Land-based Sources of Pollution and Impacts on Coral Reefs

Annadel S. Cabanban,[1] Christopher Reich,[2] and Lauretta Burke [3]

Statement of Issue

POLLUTION and sediment from land-based sources is causing widespread degradation of coral reefs. Increased nutrients in coastal waters from agricultural fertilizers and sewage discharge increase algal growth and decrease water clarity. This impedes coral growth and, in some cases causes algae to overgrow corals previously present. In addition, increased sedimentation from changes in land-use (often far upstream) and from coastal development activities can adversely impact coral reefs through smothering of coral, screening out sunlight needed for photosynthesis, scouring of the coral by sand and other transported sediment, and decreasing the survival of juvenile coral due to lack of suitable substrata for colonization.

Flood plume sediments threaten the survival of coral reefs

Photo: Great Barrier Reef Marine Park Authority

Land-based Sources of Pollution and the 9th ICRS

Several mini-symposia at the 9th ICRS included papers on land-based sources of pollution. The presentations on land-based sources of pollution covered a wide spectrum of topics and were global in context. The most popular themes of discussion were the pathways, delivery, and the impacts of pollutants to coral reefs. The presentations were based on research in the coral reefs of East Africa, Caribbean, Southeast Asia, and South Pacific.

State of Knowledge

Potential Pollutants, Sources and Pathways to Coral Reefs

Several pollutants and their sources were identified in the mini-symposium including, sediment to coastal waters from rivers, construction and alteration of land cover nearer the coastline, discharge of human sewage, application of agricultural fertilizers, and heavy metals from mines and industries.

The three major pathways for land-based sources of pollution to coral reefs are ground water, rivers, and sewage out-falls. The mechanisms for groundwater delivery to the reef are (1) tidal pumping, which drives ground water across the rock-water interface as a result of oceanic tidal variations, (2) spring discharge, and (3) diffuse seepage to bays and lagoons. Rivers are the most important pathway for land-based sources of pollution to coral reef environments. Rivers carry a vast amount of sediment, nutrients, and heavy metals. Mangroves and seagrasses filter pollutants and trap sediments. Loss of mangroves and seagrasses from coastal environments

[1] Borneo Marine Research Institute, Universiti Malaysia Sabah, Sabah, Malaysia, Phone: 60-88 438 440 ext. 5590; Fax: (60-88) 435 204; Email: AnnadelC@ums.edu.my. [2] United States Geological Survey, Center for Coastal Geology, 600 Fourth Street South St. Petersburg, Florida 33701; Phone: (727) 803-8747 Ext. 3032; fax: (727) 803-2032; Email: creich@usgs.gov; [3] World Resources Institute, 10 G Street, NE, Suite 800, Washington DC 20002, USA; Phone: 202-729-7600; fax: 202-729-7620; Email: laurettab@wri.org

results in increased delivery of sediments and pollution to coastal environments, including coral reefs. Sewage outfalls deliver either raw or primary-treated wastewater to offshore environments. Table 1 presents a summary of potential impacts from these land-based sources.

Impacts of Land-based Sources of Pollution on Coral Reefs
The impact of land-based sources of pollution on coral reefs depends upon the nature of the pollutant and the location of the reef. Sediment typically has greater impact on fringing reefs than on reefs distant from shore. Sediments tend to settle near the source, though some sediment plumes extend beyond 100 kilometers. Nutrients and other chemical compounds are dispersed farther than sediments.

Sediment reaching a coral reef blocks sunlight, which is required by the zooxanthalae for photosynthesis, thereby affecting the growth of the coral. In severe cases, sedimentation can kill corals outright through smothering. However, an experiment in the Solomon Islands on the impacts of logging in cachments did not conform to predictions: more corals grew near logged catchments versus those further from logged catchments. This suggest that factors other than the proximity to disturbed catchments influence the survival of corals. Furthermore, sediment supply to reefs is a cause for concern as it is a transport mechanism for nutrients and heavy metals as well as other contaminants.

Eutrophication, resulting from domestic and agricultural inputs of dissolved nitrogen, phosphorus, and potassium, have impacts on the coral reef ecosystem. Eutrophication can reduce sunlight and increase growth of algae, in competition with coral. These physical changes can cause changes in the composition and abundance of corals (in terms of coral cover). The species composition and coverage of coral reefs change from branching corals (*Acropora* spp.) to massive corals (*Porites* spp.) on high sewage outfalls, where eutrophication is high. Inputs of nitrogen, phosphorus, and potassium from ground water can result in massive growth of green algae (*Ulva* spp. and *Chaetomorpha* spp.) in a lagoon.

Sea urchin diversity can increase in high nutrient areas. Indeed, the high density of sea urchins in Negril Marine Park in Jamaica was positively correlated with high nitrogen in macroalgae (*Chaetomorpha* spp.) but not coral cover.

Table I. Summary of the impacts of land-based sources of pollution

Pollutant	Impact
Sediments	- settle quickly on nearshore reefs - can smother and kill coral - reduce sunlight for photosynthesis - scour coral, reducing growth - reduce substrata for recruitment of juveniles
Chronic sewage	- localised eutrophication - poor water quality – high bacterial and viral content - Infection of coral mucus - Algal overgrowth
Sewage (at out-fall)	- Decrease in coral cover of *Acropora* spp. (50 percent down to 0 percent) - Change in dominant coral from branching (*Acropora* spp.) to massive (*Porites* spp.)
Dissolved Nitrogen (N) and Phosphorus (P)	- Increase in macroalgae (e.g., *Ulva* spp., *Chaetomorpha* spp.) - Increase (>60 percent) cover of green algae - Decrease in coral cover - Increase in sea urchin density Some other observations (not impacts): - Tall, branching algae use dissolved N, P - Mat-forming algae require high rates of advective current to reduce N, P concentration - Rhizophytic algae have higher N, P than those offshore
Mine spill	- Heavy metals (Cu, Zn) disperse as far as 5 km away, and incorperate in coral skeletons

Bacteria and viruses also have indirect impacts on coral reefs. High concentration of bacteria and viruses have been detected in the water column and in the mucus that corals produce. The pathogenic effect of these organisms on corals and on those feeding on mucus of corals is not well understood.

Chemical pollutants, especially persistent organic pollutants (POPS) can be dispersed far from shore. Heavy metals (zinc, lead, and mercury) can be incorporated in the coral skeleton. These metals have an indelible mark on the skeleton that is visible under ultraviolet light in the laboratory. It is not known at present how this is incorporated into the hard matrix of the coral and whether this affects the growth of corals.

An analysis of threats to coral reefs from human activities concluded that over 35 percent of the coral reefs of Southeast Asia are threatened by pollution and sediment related to land-based activities.

Relevant Actions Being Taken to Address the Issue

Photo: Coastal Resources Center, URI

Polluted water after the prawn harvest, Lampung, Indonesia

Land-based sources of pollution are considered a major threat to the alteration or destruction of coral reefs around the world. The United Nations Environment Programme has developed a Global Plan of Action to address this concern. In the East Asian Seas (including Australia, Brunei, Cambodia, China, Indonesia, Malaysia, Philippines, Singapore, South Korea, Thailand), a review of these impacts was conducted under two activities (Impacts of Watershed Activities on Coastal and Nearshore Ecosystems; Transboundary Diagnostic Study in the South China Sea). The Regional Coordinating Unit for East Asian Seas initiates and coordinates projects to ameliorate, restore, and manage the marine environment in this Region.

In addition, the Land Ocean Interaction in the Coastal Zone (LOICZ) Project estimated wide-spread species impacts from poor land-use practices within the coastal zone. The South East Asian-Basin Project of the SEA-START is developing a model for the movement of water from the watershed to the coastal zone. The Reefs at Risk project of the World Resources Institute modeled the threat of sedimentation (among other threats) on coral reefs in Southeast Asia and is starting a similar risk assessment of the wider Caribbean.

Management and Policy Implications

Overall, it can be stated that as countries increase their populations and development keeps pace, the resultant disturbances to the land will have deleterious effects on coral reef ecosystems. But, in addition to the rates of growth and development, the nature of development implementation can have profound implications for coral reefs. For example, the nature of coastal development (whether mangroves are retained or converted; whether a development is set back sufficiently from the shoreline; whether adequate sewage treatment is installed for a new development) will effect the ultimate impact on coral reef health.

Specific Recommendations for Action

- Good planning and integrated coastal zone management are the most important tools for limiting the impacts to coral reefs associated with coastal development. Sewage and industrial waste disposal practices and land-use practices must be monitored.
- Watershed-based (catchment-based) management for reducing upstream impacts is vital. Information tools for establishing these linkages between upland activities and stresses to coral reefs are important.
- Regional initiatives, such as those of the East Asian Seas Regional Coordinating Unit (of the United Nations Environment Programme), and research on the tolerance level of coral reefs to specific land-based sources of pollution, complemented by the concept of integrated coastal zone management, can help avert the destruction of coral reefs in the world.

Useful References and Resources

This paper is based upon presentations at the 9th International Coral Reef Symposium, Mini-Symposia E5, *Pathways for Land Based Sources of Pollution and Subsequent Impacts on Coral Reef Environments*. Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/.

Rogers, Caroline S., 1990. "Responses of coral reefs and reef organisms to sedimentation." *Marine Ecology Progress Series*, vol. 62:185-202.

Caribbean Environment Programme (CEP) of United Nations Environment Programme (UNEP), 1994. CEP Technical Report No. 32, *Guidelines for Sediment Control Practices in the Insular Caribbean*.

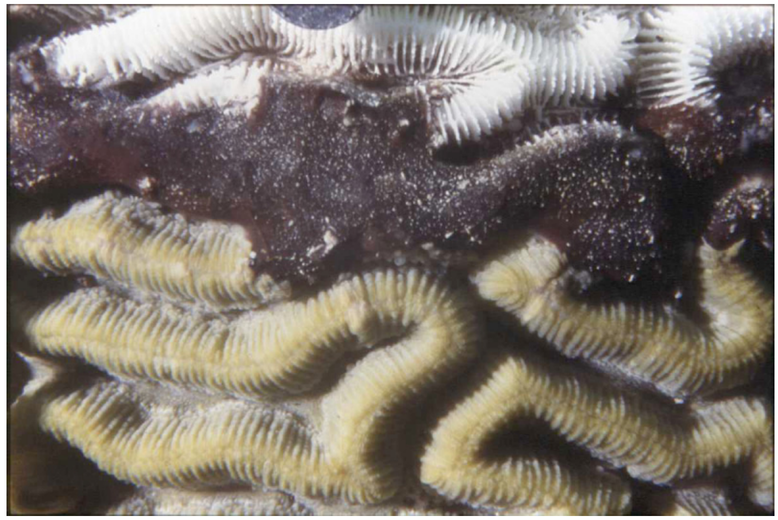
UNEP Caribbean Environment Programme Web site on land-based sources of marine pollution: www.cep.unep.org/issues/lbsp.html

Infectious Diseases Continue to Degrade Coral Reefs

Laurie L. Richardson [1] and Richard B. Aronson [2]

Statement of Issue

THE past three decades have revealed an increasingly serious threat to coral reefs worldwide – lethal coral diseases caused by an assortment of pathogenic micro-organisms. Coral diseases are detrimentally impacting individual coral species, coral populations, and entire reef ecosystems. The current status of knowledge of diseases of corals (and other marine invertebrates), including both knowledge of individual diseases and the effects of diseases on reefs, was explored by researchers representing laboratories in eight countries in a mini-symposium held in conjunction with the 9th ICRS.



Black band disease on *Diploria strigosa*. This disease consists of a microbial consortium of bacteria, which together kill coral tissue by producing a toxic, sulfide rich environment. It is wide-spread throughout the Caribbean and has recently emerged on the Great Barrier Reef

State of Knowledge

Alarming Trends:

Several alarming trends have become apparent. It is now a documented fact that coral diseases have spread to affect reefs in all areas of the world. While the Caribbean continues to be the most severely impacted in terms of the largest number of specific diseases, and the Caribbean region also hosts the most extensive disease outbreaks, for the first time there are reports of severe outbreaks in the Great Barrier Reef, the Philippines, and Hawaii. Up to 3.6 percent of coral colonies (representing 24 species) of the Great Barrier Reef were reported to have black band disease, a potentially lethal coral disease widespread throughout the Caribbean that is caused by pathogenic bacteria. New reports confirm the continued presence of disease on reefs throughout the Indo-Pacific, including the Red Sea. At the time of the 9th ICRS, the first observations of white band disease on acroporid corals around Bali and Komodo were made by delegates to the symposium. This observation is of particular concern since this disease has completely restructured many coral reefs in the Caribbean and is believed to have killed over 90 percent of Caribbean acroporid colonies.

Results of the first, quantitative, large-scale disease-monitoring program, being conducted throughout the Caribbean were presented. This program, unique in that the same monitoring and disease identification protocols are being used at all sites, revealed the presence of coral diseases at all reefs surveyed. The area studied encompassed six geographical throughout the greater Caribbean region. A total of 38 coral species were observed to be affected by at least one disease, and several coral species were susceptible to as many as five specific diseases. Other, smaller-scale monitoring projects are also being conducted, each one of which reported increasing incidence of disease.

Global Database on Coral Disease:

The World Conservation Monitoring Centre (WCMC) has compiled observational data of coral diseases from 150 sites worldwide. This program has a Web site (http://www.unep-wcmc.org/marine/coraldis/) that presents the global distribution of all reported coral diseases. The site incorporates links allowing access to regional coral disease data bases, and to a literature data base that cites each report that formed the basis for the global data set. The latter separates peer-reviewed papers and non-peer reviewed (including anecdotal) reports. While this data set includes information about diseases that have not been

[1] Department of Biological Sciences, Florida International University, Miami, Florida, USA; Email: richardl@fiu.edu. [2] Dauphin Island Sea Lab, 101 Bienville Boulevard, Dauphin Island, Alabama, USA; Email: raronson@disl.org

fully characterized (see below) and, unlike the Caribbean-wide survey cited above, does not involve use of uniform sampling and disease identification procedures, the literature link allows one to assess the status of knowledge and scientific rigor of disease observation for each site.

Relationship Between Coral Disease and Global Warming:
One important theme that arose from the session was a possible relationship between disease and global warming. Several findings were reported which together support such a hypothesis. The study that documented the new geographic expansion of black band disease to the Great Barrier Reef included physical measurements that revealed that both black band disease and white band disease emerged on these reefs after a period of historically unprecedented, sustained, high sea water temperature. While it has been known for years that black band (and other) disease outbreaks occur in the warmest months of the year in the wider Caribbean, its sudden appearance on the Great Barrier Reef at the same time as a marked elevation of water temperature represents the first suggestion of a possible link between climatic trends and the emergence of coral disease in new locations. Similarly, while it has been known for some time that elevated temperatures can induce coral bleaching *in situ*, new laboratory-based results document that bacterial bleaching of coral can be directly triggered by high temperature. Additional laboratory studies of microbial pathogens of corals which have been isolated and are being characterized have revealed a common characteristic of growth optima at and above 30 degrees Centigrade, the temperature at which corals begin to exhibit physiological stress. Determination of a link between elevated temperature and increased bacterial pathogenesis of corals *in situ* was identified as a suggested future focus for research on coral health.

Effect of Coral Disease on the Reef Ecosystem:
Another critical theme explored in the symposium was the ecological effect of coral disease on the reef ecosystem. It is clear that disease is an under-appreciated source of mortality in corals and other reef organisms. This is true despite the fact that there is quantitative evidence of a long-term restructuring of Caribbean reefs on a regional scale as a result of disease outbreaks on individual reefs. In the Caribbean, white band disease was the primary reason for the decline of *Acropora palmata* and *A. cervicornis*, two species that formerly dominated reef-crest and fore-reef habitats, respectively. Paleontological evidence suggests that the decimation of *Acropora* populations in the Caribbean over the past three decades was unprecedented on a time scale of millennia.

Identification and Characterization of Microbial Pathogens:
One area of research that continues to be active is the identification and characterization of microbial pathogens of corals. To date, the pathogens of only five coral diseases (which includes bacterial bleaching) are known, although up to 29 diseases have been proposed. The range of characterized pathogens is dramatic in terms of both type of microorganism and disease process. The microbial pathogens associated with the following diseases have been characterized to the greatest extent:

- Black band disease – caused by a microbial consortium that functions synergistically to produce a community toxic to coral. The community includes a photosynthetic bacterium, sulfide-oxidizing and sulfate-reducing bacteria, and associated heterotrophic bacteria that form a highly structured microbial mat community
- White band disease (type II) – associated with a non-structured population of gram negative bacteria
- Aspergillosis of seafans and seawhips – caused by a fungus (*Aspergillus sydowii)* of terrestrial origin
- Plague types II and III – caused by a gram negative bacterium that may be a new genus;
- Bacterial bleaching – caused by the gram negative bacterium *Vibrio shiloii.*

The status of knowledge of microbial pathogens of corals is summarized in greater detail elsewhere (Richardson and Aronson, in press).

Research presented from both field and microbiological studies of coral diseases strongly supported the caveat that extreme caution is necessary when interpreting coral pathologies in the field as potential diseases. One case study was reported which documented a detailed investigation into the cause of widespread lesions and structural damage of Caribbean corals, first reported and highly publicized as a highly contagious "rapid wasting disease." The study documented that such degradation was, in fact, the result of bite marks of the stoplight parrotfish, *Sparisoma viride.*

There was general agreement that the results of both microbiological and ecological studies must be integrated and used directly to support and interpret the results of disease surveys and coral health monitoring programs.

Implications for Management and Policy and Specific Recommendations for Action

In summary, the session on coral diseases led to the following important points that should be considered by reef managers:

- Diseases continue to increase and are now found on reefs throughout the world, including the most pristine and geographically isolated coral reefs.
- Disease outbreaks can result in the complete restructuring of reef communities.
- Results from studies that focus on coral diseases at the most basic levels (isolation and characterization of pathogens) are available to support coral disease monitoring and prevention programs.
- New monitoring programs should be modeled after current quantitative monitoring programs that incorporate well-developed methodologies in order to facilitate direct comparison between different areas.

Conclusions

Research into the microbiological and ecological aspects of coral (and other invertebrate) diseases continues to be an active area. We are slowly beginning to understand the causes and effects of diseases on reefs, and are hopeful that this knowledge will eventually be instrumental in designing management programs to counteract continued reef degradation.

Useful References and Resources:

This paper is based on presentations made at the 9th ICRS, Mini-Symposium E7, *Coral Diseases: Pathogens, Etiology and Effect on Coral Reefs*. The following papers, presented at the symposia, were especially useful in preparing this synopsis:

Banin E, Ben-Haim Y, Fine M, Israely T, Rosenberg E (in press) *Virulence mechanisms of the coral bleaching pathogen Vibrio shiloi*. Proc 9th Int Coral Reef Symp.

Bruckner AW, Bruckner RJ (in press) *Coral predation by Sparisoma viride and lack of relationship with coral disease*. Proc 9th Int Coral Reef Symp.

Dinsdale EA (in press) *Abundance of black-band disease on corals from one location on the Great Barrier Reef: a comparison with abundance in the Caribbean region*. Proc 9th Int Coral Reef Symp.

Richardson LL, Aronson RB (in press) *Infectious diseases of reef corals*. Proc 9th Int Coral Reef Symp.

Weil E, Urreiztieta I, Garzón-Ferreira J (in press) *Geographic variability in the incidence of coral and octocoral diseases in the wider Caribbean*. Proc 9th Int Coral Reef Symp.

Web site resource (cited in text): World Conservation Monitoring Centre (WCMC) Web site of observational data of coral diseases from 150 sites worldwide: www.unep-wcmc.org/marine/coraldis/

Coral Reefs: Invaded Ecosystems

Lucius G. Eldredge [1] and Jamie K. Reaser [2]

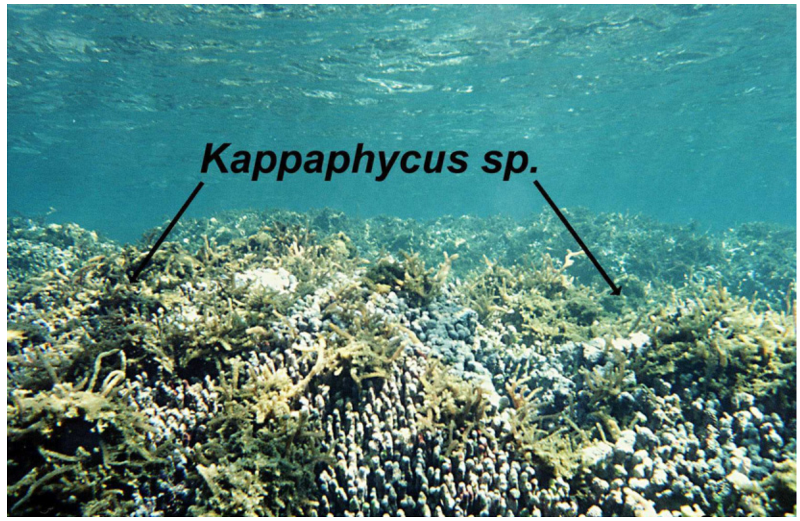


Photo: J. Smith

***Kappapycus striatum*, an invasive red algae (*Rhodophyta*) in Kaneche Bay, Oahu (Hawaii, USA)**

Statement of Issue

INVASIVE species are organisms (plants, animals, or other organisms) that have been moved from their native habitat to a new location where they cause significant harm to (or significantly threaten) economic systems, the environment, or human health.

Society pays a great price for invasive species – costs measured not just in currency, but also unemployment, damaged goods and equipment, power failures, food and water shortages, environmental degradation, loss of biodiversity, increased rates and severity of natural disasters, disease epidemics, and even lost lives.

The prevention and control of invasive species presents scientific, political, and ethical challenges. The process of invasion is often complex, resulting in considerable scientific uncertainty. Invasive species are in part a symptom of land use and climate change, as well as a result of the globalization of trade, travel, and transport. Implementing effective prevention and control measures may be costly and require new policy approaches, as well as significant advances in ecological knowledge and natural resource management.

Although terrestrial invasions have received much attention, the presence and impacts of invasive species in marine environments are little known in comparison. The marine patterns and trends of invasive species, with particular attention to coral reef ecosystems, were addressed at the 9th ICRS.

State of Knowledge

Vulnerability: Temperate vs. Tropical Systems
In temperate marine systems, invasive species are well-documented causes of environmental disturbance, disrupting native communities and having a negative impact on fisheries. Less is known about the impact of invasive species in tropical marine environments, especially on coral reef systems. Recent evidence from surveys in Australia, Hawaii, and Guam dictate that tropical and subtropical areas are also susceptible to invasion, but that the detection of invasive species may be hampered by our inability to make quick and accurate taxonomic identifications. Furthermore, most of the studies undertaken thus far have been limited to surveys in harbors and ports, where environmental conditions are usually quite different from those required by reef-building corals.

The Invaders
Non-native organisms, representing a wide variety of species, have been detected in virtually every marine environment. In the Hawaiian Islands alone, nearly 340 non-native species have been found in marine and brackish waters. Because the introduction of these organisms is influenced by human activities, non-native species are frequently associated with artificial substrates or harbors.

While the majority of non-native species remain confined to these areas, others invade into nearby habitats, including coral reefs. Some species spread, establishing populations

[1] Bishop Museum, 1525 Bernice Street, Honolulu, Hawaii 96817; Email: psa@bishopmuseum.org [2] National Invasive Species Council, 1951 Constitution Ave, NW, Suite 320, South Interior Building, Washington, D.C. 20240; Email: jamie_reaser@doi.gov, sprgpeeper@aol.com.

along coastlines and throughout island chains. Artificial substrates and harbors are, thus, both "hot spots" and epicenters of marine invasion.

Some types of invasive species are able to spread faster than others. The establishment and rate of spread of a species depends on several factors – for example, the biological characteristics of the organism, the physical nature of the environment, and the types and rates of movement along invasion pathways (see "pathways" below).

Many invasive species possess biological characteristics that enable them to produce large qualities of offspring (typically larvae), as well as tolerate wide ranges and large fluctuations in temperature, salinity, and water quality. In addition, the invasive species might also have specialized strategies for asexual reproduction, herbivore or predator resistance, or competition.

Invasive species are more likely to establish and spread if they are moved into environments that are physically similar to systems in which they evolved or systems in which the species composition has already been severely disturbed. From the perspective of the invader, important physical characteristics of marine systems may include: tolerable water chemistry and quality, availability of appropriate substrates for colonization, and connectivity to habitats needed for reproduction and the growth of different life-history stages.

Pathways of Invasion

Pathways are the routes by which invasive species are moved from one location to another, whereas *vectors* (or *modes*) are the specific means of transport in or on which invasive species travel. One pathway may involve numerous vectors.

Sometimes invasive species are moved intentionally (someone wants to do something with the organism), while other movements are unintentional (someone wants to do something with another product and the invasive comes along as a "hitchhiker" or "stowaway").

Common marine pathways/vectors include:

Intentional: releases and escapes from aquaculture, mariculture, and aquaria; as well as fisheries stock enhancement (sport and commercial).

Unintentional: ballast water discharge, hull fouling, oil platform relocation, or as accidental "hitchhikers" associated with intentional releases.

For many specific localities, the dates and pathways of invasion are unknown. This can make determining the species' geographic origin, and thus its identity, very difficult.

Sometimes marine invasives carry parasites, pathogens, and other associated organisms along with them, further compounding the ecological and economic problems.

Implications for Management and Policy

- *Ecological Impacts:* Invasive species are known to displace, out compete, or prey upon native species. They may also spread pathogens and parasites. The negative impacts can cascade throughout the entire food chain.

- *Socio-economic Consequences:* When invasive species negatively impact commercially desirable native fish, fisheries catches and profits decline. For some Small Island Developing States, declines in fisheries may also mean increased challenges in meeting local consumption needs. In recent years, the aquaculture industries (for example, shrimp farming) have been particularly hard hit by introduced diseases, resulting in significant economic losses and unemployment. Coral reefs dominated by invasive species may be less attractive to tourists, and thus threaten the stability of communities that are heavily dependent on eco-tourism.

- *An Example of Impacts from Hawaii:* In Hawaii, many non-native algal species have undergone massive blooms, spreading rapidly and creating large beds composed of a single species of non-native algae. The once highly diverse and complex coral reef ecosystem is completely modified. "Habitat shifts" such as these have a direct, negative impact upon the US $800 million per year that Hawaii earns from marine tourism. Furthermore, some of the algae pile into windrows on beaches, causing public health concerns and additional impacts on tourism.

Specific Recommendations for Action

- Raise awareness of the problem with governments, relevant industries, and local communities (especially those closely associated with coral reefs).
- Encourage the enforcement and strengthening of policies that seek to minimize the spread of invasive species in marine environments.

- Build stronger capacity for the identification of marine invasive species. This includes enhanced information sharing among taxonomic experts globally, new tools for identification (including guides and molecular analyses), and training for taxonomists.
- Establish a pool of specialists interested and willing to make species identifications as expeditiously as possible, a program for voucher specimens to be deposited in dedicated museums, and a rapid response system to investigate new and unusual sightings.
- Establish scientifically-based risk assessments and risk management programs for the introduction of marine organisms.
- Support and undertake studies of the presence and impacts of invasive species on coral reef systems, as well as methods to prevent and control invasion. Biological, social, and economic impacts should be considered. Environmentally-sound control should be emphasized.
- Reduce the vulnerability of coral reef systems to invasion by minimizing pollution, sedimentation, and physical degradation.

Useful References and Resources

This synthesis was prepared from papers presented at the *9th ICRS, Mini-Symposium E8 Coral Reef Non-indigenous and Invasive Species*. Authors and titles of presentations can be found at www.nova.edu/ocean/9icrs

Coles, S.L., R.C. De Felice, LG. Eldredge, and J.T. Carlton. 1999. "Historical and recent introductions of non-indigenous marine species into Pearl Harbor, Oahu, Hawaiian Islands." *Marine Biology* 135:147-158.

Eldredge, L.G. 1987. "Coral reef alien species." Pages 215-228 in Salvat, B. (ed.). 1987. *Human impacts on coral reefs: facts and recommendations*. Antenne Museum E.P.H.E., French Polynesia.

Eldredge, L. G., and C. M. Smith. 2001. *A guidebook of introduced marine species in Hawaii.* Bishop Museum Technical Report 21.

Hutchings, P. 1999. "The limits of our knowledge of introduced marine invertebrates." pp. 26-29 in the other 99%. *The conservation and biodiversity of invertebrates.* Transactions of the Royal Zoological Society of New South Wales.

Checklist of Hawaiian marine invertebrates [each species noted as native, introduced or cryptogenic]. www2.bishopmuseum.org/HBS/invert/list_home.htm

Marine invasions in Hawaii. www.botany.hawaii.edu/Invasive/default.htm

National Invasive Species Council. 2001. National Invasive Species Management Plan. www.invasivespecies.gov.

Crown-of-thorns and Other Coral Predators

Ian Miller [1]

Statement of Issue

THE crown-of-thorns (COTS) starfish (*Acanthaster planci*) is a coral predator. This starfish may form aggregations, termed outbreaks that far exceed the carrying capacity of their coral prey. Since this discovery in the 1950s, COTS have been found responsible for mass mortality of hard corals throughout the Indo-Pacific. Two species of the Muricid gastropod *Drupella* (*D. cornus* and *D. rugosa*) are also coral predators. To a lesser extent, *Drupella* outbreaks have also caused mass mortality of corals in the Indo-Pacific. Despite years of research no single cause of outbreaks has been found.

State of Knowledge

Papers presented at the 9th International Coral Reef Symposium provided the following results:

- *Drupella* will "switch" in food preference. When preferred food corals die from a bleaching event, *Drupella* then feed on surviving non-preferred coral species.
- *Drupella* can adapt their behavior to compensate for large variations in seawater temperature.
- COTS outbreaks appear to originate from a source population (primary outbreak) and then spread (secondary outbreaks) by planktonic larvae on prevailing water currents.
- On those reefs subjected to COTS outbreaks the ability of the coral community to recover will depend strongly upon the disturbance regime of the area in question.
- Many populations of demersal fish species remain relatively unaffected by COTS outbreaks.

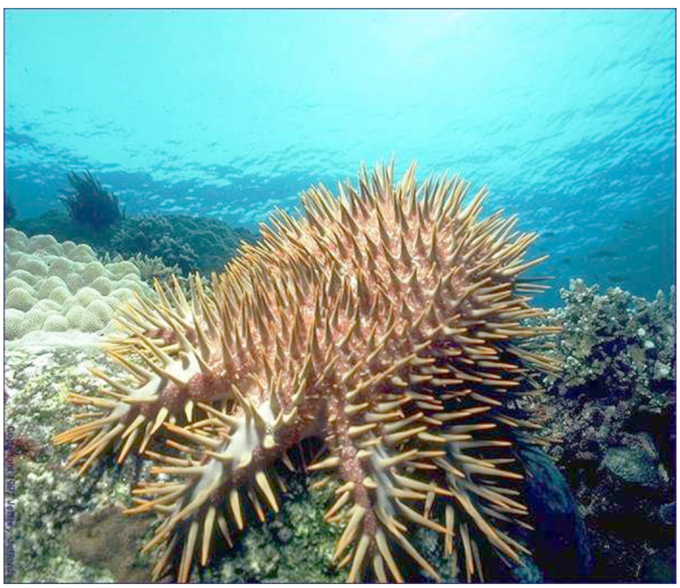


Photo: Jeffrey Jeffords, divegallery.com

Crown-of-thorns starfish (*Acanthaster planci*) devours hard coral in Batangas, Philippines

- COTS growth is indeterminate and they can change size depending upon food availability.
- There is circumstantial evidence that the removal of fish predators is a factor promoting COTS outbreaks in the Red Sea.
- COTS in the Red Sea are genetically divergent from other northern Indian Ocean populations.

Management Implications

The importance of outbreaks to the coral community and hence to the long-term health of the reef ecosystem cannot be underestimated. COTS and *Drupella* selectively feed on fast-growing corals. If feeding pressure is low, or if there is enough time between outbreaks, the removal of fast growing corals creates space for slower growing and rare corals to persist helping to maintain species diversity on reefs.

Repeated outbreaks can lead to the degradation of reefs. For reefs under stress (for example, nutrient loading, sediment, overfishing and elevated temperatures) which have less capacity to recover, outbreaks of corallivores can lead to fundamental changes in community structure. This is of particular concern given the threat that global climate change poses to coral reef ecosystems. Striking a balance that maintains reef health and hence the ability of a reef to recover from disturbance (such as a COTS outbreak) is of major concern for managers.

Specific Recommendations for Action

- Address overfishing and nutrient enhancement due to terrestrial runoff, which have been implicated as possible

[1] Australian Institute of Marine Science, Townsville, Qld., Australia; Email: imiller@aims.gov.au

causes of outbreaks. Though the exact role that human modification of the environment plays in the initiation of outbreaks remains debatable, in neither case is over-fishing nor excessive terrestrial run-off considered desirable for maintaining reef health.

- Establish integrated monitoring programs that gauge local impacts due to fisheries, changes to water quality, and the effects of coral predators. Monitoring will provide a 'benchmark' that gives managers a basis for making decisions on what levels of use are acceptable for a given management situation. It also provides the background against which managers can target research to address their particular needs. Ongoing monitoring studies are essential for the informed management of coral reefs. They must be based on sound sampling designs that are clearly defensible.

Useful References and Resources

This paper is based upon presentations at the 9th International Coral Reef Symposium, Mini-Symposia E9, *Acanthaster and Drupella on Reefs*. Authors and titles of presentations can be found at:
www.nova.edu/ocean/9icrs/

Birkeland C.E and Lucas J.S 1990 *Acanthaster planci : major management problem of coral reefs*. CRC Press, Boca Raton, Florida. 257p

Sapp J 1999 *What is natural? : coral reef crisis*. Oxford University Press, 1999. New York. 275 p.

English, S., Wilkinson, C. and Baker, V. (1997) *Survey Manual for Tropical Marine Resources* (2nd Edition). Australian Institute of Marine Science. Townsville.

Functional Roles of Sponges on Coral Reefs

Janie L. Wulff [1]

Statement of the Issue

ALTHOUGH a small group of carbonate excavating sponges can dismantle reefs, and some sponges can overgrow corals, it is now known that sponges also substantially benefit coral reefs and associated ecosystems. Sponges benefit reefs by efficiently filtering small (<5um) organic particles from the water column, binding live corals to the reef frame, facilitating regeneration of broken reefs, providing food for spongivores, sheltering juvenile crustaceans such as spiny lobsters, and harboring nitrifying and photosynthesizing microbial symbionts. Sponges uniquely perform many of these functional roles, and possibly others not yet known. However, sponges have not been included in most monitoring programs and assessments due to difficulties in identification and quantification. At the 9th ICRS, it was agreed that greater attention should be focused on sponges and their roles in reef function, particularly in light of recent documentation of rapid losses of sponges from coral reefs and closely associated ecosystems.

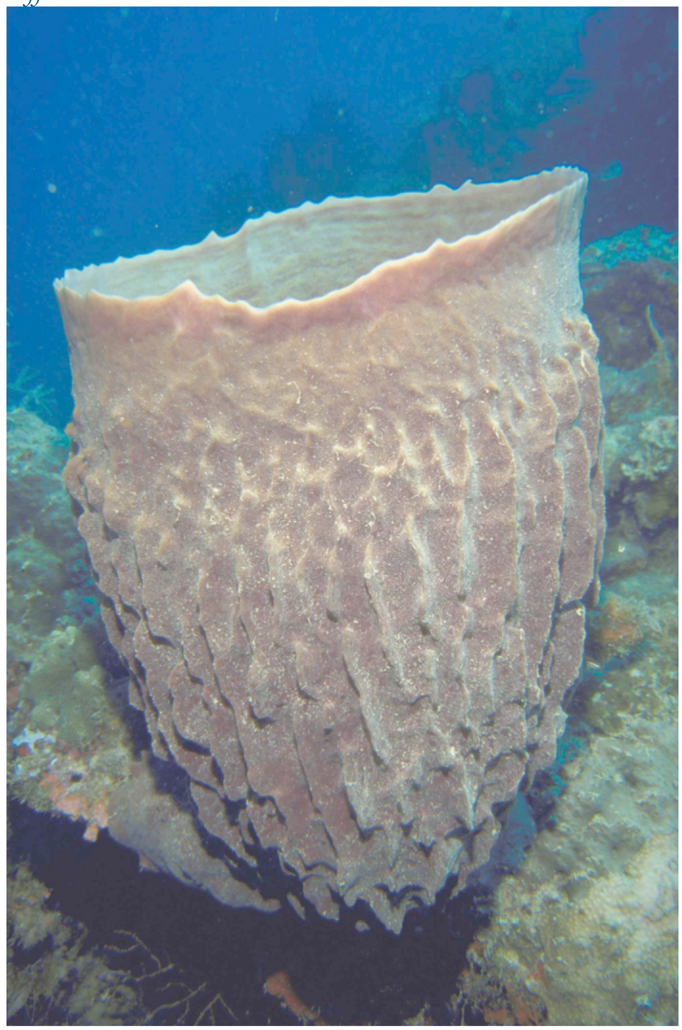


Photo: Gerald R. Allen

Barrel sponge on patch of reef in Raja Ampat, Indonesia

State of Knowledge

Interrelated aspects of the functional roles of sponges on coral reefs can be categorized as (1) interactions with unicellular organisms as symbionts, pathogens, and food; (2) interactions with macroscopic organisms as mutualists, competitors, and predators; and (3) distribution and abundance patterns on geographic and habitat scales.

1) Interactions with unicellular organisms as symbionts, pathogens, and food: Sponges simultaneously feed on, are inhabited by, and suffer disease caused by microorganisms, and it is not known how, or even if, these different interactions influence each other. Concern that sponge disease may be increasing is raised by recent documentations of dramatic losses of sponges from a diverse sponge community in Panama, from large areas of Florida Bay in the USA, from a population of a common species in New Guinea, and from various populations of a conspicuous species throughout the Caribbean. Losses from coral reefs of commercially harvested species to disease have previously been documented. Disease may also be devastating other sponges, but it is difficult to determine because long-term monitoring of sponges in permanent quadrats is rare, and sponges can die and deteriorate quickly, rendering losses invisible without prior detailed site-specific information.

Symbionts of a wide variety of unicellular taxa have become associated with sponges, apparently benefiting both partners in some cases, and influencing the entire system by contributing biochemical talents not inherent to sponges. Some sponge disease might be caused by

[1] Biology Department, Middlebury College, Middlebury, VT 05753, USA; Email: wulff@bio.fsu.edu

normally beneficial or benign microbial symbionts, if environmental conditions change such that associations are no longer favorable.

It is not known if vulnerability of sponges to microbial pathogens is influenced by their constant internal exposure to water column microbes by feeding currents, or if sponges can consume potential pathogens. Ecosystem level importance of efficient water column clearing by sponges as they feed, first demonstrated by Reiswig, is confirmed by cascading problems associated with recent sponge die-offs in Florida Bay.

2) Interactions with macroscopic organisms – mutualists, competitors, and predators: Apparently more than other reef organisms, sponges live intimately associated with a variety of sessile and mobile organisms, which may significantly influence the success of both partners. Negative repercussions of losses of sponges engaged in these associations range from the loss of juvenile spiny lobster shelter to dramatically increased coral mortality. Some interactions of sponges, especially with predators and competitors, are mediated at least in part by chemistry; presumably the intriguing bioactive chemistry of sponges, that has made them so interesting to pharmaceutical developers, has evolved in this context of protection from potential enemies. Understanding the ecological context for evolutionary development of novel chemistry, e.g., deterence of specific predators or pathogens, can help to focus attention on potentially useful species and contribute to understanding the mechanisms of evolution of bioactive chemistry. However, while pharmaceutical interest in sponges can provide additional sources of funding and impetus for biodiversity conservation, it also raises serious concerns about resource ownership and irresponsible collecting practices.

3) Distribution and abundance patterns on geographic and habitat scales: Surprising results from studies of geography of species boundaries and similarities among sponge assemblages caution us to take care in inferring connections between distant sites. Geographic history plays a large but not a readily predictable role in determining how closely related faunas of adjacent regions or provinces are. High estimates of degrees of endemism, which will increase much more if cryptic species continue to be identified at the present rate, compel us to pay attention to details of distribution data in the design of protected areas aiming to conserve diversity. On a smaller spatial scale, local physical features and environmental factors are more important in determining differences among adjacent local faunas. Understanding constraints on distribution of sponges in adjacent habitats can serve as the basis for using sponges as environmental indicators; sponges may be especially useful for habitats in which stresses (for example, turbidity, storm waves, predators) are difficult to evaluate directly because they are intermittent. Understanding how the reef dismantling action of excavating species may be enhanced by human activities, especially nutrient overloading, may be of particular importance in some areas.

Chief concerns about sponges include: 1) the extent of disease may be increasing, but is not documented due to inadequate monitoring; 2) what appear to be large populations of wide-spread species may actually be more vulnerable small populations of distinct species; 3) environmental change may alter associations with symbionts and other intimately associated organisms; and 4) sponges may play additional functional roles not yet

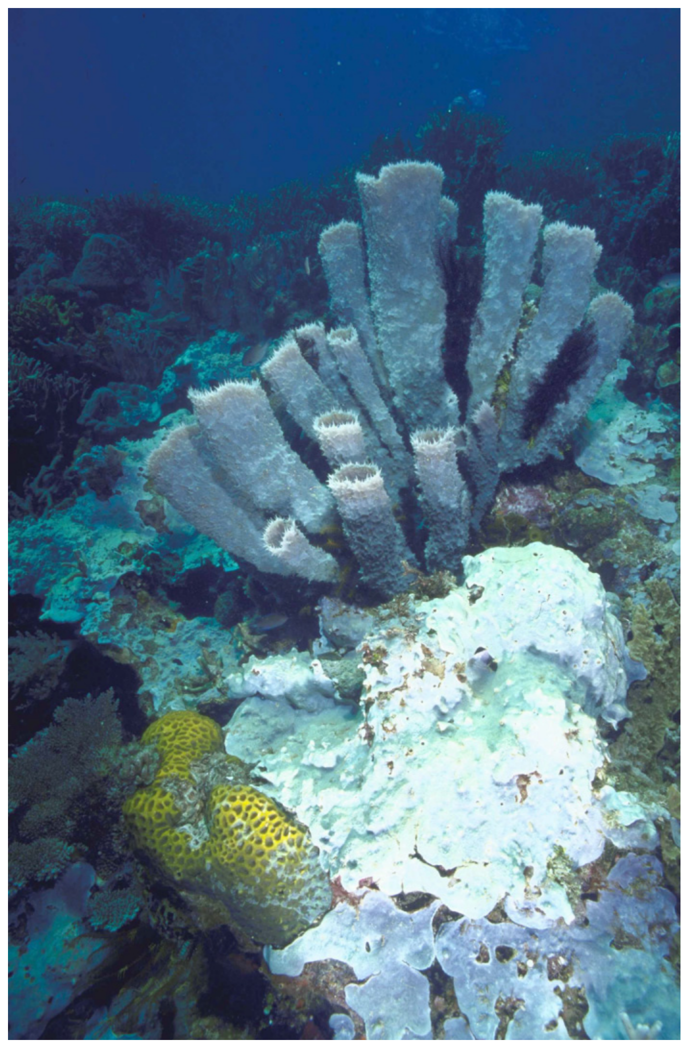


Photo: Roger Steene

Sponges with crinoids and corals on reefs of the Calamaines Islands, Philippines documented but yet vital to reef health – some of the roles that sponges play on reefs that now seem obvious were unknown a short while ago.

Management and Policy Implications

Priorities for sponge monitoring and assessment include:

- keeping track of the abundance of sponges and signs of disease;
- documenting boundaries of species and of faunal assemblages so that appropriate areas can be protected;
- learning about specific constraints on sponge distribution in order to make use of sponges as environmental monitors; and
- continuing to learn about functional roles of sponges on coral reefs.

Specific Recommendations for Action

Careful taxonomy is necessary for clear communication about using particular species as environmental indicators, for bioprospecting, and for determining species boundaries and degrees of endemism for conservation purposes. Guidance for taxonomy can be found in Rützler (1978) and Hooper & van Soest (in press). Emphasis should be given to training the next generation of taxonomists, and incorporating sponge identification in training modules for monitoring.

Permanent transects or quadrats must be used for monitoring sponges if there is any possibility that disease is an issue, because diseased sponges can disappear quickly, without a trace. While repeated random sampling can be demonstrated to provide statistically reliable results, it does not provide confident information on disappearance of organisms between sampling dates and is not adequate for monitoring sponges. Guidance for various aspects of monitoring can be found in Rützler (1978) and Wulff (in press).

The volume of sponges present in an area—even crudely estimated—is a better measure of their abundance than percent cover or number of individuals. Sponges consume food (clearing the water column), provide food for spongivores, and possibly even bind live corals and broken corals to the reef, in proportion to the volume of live sponge present on the reef.

Sponges living within crevices and under corals can be quite abundant, filter seawater efficiently, and may be especially important in enhancing coral survival and stabilizing coral rubble. However, cryptic sponges are invisible to video and other photographic monitoring methods and so must be assessed and monitored more directly.

Useful References and Resources

This paper is based upon papers and posters presented at the 9th ICRS, in Symposium A15, *Functional Role of Sponges on Coral Reefs*, as well as in minisymposia on Bioerosion and on Biogeography.

Rützler, K. 1978. In: Stoddart, D.R. & Johannes, R.E., eds. *Coral Reefs: Research Methods. Monographs on Oceanographic Methodology 5*, UNESCO, Paris: 299-313.

Diaz, C., Rützler, K. in press. "Proc. Int. Conf. on Scientific Aspects of Coral Reef Assessment, Montoring, and Restoration." *Bull. Mar. Sci.*

Wulff, J.L. in press. "Proc. Int. Conf. on Scientific Aspects of Coral Reef Assessment, Monitoring, and Restoration." *Bull. Mar. Sci.*

Hooper, J.N.A, van Soest, R.W.M. in press. *Systema Porifera.*

Requests for help with any aspect of sponge biology, ecology, systematics, chemistry, and monitoring, can be addressed to an internationally subscribed Sponge List at: www.PORIFERA@JISCMAIL.AC.UK

Targeted, Applied, and Systematic Research to Benefit Coral Reef Management

Anthony J. Hooten [1]

Statement of Issue

ONE of the most significant challenges facing all nations with coral reefs and associated resources is to clearly understand the impacts from changes in climate versus local human activities, and to use this information effectively in protecting their products and services. Over the past 30 years, the volume and diversity of information about coral reefs has steadily increased, and efforts are underway to enhance management based upon the knowledge already gained. However, significant gaps in our basic understanding of coral reef ecosystems remain, and management will eventually be limited without advancement in scientific understanding (Knowlton 1998; Buddemeier and Smith 1999). Coordinated, scientific frameworks are needed that can generate relevant information to advance the capacity of management, whether through social or natural resources management interventions. Discussions were held at the 9th ICRS and other venues as to the nature and scope of targeted, applied and systematic research that is needed to benefit coral reef management

Shallow reef coral with fish

Photo: Gerald R. Allen

Background and State of Knowledge

Since 1998, the World Bank has conducted a series of consultations with scientists in various regions around the world, including at the 9th ICRS, with the purpose of developing priorities for targeted investigations that will benefit management and policy: to examine root causes and differentiate global trends (such as increases in sea surface temperature, changes in chemical and nutrient cycles, persistent organic pollutants, increases in disease frequency) from localized anthropogenic effects (such as sediment loading, resource extraction and nearshore pollution).

The number of outstanding questions about coral reef ecosystems far exceed the scope of this summary; however, some key questions with practical implications for management include the following:

- Are factors surrounding climate change more critical to coral reef condition than local, anthropogenic stresses?
- Will coral reefs be resilient in the face of projected climate change over the next 50-100 years?
- What will be the final state of coral reefs and associated ecosystems if coral abundance decreases dramatically over time?
- How can we measure resilience in coral reefs? To what degree do Marine Protected Areas contribute toward resilience and maintenance of biodiversity?
- If a coral reef experiences a phase shift, is it permanent? If not, how long might it last? Are there ways to reverse the changed state?
- How fast will change occur within coral reef ecosystems? Do coral reefs experience net erosion when corals are no longer predominant? If so, how rapidly?
- What are the most important factors influencing recovery? Can people help facilitate recovery?

[1] Consultant, World Bank Environment Department, AHooten@worldbank.org; AJH, Environmental Services, 4005 Glenridge Street, Kensington, MD USA 20895-3708; Phone 301-942-8839; fax 301-962-9405; Email: environmental_services@attglobal.net

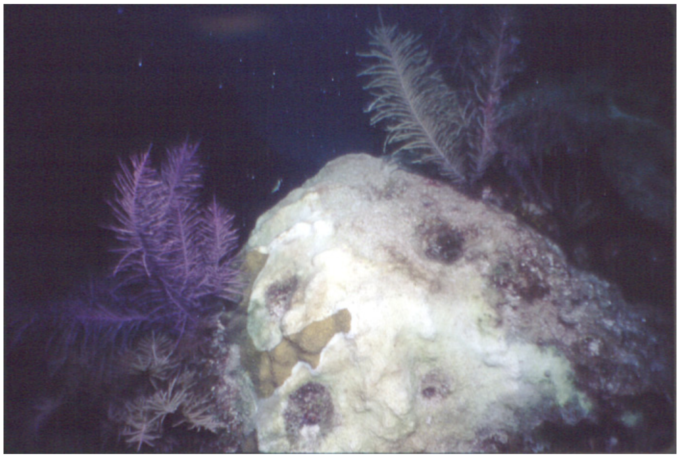


Photo: Laurie L. Richardson

Plague type III on *Montastraea annularis*. (Colony shown is >2 m diameter.) Plague has emerged in three forms on reefs of the Florida Keys. The latest form, type III, targets the largest colonies of *Montastraea annularis* and *Colpophyllia natans*. This is one of the most virulent of coral diseases and has recently spread to the Caribbean. It is caused by a pathogenic gram-negative bacterium that may be a new genus.

- In addition to temperature, to what extent is coral bleaching affected by other factors, such as light, sediment, nutrients, and pollutants (and in what combinations)? Will the presence of other stresses accelerate or retard bleaching?
- Why are some corals more immune to stress than others?
- Why are coral diseases more prevalent in some regions than others? Will diseases expand to other regions?
- How rapidly do larvae from adjacent or other reefs repopulate coral reefs?
- What is the relationship between distance and larval transport? Between coral and fish larvae and spawning aggregations?
- To what degree do other species depend on the structure created by corals?
- To what degree is maintenance of species diversity crucial to coral reef health?

Why do so many fundamental questions remain? Because coral reefs are complex, dynamic systems. The organisms that comprise them and the parameters that influence them combine to regulate their abundance and distribution at spatial scales ranging from microns to kilometers, and on time scales ranging from minutes to decades (Hughes, et al. 1999; van Woesik 2001). These multiple variables are also compounded by the complexities of human interactions by taking material away from (for example, over-fishing) or adding to (for example, pollution) coral reefs. Such factors present significant challenges in designing investigations that will provide meaningful answers to managers and policy-makers within a reasonable period of time. But even over the past 20 years the coral reef scientific community has, other than document decline, failed to collectively address the appropriate responses and information demands concerning coral reefs in many regions of the world (Risk 1999). Targeted, coordinated and systematic investigations have the potential to focus on the gaps in our knowledge about coral reefs, so that we may better relate information to management actions appropriately, and cost-effectively, to protect them (Done and Lloyd 1999; Scully and Ostrander 2001; Nyström et al. 2001).

Specific Recommendations

The recommendations stemming from the majority of consultations reinforce that while significant changes are obvious in many coral reefs, the root causes of these observed changes are still not well understood. The majority of the consultations were consistent in listing similar outstanding questions about coral reefs (see Background and State of Knowledge on previous page).

- Most researchers agreed that specific investigations are needed to improve basic understanding of coral reef biophysical processes that influence coral reef environments, community responses to disturbance, and resilience capacity.
- Investigations should include a range of screening, monitoring and experimental design, testing specific hypotheses, and investigating multiple variables.
- The majority of researchers stressed the need for longer-term studies (at least 10 years), to better understand temporal and spatial variability in population dynamics and recruitment, and how this information can be applied in a management context.
- Marine Protected Areas (MPAs) were also consistently identified as a potential focus to quantify their effectiveness in protecting habitat and fisheries.

Relevant Actions Being Taken

Based on the series of consultations, the World Bank is further developing the Targeted Research program with funding sought from the GEF and other co-financiers. Further discussion with potential co-financiers will also be taking place during this period to address the following actions:

- Promote the establishment of targeted research networks between governments and institutions that can leverage information and resources to strengthen the applied scientific information base specifically for the benefit of management and policy.

- Proceed with the completion of the project proposal to the Global Environment Facility for Targeted Research under the operational programs for International Waters and Biodiversity.
- In conjunction with the proposal, develop partnership arrangements with other interested research institutions and foundations in expanding targeted research sites worldwide.
- Identify and recruit qualified representative researchers to participate in thematic subgroups that will contribute to a guiding panel to synthesize research, revise targeted investigative priorities and help guide management interventions.

Useful References and Resources

Buddemeier, R.W. and S.V. Smith. 1999. "Coral Adaptation and Acclimatization: A Most Ingenious Paradox." *Amer. Zool.* 39:1-9.

Done, Terrence and David Lloyd, Eds. 1999. *Information, management and decision support for marine biodiversity protection and human welfare: coral reefs.* Proceedings from a workshop, Townsville, Queensland, Australia, December 6-10, 1999. UNEP/DEIA&EW/MR.2000-2.

Knowlton, N. 1998. *Hard Decisions and Hard Science: Research Needs for Coral Reef Management. In: Coral Reefs: Challenges and Opportunities for Sustainable Management.* The World Bank, 1998. pp 183-187. ISBN: 0-8213-4235-5

Nyström, M, C. Folke, and F. Moberg. 2001. "Corals and phase shifts-Reply," *TRENDS in Ecol. & Evol.* Vol 16 No. 3, March 2001. p 127.

Scully, E. P. and G. K. Ostrander. 2001. "Corals and phase shifts-Letters," *TRENDS in Ecol. & Evol.* Vol 16 No. 3, March 2001. Pp 126-127

Scientific and Technical Cooperative Agreement in the Area of Coral Reefs between the Australian Institute Of Marine Science and the Great Barrier Reef Marine Park Authority both of The Commonwealth of Australia and the National Oceanic and Atmospheric Administration of the United States of America. http://orbitnet.nesdis.noaa.gov/orad/sub/sub_pdf/crbpub_au_us_arrangement.pdf

CORDIO: Coral Reef Degradation in the Indian Ocean: www.cordio.org

Coral Reefs and Global Change: Adaptation, Acclimation or Extinction? The purpose of the workshop was to review and synthesize findings of various aspects of coral reef research with implications for research, assessment, and management. The several key recommendations developed from this workshop were echoed by the series of consultations that have followed to date. Please visit Web site at: http://coral.aoml.noaa.gov/themes/coral_cg.html.

[This page is intentionally left blank.]