

Coral Reefs, Sewage, and Water Quality Standards

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NOTE: This paper argues that the water quality standards for tropical coastal waters need to be set at or below the levels at which they are shown to damage coral reefs: in particular nutrients need to be below the level at which they stimulate massive growth of weedy algae which overgrow and kill corals. The levels of nutrients that damage reefs are around a hundred times lower than those that harm human beings, so use of human health water quality standards are deadly to coral reefs. It analyzes data on nutrient levels in Jamaican coral reefs which indicate that they are way above the ecologically acceptable water quality standards for coral reefs as established by Lapointe and Bell, and show that over fertilization by nutrients, not the lack of fishes and sea urchins, are the major reason for the almost complete replacement of corals with weedy algae. This replacement has been followed around Jamaica for 40 years, and took place at different times at each site, always following coastal development, and uncorrelated with over fishing or sea urchin mortality except coincidentally at a few places. Researchers who propose that stopping fishing will allow the reef to recover are mistaken as to the main causes of reef deterioration and are proposing remedies that cannot work: in fact the reef no longer provides habitat for fish because of habitat degradation caused by massive sewage releases to coastal waters, and only removing the nutrients before they reach the sea can allow the reefs and the fisheries to recover. Biological tertiary sewage treatment on a wide scale is needed for the water quality to be improved to a level where recovery is possible. These lessons from Jamaica also apply to virtually every populated region and tourism resort area near coral reefs. This paper was presented at the Caribbean Water and Wastewater Association Conference, and is in press in the Proceedings of that Association.

ABSTRACT Coral reefs, the most productive and species-rich marine ecosystems, are critical for the fisheries, tourism, shore protection, and biodiversity of tropical islands. However they are the most nutrient-sensitive of all habitats, requiring the lowest external inputs to trigger eutrophication, habitat degradation caused by excessive growth of "weedy" nuisance algae. Most reefs in Jamaica are currently being smothered by massive algae overgrowth fertilized by nutrients from sewage or agricultural runoff. They are now largely incapable of protecting the shore from waves, producing sand for beach renourishment, or providing a habitat for most reef fish. Recent research has established the critical concentrations of nitrogen and phosphorous in near shore waters, levels which when exceeded result in replacement of healthy growing coral reefs with seaweeds. Recent and old water quality data from Jamaican coastal waters show that reefs from one end of the island to the other are being exposed to levels many times above the critical acceptable standard for healthy coral reefs. A general model is developed for reefs which relates water quality, external nutrient inputs, population density, coastal physical oceanography, watershed hydrology, and sewage treatment. The model is applied to the Negril and Port Antonio areas, showing that almost all sewage inputs to the coastal zone need to be treated to tertiary level in all but the least densely populated sections of Jamaica if the coral reefs are to be protected from eutrophication. Population density and field observations are compared with islands throughout the Caribbean, Pacific, and Indian Oceans, indicating that eutrophication poses a major threat to the reefs of most island nations. Their marine conservation strategies are therefore dependent on prompt investment in tertiary sewage treatment for virtually their entire populations.

IMPORTANCE OF CORAL REEFS AND THEIR THREATS

Coral reefs are the most important marine natural resource for Jamaica and most Caribbean islands, providing the bulk of fisheries catches and marine bio-diversity, the source of sand for the beaches on which the tourism economy is based, and protecting the shore from erosion by storm waves. Maintaining the health of the coral reefs is therefore critical in protecting coastal infrastructure (seawalls, docks, roads, houses, hotels, etc.) and employment (in fisheries, tourism, and services). In most parts of Jamaica reefs have significantly deteriorated in recent years (Goreau, 1959; Goreau & Goreau, 1973; Goreau, 1992), compromising the valuable ecological services that the reefs provide. Degraded reefs have most corals replaced by fleshy algae. They are not attractive to divers and snorkelers except for first time novices, support very limited fish populations, and they virtually lack both growing coral which break waves in shallow water and sand-producing algae which renourish beaches. Consequently waves break with

greater force on the shore, increasing erosion, and little new sand is generated to replace that which is lost. Degraded reefs show a great reduction in water clarity, affecting their quality for recreation. When degraded reefs are damaged by natural disasters such as hurricanes, there is little recovery afterwards because young corals are unable to find bare limestone on which to settle and grow due to dense coverage by fleshy algae. Good recovery of shallow coral reefs in Jamaica from hurricane damage is now restricted to a few remote areas (Goreau, in press). As a result, visible erosion is taking place at most white reef-derived sand beaches, and coastline accretion is largely restricted to brown sand beaches derived from erosion inland, which have little tourism potential due to their muddy water.

The causes, and even the existence, of reef deterioration have been controversial, because a complex mixture of factors, including hurricanes, erosion, human physical impact, epidemic diseases of marine organisms, over fishing, and climate change, have all played roles (figure 1). Because all these factors act together to stress reef communities, protecting coral reefs requires a very broad range of simultaneous policy steps to reduce stresses to reefs whose origin lies in a) in-water activities (fishing methods, anchor damage, dredging, etc.), b) in regional activities taking place in the adjacent and up-current watersheds (pollution, erosion, etc.), and c) activities in distant parts of the planet (climate change, sea level rise, global warming).

MARINE POLLUTION IN THE CARIBBEAN

Public awareness of water quality problems usually focuses on surface contaminants which can be seen and smelled such as garbage and petroleum slicks, or toxic wastes, and insufficient attention has been paid towards the much more pervasive problems of excessive nutrient levels and declining water clarity in the coastal zone. Large oil spills have occurred in recent years around the Caribbean in Mexico, Panama, Puerto Rico, and Cuba prompting clean-up efforts which have often been too little and too late to prevent serious local damage to reefs and beaches. Tar balls and oil slicks have become increasingly common in the last two decades (Jones, in press), and submerged trash, primarily plastic bags, Styrofoam, tin cans, and bottles are now seen on almost every dive where they were once so uncommon as to elicit comment. Surveys have shown that trash on beaches derives from both from land-based and ship-based sources (Jones, in press).

As the Caribbean is an enclosed sea, floating oil or trash will ultimately wash up on shore, so a Caribbean-wide ban on dumping at sea and provision of shore reception and treatment facilities is required. Steps towards this goal are now underway under the sponsorship of the International Maritime Organization and the United Nations Environment Program. These would be far more effective if the Cartagena Convention, signed by all Caribbean states and obligating them to pollution monitoring and clean up, were to be implemented. Dumping of locally-derived toxic waste has been relatively low due to the modest level of industrial development in the region, but there is extensive offshore dumping of chemical wastes from the pharmaceutical industry in Puerto Rico which has been blamed for causing massive fish kills in Puerto Rico and the Dominican Republic, and there have been numerous attempts to use sites in the Caribbean as repositories for toxic wastes from North America and Europe.

Dramatic as the impacts of acute toxic pollution are, serious impacts on marine life have been relatively limited in space and time, whereas the impacts of excessive nutrient levels have become pervasive, threatening the health of reefs in most of the Caribbean (Lapointe, in press). Coral reefs are the marine ecosystem which is most adapted to extremely clear, clean water, and which has the least tolerance for any deterioration in water quality. While this has been known for a very long time, it is only recently that it has become clear just how low nutrient levels must be to maintain healthy reefs. While nutrients are essential for all biological growth, a healthy reef maintains an exceptionally high level of biomass and productivity by recycling very small amounts of nutrients supplied in the water. Most surface waters in the tropical open ocean contain virtually undetectable levels of nutrients, since all is taken up by the growth of microscopic planktonic algae. The rate at which new nutrients are provided by upwelling of deep nutrient-rich water is extremely limited in the Caribbean because the most nutrient-rich bottom waters in the Western Atlantic are unable to enter the Caribbean due to restricted passageways between the Lesser Antilles, and deep cold waters are effectively isolated from the surface by the extremely thick layer of warm surface water which prevents nutrients mixing upwards into surface waters. Land-based sources of nutrients therefore have a tremendous impact on the near-shore zone.

ALGAE OVERGROWTH OF REEFS AND DISSOLVED NUTRIENTS

While it might be thought that reefs would benefit from more nutrients, very small additions quickly become excessive. Any aquatic ecosystem can undergo eutrophication, the uncontrolled growth of "weedy" nuisance algae which smother normal plant and animal life when nutrient levels are elevated, just as dumping large amounts of fertilizer on land results in prolific growth of weeds unless these are removed. Eutrophic ecosystems are dominated by a handful of useless species which replace the normal healthy diverse ecosystem, and their extremely high rates of algae growth and of decomposition stimulates growth of bacteria and fungi. These can completely remove oxygen from the water wherever circulation is restricted, causing death of higher organisms and creation of zones which are virtually barren of fish and bottom-dwelling organisms such as shellfish, and which stink with the rotten egg smell

of hydrogen sulphide. This happened in Kingston Harbor, where a study of bottom-dwelling organisms ended when oxygen levels catastrophically fell to levels too low to support them (Wade, 1976). Coral reefs and sea grass beds in the Harbor died, and fish are now confined to a shallow surface layer in which oxygen dissolves from the atmosphere by winds and waves. Under calm conditions the supply of oxygen is greatly reduced, causing massive fish kills. Both a complete halt to nutrient inputs and many years, perhaps decades to centuries, would be required before the accumulated organic matter decomposes and oxygen levels can build up to allow fish and bottom-dwellers to live in deeper waters. Eutrophication of rivers, lakes, and coastal waters receiving organic wastes has long been known for causing desirable fish and shellfish species to be replaced with algae blooms, which may be toxic to organisms consuming them, and because water clarity and recreational value deteriorate. This has prompted development of water quality standards designed to identify the maximum nutrient levels that allow the original ecosystem to remain intact. Most marine water quality standards have been developed for cold climates, especially for estuaries. These are intrinsically low-diversity ecosystems compared to coral reefs. Estuaries are adapted to much higher levels of nutrients than reefs because they receive large amounts of nutrients, freshwater, and mud from river discharges which are typically largest in the early spring following snow melt and runoff. Acceptable levels of nutrients that are low enough to prevent eutrophication of temperate estuaries are many times higher than those that trigger eutrophication of coral reefs, so these criteria cannot be applied to coral reef habitats. In the absence of tropical data, nutrient standards designed for cold estuaries have been mistakenly applied to the tropical coastal zone. An even more serious error is to use drinking water quality standards, defined by nutrient concentrations capable of causing medical damage to humans (especially methemoglobinemia of infants due to excessive nitrate and nitrite concentrations in drinking water), which are even higher (1 to 10 parts per million). Because reefs are the most sensitive of all ecosystems to changes in water quality, the critical levels of nutrients which need to be maintained are far lower than any ecosystem, indeed levels which would be regarded as normal in any other marine ecosystem. Protection of reefs from eutrophication requires the use of water quality criteria specific to coral reefs.

Recent research in the Caribbean and in the Great Barrier Reef of Australia has established the critical levels of nitrogen and phosphorous which must not be exceeded if reefs are to remain healthy without being overgrown by weedy algae (Lapointe et al., 1992, 1993, in press; Bell, 1992). These concentrations are:

1.0 micromoles per litre of nitrogen as nitrate and ammonia

0.1 micromoles per litre of phosphorous as ortho-phosphate and organophosphate.

These values are in the molecular concentration units used by chemists and oceanographers. In the weight units more often used in the wastewater literature these translate into:

Nitrogen: 0.014 ppm N or 0.040 ppm NO₃

Phosphorous 0.003 ppm P or 0.007 ppm PO₄

NUTRIENT LEVELS IN JAMAICAN COASTAL WATERS

Nutrients enter the Jamaican coastal zone from streams and from submarine springs supplied by groundwater seepage. Measurements around 1980 found nitrate levels in Discovery Bay in the range of 5 to 10 micromoles per litre (Goreau, unpublished). By the late 1980s these had risen to around 10 to 15 micromoles per litre, and ecological replacement of corals by weedy algae was nearly complete (Goreau, 1992). Samples analyzed for nitrogen and phosphorous showed that the source of nitrogen was from freshwater (figures 2 - 4), and the concentrations were sufficiently high that they exceeded critical levels down to a depth of 100 feet on the outer reef slope. Similar nutrient values were found all along western St. Anns from Rio Bueno to Dunns River (Goreau, Lapointe, & Macfarlane, unpublished). Because of the much larger sewage discharges from highly developed areas near Ocho Rios, Montego Bay, and the South Coast, those areas certainly have considerably higher values. While the main source of nitrogen was from subsurface drainage of the interior of the watershed, it appears that growth of population and tourism along the shore in the 1980s provided local phosphorous inputs which had been previously lacking, causing rapid eutrophication.

Negril, located at the western tip of the island, has had explosive tourism development and population growth in the last two decades. Concentrations of nutrients were evaluated in the Negril area in 1991 by Greenaway (1991), who reported that nutrient levels were low and typical of unpolluted waters, even though every single sample analyzed exceeded the acceptable criteria for reefs for both nitrogen and phosphorous. Analyses made in 1992 by Wade (in press) showed even higher values, in the range of 10 to 20 times the acceptable levels. Over the last 4 years the reefs of Negril have been subjected to unprecedented algae overgrowth, with the result that the coverage of algae on the bottom now equals or exceeds that of corals. These values suggest that nutrient concentrations need to be reduced by 90 to 95% or more to allow ecosystem recovery. Ongoing efforts to establish a conservation area to protect the reef, on which the area's tourism is built, will not succeed unless this happens soon. The major river and groundwater nutrient sources in Negril are shown in figure 5.

The Port Antonio region in eastern Jamaica is also the site of a proposed conservation area. This part of the island has some of the lowest population densities due to mountainous topography and high rainfall. A survey was conducted of nitrate levels in all major freshwater sources, including rivers, springs, and drainage ditches along the entire proposed Port Antonio Marine Park shoreline in early 1994 (Goreau, Wirth, & Bourke, unpublished). Figure 6 shows the nitrate concentrations measured. The values of nitrate in micromoles per liter are equal to the number of times that these freshwater inputs must be diluted by pure seawater containing absolutely no nitrate in order to bring concentrations below acceptable levels. The measured inputs to the coastal zone must be diluted out by a factor of between 2 and 45 times before their nitrate contents are sufficiently low.

These estimates of needed dilution are too low for at least three reasons, so that the actual dilution of freshwater inputs needed over the reef may be considerably greater. First, only nitrate nitrogen was measured, but ammonium would be expected to be the major form of nitrogen in all those samples where nitrate was low, because these came from waters draining sewage, mangroves, or wetlands. Under such conditions organic matter contents are high, oxygen levels are low, and nitrate is rapidly consumed by bacteria and converted into ammonium, organic nitrogen, or gaseous forms of nitrogen. Therefore the dissolved nitrogen content has been underestimated for those samples. Secondly, it was not possible to analyze phosphorous contents for those samples, yet analyses in other parts of Jamaica suggest that phosphorous contents are typically more limiting than nitrogen (Lapointe, in press), and even greater dilution may be needed to bring phosphorous below acceptable levels than nitrogen. Thirdly, the dilution figure is based on assumed zero nutrients for offshore waters. A value of only 0.5 micromoles per litre of nitrate in offshore waters would require a dilution twice as great. Surface waters entering the Caribbean are influenced by seasonal discharges from the Orinoco and Amazon rivers, and often have values in this range. Bell (personal communication) has expressed the concern that nutrients from these remote South American sources could become high enough for Eastern Caribbean surface ocean water to cause eutrophication even in the absence of local land-based nutrient sources. He has obtained data suggesting that nutrient runoff from distant Australian agricultural sources is causing eutrophication in parts of the Great Barrier Reef, in areas without local nutrient sources.

EUTROPHICATION IN JAMAICA

Ecological observations on the increasing abundance and species diversity of algae around Jamaica in recent years suggest that eutrophication has become a general phenomenon in the past decade. Eutrophication has been so serious that many reefs which formerly had more than 95% live coral cover are now more than 95% algae covered. Overgrowth of reef corals and "good" sand-producing algae by "bad" fleshy algae took place at different times in different places, suggesting that local nutrient sources played a key role. Coral reefs near Kingston were affected in the 1950s and 1960s, reefs near Montego Bay and Ocho Rios are thought to have been impacted in the 1970s, the area from Rio Bueno to Runaway Bay was affected in the 1980s, and Negril and parts of Western Jamaica were affected in the early 1990s (Goreau, 1992). Algae overgrowth spread outward from source areas in expanding rings which were initially focused around local sources, but which have since begun to merge along much of the coastline. Along most of the south and north coasts eutrophication has become a persistent regional phenomenon. In addition nutrient inputs are causing permanent planktonic algae blooms, turning formerly clear blue waters dark, turbid, and green. At present only the least developed and populated areas have coral reef in good condition, with algae cover around 20% or less. Even in the Port Antonio area eutrophication is visible in all populated bays but is absent off un-populated shores (figure 7). Similar patterns are seen in Western Jamaica (Goreau, in press).

The fact that eutrophication has followed the course of coastal development and increasing resident and visitor populations, along with their releases of inadequately-treated sewage, suggests that excessive algae growth has been fertilized by increasing nutrient inputs rather than being due to destruction of corals by hurricanes, which took place at the same time at all sites, or due to overfishing, which had removed most of the top predatory fish and reached unsustainable catch/effort ratios more than 20 years ago (Aiken, 1991). It has been proposed that overharvesting of algae-eating fish and epidemic die-off of algae-eating sea urchins has caused overgrowth of algae, and that only severe reductions in fishing can allow reef recovery (Hughes, personal communication). However, in recent years sea-urchin populations have recovered towards pre-mortality levels in certain areas, but the algae have not vanished or the reefs recovered. Algae are also overgrowing deep fore reef sites where sea urchins were always rare compared to shallow back reef areas. In many parts of the island overfishing of predatory fish has resulted in much more extensive domination of fish populations by algae-eating surgeonfish and damselfish, without evidence of algae reduction. Recovery of sea urchin eating triggerfish populations would be predicted to reduce sea urchins and increase algae if the overfishing hypothesis were correct, but reef eutrophication was absent when triggerfish were still common. Algae abundance appears to be primarily controlled by available nutrients rather than by herbivory. While there is no doubt that overfishing has dramatically reduced fish sizes and species diversity, there is little reason to believe that reductions in fishing alone would have any significant impact on algae overgrowth unless nutrient sources are reduced.

PHYSICAL FACTORS. NUTRIENT SOURCES. AND EUTROPHICATION

To determine the extent of nutrient reduction that is required it is necessary to consider the balance of nutrient inputs into each segment of the coastal zone (figure 8), and the extent to which nutrients are removed through biological uptake and diluted by exchange of water between the coastal zone and offshore areas. Biological uptake and exchange are highly variable, poorly quantified, and in any case not subject to direct human control. In general, the more eutrophic an area becomes the less representative dissolved nutrient concentrations in the water column will be of the actual inputs, since most nutrients are quickly taken up by algae. The greater the degree of physical water mixing with offshore waters by waves and winds the lower the nutrient concentrations will be. Consequently bays and shores with restricted circulation will have higher nutrient levels and be much more easily eutrophied than headlands, open waters, or areas with strong offshore currents.

Because ocean currents and tides are highly variable on seasonal scales and vary strongly as a function of weather patterns, many areas may become eutrophic on a seasonal basis or for intervals following periods of extended calm weather. In addition nutrient inputs are highly variable because they depend on seasonal variations of the resident population, river runoff, and groundwater discharge. Nutrient inputs therefore need to be reduced to an extent that is both site-specific and seasonally dependent as well as subject to weather fluctuations. Therefore nutrient inputs need to be lowered sufficiently that excursions of nutrients above critical concentrations are avoided under the worst case scenario. Assuming nutrient levels measured are representative of average conditions, a general mass nutrient mass balance model indicates that the proportional input reduction needed will be $(O - S)/O$ where O is the observed average concentration and S is the standard maximum acceptable concentration. Focusing only on surface discharges or sewage is insufficient, since the total nutrient inputs from all sources must be taken into account. Where non-sewage nutrient sources are also present, such as agricultural runoff, the proportional reduction in sewage inputs needed is even higher.

It is traditional to divide nutrient sources into point and non-point sources, which are generally equated with sewage and agricultural sources respectively. But two other non-exclusive divisions are also helpful, surface and groundwater sources, and sewage and non-sewage sources. Sewage can be a non-point groundwater source in areas typical of most of Jamaica where "soak-away" septic tanks are used. Agricultural sources can be point sources where animal manure is drained or flushed out of stables and pens. The relative role of sewage, agriculture, and natural nutrient sources needs to be determined by direct measurements of each source type in each watershed. Without such a breakdown it will not be possible to determine either the amount of sewage nutrient reduction required, to determine the efficiency of fertilizer use, or to design integrated agricultural strategies which maximize agricultural production, minimize fertilizer wastage, minimize groundwater contamination, and contribute to sound coastal zone protection.

In order to minimize damage to coral reef ecosystems and promote their eventual recovery the fullest possible biological tertiary sewage treatment should be applied to all terrestrial nutrient sources. This should also include agricultural point sources from animal pens wherever this is feasible, since livestock such as cattle may excrete as much nutrients as 15 people. The rational use of fertilizers also plays a role, since fertilizer applications often exceed the uptake capacity of the crops, leaving the rest to leach into and contaminate groundwater. Fertilizer elemental ratios need to be carefully optimized to match plant uptake ratios. Plants utilize elements that they most lack, but the other elements are present in excess and will not be utilized. Fertilizer trails in Jamaica often fail to yield satisfactory growth increases; meaning most of the fertilizer is wasted. This is probably due to the geochemical peculiarities of limestone soils, which imposes strong trace element limitations, so that standard imported NPK fertilizer formulations that lack the needed trace metals do not allow plants to utilize much of the nitrogen and phosphorus.

Since most sewage in Jamaica is discharged directly into the ground, it may play at least as important a role in groundwater contamination as agricultural runoff, and some nutrients discharged via submarine springs along the North Coast could have their origin in the densely populated rural areas in the centre of the island. In the limestone mountains which cover most of Jamaica the water table is sufficiently deep down that tree roots cannot reach it, and in these areas groundwater nutrients are unlikely to be intercepted and taken up. This is why many Jamaican limestone areas have such high nitrogen levels. On the other hand, phosphorous is prevented from leaching by being adsorbed by limestone and soils. In contrast nutrients discharged into surface waters exposed to light are readily taken up by growth of algae and plants. While this causes eutrophication of the receiving bodies of water, this can readily be managed so that most nutrients are stripped out of the water in a relatively confined area. This process, biological tertiary treatment, traps and recycles the nutrients (Devi Prasad, in press; Wilson, in press), rather than allowing them to cause uncontrollable proliferation of algae over a large area of coastline. Secondary sewage treatment alone is inadequate because even if secondary treated effluents are sufficiently free of particulates, dissolved organics, and odors to be "fit to drink" (which is too often not the case), they contain invisible, odorless dissolved nutrients which are far too concentrated for coral reefs.

Coastal zone nutrient control strategies should therefore be based on keeping sewage effluents in the air and light so that the nutrients can be used for intensive production of plants on land, rather than hiding them deep and dark underground where they will flow to the sea, robbing the land of potential production and stimulating growth of weedy algae which destroy the valuable productivity of corals, sand-producing algae, and fish.

POPULATION DENSITY AND TERTIARY SEWAGE TREATMENT

Coastal zone eutrophication in Jamaica is being repeated throughout most of the Caribbean as a result of the very high population densities of all but a few islands. Tabulations of population density of tropical islands around the world (figures 9a and 9b) show that the same is true of many Pacific and Indian Ocean islands. The relationship between population density and eutrophication is especially clear in the San Blas Islands of Panama. In this archipelago there are 50 inhabited islands, each around 100 meters or less across, with an average of around 1,000 people each, and around 300 uninhabited islands. Although the Cuna Indian population are subsistence fishermen, there is little evidence of overfishing (except for lobster and octopus, which are exported). During a brief survey of the region in early 1994 all the larger populated islands were observed to have eutrophication-indicating algae all around the shoreline, but these were absent from all uninhabited islands or those which only had a few resident families (Goreau, unpublished). It appears that a coastal population density of no more than roughly 500 people per 100 meters of shore generates too much nutrients for a viable coral reef to survive in the absence of sewage nutrient removal. This can be defined as the human carrying capacity of the reef. Similar eutrophication has been observed at the Club Med in Moorea, French Polynesia, where the secondary-treated sewage from 500 people at an isolated hotel provides a point source causing eutrophication over 100 meters of coastline (Goreau, unpublished) even though this is an area with very strong tidal currents. The maximum sustainable population near a reef is therefore probably less than around 5,000 people per kilometer of shoreline. As the interior of Moorea is uninhabited, the coastal population density reefs can tolerate will be even lower when there are additional nutrient sources derived from inland via groundwater flow, shore currents are less, and sewage is treated to less than secondary levels.

Virtually every populated coastline near reefs around the world is now well above this limit, making adjacent reefs unsustainable in the face of human population density. Many reefs in Jamaica and elsewhere have now reached the point where so little live coral remains that decades will be required for new corals to settle and grow even after all excess nutrient inputs are removed. Nutrient reduction strategies need to focus first on those areas where coral cover is still sufficiently high that the reefs can quickly recover once nutrients are reduced, allowing them to help seed recovery in more damaged areas. If these reefs are lost, restoration of the marine habitat will be impossibly slow. In many places there is little time left to act. With the exception of islands with very low population density (mostly flat islands without surface water), protection of the coral reefs requires that virtually all sewage generated be treated to tertiary level to increase the fraction of nutrients intercepted and removed prior to discharge to the coastal zone. Even though coral reef habitats require the very highest technology of sewage treatment, sewage treatment plants proposed in tropical areas rarely include tertiary treatment, usually on grounds that this is too complicated and expensive. The point of this paper is that tertiary sewage treatment and use of appropriate nutrient water quality standards are nowhere more necessary on environmental grounds.

Tertiary treatment has been widely regarded as costly and complex by governments and international funding agencies because in cold countries expensive chemical treatment is needed to remove nutrients since plants can't grow year-round. In the tropics biological treatment is always effective, cheap, and requires only modest areas (Devi Prasad, in press; Wilson, in press). Often this can be done in wetlands, ecosystems which are excellent for removing nutrients and have few other economic uses unless they are drained, causing the destruction of their nutrient and sediment removal capability and deterioration of water quality in the adjacent coastal zone. In most cases biological tertiary treatment is technically practical, economically feasible, and environmentally necessary when contrasted to loss of fisheries, tourism, shore protection, and other ecosystem services which only healthy reefs can provide. Where coastal nutrients are sufficiently excessive, tertiary treatment of the entire population in coastal areas alone will be inadequate, and attention also needs to be paid to sewage entering groundwater from soak away pits in the interior of the island. The sewage collection and treatment plans for Montego Bay, Ocho Rios, and Negril, which focus on the coastal strip hotels and upscale areas along the main roads and do not include squatter settlements or hillside communities, will therefore be inadequate to reduce coastal nutrients to sufficient levels to protect reefs unless they are made far more ambitious. The remote, isolated, and mountainous character of many interior areas makes sewage collection systems and treatment plants prohibitively expensive. Soakaway pits should be replaced with sealed composting or dry toilets in such areas to prevent leaching of nutrients into the groundwater that will eventually flow into the sea.

If we are to protect reefs we must convert the source of marine environmental damage into a fertilizer for useful productivity based on nutrient recycling (Macfarlane, in press). Biological tertiary treatment systems

must be actively managed to maintain maximum productivity and nutrient removal in minimal areas by harvesting and composting the biomass produced and using it to produce useful sources of fuel and fibre where pathogens or trace chemical contaminants make them unsuitable fertilizers for food production. Harvesting is necessary because where biological tertiary treatment is un-managed, plants will take up only the nutrients they can use, and the excess will flow on into receiving waters. Prevention of coral reef eutrophication is therefore closely linked to replacing our wasteful "throw away" lifestyle with a "reduce, reuse, recycle" ethos toward sewage nutrients, rather than hiding sewage underground or in the ocean. While numerous other policy steps are also needed to protect reefs (figure 10), including limitations on climate change, full biological tertiary sewage treatment in all populated areas is one of the most important in sustaining coral reef health.

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Nitrate concentrations in rivers, streams, springs, and drains along the shore near Port Antonio. Almost all supply nitrate in excess of desirable levels.

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