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MARINE ECOSYSTEM RESTORATION: COSTS AND BENEFITS FOR CORAL REEFS

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ABSTRACT

All marine ecosystems are being degraded by human activities. Destructive impacts include over-fishing, introduction of exotic species and parasites, new emerging diseases, chemicals with negative biological impacts, over-fertilization by nutrients from sewage, fertilizers, and wastes, deforestation and soil erosion, global warming, changes in ocean circulation driven by human-induced climate change, and destruction of coral reefs and oyster reefs that create habitat for the richest marine ecosystems and wave-resistant barriers that protect coastlines. Coral reefs, the most vulnerable ecosystem to global warming and reduced coastal water quality, are rapidly vanishing worldwide, causing serious damage to biodiversity, fisheries, tourism, sand supplies, and coastal protection in over 100 countries. The sources of negative impacts are highly diverse, widespread, geographically remote from the ecosystems affected, and closely linked to population densities and fundamental economic activities (like energy use, industry, agriculture, land management, waste disposal, and fisheries). Unless they are all abated simultaneously there is little possibility for critical marine ecosystems and species to recover naturally. Therefore active global ecosystem restoration strategies are urgently needed to prevent crippling economic losses to marine biodiversity, fisheries, tourism, and coastal resources. Conventional reef restoration methods fail when water quality deteriorates or temperatures increase. Biorock electrolytic technology uniquely maintains healthy coral and fish populations under high temperatures and reduced water quality that are normally fatal. Low voltage direct electrical current provides calcareous substrate for corals (or oysters) to settle on and gives coral energy to grow it's skeleton, leaving the coral with more metabolic energy for growth, reproduction, and resisting environmental stress. Reefs can be restored in locations where they can no longer grow due to global warming and pollution, helping rebuild fisheries and protecting coastlines from erosion from sea level rise and increasing storm strength. Biorock methods are the best hope for preserving coral reef ecosystems, managing reef fisheries sustainably, and protecting tropical coastlines from erosion by accelerating global warming, sea level rise, emerging diseases, watershed erosion, coastal pollution, and eutrophication threats. Estimated costs for globally comprehensive emergency rescue operations are shown to be far cheaper than alternative restoration methods or "letting nature take its course".

INTRODUCTION: HUMAN IMPACTS ON MARINE ECOSYSTEMS

The impacts of human activities on terrestrial ecosystems and the need to mitigate them are well known even though restoration has been woefully inadequate. Far less is known about human impacts in the oceans that make up around 72% of the earth's surface. Virtually every marine ecosystem has already been severely impacted by human activity yet there has been little effort to restore damaged marine ecosystems. This paper categorizes the impacts of humans on marine ecosystems and assesses the ways in which degraded ecosystems can be restored.

The intensity of human impacts has been greatest and historically earliest near coastlines and within the 200 nautical mile national exclusive economic zones (EEZ) because of land based sources of pollution and artisanal fishing on continental shelves. However in recent years impacts in the high seas have become virtually universal (Pauly et al., 1998; 2000; 2003; Myers and Worm, 2003). Industrial fishing fleets comb the most remote parts of the ocean using increasingly sophisticated and effective gear, such as sonar gear and satellite data to find fish schools. Vast fine meshed nets and trawls indiscriminately catch all the prey, along with far larger numbers of other unwanted living organisms, "bycatch" that is discarded to rot. Because there are no restrictions on harvesting in international waters, the situation is becoming even more dire in the high seas than in EEZs, where some restriction apply in principle, even if largely un-enforced.

Although over-fishing is best known, human impacts to marine ecosystems are far more widespread than generally recognized. Here we categorize them into 5 major impact classes: top-down biological, bottom-up biological, chemical, physical, and structural, which are discussed separately below. Although these categories interact strongly, this provides a convenient analytical framework to analyze the major forces through which humans deliberately or inadvertently alter marine ecosystems and the potential steps that could be taken to mitigate them. The impact mechanisms are described in the next section and their potential remedial measures in following sections.

CATEGORIES OF HUMAN IMPACT

1) Top-down biological impacts take place when humans selectively harvest and often completely remove the organisms at the top of the food chain, like whales, seals, sharks, tunas, and other predatory fish, allowing proliferation of the prey species they used to control. This is easy for most people to understand because it is directly analogous to the effects of hunting on terrestrial ecosystems. The largest animals may be much rarer and harder to find and to kill than the small ones, but the amount of meat obtained repays the extra time to find them and energy needed to kill them. Hunters specialize in them until they are gone, when they switch to the next largest and most desirable species until they too are gone. The pattern repeats itself, descending from mammoths to mice. This same pattern has occurred repeatedly in marine ecosystems too. Since the favored food species are the largest predatory meat eating animals, these go first, then smaller fish that eat smaller prey lower down the food chain, descending from fish eaters, to invertebrate eaters, to plant eaters, and finally to detritus eaters. As this happens the food chain is increasingly shortened and concentrated at the bottom, steadily decreasing biodiversity and ecosystem complexity. This pattern is known as "fishing down the food chain" (Pauly et al., 1998; 2000). Virtually every fishery in the world has been severely affected, even the Antarctic Ocean due to whaling. It is now almost impossible to realize that the top predator in the Caribbean used to be the Caribbean monk seal, which was so abundant that the oldest archaeological deposits in Cuba are made up of massive piles of seal bones (Rouse, 1993). Only after their decline did the early Cubans switch fish and shellfish remains predominate in archaeological deposits (Rouse, 1993). Seals were largely gone from the region before the first historical records were made by Europeans. The last Caribbean monk seal was seen more than 60 years ago on the isolated Pedro Banks in the west central Caribbean.

2) Bottom-up biological impacts result primarily from nutrient inputs, new diseases, parasites, and invasive species, often accidentally introduced, that can have their primary effects at any level of the ecosystem, but which are most damaging if they affect organisms at the base. All of these processes are analogous to what is taking place in terrestrial ecosystems. Invasive species replace native species, but lack the network of species both above and below them in the food chain, which have co-evolved with them and often come to some sort

of fluctuating but stable co-dependent interaction. These inter-dependent species webs can collapse as exotic species eliminate key species. The introduced "weedy" species then come to dominate, replacing complex ecosystems with simple ones. Just as a eucalyptus plantation in Brazil is barren of birds and insects, unlike the endemic species-rich tropical forests that have been cut down for plantations, the Black Sea biomass has come to be dominated by a single introduced jellyfish-like organism which eats the larvae of all native species (Shiganova, 1998; Kideys, 2002). Invasive species may also introduce new parasites to which they are tolerant, but which native species cannot survive, much like the effects of introducing new diseases which people of Euro-Asian-African origin are adapted to but which caused mass mortality to Native Americans and Pacific peoples. The American Signal Crayfish, introduced from California, was resistant to a fungal infection that the European Noble Crayfish was not, resulting in the extirpation of the latter (Unestam and Weiss, 1970; Unestam, 1972; 1975). Cultivation of Indo-Pacific giant clams in the Caribbean could introduce parasites that no Atlantic bivalve might be able to resist (Williams and Bunkley-Williams, 1990b). Just as a host of new "emerging" diseases such as AIDS and SARS are devastating human populations, and other new diseases are increasingly attacking livestock, crop plants, and wild animals and plants on land (Garrett, 1995; Patz et al., 1996; Colwell et al., 1998), the same process is taking place simultaneously in the oceans. A host of diseases that were either very rare or previously unknown have caused devastating mortalities to one marine species after another (Williams and Bunkley-Williams, 1990a; Williams et al., 1994; Humphrey, 1995; Goreau et al., 1998; Richardson, 1998; Williams and Bunkley-Williams, 2000; Porter, 2001). Most of these appear to be pathogens of terrestrial origin, or marine species altered by land-based impacts. For example seals are dying of canine distemper (Kennedy et al., 2000), and Pfisteria and red tide mortalities of fishes appear to be linked to sewage from humans, pigs, and chickens (Burkholder, 2002). New diseases are now equally affecting marine organisms even in areas remote from human actions, with around a dozen new diseases attacking corals all around the world (Goreau et al., 1998; Porter, 2001). Most of the pathogens identified to date associated with these syndromes turn out to be new species of genera that are known terrestrial pathogens (Richardson, 1998). The syndromes they provoke are now constantly spreading but their effects are not visible in photographs more than a decade or two old. Most affect a few closely related species, and kill coral tissue at a rate of centimeters per month, but one, White Plague, kills a wide variety of corals at a rate of centimeters per day. This disease, first seen in Florida (Dustan, 1977), quickly spread around the Caribbean in the next few years (Richardson, 1998). An identical-appearing syndrome suddenly appeared in the Western Indian Ocean in early 2002 (T. McClanahan, pers. comm.), and by mid year was found in 33 of 48 monitoring sites in the Great Barrier Reef, with the most prevalent effects in offshore, and allegedly "pristine", reefs (Page, 2002). Each disease appears to have its own distinct pattern in space and time that does not correlate with known stresses, except that one, Black Band diseases, tends to be more prevalent near dense human populations and to contain bacteria found in human sewage (Frias-Lopez et al., 2002). However, this disease can also be found at low density in reefs in the central Indian Ocean that are hundreds of miles from human impact, for example in the Central Indian Ocean (Goreau et al., 2002). These diseases appear to be spread by pathogens transported by ocean currents, and are especially alarming because the base of the food chain is being directly attacked: the structure building organisms that create the habitat for all the rest.

3) Chemical impacts can be classified into two types: inhibitory and stimulatory. Humans add vast quantities of chemicals directly to the ocean, including oil and fuel slicks behind every motorized craft, accidental leaks and spills, deliberate dumping, and industrial chemicals that have strong negative or even deadly impacts on marine life (Sinderman, 1995). The effects of oil and chemical spills in the ocean are too well known to be repeated here, but they are only the tip of the iceberg. An equally vast brew of noxious chemicals are leaked from land from ports, and dissolved in rivers and groundwater that flows into the sea (Sinderman, 1995). Besides these are a large class of agrochemicals such as pesticides and herbicides that are intended for use on land, not in the ocean, where they can have completely unexpected consequences. For example, chemicals used in plastics can act as endocrine disrupters, affecting the hormonal and reproductive activity of humans and wild animals (Colborn et al., 1996). These chemicals dissolve into surface or ground waters, or are carried bound to soil particles eroded from land due to the poor land management practices that are nearly universal. In 1999 the "harmless" mosquito-killing chemical Malathion began to be widely sprayed from planes in the north eastern United States to combat the West Nile virus, which has devastated birdlife and killed many humans as it spread rapidly all across North America after introduction in contaminated birds by the Bronx Zoo. The day after Malathion was first heavily sprayed in southern Connecticut virtually all the lobsters in Long Island Sound died. Third generation lobstermen say their traditional livelihood was wiped out overnight (Johnson, 2003). Toxic genetically-engineered Fusarium fungus that is now being sprayed over Colombia by US military planes is deadly to humans and most tropical food crops (Cuero, 1980). It also causes black spot disease (Evans and Brock, 1994) that destroys the lobsters that are the major source of income for the Kuna Indians in Panama, who live downstream of the sprayed areas. Despite these negative impacts, the majority of chemicals used on land which end up in the ocean have never had their marine toxicology or endocrinology studied, so

there will be many more unpleasant surprises to come as the effects become better known. Yet another group of chemicals that are probably even more widely disseminated into the marine environment has the opposite effect: over-stimulating undesirable species. These are the nutrients and fertilizers, the most widely produced chemicals on earth. We can classify them into two groups, the chemical fertilizers and the products of organic waste decomposition. The former chemicals are spread on fields to fertilize crops, but far more is used than the plants can take up, and the excess flows into surface waters, ground waters, and then the ocean, where it acts to fertilize algae. On top of this vast amounts of human sewage, animal manure and agricultural wastes are allowed to flow into surface and ground waters, and the nutrients released by the bacteria and fungi decomposing them act as huge sources of nutrients to the ocean. The effect on aquatic ecosystems is similar to that of dumping tons of fertilizer in a waste lot, and walking away. Vast quantities of useless weeds, not roses or apples, are the inevitable result as the most aggressive weeds take nutrients up and proliferate like a green plague. All coastal waters near humans are subject to eutrophication, the massive growth of useless weedy algae that smother all more desirable forms of marine life (Hallegraeff, 1993; Nixon, 1995; Bricker et al., 1999; Howarth et al., 2000). Virtually all coral reefs near populated areas and tourist resorts have been swallowed up by masses of slimy algae that have spread outward from the point sources of nutrient discharges. In many places these expanding rings of algal blooms have merged, so whole coastlines are swamped in worthless algae overlying dead corals, and it has become impossible to tell where the sources lie (Goreau, 2003). Florida reefs have been swallowed up by algal blooms up to 50 miles long (Lapointe et al., 2002), which have smothered and killed corals and prevented any settlement of planktonic baby coral larvae. Algal proliferation is due to a variety of sources: increasing direct sewage discharges, sewage leaking from septic tanks, sewage treatment plants that do not remove the nutrients, runoff of agricultural fertilizers and cattle manure, and nutrients from sewage that is pumped down into deep wells, where it moves horizontally through highly permeable "boulder zones", emerging from the edge of the continental shelf and attacking coral reefs from offshore (Bacchus, 2002). Whole ocean basins, like the Caribbean, are now going eutrophic. These processes are so widespread that the total negative impact on marine ecosystems caused by stimulatory chemicals probably is far greater than that of inhibitory chemicals. While the effects are qualitatively analogous to those in terrestrial systems there is an important quantitative difference. Terrestrial pollutants tend to be confined near the area of release as they are bound to soil or dissolved in limited bodies of water. In contrast marine pollutants are widely dispersed by ocean currents, waves, and tides, so the chronic low level effects can be far more widespread, being analogous to atmospheric pollutants which are transported worldwide to all terrestrial and marine ecosystems. Finally, increasing atmospheric pollution of carbon dioxide, the major gas controlling the acidity of the oceans, will lower the pH of surface waters and eventually the deep sea (Caldeira and Wickett, 2003)

4) Physical impacts are those that change the forces of waves and storms and the temperature, volume, salinity, density, stratification, re-circulation, clarity, and velocity of the water. The best known effect is global warming caused by the greenhouse effect of gaseous pollutants from carbon fuel combustion, which has steadily raised the temperature of the ocean surface (Goreau and Hayes, this volume). A steady increase in ocean volume causing global sea level rise has resulted because the warmer surface water expands, and because global warming is melting mountain and polar ice caps (De Angelis and Skavarca, 2003). This sea level rise threatens the existence of the low lying island nations and threatens hundreds of millions of residents of low lying coastal areas with inundation. Up to 150 meters or more of sea level rise could take place if the ice caps melt. This would probably take a few thousand years (Lambeck et al., 2002), although it would likely proceed in jumps as large ice masses suddenly slide or break up (Weaver et al., 2003). Ocean salinity is being impacted because of changes in evaporation and rainfall caused by global warming, dilution by melting ice, and because a major portion of fresh water flows to coastal zones has been diverted by dams and irrigation. Locally, warm salty water is introduced into the ocean as the waste product of desalinization plants or from seawater used to cool nuclear, coal, and oil fueled power plants. The combined effects of changing temperature and salinity change the density of the water, which in turn controls vertical stratification and mixing of the deep ocean. Models suggest that as the ocean warms and is diluted by melting ice surface waters will become insufficiently dense to sink to the bottom in the winter, cutting off the formation of deep cold water from the poles that drive the turnover of the ocean (Manabe and Stouffer, 1995). This will cause the ocean to become more stratified, make deep waters stagnant, and cause surface warming to greatly accelerate because the heat is no longer being carried directly to bottom waters. The transparency of coastal waters has been greatly reduced by erosion of soils from land and from phytoplankton blooms caused by eutrophication. Dredging has an additional local impact. These factors have caused clear blue water to turn turbid green or brown, cutting off light to the bottom, and wiping out benthic ecosystems. Because global warming is not uniform, there are strong regional differences in rates of surface temperature rise (Goreau and Hayes, this volume), creating gradients that drive strong changes in surface wind speeds and surface currents. This is causing global changes in ocean circulation, increasing the speed of warm currents, reducing cold currents, reducing the rate of deep cold water upwelling along coastal margins, and

increasing upwelling in the interior of the ocean basins (Goreau and Hayes, op. cit.). This has profound consequences for all marine ecosystems, because small changes in ocean currents and upwelling have much larger effects on local temperatures than global warming. As a result most coral reef ecosystems are threatened with imminent extinction in areas warming more rapidly than normal, and protected to some degree in those few areas where deep-water upwelling is being accelerated by increased winds (Goreau and Hayes, op. cit.). The impacts for pelagic fisheries will be profound, because the most productive fisheries are found in areas of continental edge upwelling, which are slowing down. This will greatly reduce fisheries catches even in the absence of over-fishing. Finally as global warming increases, hurricane intensity and wind strength will greatly increase (Emmanuel, 1987) causing much greater storm damage. Of these physical impacts, only one has a strong terrestrial analog, changes in evaporation and rainfall caused by global warming.

5) Structural impacts, which have not been previously recognized, are those that destroy the major physical ecosystem structural components that create the habitat for all the other species in those ecosystems. Reef-building corals and oysters can continuously grow solid limestone rock frameworks up to thousands of kilometers in length for thousands of years. These organisms and the human impacts to them are unique to marine ecosystems. Reefs are steadily growing upwards, creating a solid wave-resistant barrier, and are self-repairing through continual growth. This creates high energy environments on the windward or wave facing sides and highly sheltered environments on the lee side, which provides vast numbers of holes and passages that create homes for myriads of other species of fishes, invertebrates, and algae. In this sense they play a role analogous to the large forest trees, that create habitat for many more species of birds, mammals, and insects. Just as the forest animals and insects vanish when the trees are cut, the fishes and marine invertebrates disappear when corals die. However, the difference is that the coral framework is solid, and lasts much longer than tree trunks, which are decomposed by termites within a few years in the tropics, and in decades by fungi in cold forests. All the water in coral reefs is filtered by sponges several times a day (Reiswig, 1971a; 1971b; 1972; 1974), maintaining the clear water that the corals need to maintain the productivity of the internal symbiotic algae (Goreau et al., 1979). In temperate zone estuaries, oyster reefs, although much smaller than coral reefs, play a crucial role in maintaining water clarity through filtering suspended detritus from the water for food. Chesapeake Bay water used to be completely filtered by oysters in a few days, but since oyster banks have been destroyed by over-harvesting and exotic diseases, they can only filter the water once every 11 months. This has greatly increased the turbidity, and since the water is no longer clear to the bottom, the increased

suspended mud has wiped the food chains depending on the light-driven production of algae on the bottom (US EPA, 2000). Oyster reefs used to fill estuaries in most parts of the world, but they have been virtually wiped out by over-harvesting, in most places so completely that no vestige remains except for archaeological deposits of dead shells along the shore banks. Oyster and clam production was once so vast that the coastlines of Florida were completely rimmed by 15 foot high shell middens over a hundred years ago, the dinner discards of paleo-indians (Bartram, 1794). No trace of even these remain, since they were bulldozed for roadbeds and railway beds. The impacts of humans on coral reefs are in many ways even greater. The world's coral reefs have already been largely destroyed by pollution, disease, and global warming, for example most corals in the Indian Ocean died of heat stroke in 1998, and in the South Pacific in 2002. While the massive limestone frameworks might be thought to be permanent, this is far from the case because they are the result of a dynamic balance between growth and erosion (Goreau et al., 1979). When coral growth stops, the dead reef rock becomes riddled with holes by a host of burrowing clams, worms, sponges, algae, and fungi, until it eventually collapses under wave stress. When organic pollution from the coast is high, boring sponges greatly increase their rate of excavation of corals and coral rock, speeding its demise (Rose and Risk, 1985). Because coral reefs are the major form of coastal protection from erosion in the tropics, virtually all tropical beaches and low lying coastlines will face greatly increased erosion after the reef goes. At the same time these regions face crippling losses to fisheries and tourism from loss of reef habitats and sand supply to beaches.

FALLACIES OF NATURAL RESTORATION

We have taken a process-oriented approach to the mechanisms by which humans have altered, and in all cases, degraded, marine ecosystems, rather than a case approach, for three reasons. Firstly, most individual cases of human caused damage to marine ecosystems have not been identified or understood, so a summary of known cases vastly understates the true damage. Secondly these mechanisms are so pervasive and widespread that they are occurring globally, and their damage is constantly mounting. Thirdly an understanding of the processes is essential to demonstrate the spurious fallacy of "natural restoration", that marine ecosystems are so "resilient" that they can restore themselves for free and bounce right back to their original conditions (Grigg, 1992; Wilkinson and Buddemeier, 1994; McClanahan, Polunin and Done, 2002). The concept of resilience of marine ecosystems used to work when stresses were extremely local in time and space, such as following the impact of a hurricane or a ship grounding, and damaged habitat could quickly be re-colonized from surrounding untouched areas. However, the stresses now operating are global in scale so there are no spatial refuges, and constantly intensifying, so there is no temporal release from stress to allow recovery. If every coral reef in the world was a strictly protected area, and if every fisherman was prevented from fishing, unlikely as these options are, coral reef fisheries could still not recover. Many or most reef habitats are already so badly degraded that they cannot regain the carrying capacity for economically valued species that they formerly had. Therefore, while abatement of stresses is essential, natural restoration processes are now inadequate and active restoration of the vast damaged areas is of utmost urgency for ecosystem value to be maintained. In the following section we briefly discuss the options for abatement, followed by discussion of active restoration of damage to structural ecosystems.

POSSIBILITIES FOR MARINE ECOSYSTEM RESTORATION

There are two basic approaches to marine ecosystem restoration, which we refer to here as negative or reduction approaches and positive or enhancement approaches. Negative approaches involve reducing or halting the negative impacts that are degrading ecosystems, and hoping that habitats will recover by themselves, while positive approaches involve direct restoration of damaged habitats by identifying, and supplying, the factors that limit growth and diversity.

Negative or reduction strategies may not have the desired impacts for many reasons. Typically, they tend to be too little too late: the stress reductions may be far too small to significantly reduce the impact, serving only for symbolic publicity purposes rather than being effective problem solving strategies, or the cumulative damage may be so large that it is irreversible. Once the top predators or structure-forming components of the ecosystem are extinct, their recovery is impossible. There are many reasons why policymakers are unwilling to mandate reduction strategies that are sufficient in magnitude. These would be so far reaching and affect so many major components of the economy (energy, industry, food, land, and waste management) that short sighted politicians inevitably regard the political costs of environmental restoration unacceptable. Furthermore, since all these impacts are acting simultaneously and often synergistically, all need to be tackled simultaneously, not one at a time. These reductive measures are discussed below in terms of the impact processes discussed in earlier sections.

Positive or enhancement strategies are so novel that some historical background is essential. This is provided in the following section, followed by an explanation of a novel new technology for structural marine ecosystem restoration, a description of results to date, and an outline of its future potential.

1) Top-down biological impacts. The solution is well known: to reduce fishing effort. Reducing over-fishing of top predators is difficult because of the vast subsidies that keep industrial fishing fleets combing the oceans for the last under-exploited fisheries, and the continual adoption of technologies that become ever more indiscriminate and effective. The richest countries like the European Union, the United States, Japan are the most damaging, and 90% of the top predatory fish are now gone (Myers and Worm, 2003). The only truly sustainable fishing technique is line fishing, because if the fish is not hungry it will ignore the bait. Modern methods locate and catch all fish, whether or not the fish would chose to bite. It is very unlikely that technology that catches more fish with less effort will be voluntarily dropped. The Maldives has the world's highest fish consumption, but only pelagic tuna is eaten, not reef fish, and these are caught using hand cast lines. The Maldivians have sustainably preserved their tuna stocks using these methods for thousands of years, but now the stocks are being depleted because the fish schools are being targeted outside Maldivian waters by industrial fishing countries using long lines and drift nets. The Turks and Caicos Islands are probably the only part of the Caribbean region with increasing stocks of lobsters and conchs, because collection is only allowed by free diving and hand collecting, and spearguns are banned. One side of each island is a strict no fishing zone, and hook and line fishing only is allowed on the other side. Hand cast nets may only be used in shallow inshore waters to catch bait fish. Fishermen defend the system because they know they can catch a big fish, conch, or lobster, any time they want. For over 300 years the people lived from the sea on barren desert islands, and they know that the modern tourist and financial services economy could collapse suddenly, and if they don't protect their resources they will starve. In contrast, the Indonesian and Philippine fisheries, the richest in variety in the world, have been virtually destroyed by bomb and poison fishing. Although these methods are illegal, they are widely admired by fishermen as a smart way to catch a lot of fish quickly and easily, even though the coral reef habitat and thereby the future fisheries are permanently destroyed. Increasing poverty means that most fishermen are former farmers who have been starved off the land, with no historical connection with fishing and no memory of how rich fish stocks were in the recent past. Reduction of fishing effort to allow fisheries to recover seems very unlikely, as more fishermen fish more often to catch ever less fish. No take zones, while they can be very effective locally, are still too few, too small, and too inadequately protected to have more than very local effects. Furthermore, the carrying capacity of these habitats is becoming so degraded that the fisheries are unable to recover significantly even in the absence of fishing. Restocking of larvae and juveniles of desired species from nurseries has been attempted for an

increasing number of species, including turtles, conch, giant clams, and many species of fishes. Unfortunately, there is little evidence yet that increases in their populations have actually resulted from these efforts, and it is thought that hatcheries are simply feeding the predators of juveniles.

2) Bottom-up biological impacts. Introduction of new species and pathogens by ship ballast water is having ever more severe impacts (Carlton, 1999). The only solution, to sterilize the ballast water itself, is likely to be unacceptably costly to shipping, and lack of compliance is undetectable since dumping is readily done out of sight of (non-existent) inspectors. There is no known reduction strategy to new diseases, as each pathogen appears to have its own pattern of distribution and since with few exceptions, almost all have proven to be regional or worldwide in spread by the time the symptoms were recognized, making identification of the sources impossible. Most pathogens have not yet been identified, and the mechanisms of pathogenicity are almost entirely unknown (Richardson, 1998). How, why, and where these organisms acquired their recent ability to spread is also unknown, but it seems likely that increasing use of mutagens, carcinogens, toxins, and hormone disrupters on land has triggered the evolution of new forms of virulence and adaptations to attack new hosts. Because the causes are unknown, no practical strategy for combating them can be proposed yet. Filling the oceans with antibiotics is impossibly costly, and would anyway cause unexpected side effects and the evolution of resistance, just as it has in terrestrial ecosystems, and perhaps worse because of the wider dissemination provided by ocean currents.

3) Chemical impacts. Virtually every chemical used on land is found in the ocean, and their chronic low-level effects are unknown in almost all cases. Removing their inputs in almost every case requires control of chemicals in terrestrial ecosystems that has proven practically impossible. Only a few of the most extremely hazardous chemicals are banned in the richest countries, but production continues as their use shifts to poor countries without restrictions on their use (UNEP, 2000). Furthermore, new chemicals are being produced and applied far faster than they can be tested, and tests focus on the effects on humans or rats, not on marine organisms. The quantities of nutrients entering the oceans from sewage and agricultural fertilizers and wastes are steadily increasing. Not even the richest countries treat all human sewage to tertiary level, and lower levels of treatment do not remove the nutrients that cause eutrophication. Agricultural wastes are not treated at all, although each cattle produces as much sewage as 15 people. Even when point sources are treated, the non-point sources of nutrients can soon overwhelm the system. An example is Kaneohe Bay in Hawaii, which was "cleaned up" by diverting sewage that entered at the shoreline into a long and deep pipeline. This resulted in partial recovery of a reef that had been overgrown

with algae (note that this was really transferring the problem from being focused on the coastline to remoter areas where it was not visible, not real "cleaning up"). Algae are once again smothering Kaneohe Bay reefs, as the nutrients from road runoff, golf courses, and lawn fertilizers have steadily built up. In no ecosystem is the need to absorb all nutrient inputs before they reach the sea more important than in coral reefs, because these are the most nutrient-sensitive of all ecosystems, going eutrophic at nutrient levels that would be oligotrophic in any other ecosystem (Goreau, 2003). Even though the nutrients killing the reef represent a loss of nutrients from terrestrial ecosystems that is a waste that must be made up with expensive fertilizers, the costs of comprehensive treatment of all nutrient inputs is regarded as prohibitive by policy makers. No politician ever ran for office promising to treat everyone's sewage, and they are unlikely to do so unless an educated public demands solution of their long term environmental, health, and education needs from politicians as the price for their votes! What sewage treatment is proposed is largely cosmetic, including hotels and vacation villas along the shorelines, but rarely including villages in watershed interiors whose wastes drain into rivers, so that not enough treatment takes place to protect coral reefs or even less sensitive marine habitats. Nutrients have a short lifetime in the ocean before they are absorbed by algae, so reductions in inputs have a rapid ecological effect, and algae soon die back if inputs are reduced (Goreau, 2003). In contrast, because of the long lifetime of carbon dioxide in the atmosphere, stopping all use of fossil fuels today would still result in increasing acidification of the ocean for centuries in the future (Caldeira and Wickett, 2003).

4) Physical impacts. The critical physical impacts to marine ecosystems are the direct and indirect impacts of global warming, which alters global patterns of temperature, evaporation, rainfall, salinity, winds, surface currents, upwelling, ocean turnover, and storms. These are all caused by global energy use patterns, the dependence on carbon based fuels like oil, coal, and natural gas and Portland cement production which contributes significant amounts of carbon dioxide to the atmosphere. Energy efficiency improvements, although desirable in themselves, are merely cosmetic in terms of global greenhouse gas emissions that are increasing due to growing populations and per-capita energy consumption. Coral reefs in particular are on the edge of extinction from these changes, and have only a few years left (Goreau and Hayes, this volume). Even if all use of carbon based fuels and Portland cement production ended overnight, reefs would still be doomed, because greenhouse gases already in the atmosphere will last for centuries, and will cause a large and irreversible future warming (Goreau, 1990). There is at present little sign of serious efforts to replace energy that produces greenhouse gases with solar or tidal energy, the two sustainable energy sources that have the global capacity to replace fossil fuels. Other forms of sustainable

energy, such as wind, geothermal, or hydroelectric, although excellent in quality, do not have the quantitative capacity to replace fossil fuels. Politicians in all countries, both rich and poor, get their pocket money and energy policies from the energy companies that are the largest, richest, and most influential of their industries. There is little likelihood of these short-sighted and damaging energy sources being replaced until long after reefs are dead and whole countries submerged beneath the waves. Thus the degradation of marine ecosystems and fisheries can only be expected to worsen.

5) Structural impacts. Abating the negative stresses of coral reef and oyster reef destruction by protecting all remaining reefs will have little impact because these are already almost entirely gone or so severely degraded as to be non-functional, and are largely incapable of natural restoration due to global warming and pollution. Traditional conservation strategies therefore can not restore lost ecosystem services and fisheries, all they can hope to do is to preserve a handful of token individuals in parks and zoos, not to replace their natural functions. Surprisingly however, these are the only ecosystems capable of being actively restored despite deteriorating conditions.

CORAL REEFS IN DANGER

Coral reefs are vanishing throughout the world because they are the most sensitive of all marine ecosystems to all human caused environmental alterations. These include direct physical damage and over-harvesting, the effects of changing water quality including increasing temperature, nutrients, pollution, and sediments in coastal waters, or the spread of new diseases. Over 100 countries could lose their major source of marine biodiversity, beach sand supplies, tourism, fisheries, and coastal protection in the next few years if current trends continue, with severe but incalculably high economic losses (Goreau and Hayes, this volume).

The great sensitivity of corals to deteriorating environment has long been known from field and experimental observations by coral specialists (Goreau et al., 1979). However this knowledge was ignored for decades by those promoting theoretical paradigms that coral reef ecosystems are "robust" or "resilient", leading to claims that coral reefs can bounce right back from any stress (Grigg, 1992; Wilkinson and Buddemeier, 1994; McClanahan, Polunin, and Done, 2002).

This notion is based on confusion between the effects of short-term local stresses and long-term global stresses. Coral reefs that have been damaged by hurricanes, storms, shipwrecks, or attacks by coral-eating predators like crown of thorns starfish, are subjected to stresses that normally last no more than a few days and affect areas no more than tens of miles across. They can recover in a decade or so if the surrounding areas are untouched and can provide new coral recruits.

In contrast, threats from globally rising temperatures, nutrients, chemicals, sediments, and pathogens are found practically everywhere, and their intensity is constantly increasing. Corals are in no way resilient to such stresses, and the conceptual confusion caused by claiming that resilience to small-scale short-term stresses confers resistance to continually increasing global stresses has effectively baffled policymakers about the effects of human activities on coral reefs. This has led them to assume that coral reef deterioration was a passing phase caused by natural cycles and would go away by itself, with the reefs recovering all by themselves. These claims have been promoted for so long, and so widely disseminated, that they succeeded in preventing action being taken in time to abate the stresses causing globally increasing coral mortality. This could have been avoided had policymakers listened to those most experienced with large-scale long-term coral ecology when it still would have made a difference. Instead they have focused on threats that are locally important but globally minor (anchor damage, tourists, ship wrecks), or those that are so remote in the future that they will only become important in centuries, like carbon dioxide induced ocean acidification (Caldeira and Wickett, 2003), long after corals have died from much more immediate causes.

RESTORATION IS CRUCIAL

Coral reef degradation has become so severe and widespread that hardly an area is now untouched (Goreau and Hayes, 1994; Goreau et al., 2000; Goreau and Hayes, this volume). Although all of those few areas of reef that are left in good condition should be strictly protected, it is clear that a conservation strategy based on marine protected areas alone can no longer serve to maintain biodiversity and fisheries. Surrounding areas are too severely degraded to allow recovery of corals, fish, and invertebrates to former levels because the habitat quality is so badly degraded that reefs have lost most of their carrying capacity for these species. Even if every reef was strictly protected and all fishermen were eliminated today, the fisheries would still not be able to recover to former levels. There is no doubt that over-fishing has been disastrous almost everywhere (Pauly et al.,1998; 2000), but far too little attention has been paid to habitat degradation. These effects have been ignored, even though they are at least as severe. Only in the absence of habitat decline marine protected areas and "no-take zones", if large enough, can help restore fisheries. But they will fail if the protected habitat no longer has the quality needed to maintain populations large enough to restock surrounding waters.

Large-scale habitat restoration of degraded areas is now the only hope for recovery of the coastal fisheries, biodiversity, sand supplies, and shore protection that only large healthy reefs can provide. Unless the vast wastelands of degraded reefs are restored, all tropical coastal countries will soon face crippling economic losses. Unfortunately, at this time there is no serious funding for large-scale coral reef restoration. Yet, money continues to be spent monitoring dead and dying reefs "to see if there is a problem" and establishing marine protected areas, in which the corals are dying from increasing temperature, excessive nutrients, and diseases. Funding agencies have their priorities backwards because they have been advised by "experts" who have either not seen the problems or do not understand them. The more money is spent on marine protected areas, the more the corals in them are seen to be dead or dying because they cannot be protected against the major causes of coral mortality in them: from global warming, emerging diseases, land-based sources of nutrients, sediments, and pollution. Current conservation strategies practiced by governments, international funding agencies, and large environmental organizations have in almost all cases failed tragically to protect and conserve corals, and diverted attention and funding from the critically urgent need to restore damaged reefs.

RESTORATION TECHNIQUES

19TH AND 20TH CENTURY CORAL REEF RESTORATION

Almost all corals can survive some degree of breakage and fragmentation, and recover to make new colonies, if they are fixed thoroughly in place before their thin and fragile tissues are abraded and buried by rolling on rocks, sand, or mud. In the past such fragmentation took place only by wave action. Now the causes, and effects, of coral breakage have been greatly expanded by anthropogenic vectors such as fishing lines and nets, garbage disposed in the sea, divers and swimmers, dredging, bomb fishing, ship groundings, anchors, submarine cables, oil rigs, and erosion caused by deforestation on land.

Charles Darwin, although he never went into the water, was aware of observations in the early 1800s that detached corals were quickly killed if they were left to roll around in the reef, but survived and grew if they were fixed in place with wooden stakes (Darwin, 1842). We refer to this as 19th century reef restoration technology.

In the following century the major innovation was that cements and glues were used to attach the corals instead of wooden stakes (Hudson et al., 1989; Rinkevich, 1995; 2000; Epstein et al., 2001; Lirman and Miller, 2003). We refer to these innovations as 20th century reef restoration technology. Long known to coral researchers, proper attachment of corals so they cannot move and get damaged continues to be re-"discovered" regularly and applied locally by individuals unfamiliar with its prior use. These approaches work no better than 19th century techniques, and like them, work only in areas where the water quality is excellent. One novel method, growing corals hanging from monofilament plastic lines, works well in laboratory tanks and aquaria where water motion is low (Soong and Chen, 2003, but is not effective under the waves and currents in the field.

Both 19th and 20th century reef restoration fail if water quality is inadequate for corals. Human population growth has made inadequate water quality, whether from excessive temperature, nutrients, pollutants, and sediments, the major cause of coral death, far outstripping direct physical damage. Where reefs have been killed from such stresses, coral reefs cannot be restored using the old methods unless the water quality is first restored to healthy conditions for corals. Most efforts at coral restoration have been carried out in areas where humans had directly or indirectly caused deterioration of water quality beyond the adaptive capacity of corals, and so consequently have been failures, if assessed in terms of increase of coral growth and numbers in the long run. However, such projects have normally been declared successes immediately after transplantation, and long term monitoring has not been carried out, which would in almost all cases show heavy subsequent mortality because of poor water quality due to excessive nutrients, sediments, and temperatures (Edwards and Clark, 1998; Clark and Edwards, 1999). A recent "Coral Garden" project to grow coral fragments for the Aquarium trade found that "losses from bleaching were unexpectedly high" (Secretariat for the Pacific Community, 2002) when the corals died after the water got hot.

Proponents of 20th century restoration usually are very quick to proclaim success immediately after transplantation, but rarely do long term follow up. A recent survey of reef restoration projects carried out in US Pacific waters shows that around 89% of them failed to meet their objectives, and only 0.7% of the damaged coral areas were in fact mitigated (Bentivoglio, 2002).

As the whole world has changed, the old strategies are now useless almost everywhere. At the very start of the 21st century, anthropogenic stresses to coral health are rapidly escalating, and coral reef ecosystems are undergoing a mass extinction. The methods of the last centuries are doomed to failure except in rare and shrinking locations of excellent water quality and no warming. With globally deteriorating conditions for corals, the only hope for long-term reef restoration lies with new techniques that redress the fundamental factors limiting coral growth. We refer to these methods as 21st century reef restoration technology. What are needed for 21st century reef restoration are methods that increase coral reef growth rate, health, reproduction, diversity, and ability to resist environmental stress. The only known approach that does so, Biorock™ technology, provides corals with energy to grow faster, to resist environmental stresses that would normally kill them, and to be restored in conditions under which 20th century technology is useless. These goals have been achieved using electrolysis of seawater to create energy gradients that directly accelerate coral growth and increase populations of all coral reef organisms, making intensive farming of coral reef ecosystems possible for the first time (Goreau and Hilbertz, 2002). These methods are also applicable to oyster reefs, and are described below.

21ST CENTURY CORAL AND OYSTER REEF RESTORATION

A major factor limiting the growth of limestone reef building corals and oysters is the large amount of metabolic energy they must spend to grow their skeleton. To do so they must create the right chemical conditions inside their cells that speed up the nucleation and growth of calcium carbonate crystals from seawater. This requires active, metabolically expensive pumping of protons and calcium ions across membranes and within cells in order to create the high pH conditions that are essential. Hobbyists growing corals in aquaria have found that the growth is greatly increased if water pH is raised by addition of calcium hydroxide. Doing so is prohibitive in the ocean due to the vast quantity that would be needed for so large a volume, and the fact that seawater is strongly buffered, resisting changes in pH. Biorock technology solves this limitation by using low voltage direct currents to cause the electrolysis of seawater. This results in precipitation of calcium carbonate and magnesium hydroxide, raising the pH within the precipitate and directly at the surface of the growing calcium carbonate crystals, not in the water (Hilbertz and Goreau, 1996).

The results are spectacular: corals and oysters grow at greatly accelerated rates on growing limestone structures that get stronger with age and are self-repairing as long as the current flows. Because they are getting the high pH they need for free, more metabolic energy is available for growth, reproduction, and for resisting environmental stresses. Corals are able to grow at record rates even under conditions that would normally kill them, and reefs can be restored where poor water quality or high temperatures would otherwise prevent it (Goreau and Hilbertz, 1996; Goreau, Hilbertz and Hakeem, 2000). Corals growing on these structures are very brightly colored and have very dense branching patterns in comparison with controls, and have higher concentrations of symbiotic algae in their tissues, which have higher growth rates than controls (Goreau Cervino and Pollina, in press). In Jamaica corals grew at 3-5 times record rates in areas where all the surrounding corals had been killed by algae overgrowth due to high nutrients (Goreau and Hilbertz, 1996). In the Maldives 50-80% of the corals survived the high temperatures that only 1-5% of the corals on surrounding reefs survived (Goreau, Hilbertz and Hakeem, 2000). These reefs have preserved coral and fish species that have vanished or become very rare in natural reefs (Goreau, Hilbertz, Hakeem and Hameed, 2000). In the Maldives Biorock reefs have effectively absorbed wave energy that they have turned an eroding beach into a growing one (Goreau, Hilbertz, Hakeem and Hameed, 2000). In Indonesia dense schools of fish in Biorock structures have caused fishermen to start building similar structures to increase catches (Goreau and Hilbertz, 2001). Settlement of larval corals can take place at exceptionally high densities, hundreds per square meter, under conditions where poor water quality has prevented all settlement on natural substrates (Goreau and Hilbertz, 1996). Larval and adult fishes are attracted to these structures at exceptional densities, quickly forming schools so dense that one cannot see across the structures. These reefs can be made in any size or shape, and a protective reef can be grown using less electricity than is used in lighting along the shore. They are so visually spectacular that hotels in the Maldives, Indonesia, and Panama have built their advertising around them, because tourists can snorkel and dive and see far more fish and coral than anywhere else. Most seafront hotels in tropical areas have to take tourists hours by boat to see corals and fish, but now it is possible to create these conditions right in front of their beaches, and protecting them from erosion at the same time. As a result these projects have been awarded the Theodore M. Sperry award for pioneers and innovators of the Society for Ecological Restoration, the Maldives Environment Prize, the Indonesian KONAS award for best coastal zone management project, and the SKAL award for best underwater ecotourism project in the world.

HOW THE BIOROCK PROCESS WORKS

The Biorock^{TM} method, also known as the Mineral Accretion Method, Seament, or Seacrete (Hilbertz, 1979; Hilbertz and Goreau, 1996), is the result of electrical currents flowing through seawater with a voltage difference between two conductive terminals. This generates pH gradients as the result of the electrolysis of water. On the cathode, the negatively charged terminal, water is broken down to form hydrogen gas and hydroxyl ions, which raise the pH at the surface. On the anode, the positively charged terminal, water breaks down to form oxygen gas and protons, which lower the pH at the surface. Since electrolysis produces balanced acidic and basic microhabitats, the net effect on ocean chemistry and carbon dioxide is neutral (Hilbertz, 1992).

Because of these pH changes, the cathode becomes coated with minerals that are supersaturated in sea water but do not naturally precipitate, in particular calcium carbonate (limestone) and magnesium hydroxide. The former mineral is hard and durable, and has been used for construction purposes since antiquity (the pyramids, the walls of Jerusalem, and the Parthenon, for example), but magnesium hydroxide, which is similar in appearance, is not suited for construction. However with exposure to seawater it dissolves and is replaced by limestone. In contrast, the anode generates acidic environments in which minerals do not grow, in fact they will dissolve.

The cathode is much larger than the anode, and since the anode acidity is neutralized by the buffering action of sea water within a few millimeters of its surface, it is possible to build vast cathode structures. There is no limit in principle to the size of the structure that can be grown by this method, but of course the size is directly proportional to the current needed. Similar results to those obtained by electrolysis could be obtained by raising the pH of the entire ocean with base, but this would take a vast amount of chemicals. In contrast electrolysis raises the pH only at the surface of the growing minerals, rather than in the external fluid, so Biorock technology is much more efficient, and of proven utility.

Corals, clams, oysters, mussels, barnacles, sand-producing coralline algae, and other organisms that make their shells and skeletons from limestone, find cathodes ideal for exceptionally rapid growth. It is metabolically very expensive to grow limestone skeletons because the organism must spend a lot of energy to create high pH conditions inside their tissue's skeleton growing cells, and pump in calcium ions from seawater in order to make limestone crystals precipitate and grow from seawater. In contrast, the Biorock™ process provides these conditions for free to organisms growing on or near the cathode. As a result they are healthier since they can save the energy they formerly consumed pumping protons and calcium ions for calcification, and use it instead to increase tissue growth, reproduction rates, and their ability to resist environmental stresses.

RESULTS

Restoration projects using the Biorock method have been successful in more than a dozen countries. For example:

Corals were grown at sites in Jamaica where all the corals in the nearby reef had been killed by algae overgrowth caused by high nutrients, and where no new coral settlement was taking place. These had coral growth rates up to three to five times the record rates for many species, and settlement of hundreds of corals per square meter (Goreau and Hilbertz, 1996).

Extremely sensitive staghorn and elkhorn corals have shown excellent growth at sites in Panama and Mexico where these species had disappeared (Goreau et al., 2001)

Corals grown in sites in Thailand with extremely high sediments show excellent growth.

Corals grown in the Maldives on Biorock structures had 50-80% survival from the severe high temperature bleaching events that killed 95-99% of the corals on surrounding reefs (Goreau, Hilbertz, Hakeem and Hameed, 2000). Survival of Biorock corals was from 16 to 50 times greater than surrounding habitats (Figure 1). A large population of corals was being grown in the same habitat using conventional cementing methods and being used as controls to compare growth rates. All the corals growing using 20th century technology died. Populations of coral species and fish species were maintained on Biorock reefs that had virtually

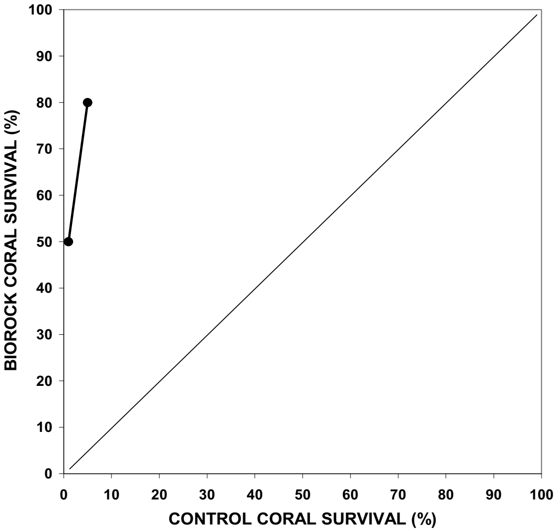

Figure 1 Survival of corals on Biorock reefs were 15 to 50 times higher than on adjacent coral reefs after the 1998 Maldives Coral Reef Bleaching Event. Observations are shown by graph connecting data points. The diagonal line shows what would be expected if there were equal survival of corals on Biorock compared to the surrounding reef.

vanished from surrounding reefs. Because Biorock structures have up to nearly 100% live coral cover, while no surviving natural reef has more than 5-10%, they are intense tourism attractions. Participants in this project have been awarded the Theodore M. Sperry award, the top prize of the Society for Ecological Restoration, and the Maldives Environment Award.

Corals grown on Biorock structures in Indonesia show exceptionally rapid growth (Figure 2), and host extremely high, and steadily increasing, density and diveristy of fishes, especially juvenile fishes, quickly building up much higher fish densities than surrounding reefs (Goreau and Hilbertz, 2001). Because of the spectacular increase in fishes, these projects have been awarded the Indonesian KONAS National Coastal Zone Management Award, the Skal Global Ecotourism Award., and been nominated for major awards by the United Nations Environment Program and the World Tourism Organization by the Indonesian Government.

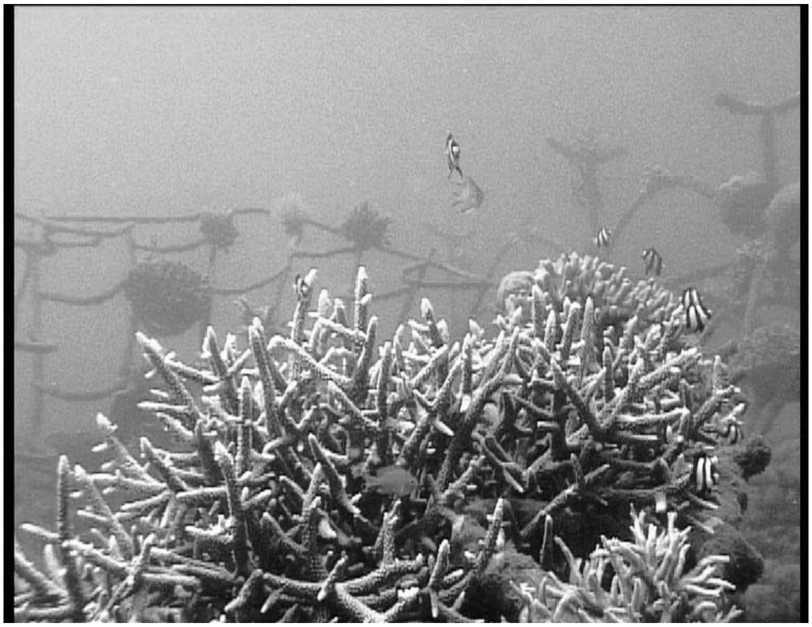

Figure 2 Prolific growth of Biorock corals in Indonesia

Biorock structures in the Maldives have turned an eroding beach into a growing one as the mass of the corals and Biorock material increase, providing more resistance to waves, slowing them down, and causing sediments to be deposited. Up to 15 meters of beach have grown in just a few years, with the effect getting steadily larger as the Biorock reef gains mass and as corals grow on it. (Goreau, Hilbertz and Azeez Hakeem, 2004)

IMPLICATIONS FOR COASTAL ZONE MANAGEMENT

Biorock structures can be built in any shape or size. The shape of the structure determines which species do best in and on it. We have built structures to maximize coral growth, coral settlement, fish, lobsters, oysters, etc. by paying attention to provide the specific shapes that these species prefer. Our results show that it is possible to quickly regenerate superior habitat and greatly increase the populations of corals, fish, and invertebrates, maintaining and restoring these rich coral reef ecosystems under conditions that they could not otherwise tolerate. With increasing global climate change, this will probably be the only way to maintain these ecosystems in the future and preserve species from extinction caused by global change.

Biorock reefs are spectacular attractions for tourism, providing prime diving and snorkeling in areas where they have been lost. At the same time they protect the coastline from erosion caused by global sea level rise. Most resort hotels around the world have lost the reefs in front of their beaches and must usually send their guests hours by boat to go snorkeling. These hotels could all be restoring coastal habitats and preserving species by building coral arks in front of their beaches.

Because it is easy to build structures that selectively increase populations of economically valuable aquarium fish, food fish, lobsters, oysters, etc., Biorock structures can allow fishermen to turn from hunters into farmers by growing their own reefs and harvesting the fish and shellfish. Unlike traditional forms of mariculture, which grow dense mono-specific populations that require large and expensive food and chemical inputs (Naylor et al., 1998; 2000; 2001; Powell, 2003), spreading coastal eutrophication and diseases that cause coastal ecosystem health to decline, the Biorock method is based on improving the quality of the habitat and its carrying capacity for economically valuable species. Although the focus is primarily on coral reef ecosystems, the Biorock method also works in colder waters, where it causes prolific growth of oyster reefs, and can aid in restoring these over-harvested habitats and improving water quality through their filtering action.

Global environmental degradation cannot be treated by hoping that nature will heal itself, because ecosystems are too sick to recover unless their health is directly improved. New technology, like Biorock, will be needed on a vast scale in the coming years if ecological and economic disaster is to be avoided.

COSTS/BENEFIT ANALYSIS OF REEF RESTORATION

There is an infinite range of shapes, sizes, and materials that can be used. Consequently costs vary considerably, depending on how much materials are used, what they cost locally, how strong the structure needs to be to withstand local wave energy until it strengthens itself through solid mineral growth, how far it is from power sources and how much cable is needed, the kind of power source used, etc. Below are some typical costs per square meter of ocean floor, for the materials and equipment of recent projects. These do not include travel and time.

Typical unit costs (US$ per square meter of covered sea floor) of larger and recent BIOROCK installations are:

1.	Linear coral stand stimulation,	US$ 1.60 - 2.80
2.	Coral rubble stabilization and coral stimulation,	US$ 3.20 - 4.00
3.	Coral arks and fish/mollusk habitat up to 0.5 m elevation above seafloor	US$ 6 - 9
4.	Coral arks and fish/mollusk habitat up to 1.0 m elevation above seafloor	US$ 10 - 15
5.	Coral arks and fish/mollusk habitat up to 2.0 m elevation above seafloor	US$ 13 - 20
6.	Coral ark and fish/mollusk habitats with elevations 2 - 5 m above seafloor	US$ 18 - 42
7.	Arks with elevations up to 15	US$ 60 - 110

Larger projects discount unit costs substantially.

Maintenance costs also depend on the size, but one can grow a reef the length of a beach using less electricity than hotel beach or dock lighting. Typical structures built to date use up to 200 Watts, as much as a single bright light bulb. Local electricity costs vary substantially from place to place.

Biorock reefs can be compared to alternative methods of reef restoration that involve just cementing fragments in place without structures, as about \$1.3 to \$4 per square meter (Cesar, 2000). Note that these costs are about the same as the lowest cost Biorock structures, but do not provide enhanced growth or resistance to pollution, sedimentation, and temperature stress, and thus have a much lower benefit per unit cost in the long run. In comparison, concrete substrate reef restoration cost estimates range from \$40 for armored chain link fence structures to \$160 for concrete structures per square meter in the Maldives, and from \$550 to over \$10,000 per square meter in Florida (Cesar, 2000). When compared to concrete structures, Biorock structures are far cheaper by orders of magnitude, while providing vastly greater benefits in terms of coral growth, survival, and fisheries habitat, as well as shore protection.

These costs can now be compared to the ecosystem benefits derived from coral reefs. Most studies of the economics of reefs have used valuations of reefs based on court legal judgements to punitively fine owners of ships that damaged reefs, questionnaires that ask tourists how much they would be willing to pay to protect reefs, or estimates of what it costs tourists to get to reefs (Cesar, 2000). These valuations are basically intellectual constructs that bear little or no relationship to the actual benefits of the ecosystem services provided by reefs, and so have no scientific basis. While most benefits of coral reefs can not possibly be quantified in monetary terms, such as the value of biodiversity, biogeochemical cycling services, and esthetic beauty, three of them are amenable to direct economic valuation: fisheries, tourism, and shore protection. The best study of the first two was done by Chan (1992), who evaluated the income that around 40 coral reef countries earned based on figures tabulated for fisheries exports by the Food and Agriculture Organization and for tourism earnings by the World Tourism Organization. Since seafood exports are often dominated by pelagic fisheries rather than reef fisheries because most reef fish are consumed locally without being tabulated as external exports, a wide range of parameters were considered to bracket the ranges of variation of reef fish catches to export figures. Similarly, because a large fraction of tourism earnings are re-exported to purchase goods and services for hotels, and as profits by foreign owners, especially in smaller economies, a range of parameters were also considered to bracket the countries' retention of tourism earnings. A wide range of reef valuations were found, varying from country to country according to the amount of reef, its richness, the size of its tourism and fisheries, the above parameters, etc. When considered as earnings per kilometer of reefs, the values for fisheries and for tourism typically ranged from several thousand dollars to several million dollars per kilometer of reef per year.

The value of the coastal protection services of coral reefs must be evaluated by a different method, since direct earnings are not provided by coastal protection, nor are they paid for in any direct way. Countries only can appreciate the value of their reefs when they lose them, and then they have to import fish because these can't be caught anymore, when jobs and earnings from tourism vanish, and when beaches disappear. The value of the first two is evaluated in Chan's 1992 study. The economic value of coral reefs for shore protection is routinely neglected, but it is likely to be one of the largest global costs of climate change. A study of the costs of flooding and coastal erosion in Great Britain suggest that they will rise 10 fold in the next 80 years because of global climate change (Evans et al., 2004). While global warming is already killing coral reefs, global sea level rise, currently around 2-3 millimeters per year (Munk, 2003), is likely to rise sharply in the future in all coastlines. As ice shelves collapse from global warming, the glaciers they have dammed are starting to surge (De Angelis and Skvarca, 2003). Global warming is virtually certain to pass the no return threshold for melting the Greenland Ice cap in this century, which would result in about 7 meters of sea level rise over the following thousand years (Gregory, Huybrechts and Raper, 2004). During the end of the last ice age, sea levels may have risen as much as 4 cm per year (Lambeck et al., 2002; Weaver et al., 2003), much faster than the ability of even healthy reefs to keep up with. Although Biorock shore protection structures are normally grown at the rate of 1-3 cm per year, around 10 times the current rate of sea level rise, they can be grown much faster, capable of keeping pace with all but catastrophic ice-cap surges. When additive Biorock reef construction is considered, the technology performs extremely well even in catastrophic scenarios.

The value of reefs for coastal protection is best evaluated by the cost of replacing the protection coral reefs provide, by building breakwaters to prevent houses, hotels, ports, airports, and roads from falling into the sea (note that if we were to include the value of the land assets lost to erosion and wave damage the cost would be much higher). The typical cost worldwide for constructing seawalls for coastal protection, whether concrete or granite boulders, is around $15,000 per kilometer (Cambers, 1998), or around $15 million per kilometer. The total value of reefs for shore protection, tourism, and fisheries can therefore range from a minimum value of around a thousand dollars per kilometer where the adjacent coast is undeveloped up to a maximum of around $20 million per kilometer. This replacement value for shore protection services is rarely included in reef valuations. The cost of building a Biorock reef to protect the shore line will depend on the height needed, but if we assume a structure 1-2 meters high, 5 meters wide, and 1 kilometer long, each kilometer of shoreline can be protected for about $50,000 to $100,000. This is only around 0.3 to 0.6% of the cost of a conventional sea wall, which provides no tourism or fisheries benefits. It is clear that the benefits of restoration greatly outweigh the costs for all coastal reefs wherever there is tourism or populated shorelines. Only in remote areas where there is only artisanal fishing, no tourism, and no local land or infrastructure to protect, and where loss of the coastline to global sea level rise incurs no financial loss, the costs of restoration may outweigh the benefits.

If we take the global area of reefs at about 300,000 square kilometers (UNEP, 2001), and if we take the geometric mean costs of reef restoration at around $10 per square meter, recognizing that it can range up to 10 times lower or ten times higher depending on the nature of the restoration, this translates into a typical restoration cost of $10 million dollars per square kilometer, or around $3 trillion dollars to restore all of the world's coral reefs. If we assume that only one tenth of the world's reefs are of direct human concern and need to be saved, the restoration cost would be around $300 billion. This is less than the estimated global coral reef annual economic benefits of around $375 billion dollars per year (Cesar, 2000) (or $1.25 million per square kilometer on the average, but as noted above, these underestimate the shore protection replacement values, and most of the value comes from the smaller portion that is intensively utilized). Restoration would of course provide these benefits year after year, and so would very quickly pay for itself. Not all reefs are equally valuable, and while the most valuable are clearly worth saving, even the low value reefs can be restored using the simplest technology costing around $2 per square meter. If we only wish to engage in mass reconstruction and protection of the ecosystem functions of coral reefs along 100,000 kilometers of tropical coastline, the cost would be around $5-10 billion dollars, a tiny fraction of what one country alone spends on weapons of mass destruction every year. Of course these estimates are rough, but no matter how one varies the conditions, there can be no question that the benefits vastly exceed the costs of restoration. Far from being an economic extravagance, reef restoration is therefore an economic bargain that coral reef countries can't afford to miss. It will be essential for over 100 countries to sustain and manage their tourism, fisheries, and shore protection in a world that with ever accelerating speed is changing from natural self organization and feedback regulation into chaotic states hopelessly out of control. Without thorough and effective human stewardship, the losses will be immense and not recoverable.

SUSTAINABLE SEASCAPE ARCHITECTURE FOR MARINE CONSERVATION, RESTORATION, MARICULTURE, AND SHORE PROTECTION

Biorock reefs can be built in any size or shape at any depth, including forms that have far more interior habitat space than natural reefs, thereby greatly increasing the carrying capacity for corals, oysters, fishes, lobsters, and a huge variety of other marine organisms. No organism has been observed to avoid them, indeed they seem to flock to them. Because of corals and oysters can be grown under conditions that would normally be fatal, reefs can be restored even in areas where global warming, sedimentation, and pollution have wiped out natural reefs and prevented any natural restoration. As global conditions deteriorate, this will prove to become be the only way to preserve reef species from extinction caused by global change, and to maintain ecosystem services including tourism, shore protection, and fisheries.

Structures can be built in shapes and sizes that selectively enhance populations of economically important species that can be sustainably managed at much higher densities, including fish, clams, mussels, and lobsters. These approaches are in many ways diametrically opposed to conventional mariculture methods, which grow mono-specific populations that are often wiped out by parasites and diseases overnight (Naylor et al., 2000; 2001). By using high concentrations of added food, pesticides, and antibiotics, they pollute the waters and kill surrounding ecosystems through eutrophication (Naylor, 1998). In contrast, Biorock technology permits naturally diverse ecosystems to be grown that have much higher carrying capacity, improving the surrounding habitats. Breakwaters can be built that not only protect beaches from wave erosion, but also produce sand by increasing the growth of sand-producing organisms whose limestone skeletons make up tropical white sand beaches. These shore protection structures can be built for a fraction of the cost of conventional stone or reinforced concrete seawalls, which deteriorate with age while Biorock structures get constantly stronger and are self-repairing in case damage occurs (Hilbertz, 1979).

In addition this technology offers many unique further potentials. Islands can be grown in the ocean (Hilbertz, 1975; 1976), and mining of coral reef rock and sand can be replaced by material that can be grown directly from the ocean, in situ or on land, preventing further destruction of reefs. Limestone structures can be grown in any size or shape, for example modular wall elements, roof components, or building blocks, which are cheaper to produce than those using Portland cement. Electrolytic form generators moving three-dimensionally in seawater can build vast coral arks and "weave" coastal defense structures (Hilbertz, 1975; 1976). Furthermore, industrial production of building materials using direct or indirect solar energy can also trap the hydrogen that is a byproduct of the Biorock process, providing sustainable and inexhaustible energy resources that could turn oceanic islands into net energy exporters instead of energy importers (Hilbertz, 1992). Floating and roaming coral and oyster arks can position themselves where conditions are optimal, where spawning is desired, or run from HotSpots and tropical storm. Powered by solar energy and connected to satellites, these intelligently moving floating islands would be extensions of sedentary arks, exporting coral ecology to be adapted to conditions in the high seas.

The emerging design discipline of "Seascape Architecture" has at its core the missions of conservation and restoration of the marine environment. Like its counterpart, Landscape Architecture, it also focuses on designed ensembles and ecologies of fauna and flora that are self-sustaining with human help, and manageable to increase the production of desirable species instead of weeds, while producing aesthetically and artistically satisfying habitats. While the tools of the Seascape Architect are different, the professional mission embodies the same philosophy and ethical code inspiring the counterpart Landscaper. Focusing primarily on the coastal zone and island ecologies, this unfolding field will play a much needed and vital role in marshalling active stewardship for marine habitats and contribute to a heightened level of conscious awareness that will be more sensitive and conducive to addressing urgent environmental conservation needs while increasing production of valuable resources.

The tools are now in our hands for saving coral reef and oyster reef ecosystems from extinction from over-harvesting, global warming, and pollution, protecting coastlines from global sea level rise, increasing fisheries, and saving beaches and tourism economies. There is of course a real cost, but the sooner large scale investments are made in marine ecosystem restoration the greater the benefits will be and the lower the expenditures needed. There is now no other alternative to effectively reverse global marine degradation that is accelerating out of control except to do nothing.

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