

PHOSPHORUS INPUTS AND EUTROPHICATION ON THE FLORIDA REEF TRACT

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ABSTRACT

The Florida Reef Tract (FRT) has experienced dramatic change and loss of coral cover during the past decade following many decades of intense human activities on the south Florida watershed. Comparative studies during 1990 showed that chlorophyll *a*, turbidity, and total dissolved phosphorus were 2-3 fold higher on bank reefs of the FRT compared to similar reefs in the less developed western Caribbean region. Sampling during summer 1992 showed high phosphorus concentrations in reduced salinity coastal waters along the eastern Gulf of Mexico, indicating land-based sources of phosphorus input. Existing data and observations also show that prevailing currents of the inner shelf waters of the eastern Gulf of Mexico move southerly, into Florida Bay, and then seaward, providing a mechanism for phosphorus transport to the FRT.

Because the carbonate-rich waters of the FRT are phosphorus-limited, cumulative phosphorus inputs from far-field sources (as well as near-field sources) mix with N-rich waters in the Florida Keys and provide a balanced nutrient supply needed to sustain nuisance algal blooms. Enrichment above a threshold of $\sim 0.10 \mu\text{M}$ total dissolved phosphorus appears adequate to support nuisance algal blooms. A Landsat satellite image taken in late May 1992 showed a dense phytoplankton bloom in the same area where we observed phosphorus-rich (N-limited) waters of the eastern Gulf of Mexico flowing into N-rich (P-limited) waters of western Florida Bay. Increased phytoplankton and turbidity resulting from mixing of these water types result in widespread algal blooms, which stress reef systems by reducing submarine light while simultaneously increasing sedimentation that smothers corals, increases coral disease, and enhances coral overgrowth by benthic macroalgae. Temperature extremes have long been assumed to exert the primary stress on coral reef development along the FRT. However, our data and observations suggest that phosphorus inputs from human activities in south Florida represent an upstream source contributing to eutrophication on the FRT.

INTRODUCTION

Coastal eutrophication resulting from human nutrient inputs is considered one of the most urgent environmental signals correlating with the global decline of coral reefs (D'Elia et al., 1991; Bell, 1992). The 220-mile long Florida Reef Tract (FRT), the largest coral reef system in North America, is adjacent to rapidly growing south Florida which generates wastewater inputs from domestic, agricultural, and industrial sources. Evidence suggests that the FRT has experienced loss and change in coral populations over the past decades (Dustan and Halas, 1987; Porter and Meier, 1992). Eutrophication -- defined here as "nuisance algal blooms" (Paerl, 1988) -- has been repeatedly cited as a major threat to the FRT (Miller, 1988; USEPA, 1992). While studies have documented the role of localized domestic wastewater inputs on eutrophication of the FRT (Lapointe and Clark, 1993), more distant but significant sources of nutrient inputs from the south Florida watershed have not been assessed.

There is cause for special concern regarding nutrient inputs from the eastern Gulf of Mexico as these coastal waters are highly enriched in phosphorus (P), the primary nutrient element limiting algal growth and eutrophication in back-reef waters of the FRT (Lapointe, 1987; FDER, 1987; Lapointe, 1989). In Floridian rivers, concentrations of soluble reactive phosphorus (SRP) correlate with the distribution of phosphatic-rock formations in the watershed (Kaufman, 1969). Odum (1953) first noted the magnitude of phosphorus pollution along this coastline. Available data indicate that the greatest contribution of phosphorus to these waters is the direct result of the activity and interference by man, particularly the phosphate mining industry (Task Group Report, 1967). The inner shelf waters of the eastern Gulf of Mexico have prevailing flow to the south and southwest (Klein and Orlando, 1992), a pattern that is enhanced during the wet season (Jones et al., 1973). We have also documented very strong net cumulative flow of Gulf of Mexico/Florida Bay waters through tidal passes in the Keys towards Hawk Channel and the FRT (Lapointe et al., 1992). These data, together with observations by scientists and commercial fishermen, indicate a transport mechanism by which P inputs from the eastern Gulf of Mexico can impact the FRT. To date, no studies have been made of the dissolved P concentrations on the FRT in relation to the south Florida watershed nor have comparative studies been performed with nearby coral reefs lacking such intense human P inputs. We here provide evidence that dissolved phosphorus pools are significantly higher on the FRT than relatively pristine reefs of the western Caribbean region. Furthermore, we demonstrate that coastal waters of the eastern Gulf of Mexico may represent a significant upstream source of P contributing to algal blooms on the FRT.

METHODS

Sampling Stations and Water Analysis

FRT-Western Caribbean - These studies were performed during summer 1990 on a research expedition aboard the R/V *Cape Hatteras*. Six reef sites were selected *a priori* from navigation charts, and included three bank reefs on Banco Chinchorro, Yucatan (Cayo Norte, Cayo Centro, and Cayo Lobos), Hol Chan and Curlew Reef on the Belize Barrier Reef system, and a fringing reef on the east side of Roatan, Honduras (Fig. 1; Table 1). Six offshore bank reef sites were also sampled on the FRT, which included Carysfort Reef, Molasses Reef, Alligator Reef, Sombrero Reef, Looe Key, and Sand Key (Fig. 1; Table 1). Six water samples (three surface, three bottom) were collected with a 5.0 liter Niskin bottle at three different stations per site in 2-8 m water depth along a transect extending from the back reef to the fore reef of each site. The samples were frozen in clean high density polyethylene bottles until analysis.

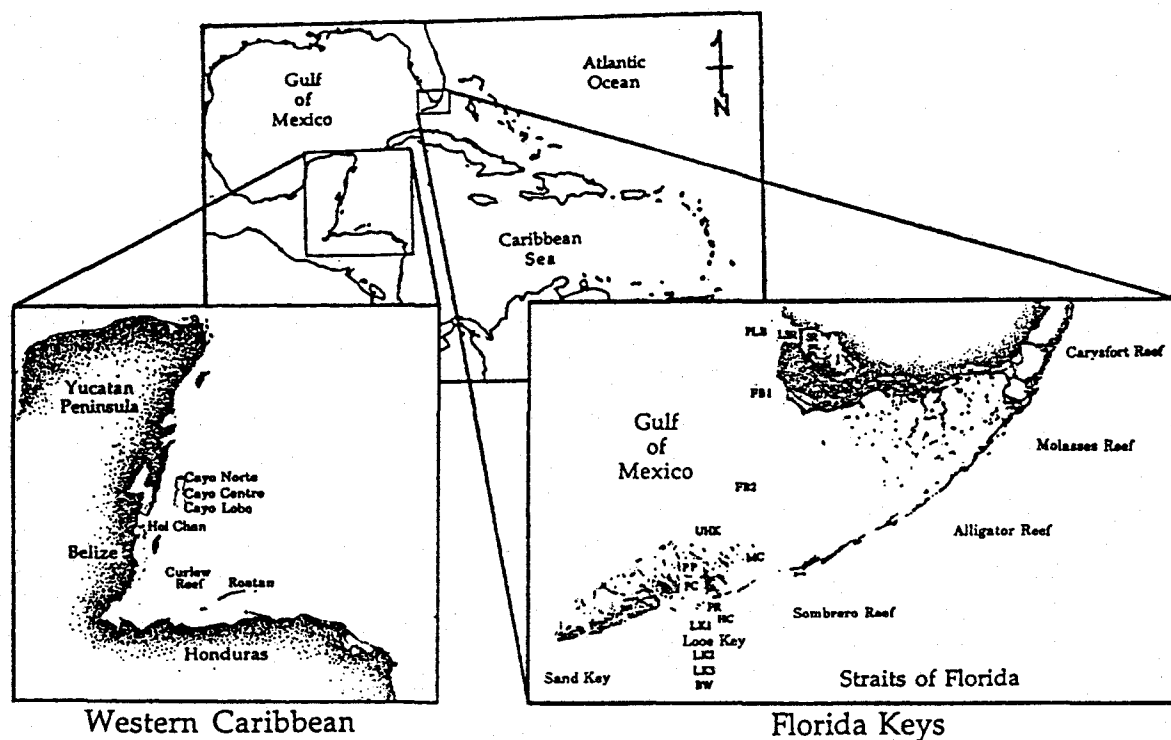


Figure 1. Maps of Florida Keys and Caribbean areas showing location of study sites.

This comparative study focused on determination of total dissolved nitrogen and phosphorus (TDN, TDP). These nutrient pools include dissolved organic nitrogen and phosphorus (DON, DOP) which are important nutrient pools supporting algal growth in oligotrophic waters (Jackson and Williams, 1985). We also measured chlorophyll *a* and turbidity as an index of algal response to nutrient concentrations. Chlorophyll *a* and turbidity are good overall indicators of eutrophication as they integrate nutrient loading over time and also had the highest negative correlation with coral growth rate along a eutrophication gradient in Barbados (Tomascik and Sanders, 1985).

Aliquots of the water samples were filtered through a GFF 0.45 μm filter prior to nutrient analysis. The filtrate was analyzed for TDN and TDP by persulfate digestion and determination of nitrate and SRP on a Technicon Autoanalyzer (DeVia et al., 1977; Menzel and Corwin, 1965). A subsample of the filtrate was also analyzed for SRP using a Bausch and Lomb spectrophotometer fitted with a 10 cm cell; dissolved organic phosphorus (DOP) was estimated by subtraction of SRP from TDP. The filters were analyzed for chlorophyll *a* by extraction with DMSO and analysis on a Turner Designs Model 10 fluorometer (Burnison, 1979). Turbidity (as nephelometric turbidity units, NTU) was determined on unfiltered water samples immediately following collection on a Hach Model 2100 turbidimeter calibrated with formazin standards. Unpaired t-tests were used to statistically compare the water quality data pooled for the two regions.

Eastern Gulf of Mexico - FRT - Our study of the eastern Gulf of Mexico and the FRT was performed on July 24, 1992 and focused on the spatial distribution of total nitrogen (TN), total phosphorus (TP), and salinity measured at 17 stations along a transect extending from estuarine waters of the Shark River to oceanic blue waters offshore Looe Key National Marine Sanctuary; the station codes for the Shark River-Looe Key transect shown in Fig. 1 are as follows: Shark River (SR), Little Shark River (LSR), Ponce de

Leon Bay (PLB), Northwest Cape (NWC), East Cape (EC), Florida Bay (FB1), Florida Bay (FB2), Moser Channel (MC), Upper Harbor Key (UHK), Port Pine Heights canal (PP), Pine Channel (PC), Munson Island Patch Reef (PR), Hawks Channel (HC), Looe Key back reef (LK1), Looe Key lagoon (LK2), Looe Key fore reef (LK3), and blue water 2 km south of Looe Key (BW). GPS data were recorded for all stations.

The samples were collected at ebbing tide by coordinating movements of two small research vessels along different sections of the transect. Samples were collected from surface and bottom waters with a Niskin bottle and stored as described above. Salinity of the waters was measured using a Hydrolab Surveyor II calibrated immediately prior to use. Concentrations of total nitrogen (TN) and total phosphorus (TP) were determined on unfiltered water samples by persulfate digestion as described above. We used total N and P pools in this study because these pools include particulate fractions that are important to nutrient transport by currents and tides (Gardner et al., 1990).

RESULTS

FRT-Western Caribbean

Mean concentrations of TDN were similar between the two regions compared to 2- to 3-fold higher concentrations of TDP on the FRT (Table 1). TDN concentrations averaged $\sim 3.1 \mu\text{M}$ in both regions whereas TDP averaged $0.19 \mu\text{M}$ on the FRT and $0.07 \mu\text{M}$ in the western Caribbean. The elevated TDP on reefs of the FRT was due primarily to elevated DOP concentrations ($0.16 \mu\text{M}$ vs. $0.04 \mu\text{M}$) as SRP concentrations were similar ($\sim 0.05 \mu\text{M}$) between the two regions (Table 1). Because of similar TDN concentrations but elevated TDP in the Keys, TDN:TDP ratios were over 2-fold higher in the western Caribbean ($\sim 56:1$) compared to the FRT ($\sim 23:1$; Table 1).

TABLE 1. Concentrations of total dissolved nitrogen, total dissolved, dissolved organic, and soluble reactive phosphorus, chlorophyll a, and turbidity on coral reefs of the Florida Keys and the western Caribbean. Values represent means ± 1 standard deviation.

VARIABLE	FLORIDA KEYS	N	WESTERN CARIBBEAN	N	SIGNIFICANCE
TDN	3.11 ± 1.65	36	3.16 ± 0.58	24	NS
TDP	0.19 ± 0.12	36	0.07 ± 0.03	32	$P = 0.000$
SRP	0.05 ± 0.04	36	0.04 ± 0.03	32	NS
DOP	0.16 ± 0.09	36	0.04 ± 0.03	32	$P = 0.000$
TDN:TDP	22.5 ± 16.1	36	55.9 ± 23.9	29	$P = 0.000$
CHL-A	0.20 ± 0.11	37	0.11 ± 0.06	24	$P = 0.002$
TURBIDITY	0.35 ± 0.22	38	0.14 ± 0.04	24	$P = 0.000$

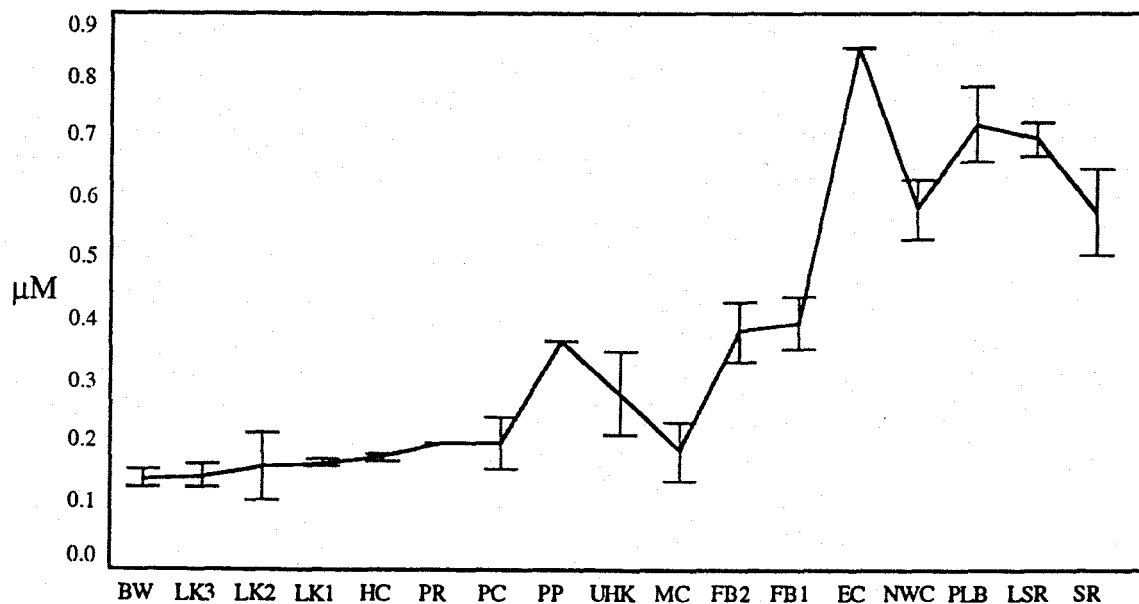


Figure 2. Total phosphorus along the Shark River-Looe Key transect. Values represent means ± 1 standard deviation.

Concentrations of chlorophyll *a* averaged $0.20 \mu\text{g} \cdot \text{l}^{-1}$ on the FRT, a value higher than the mean of $0.11 \mu\text{g} \cdot \text{l}^{-1}$ for the western Caribbean (Table 1). The mean turbidity was also significantly higher on the FRT, 0.35 NTU, compared to a mean of 0.14 NTU in the western Caribbean region (Table 1).

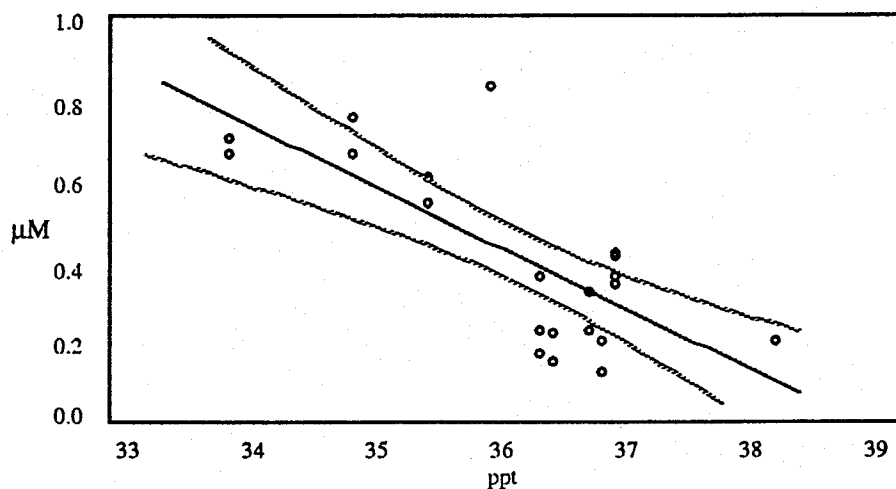


Figure 3. Regression of total phosphorus vs. salinity along the Shark River-Looe Key transect. The correlation coefficient (r) is -0.71 and the regression is significant at $p = .000094$.

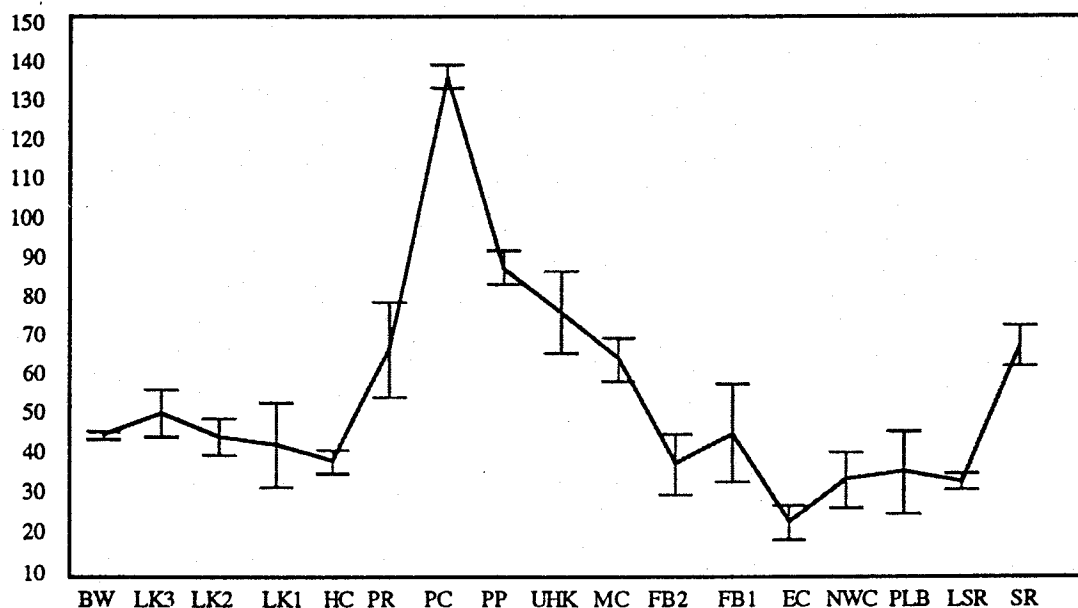


Figure 4. Water column total N:total P ratio along the Shark River-Looe Key transect.

Eastern Gulf of Mexico - FRT

Total P concentrations decreased from peak values along the eastern Gulf of Mexico, through tidal passes of the Keys and to the most offshore station south of Looe Key (Fig. 2). Total P concentrations up to $0.9 \mu\text{M}$ occurred offshore East Cape and decreased along the western edge of Florida Bay; total P concentrations increased in nearshore Keys' waters around Big Pine Key and then decreased to values of $\sim 0.20 \mu\text{M}$ at Looe Key. Total P values in blue water south of Looe Key were $< 0.20 \mu\text{M}$ (Fig. 2).

Regression analysis of the total P concentrations with salinity along this transect indicated a significant and negative correlation (Fig. 3). The highest total P concentrations occurred in reduced salinity water around the East Cape area and along the western edge of Florida Bay compared to the lowest P concentrations and highest salinities in more oceanic waters adjacent to Looe Key.

The total N: total P (TN:TP) ratio varied significantly along this transect from the lowest values around East Cape (< 30) to the highest values (> 100) in nearshore waters around Big Pine Key. The Shark River had a relatively high N:P ratio (~70) and the waters of Hawk Channel and Looe Key had intermediate values (~30 - 50; Fig. 4).

A Landsat satellite image (from Path 15, Row 43; Fig. 5) of south Florida recorded on May 29, 1992 shows the presence of a highly discolored, turbid zone in the East Cape area where the Shark River system discharges into the eastern Gulf of Mexico and western Florida Bay. The turbidity was caused by a dense phytoplankton bloom consisting largely of the blue-green alga *Synechococcus* and diatoms.

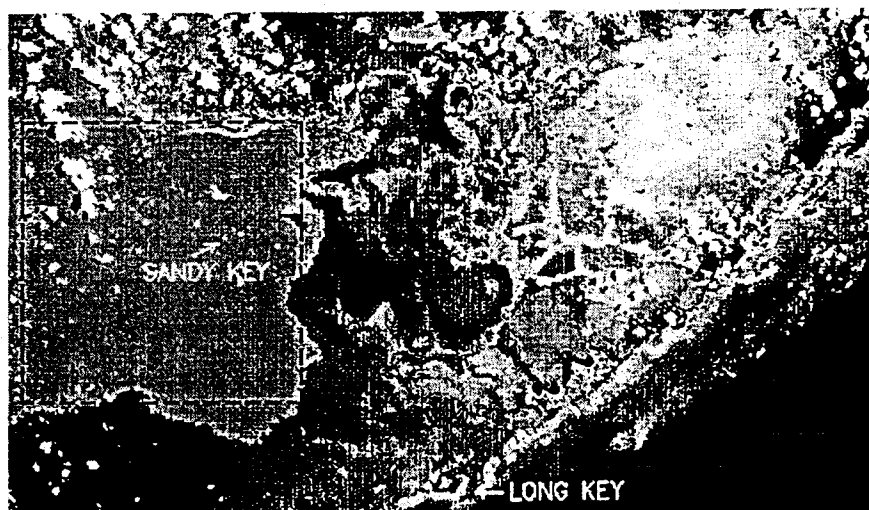


Image courtesy of Ken Haddad, Florida Marine Research Institute and EOSAT Corporation.

Figure 5. Landsat satellite image of south Florida upstream of the FRT (May 29, 1992) showing extent of algal bloom at East Cape. Boxed area is central region of algal bloom in western Florida Bay.

DISCUSSION

Our findings of higher TDP but similar TDN concentrations on the FRT compared to western Caribbean reefs suggests that algal growth on the FRT is more weakly limited by P compared to the Caribbean sites. This conclusion is directly supported by the significantly lower TDN:TP ratio in the waters of the FRT (~23) compared to those of the Caribbean (~56); algal growth is increasingly P-limited as the N:P ratio rises above 30:1 and increasingly N-limited as the ratio decreases below this value (Ryther and Dunstan, 1971). Carbonate-rich waters of the Keys and Caribbean region tend to be P-limited in contrast to siliciclastic waters in temperate latitudes that are N-limited (Ryther and Dunstan, 1971; Lapointe et al., 1992). The carbonate sediments on tropical reefs are generally organic-poor and strongly bind phosphate (DeKanel and Morse, 1982) but not inorganic N (Rosenfeld, 1979). Along with other biogeochemical processes, the end result is a general tendency towards P-limitation of algal growth in shallow, carbonate-rich waters except where P inputs occur from either natural (e.g. guano-rich seabird rookeries, Lapointe et al., 1993) or human sources (e.g. sewage, Lapointe and O'Connell, 1989; Littler et al., 1991).

In the absence of historic data on TDP concentrations on the FRT, one might assume that TDP concentrations of the FRT were historically comparable to those that currently exist on the Caribbean sites. Globally, human activities have increased the average P concentration of river water by approximately 300% (Meybeck, 1982). Between 1974 and 1981, nitrogen and phosphorus loads entering the Gulf of Mexico increased by 46 and 55%, respectively (Smith et al., 1987). In fact, rivers along the entire southwest coast of Florida, which are upstream of the FRT with prevailing currents, have P concentrations substantially higher than most rivers in North America (data from Lovejoy et al., 1990; Flannery et al., 1991). These large P burdens result largely from phosphate mining and associated pollution that make the Alafia, Peace, and Fenholloway rivers the greatest P carriers in Florida (P concentrations in the Alafia are > 200 ppm; LaRock and Bittaker, 1973).

Additional P inputs to the FRT result from agricultural and domestic wastewater inputs in south Florida and the Keys. Over one-million acres are intensively farmed for sugarcane, sod, vegetables and cattle, practices that have increased phosphorus loads to the Everglades (Belanger et al., 1989). Freshwater wetlands like the Everglades have limited capacities for P retention and do not offer long term protection of downstream receiving waters from eutrophication (Richardson, 1985). Sewage generated by an average population of 75,000 residents (a value that approximately doubles during peak tourist periods) living within the Florida Keys also contributes significant P directly into surface waters of the FRT; specific sources include Key West's 7 MGD of secondarily-treated effluent discharged from a shallow coastal outfall. Approximately 65 % of the Key's wastewaters are disposed of by on-site sewage disposal systems (~ 30,000 septic tanks and cesspits), which elevate nutrient concentrations of groundwaters that discharge into adjacent coastal waters (Lapointe et al., 1990). An additional ~ 1,100 shallow injection wells also introduce N and P to groundwaters that could also enter surface waters via submarine groundwater discharge.

A SRP concentration of $\sim 0.10 \mu\text{M}$ is considered a threshold for eutrophication on coral reefs (Bell, 1992). While this value may be useful in a general comparative sense, concentrations of other available P sources need to be considered. A threshold based only on SRP ignores the widely recognized role of DOP in supporting algal growth demands via phosphatase enzymes that allow cycling from DOP pools. For example, the shallow waters of the FRT contain extensive populations of filamentous and micro-filamentous macroalgae that have high alkaline phosphatase activities (APA; Lapointe, 1989). This fact explains how eutrophication on the FRT, including macroalgal overgrowth of seagrasses and corals, can occur in waters with $< 0.10 \mu\text{M}$ SRP (Lapointe and Clark, 1993; Lapointe et al., 1993). Our findings of a mean DOP concentration of $\sim 0.19 \mu\text{M}$ on the FRT, together with knowledge that large labile fractions of DOP pools are important to phytoplankton growth in oligotrophic waters (Jackson and Williams, 1985), provides a kinetic mechanism by which low but significant levels of DOP enrichment can support algal blooms.

Considering that the mean concentration of TDP on relatively pristine Caribbean reefs was $< 0.07 \mu\text{M}$, we suggest that a TDP concentration of $\sim 0.10 \mu\text{M}$ represents a threshold for algal development and eutrophication on the FRT. We believe that the elevated chlorophyll a and turbidity on the FRT compared to the Caribbean sites is direct evidence of a widespread algal growth response to increases in the TDP concentrations on the FRT. Many commercial fishermen, residents, and scientists alike have witnessed the increasing algal blooms and associated turbidity over broad areas of the FRT over the past decade, especially in the waters of western Florida Bay in the vicinity of East Cape where the Shark River system discharges into the eastern Gulf of Mexico and western Florida Bay. The increased burdens of P to coastal waters of the eastern Gulf of Mexico over past decades have very likely increased inputs of P into the downstream N-rich waters of Florida Bay and the FRT (Lapointe and Clark, 1993) where they would result in "balanced" algal growth and development of algal blooms. Over time, cumulative P inputs would reduce the TDN:TDP ratio -- as suggested by this study -- and shift limitation of algal growth from P-limitation towards N-limitation. The relatively low N:P ratios around East Cape suggest that cumulative P inputs may have already shifted the waters in this "mixing zone" to N-limitation.

The FRT thus appears similar to freshwater lakes that also undergo downward shifts in the N:P ratio with increasing P-enrichment and eutrophication, favoring dominance of N-fixing blue-green algae (Schindler, 1977). Several species of nuisance blue-green algae have become abundant on the FRT over the past decade, and include not only the phytoplankter *Synechococcus* but also the filamentous *Phormidium* (a coral pathogen and the causal agent of "black-band disease") and *Lyngbya* (Porter and Meier, 1992; Lapointe and Clark, 1993). Some have suggested that the upper latitudinal limits of coral reef development are often set by competition of macroalgae with corals and that macroalgae are favored at higher latitudes that have higher nutrient concentrations (Johannes et al., 1983); indeed, increased abundance of macroalgae has correlated with the decreased coral cover on the FRT (Porter and Meier, 1992), suggesting eutrophication has already enhanced macroalgal competition with reef corals.

CONCLUSIONS

Large-scale anthropogenic nutrient enrichment is widely recognized by scientists modeling the effects of eutrophication on the productivity of the continental shelves (e.g. see Walsh, 1988) and the open ocean (Fanning, 1989). Inputs of P to coastal waters of the eastern Gulf of Mexico appear to be carried downstream by prevailing currents to the N-rich, P-limited waters of the FRT. This nutrient enrichment model is a plausible mechanism that can explain the recently recognized eutrophication occurring over broad areas of the FRT. Although low temperature stress is considered a primary factor affecting coral reef growth and distribution in Florida (Porter et al., 1982; Burns, 1985), our data and observations suggest that eutrophication has recently become a major stress to reef development and may lead to further reef decline and extinction. Eutrophication is a major cause of coral-reef decline worldwide, due to interactive stresses related to phytoplankton blooms, sedimentation, epiphytic algal growth, coral disease, elevated water temperatures and coral bleaching, and light limitation (Bell, 1992). Our findings are consistent with results of a recent NSF-sponsored workshop on coral reef ecosystems that "anthropogenic stresses resulting directly from population growth and development are the strongest environmental signals and the greatest threat to coral reefs" (D'Elia et al., 1991). It appears that the threshold phosphorus concentrations for critical eutrophication in the shallow, carbonate-rich, and macrophyte-dominated waters of the FRT are quite low (e.g. TDP $\sim 0.10 \mu\text{M}$) and comparable to sensitive freshwater ecosystems.

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COVER: Charles Darwin's map of the world's reefs appeared in his landmark work, *THE STRUCTURE AND DISTRIBUTION OF CORAL REEFS*, 1842. In the original, colored version he distinguished between atolls, barrier reefs and fringing reefs.

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