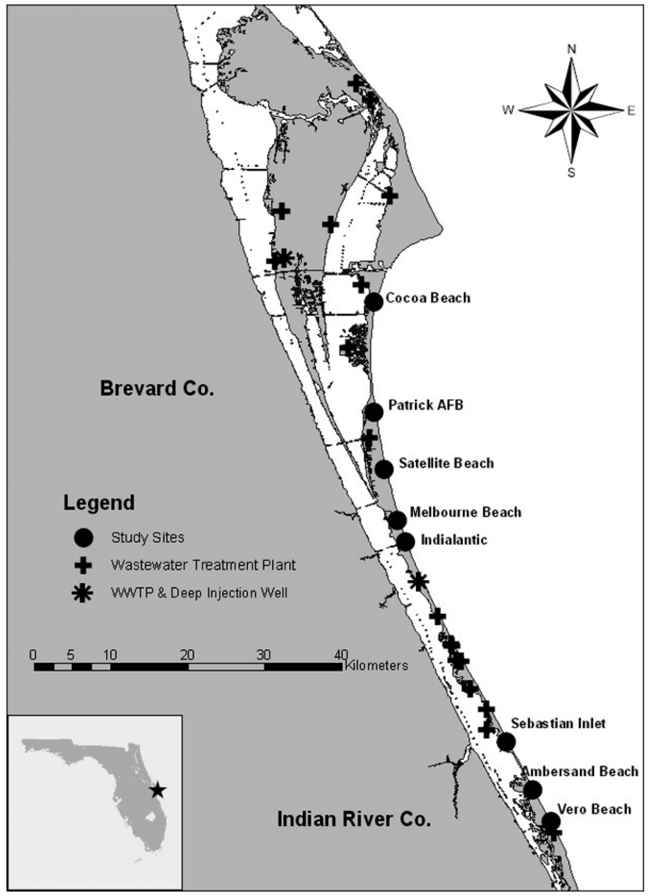

Figure 1. Map of study area including study sites and wastewater treatment plant locations on the barrier island in Brevard and Indian River Counties, Florida.

METHODS

Study Sites and Sample Collection

A series of sampling stations were established along the littoral beach environment of east-central Florida in Brevard and Indian River Counties, FL (see Figure 1) to collect: (1) bi-monthly water samples to assess the concentrations of dissolved inorganic nutrients (nitrate-nitrite, ammonium, soluble reactive phosphorus), and (2) resident benthic macroalgae for analysis of natural abundances of stable nitrogen isotopes. The sample stations included the 1m depth strata of the littoral environment at: (1) Cocoa Beach (at the CB Pier), (2) Patrick Air Force Base, (3) Satellite Beach, (4) Indialantic, (5) Sebastian Inlet, (6) Ambersand Beach (Wabasso), and (7) Vero Beach (Humiston Park). The first sample collection at Cocoa Beach was made near the Port Canaveral Jetty, but subsequent samples were collected several kilometers to the south at Cocoa Beach Pier. Indialantic macroalgae sample collections were made several kilometers to the north at the Melbourne Beach site where anastasia beach rock formations facilitated collection of macroalgae. Collections of water samples were initially made several days following a rainfall event on 18 March 2003, with subsequent sampling following bi-monthly through December 2003. Duplicate seawater samples were collected in EPA-certified pre-cleaned 125 ml wide mouth polyethelyne bottles. Samples were collected at mid-

Table 2. *List of macroalgal species utilized for $\delta^{15}N$ analysis as a function of study site.*

Taxon/Species	CB	PA	SB	MB	SI	AB	VB
Chlorophyta							
Ulva lactuca	×		×	×	×	×	×
Chaetomorpha linum	×			×	×		×
Enteromorpha intestinalis					×		
Codium isthmocladum						×	
Caulerpa prolifera		×	×			×	
Caulerpa racemosa					×		×
Caulerpa sertularioides					×		
Rhodophyta							
Bryothamnion triquetrum		×		×		×	×
Gracilaria tikvihae	×			×			×
Botryocladia spinulifera							×
Laurencia poiteaui					×		
Phaeophyta							
Colpomenia sinuosa	×					×	×

depth (<1m depth) at the previously described sites, and stored on ice. Samples were then filtered through a 0.45 μm GF/F syringe filter, and held frozen until analysis, performed within 28 days per USEPA (1979) protocol.

Sample Analyses

Seawater samples were analyzed for NH_4^+ (Berthelot Method), NO_3^- plus NO_2^- (EPA Method 353.2), and SRP (EPA Method 365.1, see USEPA 1979). Measurements of these inorganic nutrients were made on a Technicon Auto-Analyzer II, and a two channel Technicon TRAACS 800 Nutrient Analyzer at the Nutrient Analytical Servies Laboratory at the University of Maryland–Chesapeake Biological Laboratory in Solomons, MD. The analytical detection limits were 0.21 μM for NH_4+, 0.05 μM for $NO_3^- + NO_2^-$, and 0.02 μM for SRP.

For $\delta^{15}N$ analysis, abundant macroalgae species (see Table 2), particularly those common to all stations to allow intraspecific spatial and temporal comparisons, were sampled in the study area. Composite samples of macroalgae (n = 2) were dried in a laboratory oven (60 °C) to constant weight and then analyzed in a Carlo-Erba N/A 1500 elemental analyzer using Dumas combustion and the purified nitrogen gas was then measured by a VG Isomass mass spectrometer. The standard used for stable nitrogen isotope analysis was N_2 in air. $\delta^{15}N$ values, in per mil (‰) concentration were calculated as $[(R_{sample}/R_{standard}) - 1] \times 10^3$, with R equal to $^{15}N/^{14}N$.

RESULTS

Nutrient Concentrations

In 74 water samples collected for ambient nutrient analysis (see Table 3 for summary), dissolved inorganic nitrogen (DIN) concentrations ranged from 0.69 to 8.11 μM with a mean of 2.10 μM (Figure 2). Values did not appear to be skewed toward any apparent spatial or temporal trend.

On average across all sites and over the year 56% of the DIN was in the form of ammonium. The disproportion of ammonium to nitrate in the littoral surfacewater persisted during the June and August sampling sessions (~61% ammonium) even when upwelling depressed temperatures to <20° C on the shelf in the Cape Canaveral bight. Reported *f*-ratios (proportion of nitrate to total DIN pool) for upwelling events are near 0.9 or 90% of the DIN (EPPLEY and PETERSON, 1979). In only 25% of the sampling events did nitrate have a higher proportion of the measured DIN pools. The highest DIN concentrations (ammonium = 2.75 μM, nitrate = 4.66 μM) measured were associated with rainfall events, and likely resulted from surfacewater runoff and submarine groundwater discharges that preceded the March and December sampling.

Soluble reactive phosphorus (SRP) concentrations ranged from 0.13 to 0.50 μM with a mean of 0.25 μM. Significantly elevated SRP values of nearly double this mean value (0.42–0.50 μM) were measured following rainfall events preceding the March and December sampling at the Wabasso-Ambersand Beach site, that is down-gradient from residential homes with septic tanks.

Nitrogen to phosphorus ratios (N:P) of water column inorganic nutrients (Figure 3) averaged nearly 8:1, significantly lower than Redfield ratios for balanced growth of phytoplankton (16:1) and marine macrophytes (~30:1). These data suggest nitrogen-limitation of the water column with respect to inorganic phosphorus availability. In only three measurements did N:P concentrations exceed Redfield ratios for N:P, and these samples followed rainfall events where excessive nitrate concentrations (~4 to 8 μM) created disproportionate ratios with respect to P availability.

Stable Nitrogen Isotope Values in Macroalgae

Many of the macroalgae utilized for these analyses were persistent spatially and temporally at the study sites and facilitated the following analyses (Table 2). Macroalgae from littoral anastasia beach rock and sabellariid worm reefs at all study sites from Cocoa Beach to Vero Beach had mean $\delta^{15}N$ values of +8.7 to +9.9‰ (Figure 4). These elevated values persisted during the June and August sampling periods, coinciding with a strong and persistent upwelling event. The lowest values of ~+6 to +7‰ were measured in October and December, but are still within the ranges reported for nearby sewage nitrogen sources.

DISCUSSION

A Region-Wide Human Nutrient Enrichment Problem?

This report constitutes the first published record of an annual water quality assessment of the littoral waters of east central Florida. Current State of Florida public health monitoring of human fecal bacteria colonies in these same littoral waters has limited value for discriminating human sewage contamination, including many fecal pathogens (see GRIFFIN *et al.,* 2001), and generally says little about the trophic state of the system that may have cascading or indirect effects upon human health. In many cases, marine surface water monitoring programs for human fecal bacteria (coliforms, enterococci) indicate "good" water quality where more in depth analyses reveal significant sewage-related contamination of human enteroviruses, such as polioviruses, Hepatitis A, and

Table 3. *Nutrient concentration mean ± SD values (uM) for study sites.*

Site	Metric	Month				
		March	June	August	October	December
Cocoa Beach	ammonium	2.75 ± 0.21	0.90 ± 0.01	0.90 ± 0.57	1.85 ± 0.07	0.60 ± 0.07
	nitrate-nitrite	1.43 ± 0.11	0.58 ± 0.21	0.56 ± 0.28	1.00 ± 0.11	0.39 ± 0.12
	DIN	4.18 ± 0.32	1.48 ± 0.21	1.46 ± 0.84	2.85 ± 0.04	0.90 ± 0.19
	SRP	0.36 ± 0.01	0.28 ± 0.01	0.32 ± 0.06	0.34 ± 0.04	0.27 ± 0.04
	f-ratio	0.32	0.39	0.38	0.35	0.39
Patrick AFB	ammonium	1.10 ± 0.01	0.40 ± 0.01	0.50 ± 0.14	1.45 ± 0.07	0.50 ± 0.14
	nitrate-nitrite	0.64 ± 0.09	0.29 ± 0.01	0.44 ± 0.12	0.41 ± 0.05	0.39 ± 0.01
	DIN	1.74 ± 0.10	0.69 ± 0.01	0.94 ± 0.26	1.46 ± 0.07	0.90 ± 0.16
	SRP	0.23 ± 0.01	0.18 ± 0.01	0.18 ± 0.05	0.18 ± 0.02	0.25 ± 0.06
	f-ratio	0.37	0.42	0.47	0.22	0.44
Satellite Beach	ammonium	0.55 ± 0.07	1.00 ± 0.56	0.55 ± 0.07	2.55 ± 0.21	0.90 ± 0.35
	nitrate-nitrite	0.95 ± 0.41	0.44 ± 0.01	0.55 ± 0.35	2.01 ± 0.01	0.32 ± 0.03
	DIN	1.50 ± 0.48	1.44 ± 0.56	1.10 ± 0.42	4.56 ± 0.22	1.20 ± 0.38
	SRP	0.27 ± 0.06	0.28 ± 0.02	0.21 ± 0.11	0.29 ± 0.01	0.23 ± 0.04
	f-ratio	0.63	0.31	0.5	0.44	0.26
Indialantic	ammonium	3.45 ± 1.48	1.05 ± 0.07	1.05 ± 0.49	1.00 ± 0.14	1.0 ± 0.42
	nitrate-nitrite	4.66 ± 1.19	0.56 ± 0.21	0.54 ± 0.31	0.71 ± 0.03	0.28 ± 0.01
	DIN	8.11 ± 2.67	1.61 ± 0.13	1.59 ± 0.81	1.71 ± 0.11	1.28 ± 0.42
	SRP	0.24 ± 0.04	0.32 ± 0.06	0.33 ± 0.07	0.21 ± 0.05	0.22 ± 0.04
	f-ratio	0.57	0.35	0.34	0.42	0.22
Sebastian Inlet	ammonium	0.40 ± 0.01	0.50 ± 0.14	1.35 ± 0.92	0.80 ± 0.14	0.90 ± 0.35
	nitrate-nitrite	0.43 ± 0.01	0.35 ± 0.01	0.52 ± 0.25	0.42 ± 0.08	1.00 ± 0.06
	DIN	0.83 ± 0.01	0.85 ± 0.14	1.87 ± 0.66	1.22 ± 0.06	1.9 ± 0.29
	SRP	0.29 ± 0.01	0.20 ± 0.02	0.13 ± 0.01	0.15 ± 0.02	0.18 ± 0.03
	f-ratio	0.51	0.42	0.28	0.34	0.53
Wabasso Beach	ammonium	1.1 ± 0.01	0.75 ± 0.21	0.80 ± 0.28	2.05 ± 0.78	1.30 ± 0.07
	nitrate-nitrite	1.30 ± 0.02	0.68 ± 0.04	0.46 ± 0.15	1.21 ± 0.01	4.10 ± 0.04
	DIN	2.4 ± 0.01	1.43 ± 0.25	1.26 ± 0.43	3.26 ± 0.78	5.4 ± 0.04
	SRP	0.50 ± 0.01	0.29 ± 0.07	0.22 ± 0.01	0.19 ± 0.01	0.42 ± 0.01
	f-ratio	0.54	0.48	0.37	0.37	0.76
Vero Beach	ammonium	0.45 ± 0.01	0.80 ± 0.28	0.45 ± 0.07	1.35 ± 0.21	1.30 ± 0.08
	nitrate-nitrite	1.41 ± 0.04	0.40 ± 0.12	0.45 ± 0.06	2.56 ± 1.87	3.29 ± 0.01
	DIN	1.86 ± 0.11	1.20 ± 0.16	0.90 ± 0.12	3.91 ± 1.65	4.59 ± 0.08
	SRP	0.30 ± 0.01	0.20 ± 0.02	0.22 ± 0.01	0.19 ± 0.02	0.20 ± 0.01
	f-ratio	0.76	0.33	0.5	0.65	0.72

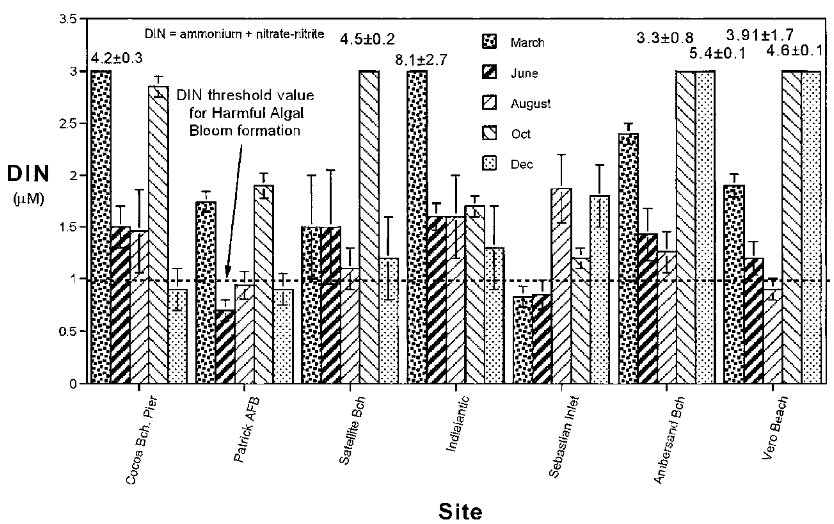

Figure 2. Summary of mean ± SD dissolved inorganic nitrogen concentrations (DIN) for Brevard-Indian River County study area water quality stations for 2003 sample dates.

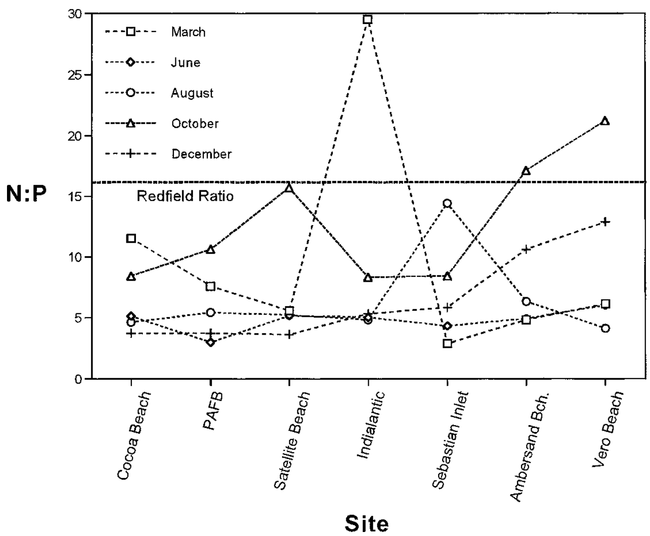

Figure 3. Nitrogen (N) to phosphorus (P) ratios for Brevard-Indian River County study area water quality stations for 2003 sample dates.

Norwalk viruses (see GRIFFIN *et al.,* 1999; NOBLE, 2001). Further, bacteriological testing may not show signs of any human health related threat until an advanced stage of eutrophication, where chronically poor water quality (as the result of excess nutrient enrichment) may already cause: harmful algal blooms with toxin production, diseases of marine organisms (skin lesions), and subsequent fish, seabird and marine mammal die-offs. This report suggests a source-sink linkage of anthropogenic nutrient availability to littoral eutrophication-indicator macroalgal species in this system.

How Much Nitrogen is too Much?

Concentrations of the primary limiting macronutrient, dissolved inorganic nitrogen (DIN), measured in this study are in excess bio-available concentrations above and beyond physiological thresholds of ~1.0 μM reported to support and saturate growth of Florida's dominant red tide organism, *Karenia brevis* ($K_s = 0.47$, see STEIDINGER *et al.,* 1998) and for macroalgae (see LAPOINTE, 1997; LAPOINTE, 1999), in subtemperate coastal waters. Accordingly, both *Karenia brevis* and the macroalgae species reported in this study have high uptake affinities for low concentrations of inorganic nitrogen, and the ambient mean DIN value reported for all sites and seasons in this study are two-fold (2.10 μM) over these known growth saturation threshold concentrations. Likewise, the Indian River Lagoon, located parallel to this coastal setting on the adjacent landward side of the east-central Florida barrier island, has been classified as "hyper-eutrophic" with respect to excess production and bio-available nutrient concentrations, with nitrogen being the primary limiting nutrient from productivity bioassays (NOAA, 1996; NOAA, 1999; PHLIPS *et al.,* 2002). This system, widely reported to be affected by non-point source nutrient loading from it's watershed with ~120,000 septic tanks (HORSLEY and WHITTEN, 2000) and runoff from massive inland agricultural land-use has been noted for it's persistent harmful algal blooms (*i.e.* dinoflagellate, diatom, cyanobacterial, and macroalgal), in flow restricted regions (NOAA, 1996; HALL *et al.,* 2001; PHLIPS *et al.,* 2002). Specifically, the toxin producing dinoflagellate species *Prorocentrum minimum* and *Pyrodinium bahamense* var. *bahamense* (a saxitoxin producer, see LANDSBERG, 2002), and the toxin (domoic acid) producing diatom *Pseudo-nitzschia pseudodelicatissima* have recently been reported in bloom concentrations (PHLIPS *et al.,* 2002; PHLIPS *et al.,* 2004).

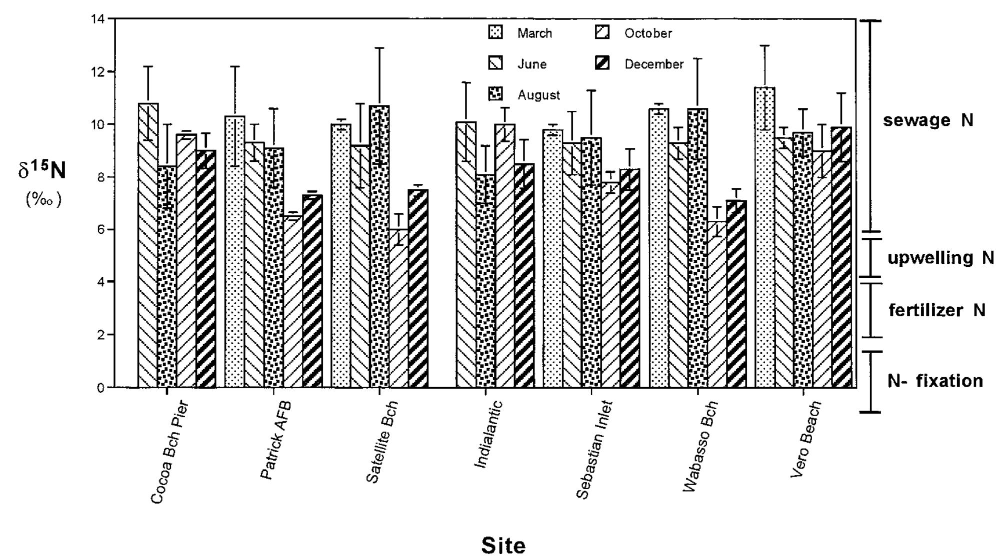

Figure 4. Mean ± SD stable nitrogen isotope ($\delta^{15}N$) values for macroalgae at Brevard-Indian River County study area water quality stations for 2003 sample dates. Ranges on right X-axis correspond with values on the left X-axis, and denote ranges for previously published endpoint values.

Elevated ambient inorganic phosphorus concentrations with respect to bioavailable inorganic nitrogen concentrations (mean N:P ~8:1) from this study suggest that the littoral coastal waters are generally, nitrogen-limited, despite excess bioavailable inorganic nitrogen concentrations (primarily ammonium) in the water column. The excessive DIN values (mean = 2.10 μM) and Redfield N:P proportions (*i.e.* significant N-limitation) are similar to those of the adjacent Indian River Lagoon, suggesting a region-wide eutrophication of estuarine and nearshore oceanic waters.

Benthic macroalgal communities are excellent indicators of water quality because they integrate water column nutrients over extended periods of time, and are of course sessile, lending them to be likewise spatially discrete water quality indicators (see LEVINE, 1984). Because of their dependence on water column nutrients, the taxonomic composition of macroalgal communities, specifically, is an important indicator of water quality. Macroalgae that have high nutrient requirements, such as the chlorophyta (*e.g. Ulva lactuca, Enteromorpha* spp., *Caulerpa* spp., see RAFFAELLI *et al.,* 1998) and rhodophyta (*e.g. Gracilaria tikvihae, Laurencia* spp.), are widely known indicators of excess nutrient availability in such eutrophic coastal water bodies such as; Venice Lagoon, Italy (SFRISO *et al.,* 1992), Boston Harbor, MA (SAWYER, 1965), Waquoit Bay, MA (VALIELA *et al.,* 1997), Indian River Lagoon, FL (WHITE and SNODGRASS, 1990), south Florida (LAPOINTE and BARILE, 2001) and Florida Bay, FL (LAPOINTE, 1989). The most conspicuous macroalgae on the littoral reefs in the study area were dominated by widely known eutrophication indicator species (*i.e.* primarily chlorophyta (green) and rhodophyta (red) species, such as *Ulva lactuca, Caulerpa prolifera* and *Gracilaria tikvihae*). In the following section, tissue biochemical information from these macroalgal species are considered with respect to specific temporal and spatial variability of nitrogen sources in the study area.

Sources of Anthropogenic Nutrients to Littoral East-Central Florida

From a loading perspective, the ambient nitrogen concentrations in nearshore waters are adequate to support harmful algal bloom formation, despite other assertions that far-field sources, such as Aeolian (Saharan) dust (purported to stimulate nitrogen-fixation), and "natural" upwelling nitrogen loading may be important for stimulating bloom events. Dinoflagellate bloom events along the east-coast of Florida, particularly in the Indian River Lagoon, are most often at peak densities in the late summer/fall when anthropogenic nitrogen flux associated with peak seasonal rainfall and stormwater advection processes are at a their peak (*e.g.* see PHLIPS *et al.,* 2004). Simulation models by LIU *et al.,* (2001) suggest that elevated coastal nutrient concentrations, such as these reported in this study, supercede the importance of those contributed by Saharan-dust induced nitrogen fixation or upwelling nutrient enrichment with regard to sustaining red tide blooms, such as the significant *Karenia brevis* bloom reported for the east coast of Florida for the fall of 2003.

Two of the sample stations, Sebastian Inlet and Ambersand Beach, are located in proximity (<10 km) to an oceanic inlet where discharge from the hypereutrophic Indian River Lagoon may be a significant nutrient loading source, and may subsequently be affected by plumes of fresh water discharge and poor water quality (see Figure 1). However, other sites more remote (12–60 km) from direct estuarine surfacewater discharges, are more likely to be affected by groundwater discharges. The Holocene quartz sand barrier island system of the east-coast of Florida is highly transmissive with respect to groundwater flow, and Ghybeh-Herzburg fresh/saline aquifer confluences produce a GLOVER (1959) seepage interface in the littoral zone, where discharges of barrier island aquifers produce positive discharge associated with tidal pumping (VACHER, 1988a; VACHER, 1988b; VACHER *et al.,* 1991; MILLER, 1997; RAWLINS *et al.,* 1998). The significance of the delivery of anthropogenic nutrients via submarine groundwater discharge (SGD) to the beach environment on the southeast Atlantic coast of Florida, has been reviewed by FINKL and CHARLIER (2003). Further, the general topic of SGD nutrient loading from beach environments has likewise been previously reviewed (see JOHANNES, 1980, MCLACHLAN and TURNER, 1994). The anastasia beach rock and sabellariid reefs of east-central Florida are located in the intertidal/subtidal zones where GLOVER (1959) groundwater discharges are reported to be at a maximum. Many of these beach rock and sabellariid reef formations are covered with the eutrophication indicator species discussed in the previous section (see Table 2), and were utilized for stable nitrogen isotope analyses. Because the $\delta^{15}N$ signatures of the macroalgae were elevated in the +8–12‰ range at sites remote from estuarine surface water discharge, as well as the inlet influenced sites, it is likely that barrier island groundwater discharges are equally or more significant in delivering sewage nitrogen to the littoral macroalgal communities. These elevated $\delta^{15}N$ values in littoral macroalgal communities are similar to values reported for macroalgae for other coastal waters around the globe affected by sewage nitrogen loadings (see HOBBIE *et al.,* 1990; LAPOINTE, 1997; FRANCE *et al.,* 1998; MCCLELLAND and VALIELA, 1998; COSTANZO *et al.,* 1999; ROGERS, 1999; LAPOINTE and THACKER, 2002; LAPOINTE and BARILE, 2001; WAYLAND and HOBSON, 2001; GARTNER *et al.,* 2002; SAVAGE and ELMGREN, 2004). The elevated $\delta^{15}N$ values reported in this study are similar to endpoint values for secondarily treated sewage effluent (+8‰) in south Florida's ocean outfalls (HOCH *et al.,* 1995), and for nitrified and denitrified septic tank effluent (~+12‰) in tributaries of the southern Indian River Lagoon (LAPOINTE and KRUPA, 1995). It is also not likely that these elevated values were the result of denitrified organic matter in the littoral zone. First, the dynamic siliciclastic sediments in the littoral zone are low in organic matter, and it is highly unlikely that the DIN source of the macroalgae is "regenerated" either from within the water column or the sediments. Also, because the water column has significant natural concentrations of phosphorus with respect to DIN, macroalgae that are nitrogen-limited do not fractionate the $\delta^{15}N$ value of their nitrogen source, and therefore in these conditions, $\delta^{15}N$ values within macroalgal tissue should be similar to their endpoint source values. Another interpretation of these elevated values is the concept that excessive UV-B radiation associated with high irradiance may cause enrichment with $\delta^{15}N$, as demonstrated with coral tissue (see HEIKOOP *et al.,* 2001). Although subtidal in nature, these littoral habitats are turbulent with turbid conditions being commonplace. Alternatively, for macroalgae, low $\delta^{15}N$ (~+0.5‰) values are typical in macroalgae on shallow reef crests in oligotrophic reef systems that experience high irradiance, but receive natural nitrogen sources, such as nitrogen fixation. In summary, these elevated macroalgae $\delta^{15}N$ values suggest that the littoral waters of east-central Florida are being contaminated by sewage nitrogen, and represent a growing list of reported sewage contamination problems in other coastal Florida sites, such as the tributaries of the lower Indian River Lagoon (LAPOINTE and KRUPA, 1995), the southeast coast of Florida (LAPOINTE and BARILE, 2001) and the Florida Keys (LAPOINTE *et al.,* 1990; PAUL *et al.,* 1995a; PAUL *et al.,* 1995b).

The Importance of Upwelling Nitrogen to the East Florida Littoral Beaches and Reefs

This study area has historically experienced significant upwelling during the summer months (see GREEN, 1944; TAYLOR and STEWART, 1958; SMITH, 1982; ATKINSON *et al.,* 1984). During the summer sampling periods of 2003, a persistent upwelling was reported along the majority of the U.S. Atlantic coast, roughly from New Jersey south to the Palm Beaches. A recent ECOHAB project (LAPOINTE and BARILE, unpublished data) on the deep reefs (30m) of Palm Beach measured ~13° C seawater temperatures at depth with complementary DIN values of ~22 μM (NO_3-NO_2 = 21.6 μM, NH_4^+ = 0.5 μM, *f*-ratio = 0.98). Despite the unseasonable cool temperatures associated with upwelling in this study area, nitrogen from upwelling did not appear to be a significant source to the littoral environment. In the two samplings (June and August) during the upwelling event, DIN concentrations in the littoral zone did not exceed 2 μM, with the DIN being dominated by ammonium (f-ratios = 0.28–0.50). Also, $\delta^{15}N$ values of macroalgae were in the range of +8–10‰ for the June and August months coinciding with the peak upwelling. However, these months are also the peak of the rainy season, and it is likely that the higher ammonium versus nitrate concentrations were the result of storm water runoff or groundwater discharge following excess infiltration associated with significant rainfall events. During the summer season in 2001, $\delta^{15}N$ values of macroalgae at the 130′ shelf break at Juno Beach, decreased with upwelling events to ~+4.6‰ (LAPOINTE and BARILE, 2001). Upwelling in zones of high denitrification, such as the Pacific coast of California (LIU and KAPLAN, 1989), can elevate $\delta^{15}N$ values to +10–12‰, but are not characteristic of the Atlantic coast of South Florida, where high rates of nitrogen fixation decrease $\delta^{15}N$ source values (MONTOYA *et al.*, 2002).

CONCLUSIONS

(1) On the east-central Florida littoral zone, the primary limiting nutrient, dissolved inorganic nitrogen, is available in excessive bio-available concentrations, on average, two-fold over known physiological thresholds for red-tide *Karenia brevis* and macroalgae growth and bloom formation.

(2) Stable nitrogen isotope analyses of macroalgae on subtidal reef formations from Cocoa Beach to Vero Beach provide strong evidence of a spatially and temporally persistent sewage nitrogen source to the littoral system.

(3) Application of sewage effluent wastewater (~100 million liters/day) in septic tanks, percolation ponds, subsurface drainfields, and deep injection wells, particularly those known to have upward vertical effluent migration, on the siliciclastic barrier island of east-central Florida are wastewater management practices incompatible with sustainable coastal water quality and environmental health.

ACKNOWLEDGMENTS

This work was performed during a Link Foundation-Post Doctoral Research Fellowship at Harbor Branch Oceanographic Institution. Support for this work was provided by the Sebastian Inlet Chapter of the Surfrider Foundation. Special thanks especially to John Davis, Andy Marshall, Vincent and Allison Sharkey, and Marilyn Mazzoil, who's assistance, participation, persistence, and support were critical to the success of this study. This is contribution # 1560 from Harbor Branch Oceanographic Institution.

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