Impacts of Land-Based Nutrient Pollution on Coral Reefs of Tobago

Buccoo Reef Trust
research education conservation

Harbor Branch Oceanographic
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“In some areas human activity has destroyed entire reefs, converting them to algal-covered rubble. Who knows what species, known and unknown alike, have already been wiped out? Who can say which ones will be winking out in the near future, their intricate genetic codes, formed over millenia, suddenly gone...”

- Osha Gray Davidson, The Enchanted Braid

Summary

The Republic of Trinidad and Tobago, located in the southeast corner of the Caribbean Sea off the coast of Venezuela, is influenced seasonally by floodwaters of the Orinoco River. Because of the direct influence of the Orinoco plume, Trinidad has little coral reef development compared to its more offshore sister island of Tobago. Discharges from the Orinoco River influence Tobago’s coral reefs during the wet season with lower salinity and higher turbidity floodwaters, which reduce light availability needed for coral growth. This chronic, seasonal stress has long affected Tobago’s coral reefs but has not prevented the development of massive and biologically diverse coral reef formations, such as those found at Buccoo Reef and Culloden Reef.

Over the past two decades there has been increasing concern among scientists, resource managers, and the public alike regarding the ecological impacts of localized runoff and nutrient pollution on Tobago’s coral reefs. Increased turbidity and sedimentation from deforestation is well known to stress corals and can be fatal in some situations. Enrichment of coastal waters with nitrogen (N) and phosphorus (P) from deforestation, agricultural and urban runoff, and sewage, although more subtle, has
become the largest pollution problem facing the vital coastal waters of the wider Caribbean region. Nutrient pollution is the common thread that links an array of environmental problems that include eutrophication, harmful algal blooms, “dead zones”, fish kills, loss of seagrasses and coral reefs, and even some marine mammal and seabird deaths. Because coral reefs have adapted over hundreds of millions of years to clear, clean water with low concentrations of N and P, the impacts of nutrient pollution on coral reefs can be particularly severe.

To address the status and extent of nutrient pollution on Tobago’s fringing reefs, a seasonal (“wet” versus “dry”) study of water quality and benthic biota was undertaken at a variety of Tobago’s fringing coral reefs in 2001.

THE RESULTS SHOWED:

• Nutrient over-enrichment of Tobago’s fringing coral reefs, especially Buccoo Reef, from local nutrient sources has triggered ecological changes that have decreased living coral cover and biological diversity.

• At Buccoo Reef, reduced coral cover correlated significantly with increased cover of macroalgae and the zoanthid Palythoa both of which are indicators of nutrient enrichment on Caribbean coral reefs.

• Recent encroachment of the seagrasses Thalassia testudinum (turtle grass) and Halodule wrightii (Cuban shoalweed) into the sandy sediments of Nylon Pool are symptomatic of nutrient enrichment.

• Coral diseases, including white band disease, yellow band disease, and black band disease, occurred at a number of reef sites around Tobago. The dominant coral at Culloden Reef -- Montastrea annularis -- was impacted by an outbreak of yellow band disease that has apparently developed in just the past few years following increased deforestation and development of its watershed.

• Concentrations of dissolved inorganic nitrogen (DIN) increased significantly on reef sites around Tobago from the dry season to the wet season. The increased DIN concentrations resulted in significant decreases in concentrations of soluble reactive phosphorus (SRP). Low DIN:SRP ratios (< 15:1) year-around indicate N-limitation of algal growth in Tobago’s coastal waters.

• High values (> 3 o/oo) of $^{15}$N/$^{14}$N in macroalgae from the Buccoo Reef Complex and other fringing reefs off southwestern Tobago occurred during both wet and dry seasons and were indicative of land-based sewage N pollution from the upland watershed.

• The $^{15}$N/$^{14}$N values of macroalgae from Black Jack Hole off Little Tobago Island increased from relatively low values (< 3 o/oo) in the dry season to high values (> 5.0 o/oo) in the wet season, indicating increased dispersion of sewage N during periods of peak runoff.

• Levels of phytoplankton biomass, measured as chlorophyll a, increased from the dry season to the wet season at reef sites around Tobago that had relatively low impacts of sewage enrichment (e.g. Black Jack Hole and Kelliston Drain off Speyside). Reefs that were chronically impacted by sewage pollution showed relatively little effect of the wet season runoff on chlorophyll a.

• Some of the highest coral cover of the study occurred at Black Jack Hole off Little Tobago Island, the site with the lowest annual mean concentrations of DIN, chlorophyll a, and $^{15}$N/$^{14}$N in macroalgae.

These results support the hypothesis that recent increases in local nutrient pollution, especially from sewage, have pushed Tobago’s coral reefs over the threshold indicative of eutrophication on Caribbean coral reefs. To restore and protect its vitally important coral reefs, Tobago should work to reverse nutrient pollution and sedimentation wherever possible. Meeting this goal will require an array of strategies and approaches tailored to specific reefs and upland developments. For some reefs such as the Buccoo Reef Complex and Mt. Irvine, diversion of human sewage and animal wastes may be sufficient to reverse eutrophication and restore reef health. For most fringing reefs, however, the solutions will be more complex and may involve incentives to reduce deforestation, sewage pollution, urbanization, fertilizer use, and agricultural activities.
Introduction

Tobago, a volcanic island located 29 km northeast of its sister island of Trinidad, is referred to as the “Jewel of the Caribbean”. The northern half of Tobago is characterized by mountainous terrain, steep slopes, and contains the oldest Rainforest Reserve in the western Hemisphere (Figure 1). The southern portion of Tobago has lower elevations and is more urbanized; most of the island’s 50,000 inhabitants live in Scarborough and the surrounding areas (Figure 2). Tobago’s climate is typical of the “wet and dry” tropics. Mean sea surface temperatures over the past century have varied from 26.3 °C in February to 28.6 °C in September. The wet season is from June to December, with a short dry season in late September and peak rainfall in October. The dry season extends from January through May.

One major environmental factor that has influenced development of Tobago’s coral reefs is the seasonal discharge of the Orinoco River from nearby Venezuela. The Orinoco flow is greatest during the wet season, June to December, when floodwaters with lower salinity and higher turbidity are transported by the Guyana Current into coastal waters of Trinidad and Tobago (Figure 3). The impact of the Orinoco plume is more severe in Trinidad than Tobago yet is thought to have minimal effects on coral reefs along Tobago’s northern coastlines. However, there is evidence that corals all around
Tobago have been significantly influenced by turbidity from the Orinoco plume. For example, the common reef-forming (hermatypic) coral, *Montastrea annularis*, typically grows as large “boulders” in shallow, clear waters of the Caribbean; at depths of ~50 m where light limitation of coral growth becomes critical, the morphology of *M. annularis* changes to a flat “plate form.” However, even in shallow waters < 10 m deep on Tobago’s reefs, the plate form of *M. annularis* is the typical growth form, presumably because of chronic stress from light limitation associated with the seasonal Orinoco discharges (Risk et al. 1992, Figure 4).

Despite the environmental stress associated with the Orinoco floodwaters, a large number of Caribbean corals have thrived on Tobago’s fringing reefs (*Figure 5*). Tobago’s reefs contain a total of 36 species of scleractinean corals, which represent 56% of the total number of corals recorded for the Caribbean (Laydoo 1990). That favorable environmental conditions for coral reef growth historically occurred on Tobago is particularly evident at the Buccoo Reef Complex on the southwest side of Tobago where extensive coral reef growth over thousands of years resulted in accretion of limestone over the volcanic foundation (*Figure 6*). The Buccoo Reef Complex is the largest coral reef on Tobago and a major tourist attraction. Glass bottom boat tours use Buccoo Reef for reef viewing, snorkeling, and “reef walking”; the latter can be particularly damaging to the delicate coral formations (*Figure 7*). The Buccoo Reef Complex encompasses an area of ~ 7 km² and was officially designated as a Marine Protected Area (MPA) by the
Tobago House of Assembly (THA) in 1973. However, other fringing reefs around Tobago have become increasingly important to Tobago’s growing SCUBA diving industry. These include Kelliston Drain and Black Jack Hole off Little Tobago Island (Figure 8) on the northeast coast; Diver’s Thirst, Diver’s Dream, Mt. Irvine Reef, and Arnos Vale on the southwest coast; and Culloden Bay, Englishman’s Bay, and Sisters Rocks (Figure 9) on the northwest coast. The number of SCUBA divers visiting Tobago has increased to ~ 40% of the total tourism market and currently supports 21 dive shops on the island.

During the past two decades there has been increasing concern among scientists, resource managers, and the public alike about the accelerating degradation of Tobago’s coral reefs from local sources of pollution. Deforestation on the steep slopes has resulted in increased erosion, runoff, and turbidity on downstream coral reefs (Figure 10). Increased turbidity and sedimentation stress corals through light limitation and the increased energy required for corals to clean themselves. Enrichment of coastal waters with nitrogen (N) and phosphorus (P) from deforestation, agricultural and urban runoff, and sewage has become the largest marine pollution problem facing the vital coastal waters of the wider Caribbean region. Nutrient pollution is the common thread that links an array of environmental problems in coastal waters that include eutrophication (organic enrichment of a water body), harmful algal blooms, “dead zones,” fish kills, loss of seagrasses and coral reefs, and marine diseases, some of which have been linked to some marine mammal and seabird deaths.

Coral reefs are often compared to their terrestrial counterparts -- tropical rainforests -- for several reasons. First, both ecosystems have unusually high species diversity -- the number of species inhabiting these ecosystems. Coral reefs and other marine ecosystems contain more varied life forms than do terrestrial habitats. All but one of the world’s 33 phyla are found in the marine environment -- 15 exclusively so. From a functional perspective, both rainforests and coral reefs also thrive under nutrient-poor conditions. This is possible because of the high degree of nutrient recycling among the diverse life forms in these ecosystems, which allows coral reefs to flourish in warm, oligotrophic (low nutrient) waters. Because coral reefs have adapted over millions of years to clear, clean water with very low concentrations of N and P, the ecological effects of nutrient pollution can be both complex and severe.

Only limited studies of nutrient pollution and eutrophication on Tobago’s reefs have been conducted. Studies by the Institute of Marine Affairs (IMA) in the 1980’s reported deleterious effects from human sewage at Buccoo Bay; in their subsequent management plan, the IMA (1994) specifically recognized fecal contamination (bacterial) of the inshore waters of Buccoo Bay but did not address the more widespread problem of chronic
eutrophication in the coral reef communities. More recent studies of P concentrations in coral skeletons from Buccoo Reef suggested a correlation with human activities on the watershed, but the overall range of P values observed were comparable to other Caribbean sites considered pristine (Kumarsingh et al. 1998). To date, no studies have specifically addressed the effects of anthropogenic N enrichment from sewage on chronic eutrophication of either the inshore or offshore coral reef communities at the Buccoo Reef Complex or the other fringing reef sites around Tobago.

To better understand the impact of local land-based nutrient pollution on Tobago’s coral reefs, a study of water quality and reef health was undertaken in 2001 at the reef sites shown in Figures 5 and 6. The study had three primary objectives. The first objective was to use underwater digital video to quantify the cover of hard corals, octocorals, macroalgae, turf algae, and other biota and coral diseases on various reef communities to gauge the status and degree of ecological damage associated with chronic eutrophication. The second objective was to measure low level concentrations of dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP), chlorophyll a, and transparency of the water column to determine which nutrient (N or P) is most important to nutrient over-enrichment and the eutrophication process. The third objective was to use stable nitrogen isotopes ($^{15}\text{N}/^{14}\text{N}$ ratios) of reef macroalgae to “fingerprint” the source (sewage, fertilizers, etc.) and degree of N-enrichment of various coral reefs around Tobago.

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**Ecological Damage from Nutrient Pollution**

Case studies of the effects of sewage pollution on coral reefs have shown a range of ecological responses to nutrient over-enrichment. In general, nutrient pollution results in decreased cover of hard corals and increased cover of octocorals, zoanthids, sponges, macroalgae, turf algae, and coralline algae -- along with an overall reduction of biological diversity (National Research Council, 2000). To assess geographic patterns of biotic cover that could reveal ecological damage associated with eutrophication on Tobago’s reefs, reef sites in the Buccoo Reef Complex and around Tobago were surveyed using SCUBA and a digital underwater video camcorder to record images of biota along two replicate 50 m long belt transects. The high resolution digital images were analyzed on a color monitor in the laboratory using the random point-count method. This technique provided a relatively unbiased estimate of the percent cover of various reef biota (hard coral, macroalgae, algal turf, coralline algae, octocorals, etc.) and facilitated quantitative comparison of different reef sites.

The video surveys revealed significant patterns of coral and macroalgae among the reef sites. Within the Buccoo Reef Complex, low % cover of hard corals and high % cover of macroalgae occurred at Princess Reef and Buccoo Point Reef in the inner Buccoo Reef Complex near Buccoo Bay (Figure 11). On Princess Reef, blooms of the green macroalgae *Halimeda* and *Caulerpa* spp. covered large areas of dead coral skeleton (Figure 12). At Buccoo Point...
Some scientists have attributed macroalgal blooms on coral reefs simply to overfishing of herbivorous fishes and a lack of sea urchins. However, there is no evidence that this is a major factor at the Buccoo Reef. Fishing has been restricted in the Buccoo Reef Marine Park since 1973 and by practice local fishermen do not target herbivorous species of fishes, such as parrotfish (Scarids) and surgeonfish (Acanthurids), large roving schools of blue tangs and parrotfish, including large adult parrotfish, were observed grazing on algal turf and live coral within the Buccoo Reef Complex. The increased cover and nitrogen content of algae (turf and macroalgae) resulting from land-based nutrient enrichment in the Buccoo Reef Complex have likely increased the growth-limiting food resource (protein) available to these herbivores, allowing expansion of their populations. Because repeated bites by adult parrotfish are a major cause of mortality and bioerosion of reef corals, an overabundance of these fish, over time could actually be detrimental to the longevity of live coral. In addition, the largest populations of sea urchins encountered in these studies were at Princess Reef, where high densities of the reef urchin – Echinometra viridis – were associated with a high cover of macroalgae. Similarly, abundant populations of the long-spined black urchin Diadema antillarum were observed off the Mt. Irvine reefs, an area directly influenced by the sewage discharges from southwest Tobago.

Overall, a significant negative correlation between % cover of macroalgae versus coral was observed for the sites surveyed at Buccoo Reef and other sites around Tobago (Figure 13). Blooms of the green seaweed Ulva (sea lettuce), which is an indicator or nutrient enrichment were observed on Buccoo Reef during the summer of 2001 (Figure 14). Blooms of the green seaweed Ulva (sea lettuce), which is an indicator or nutrient enrichment were observed on Buccoo Reef during the summer of 2001 (Figure 14).
Recent studies in Jamaica have linked high densities of *Diadema antillarum* and other reef urchins to increased nutrient levels in both the water column and macroalgae from land-based runoff of sewage (Lapointe and Thacker 2002).

Other biotic indicators of ecological damage from nutrient pollution were evident from the video surveys. In the Florida Keys, increasing concentrations of DIN and SRP at Looe Key National Marine Sanctuary over the past two decades correlated with decreasing % cover of coral and increasing % cover of the opportunistic zoanthid *Palythoa cariboreum* (Lapointe et al. 2002). This zoanthid was also abundant at Buccoo Point Reef and outer Buccoo Reef where it has overgrown expansive areas of reef-building corals (*Figure 15*). Little is known about the growth requirements of this organism but it appears that elevated nutrient concentrations from sewage or other sources, combined with high grazing rates by roving schools of parrotfish and surgeonfish, are environmental factors that favor its growth. Another symptom of nutrient enrichment in coral reef regions is encroachment of seagrasses as recently observed in Nylon Pool (*Figure 16*). Growth of seagrasses are dependant on nutrient availability so that increased nutrient pollution from sewage and other sources can result in their expansion. Seagrass epiphytes are well known indicators of elevated nutrient concentrations in the water column. Their proliferation on seagrass blades in Nylon Pool (*Figure 16*) is further evidence of nutrient pollution.

Several coral diseases associated with nutrient enrichment and eutrophication were also encountered during the reef surveys. At Buccoo Reef, White-Pox Disease (WPD) was observed on elkhorn coral, *Acropora palmata* (*Figure 17*). WPD has been identified as *Serratia marescens*, an opportunistic bacterium that is associated with human sewage and has been a leading cause of die-off of *A. palmata* in the nutrient polluted waters of the Florida Keys (Patterson et al. 2003). Black-Band Disease (BBD), which is caused by outbreaks of the pathogenic cyanobacterium *Phormidium corallyticum*, was also observed on *Montastrea annularis* at Buccoo Reef.

![Figure 15](image15.png) The zoanthid *Palythoa cariboreum* overgrowing coral in Buccoo Reef.

![Figure 16](image16.png) Tourboat at Nylon Pool in the Buccoo Reef Complex. Dark patches in the photograph are seagrass (see inset) overgrowing the sand bottom.

![Figure 17](image17.png) White-pox disease on elkhorn coral *Acropora palmata*.
and Culloden Reef (Figure 18). An outbreak of this pathogen on coral reefs of the Florida Keys followed increased N loads from agricultural areas in the northern Everglades in the mid-1980’s (Lapointe et al. 2002). The most abundant disease observed on Tobago’s reefs was Yellow-Band Disease (YBD), which was rapidly eroding living coral cover of *M. annularis* at Culloden Reef, the only high relief “spur-and-groove” coral reef on Tobago (Figure 19). The resulting dead coral skeletons at Culloden Reef were colonized by pink and white coralline algal crusts, which are known to replace living coral on reefs experiencing nutrient enrichment from sewage, deforestation, or other sources. Culloden Reef was considered “pristine” reef by scientists in the past but this recent ecological change, which followed deforestation and development of its watershed during the past several years, may change this classification.

![Fig 18] Black-band disease on the star coral *Monastrea cavernosa.*

![Fig 19] Yellow-band disease on *Monastrea annularis.* Inset shows pink and white crusts: coralline algae overgrowing dead coral skeletons at Culloden Reef.

#### Which Nutrients Matter?

The major nutrients that cause eutrophication and other adverse impacts associated with nutrient pollution are N and P. Nitrogen is of paramount importance both in causing and controlling eutrophication in coastal marine ecosystems. Previous studies of nutrient pollution in coastal waters of Trinidad and Tobago have considered P enrichment from sewage and industrial effluents (Kumarsingh et al. 1998) but relatively little attention has been afforded to N.

The most useful parameters to measure in monitoring studies of coastal nutrient pollution are dissolved inorganic nitrogen (DIN = NH$_4$ + NO$_3$ + NO$_2$), soluble reactive phosphorus (SRP), chlorophyll *a*, and water transparency. The dissolved inorganic nutrients, DIN and SRP, represent the proximal “signal” of nutrient pollution and are of utmost importance to measure. However, careful attention to the details of collection, handling, processing, storage, and analysis are required to achieve high quality data for oligotrophic (low nutrient) systems such as coral reefs. In the marine environment, these dissolved nutrients are rapidly assimilated by phytoplankton (single cell algae) in the water column, such that measurement of chlorophyll *a* as an estimate of phytoplankton biomass is a good, long-term “integrator” of nutrient pollution in coral reef environments. Finally, measurement of light attenuation through the water column provides an estimate of the optical properties of the water relating to how much light is absorbed by phytoplankton and suspended solids.
as a result of turbidity associated with nutrient pollution (e.g. high phytoplankton biomass) and land-based runoff.

To obtain quantitative data regarding nutrient pollution of Tobago’s coral reefs, we conducted a monitoring program to collect relevant data in the dry season when minimal runoff occurred (April to June) and the wet season when maximal runoff occurred (September to October) during 2001. SCUBA divers used one liter Nalgene bottles to collect replicate water samples that were processed for DIN and SRP analysis following a quality assurance/quality control protocol developed by Harbor Branch Oceanographic Institution’s Environmental Laboratory in Ft. Pierce, FL. In addition to DIN and SRP analysis, the water samples were analyzed for chlorophyll a and salinity. In October, a Li-Cor spherical quantum sensor coupled to a Li-Cor 1000 data logger was used to determine light attenuation coefficients (Kd, 1/m) for some of the reef sites.

The results of the water quality monitoring in the dry season showed that reefs in the Buccoo Reef Complex were the most nutrient-enriched of all of Tobago’s reefs. Data collected in April in the Buccoo Reef Complex showed very similar SRP concentrations from the inshore reef sites (Buccoo Point Reef, Princess Reef) to the most offshore site at Outer Buccoo Reef, averaging ~ 0.20 µM (Figure 20). In contrast, DIN concentrations were more variable and correlated negatively with phytoplankton biomass (chlorophyll a), which was elevated to “bloom” levels on the inner reefs (Figure 20). In other words, phytoplankton blooms at Princess Reef -- the most eutrophic reef studied in the Buccoo Reef Complex -- were assimilating the DIN, resulting in relatively low DIN concentrations compared to the outer stations where lower phytoplankton biomass coincided with higher DIN concentrations. It is also possible that groundwater contaminated with DIN from septic tanks and “soak-aways” on the watershed were discharging in areas of the outer reef, which would also increase DIN concentrations. Overall, the DIN concentrations averaged ~ 1 µM throughout the Buccoo Reef Complex, a threshold level noted for the demise of coral reefs from eutrophication. Low DIN:SRP ratios of ~ 5:1, together with the negative correlation between DIN and chlorophyll a, clearly showed that DIN rather than SRP controls algal blooms and the eutrophication process within the Buccoo Reef Complex. Chlorophyll a concentrations > 0.3 µg/l occurred in the inner Buccoo Reef Complex, levels indicative of eutrophication on coral reefs. Hence, efforts to restore water quality in the Buccoo Reef Marine Park need to focus on N-rather than P-removal of wastewater discharges from the watershed.

The water quality monitoring at eight fringing reef sites around Tobago in June 2001 showed, in general, lower DIN concentrations than the Buccoo Reef Complex (Figure 21 - next page). Like Buccoo Reef, the SRP concentrations were similar among the eight reef sites (averaging 0.26 ± 0.05 µM) whereas DIN was more variable, ranging from 0.14 µM at Black Jack Hole off Little Tobago Island to > 1 µM at Arnos Vale and Culloden. These elevated DIN concentrations at Arnos Vale and Culloden correlated with increasing human activities and runoff from the watershed along Tobago’s northwest coast. Further to the southwest at Mt.Irvine and the shipwreck “Maverick,” the DIN concentrations decreased as chlorophyll a increased.
with increasing inputs of human sewage from the densely populated areas in southwestern Tobago. This pattern at Mt. Irvine is similar to that in the inner Buccoo Reef Complex where nutrient pollution from sewage inputs resulted in high phytoplankton biomass that reduced the limiting nutrient -- DIN -- from the water column. Overall, DIN averaged 0.57 ± 0.35 µM at the eight fringing reef sites, a value that approaches the threshold (1 µM) noted for eutrophication on coral reefs. However, chlorophyll a concentrations averaged 0.31 ± 0.21 µg/L among the reef sites, levels indicative of eutrophication on coral reefs. High concentrations (> 0.5 µg/L) at both Mt. Irvine and the “Maverick” reflected advanced eutrophication resulting from the large sewage discharges from southwest Tobago.

Sampling in the Buccoo Reef Complex in September following heavy rainfall showed much higher DIN concentrations than those observed in the dry season (Figure 22). Similarly, increases in DIN were measured at the eight fringing reef sites during the sampling in October that followed increased rainfall and runoff (Figure 23). Increased runoff from rainfall was indicated by salinity values, which were lower in the surface waters (33 to 35 ppt) compared to the near-bottom waters (36 to 38 ppt) at most of the reef sites in October. DIN averaged 2.55 ± 0.31 µM in October -- a five-fold increase in DIN concentrations in Tobago’s coastal waters compared to the dry season. However, DIN concentrations were not higher in the surface water samples compared to the near-bottom samples, pointing to local land-based discharges rather than the Orinoco plume as the DIN source. The higher DIN concentrations stimulate uptake of SRP by phytoplankton and microbes in their effort to achieve “balanced growth”, which accounted for the generally lower SRP concentrations in the wet compared to the dry season for both Buccoo Reef (Figure 24) and the fringing reef sites (Figure 25). Overall, chlorophyll a concentrations at in the Buccoo Reef Complex and the eight reef sites
were similar between the wet and dry season sampling. Higher chlorophyll $a$ values at Mt. Irvine and the "Maverick" in the dry season may reflect the increased sewage nutrient loads at the end of the winter tourist season. In contrast, significant increases in chlorophyll $a$ occurred at Kelliston Drain and Black Jack Hole off Little Tobago Island in October, indicating increased nutrient inputs to these reefs in the wet season. The highest chlorophyll $a$ values at these reefs sites were in the stratified, lower salinity surface waters -- indicating elevated phytoplankton biomass from a combination of nutrient enriched Orinoco floodwaters as well as localized runoff.

Increased concentrations of chlorophyll $a$, suspended solids, and dissolved organic matter (DOM) resulting from land-based runoff can reduce water transparency and accordingly, the amount of light penetrating to coral reefs at depth. This characteristic of a water mass is quantified by measuring light levels at various water depths and mathematically determining the light attenuation coefficient ($K_d$). Coral reefs typically thrive in clear, oceanic quality waters with $K_d$ values $< 0.1$. Measurements made at nine reef sites in October showed values ranging from 0.15 at Black Jack Hole to $> 0.25$ at Mt. Irvine, Englishman's Bay, and Kelliston Drain (Figure 26). These elevated $K_d$ values illustrate the reduction of light availability to these reefs from land-based runoff. The fact that the lowest (Black Jack Hole) and highest (Kelliston Drain) $K_d$ values were measured on the same day in close proximity to each other off Little Tobago Island illustrates the great variability in water quality that can occur during the wet season when the Orinoco floodwaters mix with local stormwater discharges and the clear, oligotrophic waters of the Guyana Current.
To “fingerprint” the sources of land-based N pollution on Tobago, stable nitrogen isotope ratios \( \delta^{15}N = \frac{^{15}N}{^{14}N} \) were measured in reef macroalgae (seaweeds) collected from the Buccoo Reef Complex and other fringing reef sites in both the dry season and wet season. Numerous studies using this technique have demonstrated its ability to discriminate between natural (nitrogen fixation) and anthropogenic (sewage, fertilizers) N sources. The method is based on the fact that wastewater N derived from human or animal wastes, septic tanks, or sewage treatment systems are enriched in the heavy isotope of nitrogen, \( ^{15}N \). This enrichment of \( ^{15}N \) relative to \( ^{14}N \) \((\delta^{15}N)\) results from nitrogen transformations that occur prior to, during, or following the treatment and discharge of wastewaters; volatilization of ammonia and isotopic fractionation by microbes during nitrification and denitrification produce residual DIN with elevated \( \delta^{15}N \) values (+5 to +22 o/oo). Other potential sources of N on coral reefs have lower \( \delta^{15}N \) values, such as that derived from microbial nitrogen fixation (+1 o/oo) or fertilizers (-3 to +3 o/oo).

The highest mean \( \delta^{15}N \) values measured in the entire study were in macroalgae growing on Princess Reef and Buccoo Point Reef (Figure 25 & 26). High \( \delta^{15}N \) values (> +3 o/oo), which are indicative of sewage N enrichment, also occurred in macroalgae from Outer Buccoo Reef, Walkabout Reef, and Mt. Irvine Reef that were in close proximity to land-based sewage discharges. Lower \( \delta^{15}N \) values (+5 to +6 o/oo) at more offshore reefs at Diver’s Thirst, Diver’s Dream, Coral Gardens, and Kelliston Drain still indicated significant enrichment with sewage N. The lowest \( \delta^{15}N \) value (+2.88 ± 0.16 o/oo) during the April sampling was at Black Jack Hole, the most “upstream” site sampled and therefore the least affected by land-based sewage discharges. The lowest \( \delta^{15}N \) values at Black Jack Hole in April indicated minimal levels of sewage pollution and reflected the low \( \delta^{15}N \) values of “background” sources of oceanic N to Tobago’s reefs.

The wet season sampling showed a similar pattern of \( \delta^{15}N \) in macroalgae to that of the dry season for most reef sites, corroborating the minimal effects of the Orinoco River on dissolved N inputs to Tobago’s coral reefs. The highest values (> +6 o/oo) during the wet season sampling again occurred at sites directly influenced by land-based sewage discharges. For example, Princess Reef, the Hilton Reef, Bon Accord Lagoon, Buccoo Point Reef, Latour’s Jetty, and Outer Buccoo Reef (back reef) all had \( \delta^{15}N \) values > 6 o/oo, indicating a high degree of wastewater N enrichment at these locations (Figure 23). Lower levels of sewage N enrichment occurred at the more offshore and downstream sites, such as Diver's Dream, Maverick, Coral Gardens, Arnos Vale, Outer Buccoo Reef (fore reef), Kelliston Drain, Walkabout Reef, and Mt. Irvine. The most significant difference between the April and October samplings occurred at Black Jack Hole, where macroalgae had a two-fold higher mean \( \delta^{15}N \) value in the wet season (+5.44 ± 0.72 o/oo) compared to the dry season (+2.88 ± 0.16 o/oo, Figure 25). This difference indicates a greater spatial extent of sewage dispersion and contamination in the wet compared to the dry season. Overall, a significant correlation between \( \delta^{15}N \) values of macroalgae and % coral cover at the reef sites illustrates the negative impact of sewage on coral reef growth (Figure 26).
Towards a Solution for Nutrient Pollution

The scientific evidence of nutrient (especially N) pollution of Tobago’s coral reefs from human sewage is consistent with recent conclusions that human sewage is the most significant form of marine pollution originating from cities and towns of Trinidad and Tobago (Agard and Gobin 2000). Like other coastal waters around the world, Tobago’s coastal waters are experiencing nutrient pollution from sewage as a result of the “tragedy of the commons”. Specifically, the rationale man finds that his share of the cost of the wastes he discharges into the “commons” is less than the cost of purifying his wastes before releasing them. Since this is true for everyone, people everywhere are locked into a system of “fouling their own nest” so long as they behave as independant, rational, free-enterprisers (Hardin 1968).

The information from this study should be viewed as a call to action by both private and governmental organizations on Trinidad & Tobago. In the United States, the National Research Council’s “Clean Coastal Waters” report recently called for a 20-year national effort to reverse the trend of nutrient pollution and begin restoration of its coastal waters. At a minimum, the report called for restoring 10 % of degraded systems by 2010 and 25 % by 2025. In addition, the report recommended that steps be taken to ensure no coastal areas currently ranked as healthy are allowed to develop symptoms of nutrient over-enrichment.

For Tobago, meeting similar goals will require a multitude of strategies and approaches tailored to specific watersheds, bays, and reefs. For some reefs...
like Buccoo Reef and Mt. Irvine, improved sewage collection, advanced treatment (which includes nutrient removal), or diversion of treated sewage to an ocean outfall, will be required. Although cattle farming on the watershed of Buccoo Reef has decreased since the 1970's, the residential and tourist population has increased nutrient pollution of downstream waters of the Buccoo Reef Complex. Concurrent with this development were the construction and commissioning of sewage treatment plants at Coral Gardens in Buccoo Village and Bon Accord. The goal of these sewage treatment plants was to remove organic matter (secondary treatment), not N or P. Furthermore, much of the population at Buccoo rely on septic tanks and "soak-aways", which contaminate the porous limestone groundwaters with high N concentrations that flow downgradient into waters of the Buccoo Reef Marine Park. One strategy could be to expand wastewater collection and treatment throughout the Buccoo Reef watershed. This could include offshore discharge as well as reuse of the final treated effluent for beneficial purposes -- such as irrigation of yards, golf courses, etc. A variety of strategies will need to be considered to minimize sewage contamination of groundwater and surface water in communities all around Tobago. Protection from increasing nutrient pollution is especially important for the Speyside area, which currently enjoys the best water quality around Tobago and is one of the most popular dive destinations (Figure 27).

In addition to sewage, deforestation, burning, and fertilizers can also be significant sources of N to coastal waters. Land clearing and development on the steep slopes of Tobago increases erosion and runoff of topsoil, which increase N inputs to coastal waters. These activities need to be controlled to the maximum extent possible -- to ensure that topsoil remains on land -- for the benefit of humans and coral reefs alike. Currently, little intensive agriculture occurs on Tobago but, nonetheless, these activities need to be carefully monitored for their potential contribution to soil erosion and N runoff.

Clearly, the solutions to nutrient pollution of Tobago's coral reefs are mostly on land, especially Buccoo Reef Marine Park (Figure 28). A “whole-watershed” management plan could provide a framework by which to design and implement future actions to reduce land-based nutrient pollution. The initiation of a long-term water quality monitoring network for the various sub-watersheds on Tobago, including the major streams and rivers, would be an invaluable tool to guide future efforts for reducing nutrient and sediment runoff. This approach has recently been used in Negril, Jamaica, with great success (Lapointe and Thacker 2002).

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