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A non-profit organization for protection and sustainable management of coral reefs

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December7 2003

CASE STUDY
WASTE NUTRIENTS: IMPACTS ON COASTAL CORAL REEFS AND FISHERIES, AND ABATEMENT VIA LAND RECYCLING

UNITED NATIONS EXPERT MEETING ON WASTE MANAGEMENT IN SMALL ISLAND DEVELOPING STATES
October 27 - November 1 2003
Havana, Cuba

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Excessive nutrients released to the coastal zone from poor human waste management is the major factor causing coral reefs to be killed by algae. Coral reefs are the most nutrient-sensitive of all ecosystems. They are overgrown by algae at such low levels of nutrients that no other ecosystem would be affected. Water quality standards based on human health permit nutrient levels hundreds of times too high for corals. Much stricter, environmentally-sound, nutrient standards are needed to protect coral reefs because natural sources of nutrients are close to the limits that corals can tolerate in most reefs. A strict policy of zero waste nutrient discharge to the coastal zone is needed. When nutrient inputs are reduced, the algae quickly die off. Waste nutrients in the coastal zone not only destroy the ecological and economic value of coral reefs for fisheries, tourism, shore protection, and biodiversity, they represent a wasteful loss of fertilizers that are badly needed on land. Most plant growth, especially on islands, is well below potential due to lack of nutrients, An integrated nutrient management approach for whole islands and coastal zones is essential to minimize waste and maximize useful production on land and in the sea. Recycling nutrients on land is readily done using many approaches, whose effectiveness and cost depend on population density and land availability. Effective nutrient recycling would allow much greater production of food and energy on land while preventing destruction of reefs and fisheries. At present no coastal zone management unit knows how much nutrients are entering the coastal zone, where they are coming from, and the effects of natural variations or management of them. None is using currently available state of the art technology, which would allow continuous real-time measurements of nutrients to locate and every source and their magnitude and changes. Developments of these tools are essential to placing coastal zone management on a scientific basis and optimizing useful production in our lands and waters, the very point of sustainable development. They need to be applied not just to the coastal zone but to the whole adjacent land watersheds. Integrated management and recycling of all waste nutrients on land would result in true sustainable development of natural resources in both land and sea. Failure to manage nutrients properly will result in crippling losses as global warming, sea level rise, storm intensity, and pollution rise out of control.

INTRODUCTION

Island Nations are literally drowning in wastes. Until our policymakers recognize this simple truth and make cleaning up our environment a major priority, the health of our natural resource base and our quality of life will simply get worse. The waste problem is visible and invisible, local and global. It includes what we can see, the plastics and garbage of local origin along with that carried by ocean currents from remote sources all over the globe (Moore, et al., 2001; Derriak, 2002). But the most widespread and insidious effects come from the pollution we can't see. It includes nutrients from wastes over-fertilizing our waters, causing algal blooms that smother corals. It includes chemicals that are disrupting biological systems and reproduction (Colburn Dumanoski, & Myers, 1996; http://www.ourstolenfuture.org/), and promoting mutations, cancers, and the evolution of more virulent pathogens. And it includes bacteria, fungi, and protozoa that are making people and marine organisms of all kinds sick (Patz, Epstein, Burke, & Balbus., 1996, http://www.greencampus.harvard.edu/recommend_resource/presentations/bpe_20021219_paul_epstein.pdf). Finally low-lying islands are literally drowning in wastes that are not of their making, the greenhouse gas pollutants, largely from the rich countries, especially the United States. These have caused accelerating global warming, killing corals world wide (Goreau et al. 1993; Goreau & Hayes, 1994; Goreau et al., 2000), global sea level rise that is flooding whole low lying island nations, and more severe storms. Reversing the ways that we are drowning in wastes is essential to our sustainable development. All of these issues must be dealt with simultaneously to save our reefs and fisheries, but here the focus is on local waste management as it affects nutrients in the coastal zone that affect coral reefs and fisheries.

Many coral reefs around the world, especially those near populated coasts, are being increasingly smothered and killed by dense blooms of bottom dwelling ("benthic") algae. The dead, algae-covered coral is no longer able to serve as high quality habitat for marine animals such as clams, crabs, lobsters, and fish, so fisheries and biodiversity decline, Once the corals die, the reef framework begins to be broken up by boring organisms and wave energy. Its capacity to protect the coastlines from erosion steadily deteriorates, coincident with globally rising sea levels and increasing storm energy. As a result coral reef countries stand to lose much of the economic benefits of tourism, fisheries, shore protection, and biodiversity that only healthy reefs can provide.

Around the world harmful algal blooms are dramatically increasing (Hallegraeff, 1993; Anderson, 1995), and thought to be due to excessive amounts of nutrients entering the coastal ecosystem from land-based sources of pollution (Smayda, 1989; Boyer & Brand, 1998; NRC, 2000; Howarth et al., 2000). Harmful algal blooms are characterized by "green" water conditions in which the free-floating microscopic algae ("phytoplankton") greatly increase, changing the color of the water from blue to green. Certain phytoplankton species, the so called "red-tide" algae, produce toxic chemicals that can kill fish, shellfish, and even humans, so harmful algal blooms are generally thought to be of concern only when death results from poisoning. However it is important to include large benthic algae blooms, that can stretch for tens or hundreds of kilometers, and kill by smothering rather than poisoning, as perhaps the most environmentally damaging and economically costly aspect of harmful algal blooms due to their size and duration (Lapointe, 1997). Phytoplankton algal blooms can be very damaging, but tend to be localized, episodic, and of short duration. Most benthic algal blooms, although showing seasonal variation, tend to get progressively larger and become permanent, with irreparable ecological effects, despite episodic short relief after intense storms clear the loose algae away, at least until they grow back.

The cause of benthic algal blooms in coral reefs has been extremely controversial, with viewpoints generally falling into two diametrically opposed hypotheses, the "top-down control" theory and the "bottom-up control" theory. The first sys that algae are caused by lack of plant-eating animals ("herbivores"), while the second says they are due to too much food, i.e. nutrients.

Top-down theory is based on the study of animals. Its advocates blame 1) fishermen, who they say have caught and eaten the plant-eating fish, causing the algae to grow without control, and 2) diseases that killed most of a single species of sea urchin, in the Caribbean only, during 1983 (Lessios, Robertzon, & Cubit, 1984). They say that nutrients are irrelevant, and algae will disappear only if fishermen are prevented from fishing and/or if sea urchins reach dense populations. Top-down theory is the current orthodoxy in the field, if orthodoxy is defined by the quantity of publications as opposed to their quality. The reason that this theory is so popular is because anyone can swim over a reef and count fish and sea urchins, and every course in tropical marine biology sends hordes of students out to just this. As a result of the "publish or perish" mentality of their academic advisors, these counts are quickly converted into vast numbers of published reports from algae overgrown reefs that note the few fish, and sometimes sea urchins,, seen, and conclude that this is the cause of algae. Very few of these quick and easy studies include accurate studies of nutrients, which requires considerable expertise in sampling methods, instrumentation, and chemistry, and are much more difficult to do.

Bottom-up theory is based on the study of plants. Plant growth is limited by the availability of light, water, carbon dioxide, and nutrients (in particular nitrogen and phosphorus and a host of trace metals). In the shallow ocean light is never limiting unless the muddiness is increased by dredging and by deforestation followed by erosion. There is no shortage of water in the ocean, and carbon dioxide is very abundant and only becomes limiting under conditions of truly exceptional growth. In coastal waters adequate trace metals are almost never lacking, although they can be in the open ocean remote from land. The major factors limiting growth of marine plants are almost always nitrogen or phosphorus or both. Studies of plant growth rates at different levels of nitrogen and phosphorus show that when these are low, growth is very slow, but at levels typical of polluted coastal waters, plants grow at close to maximum possible rates. Bottom-up theory says that nutrients control the production of marine plants, but that herbivores, by eating some plants preferentially and avoiding others (often because they are toxic or too tough) can influence WHICH algae are most abundant. Bottom-up theory says that excessive abundance of algae can be controlled by reducing nutrient s.

The distinctions between the two theories are not just an academic quarrel if they affect practical management issues. Following the wrong paradigm will result in failed efforts at control. Because bottom-up and top-down theories recommend such different policy prescriptions (stopping fishing versus stopping sewage), effective management of algae on reefs will fail if the factor being controlled is not really the most important one. There are two ways to test these hypotheses. The first is to do carefully controlled experiments manipulating both nutrients and herbivores separately, and the second is to study the natural distribution of algae under a wide range of conditions of differing nutrients and herbivore density to see what general patterns emerge. The evidence for and against both theories is presented in boxes in the following section.

SITUATIONAL ANALYSIS

Until nutrient criteria for coral reef eutrophication were developed it was not recognized just how sensitive coral reefs were to exceedingly low nutrient concentrations, and even now uninformed researchers measuring nutrient values well in excess of them erroneously persist in claiming that their values are "low". It is now clear that coral reefs are the most nutrient-sensitive of all ecosystems. Ecosystems are classified in terms of nutrients as being "oligotrophic" or low in nutrients, "mesotrophic" or intermediate, and "eutrophic" or excessive in nutrients. Eutrophic systems are dominated by fast-growing weeds. A fourth category, "hyper-eutrophic" refers to systems that are overwhelmingly dominated by a few species of the worst weeds. Any aquatic ecosystem will go eutrophic if there are enough nutrients, but the nutrient concentrations that cause a coral reef to go eutrophic are so low that the same levels would be oligotrphic in any other ecosystem. For example the next most sensitive ecosystem, seagrasses, require nutrient levels 20 to 30 times higher than coral reefs before the weedy algae overgrow the seagrasses (Lapointe, Tomasko, & Matzie, 1994). Cold water marine ecosystems and freshwater ecosystems are even less sensitive to nutrients. Since almost all published work on eutrophication is in lakes and cold water bays, the nutrient limits for them are commonly, and incorrectly, applied to coral reefs by many uninformed researchers. Environmental water quality standards are inevitably based on cold and fresh waters, making them at the least irrelevant and at worst dangerous if applied to coral reef ecosystems.

To be effective in protecting natural resources, water quality standards must be ecologically-sound and ecosystem-specific. In most cases they are neither. If they are based on ecosystem responses they are irrelevant if they are adopted from values from less nutrient-sensitive ecosystems. But in general the situation is even worse. Almost all water quality standards are based on human health. Humans are extremely tolerant to very high levels of nutrients in drinking water, and the limits are largely determined by the extremely high concentrations of nitrate that cause methemeglobinemia, or "blue baby" syndrome, in which the hemoglobin of the babies is bound up by nitrogen and they literally asphyxiate. This typically is found only where drinking water wells are right next to cattle pens full of manure (http://www.alphausasystems.com/nitratinfo.html). Nitrate is dangerous at much lower levels, causing high levels of stomach, intestinal, and colon cancer that is very common on limestone islands of the Caribbean and Pacific. Even so, the "safe levels" of nutrients in drinking water are hundreds of times higher than what corals can stand. We can safely drink sewage effluents (from which bacteria are filtered out of course) that would kill a reef (Goreau & Thacker, 1994). By the time people start to get sick form poor water quality, or ear infections and coliform bacteria become a problem, their reefs will already be dying or dead.

The historical process of coral reef eutrophication is best known from Jamaica, where it has been followed around the island for over 50 years (Goreau, 1992a). Reefs inside Kingston Harbour, next to the island"s greatest concentration of people, were eutrophic in the 1950s and died soon afterwards. Reefs outside the harbor went eutophic by the 1960s, followed by those of the rapidly expanding tourist towns, Montego Bay in the 1960s, and Ocho Rios in the 1970s. In the 1980s the smaller north coast tourist towns went eutrophic, including the reefs near the Discovery Bay Mairne Laboratory. The Negril area and the more remote parts of the island went eutrophic in the 1990s, by which time the only non-eutrophic areas left were along the extremely rugged east coast, with few people because of the high wave exposure, lack of flat land, and extremely rainy climate. At all of these sties the same pattern was seen. Algae species were zoned by nutrient preferences around the point sources of pollution like sewage outfallls, river mouths, and springs, and these zones spread outward from them. With time until they merged and the sources could no longer be clearly seen from the algae distributions (Goreau 1992b). Coincident with this process of benthic algae blooms smothering reefs, the water turned from clear blue to dark and green as visibility declined due to phytoplankton blooms.

Ironically, despite the long observations of these trends in Jamaica, the island has also been the key study site for many papers claiming that the cause of algae is low herbivory even though the fish are now almost entirely herbivorous and the sea urchins have recovered in many places. These studies, almost all based on one time or short-term observation of fish and sea urchins, at one or a few sites without nutrient data, by short-term foreign visitors, have all ignored the long term Jamaican literature on the subject.

Eutrophication is clearly visible all around the world wherever nutrient inputs from land-based sources increase due to increased coastal populations and development. One can see this on the scale of individual villages and fishing beaches in almost every country and island, for example in Philippines fishing villages and resorts (Goreau, Goreau, & Cervino, 1997) and hotel islands in the Maldives (Goreau, 1997). In Seychelles green water is confined to the populated east coast of the main island and the interiors of atoll lagoons with poor circulation that trap large amounts of seagrass detritus (Goreau 1998 a, b, c). In front of Havana Harbor there is a sharp line where the green polluted water from the harbor meets clean blue waters brought in by prevailing currents, and while the downstream shores are algae covered, the upstream ones are clean. In the Grenadines algae are found in large numbers only next to the largest villages and wherever the cruising yachts anchor and discharge their toilets (Goreau & Sammons, 2003). The shorelines of the inhabited islands of Kuna Yala in Panama are lined by outhouses over the water. All have dense growths of high nutrient-indicating algae, which are not found around the uninhabited islands (Goreau et al., 1997). The process can take place very quickly. In 1991 the lagoon in front of the densely populated western part of Tahiti (population 150,000) was filled with weedy algae. The sister island of Moorea, with 4,500 people, was free of them except directly in front of the 450 room Club Med Hotel, the largest source of pollution on the island. Although the Hotel had a secondary sewage plant, this does not remove significant nutrients, and the effluents were released into the sea in front of the hotel through a pipe. The end of the pipe was completely clean of algae, and full of fish. It was clear that no sewage came out of it. Instead the algae clearly showed that the pipe was broken underneath the beach, and the place where the nutrients flowed into the sea was marked by dense green growths of an algae indicating very high nutrients, the only place on the island where these were seen. Three years later, following a tourist boom, the Moorea Lagoon was eutrophic and the high nutrient algae were smothering corals all along the north coast (Goreau & Hayes, 1996).

Unfortunately the role of nutrient gradients in controlling algae abundance and species composition has generally failed to be recognized by marine biologists who do detailed transects and counts in small areas rather than looking at large scale gradients along and parallel to nutrient sources. Most algae researchers simply produce species lists that do not look at abundance or spatial and temporal gradients, so the ecological information is lost, and the number who know the ecology of the different species in regard to nutrients can be counted on one hand. Yet algae show more clearly zoned patterns along gradients than any other group of coral reef organisms, and so are the best bio-indicators of coral reef health of all except for live coral cover. Unfortunately the information needed to interpret them has never been published, and it is of the greatest importance to do so, in order to allow the great amount of information to be gained from their study to be more widely applied.

Algae species show such sharp zonation by nutrients that it is possible to identify nutrient sources and relative concentrations from study of the algae alone. This can be used to track pollution directly to the source (Lapointe et al., 2004). For example one can see patches of high nutrient algae marking every site where septic tank effluent soaks through sand and rock into the sea in front of hotels and towns, even in islands with small populations, such as the Maldives, Bonaire, and Tuvalu. Algae overgrowth, although affecting reefs up to a kilometer away, gets dense and more dominated by the highest nutrient-indicating species as one approaches captive dolphin enclosures from the downcurrent side, yet they are absent from the upcurrent side (Goreau, 2003). Algae show that these areas are the major local source of nutrients (http://www.globalcoral.org/Following%20the%20Death%20of%20the%20Corals.htm). A recent study of algae distributions by the author (in preparation) in Grand Cayman showed that the turtle farm effluents are the major source of nutrients in the northwest, where it has killed a large area of reef, that the garbage dump is the main source in the North Sound, septic tank seepage on the west and south, and upwelling of deep water nutrients on the north east.

Although largely unexploited, algae distributions are in fact a better indicator of nutrient inputs than the nutrient concentrations themselves. The reason for this is that nutrients vary very quickly in space and time as the pattern of water movement shifts with currents, tides, winds, and waves, and because they can be rapidly taken up by algae. If seriously eutrophic waters remain over a reef for long enough, algae will remove most or all of the nutrients. As a result a eutrophic reef can have low measureable nutrients in the water, because they have been taken up and are part of the algae biomass, to be released again when the algae dies and decomposes. Chlorophyll concentrations, which measure phytoplankton concentrations, are a crucial indicator of absorbed nutrients. Benthic algae integrate the nutrients they receive over their lifetime, and so while dissolved nutrients vary rapidly, the algae gradients can point to the sources much more clearly than the nutrients themsleves, unless nutrients are very densely and repeatedly mapped. Because the Caribbean has much lower tides and currents than do islands in the Pacific and Indian Oceans, the water sits around much longer and is less diluted. As a result Caribbean islands are much more vulnerable to eutrophication than those in the Pacific and Indian Oceans for the same nutrient input (except for enclosed lagoons).

Algae respond to nutrients directly, regardless of their source. They do not distinguish between natural and human-caused sources. Natural nutrient sources include: 1) surface and groundwater runoff from land ecosystems (which are greatly elevated wherever deforestation, agriculture, and pit latrines or septic fields are found), 2) excrement from bird nesting sites, 3) upwelling of deep nutrient-rich ocean waters (which can be locally or seasonally important due to the patterns of currents, mixing by hurricanes, tidal pumping, tsunamis, and breaking of internal waves), and 4) transport from distant sources (for example the Amazon and Orinoco river plumes in the southeastern Caribbean, or the effects of Hurricane Mitch runoff from Honduras on the reefs of Mexico and Belize). Wherever there are significant natural sources, the amount of human-caused nutrients that can be tolerated by reefs is diminished. The human caused sources include: 1) human sewage whether directly into the sea or via rivers or groundwater 2) Livestock wastes and fish cannery wastes, 3) crop residues and organic wastes, 4) soil erosion, 5) leaching from garbage dumps, and 6) captive dolphins and turtle farms. The eutrophication limit is so low that most coral reefs have natural sources that place them close to the limit, even in the absence of human populations. Therefore the only prudent policy is to permit zero discharges of human-caused nutrients to the coastal zone.

It is important to realize that all nutrient sources from the breakdown of organic wastes must be included, not just human sewage, Lagoons surrounded by bird nesting sites are eutrophic, for example in Cozumel and Contoy Islands in Mexico, or Barbuda. Cattle wastes, prig wastes, captive dolphin wastes, and turtle farm wastes, none of which undergo sewage treatment, have all been seen to cause coral reef eutrophication too. In many islands garbage dumps are located in mangroves next to the sea. The nutrients that leach into the groundwater after the organic wastes decompose flow into the sea and have destroyed whole reefs. In Jamaica the reefs of Orange Bay were exceptional because they had the largest, oldest, healthiest, and fastest growing corals. When a garbage dump was put in the mangroves this magnificent reef of immense ancient corals was killed by weedy algae in a few years (Goreau, 1992b).

BOX 1. EVIDENCE FOR AND AGAINST THE TOP-DOWN THEORY

Most tests have focused on one hypothesis and have ignored the other. Most studies have found that fish grazing is not sufficient to control algae (Gacia, Littler & Littler, 1996, 1999). However such control has been widely claimed in the literature for the Caribbean spiny sea urchin Diadema antillarum, A classic study of the effects of sea urchin grazing, was done by Samamrco in Jamaica in the early 1970s, who placed cages over sea urchins to confine them or to exclude them (Sammarco, 1974). Hungry enclosed sea urchins ate all the algae available to them, like a tethered goat eating all the grass that it's leash allows it to reach, while areas that were caged to prevent urchin grazing grew algal lawns. However nutrients were not measured or manipulated, so these experiments cannot decide if nutrients or gazing was the major control on algal growth under natural densities of urchins. Other studies quantifying grazing by fish and sea urchins generally failed to measure or manipulate nutrients. They cite intense local grazing within dense swarms of sea urchins to suggest that nutrients are not a factor in algae abundance (Edmunds & Carpenter, 2001). But larger scale observation show that grazed patches are surrounded by algae-rich areas through which urchins slowly migrate, and that both algae and urchins are most abundant near nutrient inputs. An example is a sea urchin counting study conducted by a student in Jamaica, who laboriously counted all sea urchins in small adjacent areas in relation to algae abundance. At the end of the study, taking a whole morning, exhaustive counts had been made in a single small patch of shallow back reef habitat near the shore, and the student found that the algae were less dense where there were the most urchins, and concluded that urchins controlled algae. Simultaneously while this study was being done in a single habitat, the author swam for miles and looked at around a dozen distinct habitats along the coast and in deeper reefs. The site where the urchin study was done had FAR higher concentrations of BOTH algae and sea urchins than any other habitat in the region. A more extensive study of all habitats would have come to the opposite conclusion from that made in only one habitat, i.e. that sea urchins were associated the areas of richest algae growth, which was enriched by land-based sources of nutrients. This suggests instead that it is algae availability that controls urchin abundance rather than the opposite! A study that purports to show that areas with high urchin densities had eliminated algae (Edmunds & Carpenter, 2001) was merely a study of small selected patches that had just been grazed, amid a forest of algae. The algae in these temporarily bare patches quickly grow back.

Much of the support for the top down theory has come from studies after a disease wiped out almost all Diadema in the Caribbean in 1983 (Lessios, Robertzon, & Cubit, 1984). If Diadema had in fact controlled algae, there should have been a sudden Caribbean-wide algal bloom in 1983. This has been claimed in widely cited papers from Jamaica (Hughes, 1994), Panama (Shuman & Robertson, 1996), and Curacao.(Ruyter van Steveninck and Bak, 1986). The Jamaica study measured algae and coral cover of the bottom at a single site and reported that algae took over in 1983. In fact the data in that paper show that the transition was not rapid but linear and gradual over many years, and began before 1983. The paper claimed the site had no nutrient inputs, citing a study on long term change in reefs around Jamaica (Goreau, 1992a). But that paper had in fact identified that very site as being immediately down-current from the single largest source of nitrogen on the island: from rivers and springs draining densely populated agricultural areas in the center of the island. In addition a large dairy cattle operation began right next to the site, which shoveled all the cow manure every morning into the river where it swept over the "nutrient-free" site to the extent one could smell it in the water. Algae dominance in Jamaica in fact did not take place suddenly everywhere in 1983, but took place progressively over a 40year period from the 1950s to the 1990s, following the growth of local population and tourism at each site (Goreau, 1992a). The regioon for which sea urchin die off was claimed to be the cause of algae coincidentally underwent strong tourism and population growth in the 1980s. Furthermore algae overgrowth of corals took place in deep reefs where Diadema had never been present in significant numbers, having being almost entirely confined to shallow back reef areas.

A similar study in Panama (Shulman & Robertzon, 1996) reported a transition from coral to algae dominance that was claimed to coincide with

Diadema mass mortality. Once again the data actually shows a gradual transition taking place over many years, starting before 1983, and with no sudden jump in that year. Although nutrients were discounted as a cause, the site in fact lies in the outflow of a lagoon that is densely populated, with a rapidly growing population, in which all the sewage goes directly into the sea (Goreau et al. 1997). 15 years after the urchins died, studies in the same area found that in the major channels, the sides with outflow from the densely populated lagoon were algae dominated. However, the opposite sides of each channel where clean open ocean water flowed in were coral dominated even though no sea urchins were to be seen (Goreau et al. 1997). The third study in support of urchin control, in Curacao (Ruyter van Steveninck and Bak, 1986), reported that a brown algae was abundant in deep reefs after 1983. However this same algae species had been found to abundant in these deep reefs in the earliest studies of algae there in the 1960s (Van den Hoek, Cortel-Breeman, & Wanders. 1975), that is to say it was there all along. Furthermore Diadema had only been abundant in the shallowest waters and very rare in deep reefs, where the algae are affected by cold nutrient rich waters that bathe the deep reefs in Curacao.

So widely cited have these flawed studies been, that almost all subsequent authors noting high algae have blamed them on post 1983 lack of sea urchins, even when algae dominance took place up to 20 years later or more than 20 years before! Coral reefs near urban areas of Kingston, Jamaica were algae dominated in the 1950s, event though Diadema were very abundant (ref). A study of Veiques Island, Puerto Rico (Hernandez Delgado, in prep,), found that algae became dominant around 2000, yet blamed lack of herbivores. But algae dominance took place nearly 20 years after the Diadema died, and was accompanied by a dramatic INCREASE in algae-eating parrrotfish, as would be expected if the herbivores were controlled by algae abundance rather than top down control. In other parts of the Caribbean, areas with nutrient inputs are algae dominated and areas with low nutrients are low in algae, whether or not Diadema or herbivorous fish are present. In many parts of the Caribbean Diadema populations have now recovered to dense levels, but wherever there are nutrient inputs Diadema are completely unable to control algae, except in patches just grazed by dense swarms. When nutrients were low, Diadema would hide under corals in the day, and hunt for the few algae at night. Now they sit in the open, fat and lazy, grazing a ring around a centimeter or so wide. Beyond the narrow grazed halo lies dense algae forests that the urchins are unable to control.

BOX 2. EVIDENCE FOR AND AGAINST THE BOTTOM-UP THEORY

Long term observations of algae species abundance in Jamaica shows that there is a predictable sequence of species that come to dominate as land based sources of nutrients increase (Goreau 1992b). This transition is independent of the sea urchin die off, except coincidentally at a few sites that became algae dominated in the early to mid 1980s (Goreau 1992a). Furthermore the pattern in Jamaica rejects the hypothesis that over-fishing has removed the herbivores. In the 1950s and 1960s when the reefs were already overfished, they were coral dominated with little or no algae except around the highly polluted Kingston urban area. Fish populations were dominated by dense schools of species that eat other fish or eat coral reef animals such as crabs, shrimps, worms, etc. But as the reefs became algae dominated these foods vanished, and the reef fish became dominated by fish that eat algae, because there was no other food available. So, far from the algae being due to lack of animals to eat them, it seems that abundance of algae have instead caused an INCREASE in the number of fish that eat them, indicating that the fish are under bottom-up control by algae.

The same pattern is seen in coral reefs all around the Caribbean, Indian Ocean, and Pacific: dense populations of algae-eating fish and sea urchins are found only at sites that have a lot of algae. While diseases and over-fishing can result in removal of herbivores, dense algae populations are found at all sites with nutrient sources, and are very low where these sources are absent, whether or not herbivores are present. In Jamaica where overfishing was intense long before algae domination, the fish caught were originally not the algae eaters, which were regarded as inedible, but the fish-eating fish species. The result was an explosion in herbivore populations because they were the last group to be targeted by fishermen. Only after more desirable species were eliminated did fishermen turn to eating herbivorous fish because nothing else was left. So the change of herbivore populations are the opposite from what the top down theory predicts. Reefs with high algae are dominated by algae-eating fishes, such as damselfish, parrtofish, and surgeonfish. Reefs that are low in algae are dominated by fish that eat other fish or invertebrate animals in the reef, or feed on zooplankton carried by the currents. This pattern is seen in the distributions of fishes in the Seychelles (Jennings et al., 1996a,b) where active reef fishing takes place. But it is also seen in the Maldives (Goreau, 1997), where reef fish are not eaten because, unique among coral reef countries, Maldivians eat only offshore tuna and regard reef fish as inedible. In both countries high densities of sea urchins are found only in polluted algae-rich reefs near urban areas.

Direct tests of bottom-up theory are based on the environmental distribution of algae with regard to nutrients and the experimental response of algae to nutrients. Classic studies were done in Belize and Australia, and have since been backed up in many other places. In Belize the patterns of algae and nutrients were studied around a group of remote mangrove islands on the Barrier Reef, in an area of low fishing pressure. One of these islands was a bird nesting site, while the others were not. The bird island trees were white with bird excrement, and the surrounding waters were lush with algae that gradually decreased away from the island as coral increased. The concentrations of nutrients were measured with regard to distance and coral and algal cover. This showed that nutrients were much higher near the island and decreased away from it. The transition from algal to coral domination took place at a nutrient concentration of around 1.0 micromole per liter of nitrogen, as the sum of ammonium, nitrate, and ntirite, and 0.1 micromole per liter of phosphorus, as orthophosphate and dissolved organic phosphorus (Lapointe, Litttler, & Littler, 1992, 1993). These values correspond to only 0.014 parts per million of nitrogen and 0.003 parts per million of phosphorus. In Australia the area studied was the inner Great Barrier Reef. Adjacent to the Queensland coast the reefs are covered with algae and soft corals. In the living memory of the oldest aboriginal residents, these areas were healthy coral reefs that they used as fishing grounds. Offshore the algae and soft corals decrease, and hard corals dominate. A strong onshore-offshore nutrient gradient was found, and once again the transition between algae and coral dominance was independently found to be at exactly the same nutrient concentrations as that found in Belize. In addition chlorophyll was measured in the water, reflecting the concentration of microscopic phytoplankton algae, and the transition was found to take place at a chlorophyll concentration of 0.5 parts per billion (Bell, 1992). In Australia the source of the nutrients was from the runoff of fertilizer from sugar cane production inland.

Since these classic studies were done, the same pattern has been seen wherever careful nutrient gradient studies have been performed, in sites ranging form Florida (Lapointe & Clark, 1992; Lapointe, Matzie, & Barile, 2002), Jamaica (Goreau & Thacker, 1994; Lapointe 1997), Martinique (Litttler, Littler, & Lapointe, 1993). Bermuda (Lapointe & O'Connell, 1989), Bahamas (Lapointe et al., 2004), Tobago (Lapointe et al. 2001), Barbados (Tomacsik & Sander, 1985, 1987a,b), and Hawaii (Larned, & Stimson. 1996). Studies that have not reached this conclusion have generally used inadequately sensitive nutrient analytical chemistry techniques and so are procedurally flawed, giving values that reflect only the limit of detection (and hence defined as undetectable) not the real concentrations (which are even lower than the methods used can measure). In addition there are a large number of studies that have measured nutrient concentrations above the Lapointe-Littler- Bell critical limits, but were erroneously interpreted as being too low to account for algae abundance, based on comparison with levels found in non-coral reef ecosystems. For example a study in Florida concluded that sewage outfalls in the sea were not an environmental problem because the nutrients would be diluted to "background" levels in nearly half a kilometer (Proni, Huang, Dammann, 1994). The "background" levels for ammonium, assumed to cause no-harm, were more than 6 times greater than the eutrophication.limits for total nitrogen at one site and more than 60 times too high at the other! The reefs around the sewage outfalls are being killed by huge slimy growths of algae and bacteria mats that are spreading outwards (http://www.globalcoral.org/Divers%20Plunge%20into%20Countywide%20Effort.htm).

Further support for these low threshold nutrient concentrations stimulating greatly increased growth of algae comes from studies in which algae are grown at different nutrient levels. While different species show different response to nutrients, most coral reef algae respond quickly to nutrient concentrations in the range of 1 micromole of nitorgen and 0.1 micromole of phosphorus with greatly increased tissue growth and photosynthesis (Littler & Littler, 1992). These data show that nutrients alone are both necessary and sufficient for greatly increased algal growth in coral reef ecosystems. Experiments that enriched algae with nutrients and monitored herbivory by fish in samples suspended form lines and protected from grazing in cages, found that nutrients were the dominant control on biomass, not grazing (Macfarlane, et al., 1988) although this is highly species specific depending on edibility (Goreau & Goreau, 1988).

Only a few studies are known that looked at both grazing and nutrients, from Belize, Florida, and the Great Barrier Reef. Although the Belize data results showed that addition of nutrients had a much larger effect on increasing algae biomass than preventing grazing, the opposite conclusion was drawn by the authors (McClanahan, Cokos, & Salas, 2002). Furthermore the only nutrient manipulated was phosphorus, although algae growth at the site is limited by lack of nitrogen (Lapointe, Littler, & Littler, 1993), addition of which would have produced even more dramatic results. Nitrogen is generally the limiting nutrient for algae, except near limestone areas with high groundwater discharge, which did not occur at this site (Lapointe, Littler, & Littler, 1992), Although insufficiently sensitive analytical methods were used (McClanahan, Cokos, & Salas, 2002)., these showed nutrient levels well above the threshold for high algae growth The study in the Great Barrier Reef added nutrients in high levels to a reef, and reported little change in the abundance of algae (Koop et al., 2001). However nutrients were already above the threshold for high growth rates, and the system was already dominated by algae before the nutrients were added. In the Florida study lawn fertilizer spikes were driven into the reef flat to slowly release nutrients. The authors concluded that grazing controlled the algae, and that nutrients inhibited algae, because the fertilized areas had less algae than areas further away (Miller et al., 1999). The authors of the study did not realize that the lawn fertilizer spikes they used contain chlorine releasing compounds that kill algae around them, because if they don't they are quickly overgrown by algae (Litler & Littler, 2000).

RESULTS AND DISCUSSION

The spreading problem of algae overgrowth of reefs is wiping out tourism, fisheries, biodiversity, and shore protection where they are most needed. Even if these areas were to be made into no-fishing zones the fisheries would still not recover because the entire food chain for the most useful fish species has collapsed. Restoration of the vast degraded areas, more than conservation of the few remote areas left tin prime condition, is essential to real sustainable development for the vast majority of our coastal populations. There are only three possible ways to get rid of the algae: to cut it off, eat it, or starve it. I am often asked, 'why not just hire young boys to collect it all? My answer is that as a gardener I control weeds by pulling them up, and I spent some years doing the same in reefs in Jamaica, especially around corals whose long term growth rates

I was measuring. When nutrients are high the algae grow back so fast that it is impossible to keep up with it. You feel good that you are doing the right thing, but the gains are so temporary they really make no difference. It must be done constantly everywhere. If weeding doesn't work, neither does eating it. When herbivore populations recover all they do is produce small temporary grazed patches because when nutrient s are high the grazers simply can't keep up. With algae growth The net result is to push the system to algae that can't be eaten because they are too toxic, too tough, or very dense rapidly growing turf algae that are too short to be grazed (Littler & Littler, 2000). Despite the claims of the top-down enthusiasts, they have yet to clean up large areas. Only the third method really works, starving the algae.

There are millions of cases of failure, and the successes can be counted on the fingers of one hand, but they are very dramatic and telling: when nutrient supplies are cut off, the algae die off and do not come back as long as nutrients are kept low. The known cases are described below, along with the lessons learned.

The reefs of Kaneohe Bay Hawaii, where sewage flowed directly into the sea, went eutrophic in the 1970s. The pattern of spread of algae away from around the sewage outfalls left no doubt that sewage nutrients were the cause (Banner, 1974). The impact of sewage was eliminated by building a very long, deep, and expensive sewage outfall pipe that dumped the sewage far away at sea, where luckily it did not wash back on them or affect other areas. The algae died back quickly and over the next decade the corals gradually recovered, though not to the diversity or density it had previously had (Smith, S. V., W. J. Kimmerer, E. A. Laws, R. E. Brock, and T. W. Walsh. 1981). But in the 1990s the build up of population in the watershed resulted in a buildup of nutrients, and the system again went eutrophic (Laws & Allen, 1996; Larned & Stimson, 1996). The point source of nutrients was eliminated, but now the widespread and untreated non-point nutrient sources from road runoff, lawn fertilizers, and golf courses built up to the point that the reef was again overwhelmed by weeds. This shows that while algae can be starved, the nutrients must be kept permanently low for long term success.

Coral reefs around Key West, Florida were smothered by massive algal blooms in the 1980s and 1990s. The cause was clearly identified as being from the sewage outfall (USEPA, 1999). Despite much resistance from government officials, a grass roots campaign led by a local Non-Governmental Organization, Reef Relief, succeeded in forcing the authorities to build a sewer collection system, and apply advanced waste water treatment (Quirolo, 2002). The effluents, instead of being released into the water, were pumped underground in a deep injection well. In the last few years the algal forests that had killed almost all the corals in nearby reefs such as Eastern Dry Rocks have died back, and the coral is now starting to re-colonize the clean bottom (http://www.reefrelief.org/stateofthereef/2003/index.html).

The El Nido resorts, on spectacular but tiny islands off the northwest coast of Palawan in the Philippines, have standard secondary sewage treatment plants, but instead of letting the effluents flow into the sea they use them to water the plants in the resort and forest inland. Investigation of the reefs directly offshore from where the sewage effluents are applied show that there are no more algae near than away from the site because all the nutrients are being absorbed by the land vegetation (Goreau, Goreau, & Cervino, 1997). The diving resort town of Akumal in Mexico has all of the hotels in town on advanced wastewater gardens designed by Mark Nelson, Gonzalo Arcila and associates to absorb all their nutrients (http://www.luna-azul.com/eco.html). This was done to protect the reefs, the economic lifeline of the community, which is based on diving. Although Akumal is absorbing all of their own nutrients the strategy is sadly failing because the entire coastline is under uncontrolled development, and the neighboring communities refuse to mandate clean sewage treatment, so Akumal reefs are being overgrown with algae fertilized by nutrients from either side. This points out the need to have treatment of all sources affecting the reefs, not just some of them.

At Zion Hill Beach in northeastern Jamaica (renamed Dragon Bay by a developer) a single large hotel occupied all of the land around a beautiful small bay with a well-developed reef. The coastline up-current of the Bay is not eutrophic, as it is on the up-current side of the island and faces clean open ocean currents, and located in the least densely populated part of the island's coast, but the corals in the bay were being killed by algae. I made measurements of nutrients in the bay and found them about 2-3 times above the eutrophication limits. The sources of the nutrients were clear from the algae distributions. The hotel had a secondary sewage treatment plant, the only one that was working in that part of the island (the only other had failed, but this was being covered up by over-chorinating the effluent. The high chlorine killed algae growing around the outfall). Secondary sewage treatment removes almost none of the nutrients, and the effluents were being released through a pipe into the north west of the Bay where the waves washed it straight back to the beach. The reefs of the whole west side of the bay down-current from the outfall were being smothered in dense growths of red algae., decreasing away from the outfall On the southeast corner of the bay a river ran in, fed by a spring. The hotel dumped their laundry effluents, containing high phosphate detergents, into the river. The seagrasses and coral reefs on the east side of the bay near the river were being smothered in dense growth of green algae that increased towards the river mouth. The bay had dense schools of herbivorous fish because local spearfishermen were not allowed to fish there for fear they might spear a guest by mistake, and there were large swarms of Diadema, but the herbivores were unable to control the algae. As scientific advisor to the local environmental organization, The Portland Environmental Protection Association I met with the hotel management. I explained to them that they had a wonderful snorkelling reef that was being destroyed by nutrients coming from the hotel as there was no other source of nutrients to the bay. The hotel was fouling it's own nest and could not blame anyone else. This situation was unique in Jamaica, as every other bay had up to hundreds or thousands of separate polluters. I told them they could easily solve the problem with just two steps. I asked them to not release the laundry effluents into the river and to put them into the sewage plant instead, and to stop putting the sewage effluents into the bay, and instead use them to water the lawns, the ornamental plants, and ponds of aquatic plants. The hotel refused to act because they were unwilling to make the minor expenses needed. Two years later the Government of Jamaica received foreign funds from USAID to clean up nearby Port Antonio Harbour. The Harbour had wonderful reefs in the 1960s, but population growth and complete absence of treatment of the raw sewage had caused these to be killed by massive growths of high-nutrient algae. No action was taken until people began to get cholera from eating oysters from the harbour. At his point expert advice was sought, but no effort was made to consult local experts who knew the area, the reefs, or the algae. Instead a very high priced American consultant, who knew nothing about reefs, was brought in. The foreign "expert" was put up in the hotel, went swimming in the bay, got an ear infection, and sued the hotel! Suddenly the hotel did exactly what we had been begging them to do for years. Within weeks of their stopping putting sewage effluent into the bay the dive shop there noticed that the algae were dying back. When I returned two months later the weedy algae were completely gone, except for the last few dying clumps at the base of the seagrasses. The ornamental plants had never looked more lush.

If successes are so few, the failures are so widespread as to be uncountable. They can be seen in every island nation, even the smallest, and every coral coastline of continents. They are constantly expanding and getting worse due to population growth and development. Here I will give only one example of failure because it illustrates the key points clearly.

Negril, at the western tip of Jamaica, has the largest beach on the island. Because of a large swamp next to it, it was completely undeveloped since it was unreachable by land until 1960. In that year the reefs were studied by my father, Thomas F. Goreau, the first Professor of Marine Science at he University of the West Indies in Jamaica and the world's first diving coral reef scientist. He immediately drew up a management plan for a marine park to protect it. Like his earlier management plans to protect the reefs of Montego Bay and Ocho Rios, this was completely ignored by Government (Goreau 1992 a,b, c). Roads were put into the beach and the swamp was drained. At first the growth of tourism was slow, and by the mid 1980s the weedy algae were confined only to the vicinity of the mouths of two canals draining the swamps, where they were sharply zoned by species in concentric rings around the point sources of nutrients. Coral growth rates were lowest, but increasing slightly, directly in front of the canals, but the faster growing corals further away were sharply decreasing their growth rates, probably because of all the swamp peat draining from the swamps (Goreau, Dodge, & Goreau, 1988). In the next 5 years the tourism expanded to cover the entire beach, and the algae began to kill corals across the entire bay. The local divers, the Negril Coral Reef Preservation Society, and later the Negril Environmental Protection Trust, alarmed at the sudden and rapid decline of the reefs, asked me to be their advisor. In response to our documentation of the algae problem (Goreau, 1992c), and grass roots organizing efforts to ensure that the untreated sewage entering the bay was eliminated, the European Union, realizing that one of the country's major sources of foreign exchange earnings was threatened, offered to fund a sewage treatment plant (Jelier & Roberts, 1992). We insisted that sewage from the entire watershed needed to be collected, and since secondary sewage treatment does not remove nutrients, we asked that biological tertiary treatment be included (Goreau, 1993). The funding agency refused on both grounds. The sewage collection system only collected the sewage from the hotels and the rich people's villas along the shore, but completely ignored the hill villages and slums where the vast majority of the population lived. As a result, the vast bulk of sewage in the watershed was not collected by the sewage plant. The sewage plant design consultants refused to include tertiary treatment, on the (incorrect) grounds that this was too complicated and expensive for a small island developing state, and was not needed anyway. The claim that tertiary treatment was too complicated and expensive was based on their experience in cold countries, where expensive systems, highly prone to failure, must be used to remove nutrients by chemical and microbiological means. These objections were irrelevant in a tropical country, where plants could absorb nutrients year round, but were ignored by the EU design consultants who were unfamiliar with biological tertiary treatment. We pointed out that since most of the nutrients would continue to flow into the sea, the reef would not be protected, and that when the secondary treatment ponds filled up and started to flow into the rivers and the sea, it would deliver the final killing blow to the reef (Goreau, 1993). We were told that we should shut up because saying there were problems was bad for business, and that we should be grateful to get an inadequate sewage system rather than none at all. We conducted water quality studies in every reef, mangrove, river, wetland, spring, and groundwater bodies in the entire western Jamaica watershed, finding that over 99% of all sites were already above the nutrient eutrophcation limits (Goreau & Goreau, 1997). After the sewage treatment plant went in, the nutrients continued to increase (Lapointe & Thacker, 2002) and the algae continued to kill the corals (Porter et al., 2002). When the sewage ponds filled and flowed into the sea there was a massive pulse of nutrients that delivered the final blow to the reef (Lapointe & Thacker, 2002), just as had been predicted. The lesson here is that even in those very rare cases when the problem is understood and the right recommendations are made, it is useless if those who control money and policy refuse to act responsibly.

Ironically, despite its failure, this effort to manage the nutrients of entire coastal zones and watersheds as a single unit (Goreau et al. 19997) led directly to USAID's "ridge to reef" program and to the UN "hilltop to ocean (H2O)" programs. These are doomed to failure if they simply continue to pursue cosmetic projects that are not broad enough to eliminate ALL of the nutrient inputs to the coastal zone from the adjacent watersheds. Much more serious and comprehensive approaches are needed to restore the health of coral reefs, especially in small islands that are so critically dependent on their marine resources. These are discussed in the next section.

CONCLUSIONS

Land-based sources of pollution have been recognized as a significant threat to marine resources of island nations (UNEP Caribbean Environment Program, 1994) but standards and enforcement needed to protect coral reefs and fisheries have not been enacted. To reverse the accelerating destruction of coral reefs and fisheries from inadequate waste management the following steps are required:

1) Adoption of environmentally sound water quality standards
Coastal zone water quality standards for nutrients must be sufficiently low to protect coral reefs and fisheries from eutrophication. The Lapointe-Littler-Bell standards should be adopted as they are based on sound science and have shown their value worldwide.

2) Enforcing a "no nutrient discharge" policy
We must recognize that coral reefs are very near their upper nutrient limit and can't take any more nutrients, especially when subject to additional stresses like global warming and new diseases. We need to adopt a "zero discharge" policy for human-caused nutrients (land-based plus boats) into the coastal zone.

3) Water quality monitoring to identify all sources of nutrients
No coastal zone manager anywhere in the world really knows where the nutrients are coming, from or how much, because they lack sufficiently dense mapping of nutrients and of algae. Portable instruments now exist that can be used in small boats that can go around whole islands to make continuous real time monitoring of the coastal zone water quality parameters (nitrate, ammonia, phosphate, chlorophyll, salinity, temperature, oxygen). This would find every single source of nutrients, track each to the source, determine the seasonal variations, and determine the quantitative impact of policy steps to reduce them. These tools are not now being applied for this purpose, and they need to be used. Their use will revolutionize coastal zone management by putting it on a sound scientific and quantitative basis for the first time.

4) Integral nutrient management planning
Nutrients themselves should be prime focus of management because they are the driving force behind over-fertilizing the sea. At present there is a

focus on secondary parameters, like biochemical oxygen demand, pH, and coliform bacteria, which have far less direct significance and environmental impact. Coastal zone nutrient management cannot be separated from its sources on land or from its oceanographic context: a holistic approach is essential to success: ALL inputs must be included.

5) Recycling all nutrients on land
Nutrients should be recycled on land wherever possible. Most of the land vegetation on islands shows clear signs of nutrient starvation, reflected by the color of the leaves, the leaf to stem ratio, and low growth rates and productivity. The exception are tourist hotel gardens and golf courses which are heavily fertilized with expensive imported fertilizers, which are typically overused, polluting rivers and groundwaters with nutrients, or bird nesting islands, where the vegetation is usually lush due to the bird droppings. Poor vegetation and crop growth is a major threat to sustainability of island societies, yet instead of recycling nutrients to make them more productive we throw the nutrients into the sea, killing our reefs and fisheries. We are degrading both the land and sea simultaneously, yet we could simply and cheaply restore both without external inputs by recycling on land. Nutrients are a precious resource that we are wasting in the worst way, and whose value should be maximized by repeatedly recycling it through useful biological production rather than thrown away. Other options to recycling simply hide the problem or transfer it elsewhere. For example deep ocean outfalls are expensive and only work where the currents do not carry them to other reefs, as well as wasting the nutrients. Deep well injection into the ground simply causes them to flow underground and pop up elsewhere. They are widely used in Florida, but instead of solving the problem they are killing the reefs where the water re-emerges at sea (Bacchus, 2002). There are many well developed and highly cost effective methods for recycling nutrients on land, with a wide range of suitability for different situations that depend on the climate, population density, availability of agricultural, forest, and wetland ecosystems to absorb the nutrients. Biological tertiary treatment of nutrient wastes is cheap and simple in the tropics. For example, in the coastal deserts of Eritrea, where no mangroves had naturally grown, the Manzanar Project is growing huge forests of mangroves for goat feed by simply adding nutrients around mangrove seedlings (http://www.tamu.edu/ccbn/dewitt/manzanar/mangroveinit.htm). There are a huge variety of options including managed wetlands, wastewater gardens, and composting toilets that can be used on a small local scale where population density and income do not permit centralized systems (Del Porto & Steinfeld, 2002; R. Crites & Tchobanoglous, 1998).

6) Public/Policymaker education
There is a huge public education gap because we are habituated to think of wastes as filth, to be concealed or thrown far away, rather than as an

essential resource. Public education should begin in the elementary schools. Students should learn about science, sanitation, and their environment by learning at the most basic level about the reality of bacteria and what they do, both good (recycling nutrients) and bad (pathogens where sanitation is poor). Practical demonstrations and experiments will give children the tools to understand their environment and to live more productive and healthy lives, far more than the material that most schools teach. The children will do much to teach the parents to overcome ignorance and often unsanitary habits. Public education is also badly needed for policymakers, whose priorities are often so badly misplaced away from their real task: optimizing all aspects of the quality of the environment we live in. And the public needs to be educated to only vote for politicians who will solve their real needs: health, education, environment, natural resources, and wastes. Only then will our "leaders" make our real problems a policy priority to the international funding agencies. More biological tertiary treatment of sewage to recycle nutrients into food and help the fish come back to our restored reefs, will help our quality of life infinitely more than stadiums named after dead politicians or amassing weapons. "We are drowning in wastes" must become our mantra for effective action.

ACKNOWLEDGEMENTS

The author thanks Brian Lapointe, Bill Wilson, Carol Steinfeld, Cy Macfarlane,, Peter Bel, Mark Littler, Diane Littler, and Maya Goreau for discussions.

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