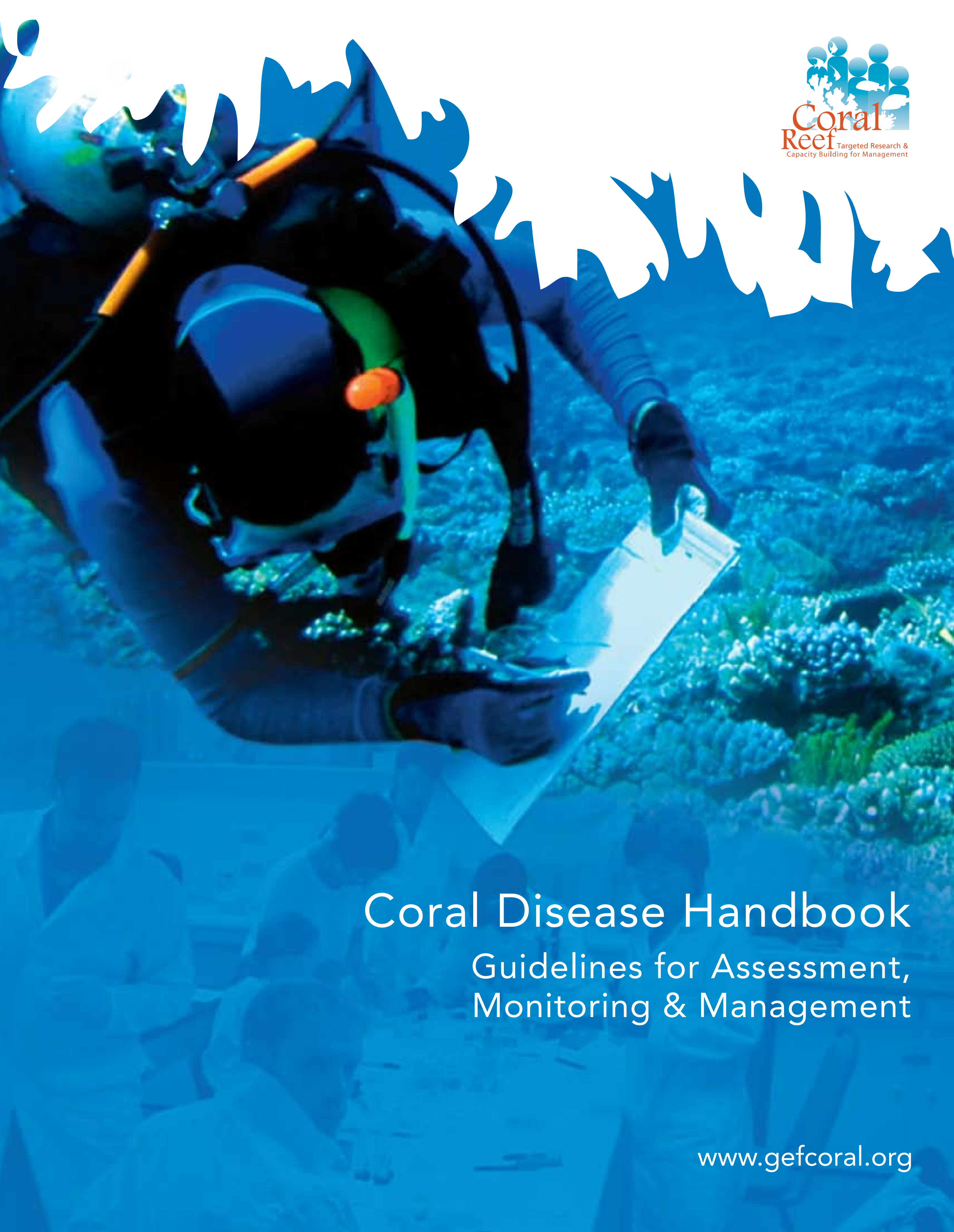

Coral Reef Targeted Research & Capacity Building for Management

Coral Disease Handbook

Guidelines for Assessment, Monitoring & Management

www.gefcoral.org

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The Coral Reef Targeted Research & Capacity Building for Management (CRTR) Program is a leading international coral reef research initiative that provides a coordinated approach to credible, factual and scientifically-proven knowledge for improved coral reef management.

The CRTR Program is a partnership between the Global Environment Facility, the World Bank, The University of Queensland (Australia), the United States National Oceanic and Atmospheric Administration (NOAA) and approximately 50 research institutes and other third-parties around the world.

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Foreword

Our research careers began in Discovery Bay, Jamaica, in the mid 1970s, where we both studied the behavior of coral reef organisms, rather than the corals themselves. At that time, living coral covered 70 percent of the bottom, and no one worried about the long term persistence of the reefs, even though the reefs were clearly impacted by people via severe overfishing. Quite simply, we took the reefs for granted.

That sunny confidence turned out to be totally unfounded. In 1980, Hurricane Allen, a category five storm, struck and turned much of the reef into a rubble ground. However, reefs routinely get hit by hurricanes and typhoons, so they should have recovered. But in 1982 the sea urchin *Diadema antillarum* was decimated by an as yet unidentified pathogen, and losing this last remaining major grazer contributed to the overgrowth of corals by seaweeds throughout the region. By 1995, coral cover stood at less than 10 percent.

But the loss of grazers was not the only thing happening to these reefs. A more subtle and gradual but no less important killer was also taking its toll – the white band disease of the branching staghorn and elkhorn corals. These two species used to be so common that as students we were taught about the "*Acropora cervicornis* zone" and the "*Acropora palmata* zone". Now both species are listed as endangered under the Endangered Species Act, having lost over 90 percent of their numbers in the ensuing decades. Like the elms and chestnuts of US forests, they have largely vanished due to disease.

And they are not alone – white plague, yellow band, black band, and many others have since been documented as major reef killers, not only in the Caribbean but in the Pacific as well. For most of these diseases we still do not know the causative agent – nor the extent to which pollution and increased sea surface temperatures may be contributing to disease outbreaks or affecting the ability of corals to recover from infections. Yet progress is being made, and simply reliably recognizing and documenting these syndromes and their patterns of infection are important first steps in addressing this problem.

This handbook makes it much easier to do just that. Designed for managers, it outlines procedures for describing signs, measuring disease impacts, monitoring disease outbreaks, assessing causes, and managing reefs to minimize losses due to disease. As the authors note, information and expertise on coral disease are inadequate relative to the scale of the problem. This handbook helps managers not only to document and manage disease on the reefs they are responsible for, but also allows them to contribute to our scientific understanding of this grave threat.

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Chapter 1
The Objectives and Scope of This Manual

In this chapter you will find:

A general introduction to infectious diseases in corals – what they are, why they are a growing problem, and what is currently understood about them.

A look at the current global patterns and hotspots in regard to coral reef diseases.

A summary of the impact of ocean warming and poor water quality on coral reef diseases.

The Objectives and Scope of This Manual

L. Raymundo and C. D. Harvell

1.1 The state of coral reefs and the purpose of this manual

Coral reefs are the most diverse and among the most productive ecosystems on earth. Millions of people directly rely on the harvest derived from coral reefs as their major source of protein and income. In addition, the revenue coral reefs earn from tourism, recreation, education and research is of major importance to their local and national economies. And finally, current research in such areas as natural products chemistry suggest that coral reefs support an unknown number of organisms that may prove to be of major benefit in the treatment of critical human diseases. Yet, in spite of their obvious importance, reefs continue to be impacted by "the big four" human activities that threaten their sustainability: climate change, land- and marine-based pollution, habitat degradation and over-fishing.

Many of these impacts have obvious and immediate effects, such as smothering or fragmentation of coral to the point of total mortality. However, some effects, such as those from chemical pollutants, waste or excess nutrients, are more insidious, and their impacts may be more difficult to understand and quantify. One phenomenon which has recently gained the attention of coral reef scientists and managers is disease. Diseases affecting corals, particularly in the Caribbean, have increased in both frequency and severity within the last three decades and caused major community shifts on Caribbean reefs. Yet we are only beginning to understand enough about drivers of disease outbreaks to consider management actions.

While diseases affecting corals have increased since the 1970's, there are few individuals throughout the world trained to recognize diseases on coral reefs. In addition, there are many areas where there is absolutely no information regarding the status of coral health and disease.

Written for coral reef managers, this manual aims to fill the knowledge gap by bringing together what is currently known about coral diseases, how they are studied, and what options are available for managing them. We first present some general concepts about disease to put this manual and its scope in perspective. We then present the most current descriptions of known coral diseases, with information to assist in their field identification. Subsequent chapters are devoted to confirming field identifications, quantifying impacts of disease to coral communities, assessing disease on reefs, and setting up monitoring programs. We then provide information as to what is currently understood regarding disease outbreaks and how to track and study them. We end with guidelines on management practices and suggestions for where to obtain further information and direction.

Included in the appendices are categories of additional information which we hope will be useful. Underlined terms throughout the text indicate words listed in the glossary in **Appendix 1**.

1.2 What is disease?

Diseases are a natural aspect of populations, and are one mechanism by which population numbers are kept in check. For the purposes of this manual, we will use the term disease to mean "any impairment to health resulting in physiological dysfunction". Disease involves an interaction between a **host**, an **agent**, and the **environment**. The focus of this manual is *infectious biotic diseases*; those that are caused by a microbial agent, such as a bacterium, fungus, virus, or protist, that can be spread between host organisms and negatively impact the host's health. Other forms of disease that impact corals may be considered *abiotic diseases*; they do not involve a microbial agent but impair health, nonetheless. Examples may be those caused directly by environmental agents such as temperature stress, sedimentation, toxic chemicals, nutrient imbalance and UV radiation. In addition, *noninfectious biotic diseases* are not transmitted between organisms, though they may be caused by a microbial agent. For example, certain microbes secrete a toxin which damages the host animal or plant. A good example of this is botulism; toxins released by the bacterium *Clostridium botulinum* cause a non-infectious but deleterious disease in organisms that consume it.

1.3 Why study infectious diseases of corals?

Pathogenic microorganisms, having very short reproductive cycles, evolve more rapidly than multicellular organisms. They are also continually transported to new environments in the oceans by runoff, shipping vessels, aquaculture, and changing ocean currents. Therefore, we can expect that new diseases will continue to emerge. Recent examples of **emergent** infectious diseases on land that are threats to humans and wildlife include AIDS, bird flu, and SARS. Under specific conditions, disease levels may exceed a population's ability to cope, resulting in rapid and widespread mortality.

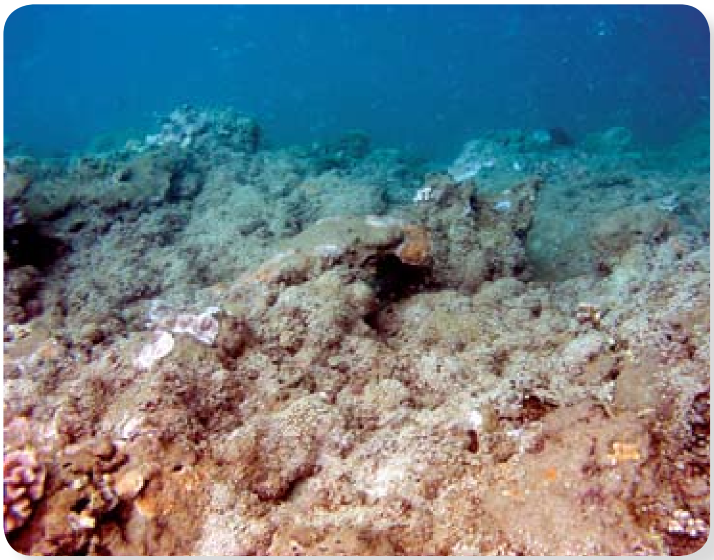

Figure 1.1 Reef in Hanalei Bay, Kauai, Hawaii, which has experienced extreme sediment stress, resulting in reduced coral coverage and the proliferation of the zooanthids. Photo: G.S. Aeby

A disease is considered an **outbreak** when the rate at which new hosts become infected increases. Technically, an outbreak is defined as R_0 >1. R_0 is the ratio of new infections to existing infections (see **Chapter 5** and **Appendix 1**).

Over the past three decades, coral reefs worldwide have experienced major changes in structure and function due to both anthropogenic and natural impacts (15-18). Virtually all of the most pervasive threats impacting coral reef ecosystems, including land-based and marine pollution, overfishing, global climate change, and ocean acidification, have been suggested as synergists or facilitators of infectious disease (**Figure 1.1**). Infectious disease in corals has increased in frequency and distribution since the early 1970's when a white band disease outbreak took a heavy toll on Caribbean acroporids. There has since been an exponential increase in numbers of reported diseases, host species and locations with disease observations. This rate of change is not normal, and has resulted in significant loss of coral cover.

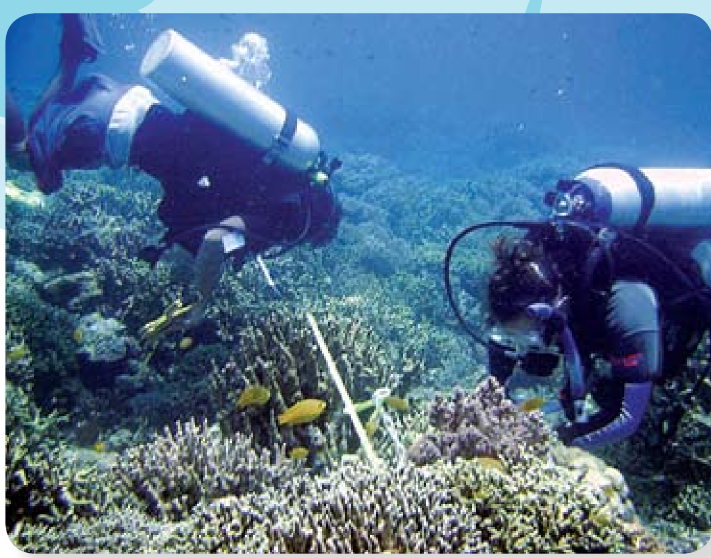

Figure 1.2 Students being trained in coral disease assessment methods in the Zaragosa Marine Protected Area, Central Philippines. Photo: L. Raymundo

Currently, the study of coral disease is in its infancy and those who devote their time and expertise to it are virtually "learning as they go along". However, through the experience of others who study and manage diseases in wildlife, farmed and cultured animals and plants, and even human populations, we can adapt methodologies and strategies to coral diseases that have been successful in other medical arenas.

This manual aims to address an urgent need: to update coral reef managers regarding our current understanding of the basic ecology of coral diseases. This will help improve monitoring efforts and aid in proper recognition of coral diseases and related issues of coral health (**Figure 1.2**). Although it is important to remember that detailed laboratory investigation remains essential for proper disease **diagnosis** and a complete understanding of the impacts to the coral host, we also hope that this manual will help increase the number of individuals able to provide information on the state of health of the world's reefs. By studying disease and establishing baselines prior to a crisis, we can arm ourselves with a better knowledge of appropriate management options for a given situation.

1.4 The emergence of coral disease

Damage to coral by abiotic and biotic factors acting alone or in synergy have led to a global reduction in coral cover (6,18,22-24). To date, the most infectious **syndromes** of coral for which a causative agent has been isolated involve bacteria (26). In addition to the loss of coral tissue, disease can cause significant changes in reproduction rates, growth rates, community structure, species diversity and abundance of reef-associated organisms (28,29). While an unprecedented increase in coral disease has been well-documented in the Caribbean over the last decade (11,25,30-32), and some argue that climate warming has driven part of the increase in damaging outbreaks (Causey, pers. comm.), much less is known about the status of disease throughout the Indo-Pacific (26). However, preliminary surveys in Australia (33), the Philippines (34), Palau (35), Northwestern Hawaiian Islands (36), American Samoa (37), the central Pacific (38), and East Africa (39,40), have revealed significant and damaging new diseases in all locations surveyed. Many of these are suspected or confirmed as infectious.

Figure 1.3 Coral bleaching within the Basdiot Marine Protected Area, Philippines, summer 2006. Photo: K. Rosell

What has prompted this emergence of coral disease? Current research suggests that humans may not only be introducing new pathogens into the oceans though aquaculture, runoff, human sewage, and ballast water, but may also be exacerbating existing **opportunistic infections** due to stressors such as poor water quality and climate warming (16,41). Climate warming is now established as an important factor in some current outbreaks (23,32,42). Some experts, such as Billy Causey (Superintendent, Florida Keys National Marine Sanctuary), argue that stressful warming events may have driven even more outbreaks than we have detected to date (Causey, pers. comm.). Because reef-building corals have a narrow range of thermal tolerance (between 18°C and 30°C), they are extremely susceptible to temperature stress. It is well known that corals "bleach" (lose their symbiotic zooxanthellae) at high temperatures (**Figure 1.3**). The coral bleaching observed worldwide following the 1998 El Niño was the most massive and devastating recorded up to that point (43), only to be exceeded by another bleaching event in Australia in 2002. The latter part of 2005 brought widespread bleaching to the Caribbean, caused by the largest warm thermal anomaly in 100 years (Eakin, pers. comm.). The Caribbean thermal anomaly of 2005 was immediately followed by outbreaks of white plague, yellow band disease (42) and white patch disease (32).

Our working hypothesis is that, in some cases, the death of coral during hot thermal anomalies is exacerbated by opportunistic infectious pathogens whose **virulence** is enhanced by increased temperatures. Changing environmental conditions could also influence disease by altering host-pathogen interactions. Increased temperatures could affect basic biological and physiological properties of corals, particularly their ability to fight infection, thus influencing the balance between potential pathogen and host (44). In addition, the pathogens themselves could become more virulent at higher temperatures (45). This is particularly challenging to study because of the complexity of the coral **holobiont**. The animal itself consists of the coral polyp, the unicellular algae (zooxanthellae) with which it co-exists in a **mutualistic** relationship, and a bacterial community existing within the surface mucous layer (SML), the coral tissue itself and its skeleton. This is very similar to the human **holobiont** that has its own unique and critical gastrointestinal mucosal microbiota which produces essential vitamins and amino acids not otherwise available to the human host. The coral SML contains a complex microbial community that responds to changes in the environment in ways that we are just now beginning to appreciate (46,47). The normal microbial flora within the mucus layer may protect the coral against pathogen invasion, and disturbances in this normal flora could lead to disease (48). The massive introduction of non-indigenous pathogens, which may occur with aquaculture and ballast water release, could also disturb the microbial community (16).

1.5 What is our current state of knowledge?

The current, and rather urgent, focus of research is the biology of microorganisms that can be pathogenic to corals. We are working diligently to develop new molecular and biomedical tools to identify specific agents and their origins, and determine the role of these agents in causing disease in corals. In **Figure 1.4**, we present five diseases with documented causal agents. The process by which causation is verified is explained in detail in **Chapter 3**. Undoubtedly as we learn more, we will continue to find that certain diseases may be caused by more than one microorganism, though whether this may be a matter of location, seasonality or other environmental parameters is unknown. For instance, the species comprising the microbial consortium associated with black band disease appears to vary with different geographic locations (49). Similarly, there is evidence that Caribbean yellow band disease (YBD) is caused by a consortium of bacteria (50). Because of inherent difficulties in the process, proving causation may be based on relatively few corals or disease events. For example, the demonstration of causation for both white plague type II and white patch disease are based on tests of relatively few corals, each from a single location or outbreak event. Our vision is that coral disease managers will eventually be equipped with molecular diagnostics to reliably verify the identity of a given infectious micro-organism. Thus the process of continuing to verify these agents is important (51).

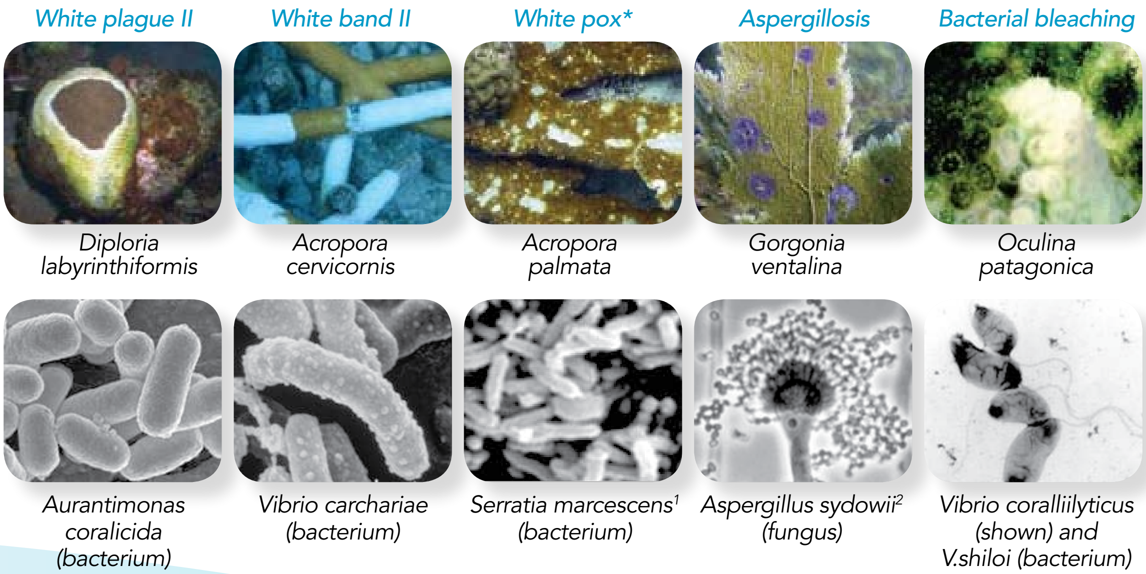

Figure 1.4 The five coral diseases for which Koch's postulates have been fulfilled, showing disease, host coral and microbial pathogen. The classic way to prove a microorganism causes disease is to satisfy Koch's postulates. A microorganism must be isolated from a diseased individual. That "isolate" is then used to infect a healthy individual. The same disease must develop, and the same organism must be isolated from the new infection. This classic method is a tough challenge in the face of unculturable marine microorganisms and polymicrobial syndromes, requiring molecular approaches.

*Originally named white pox, but field signs for this disease are now termed "white patch disease"; this name will be used in this book.

[1] source: http://commtechlab.msu.edu/sites/dlc-me/zoo/microbes/serratia.html

[2] source: http://www.cdc.gov/ncidod/dbmd/mdb/images/aspergillos.JPG

Harvell et al. (26). Photos by: A. Bruckner and E. Weil.

The last decade has been a time of intense research into causative agents of coral disease. Though we still lack evidence showing the origin of any coral disease, the role of specific pathogens in causing various diseases, their pathogenesis, and agent-host interactions, significant progress is being made in all of these areas. Some infectious agents that cause disease in marine animals, such as that of aspergillosis of **octocorals** (**Figure 1.5**) and toxoplasmosis in sea otters, are thought to originate on land.

Figure 1.5 Caribbean sea fan *Gorgonia ventalina* with multiple aspergillotic lesions. Photo: E.Weil

Others, such as viruses inadvertently introduced from shrimp or abalone farms to wild populations (McCallum, pers. comm.), originate in aquaculture farms (16). Tracking the origins of pathogenic agents might reveal sources that can be controlled before being introduced into the ocean. For example, *Serratia marcescens* is a ubiquitous bacterium introduced into coastal waters via sewage that may be the cause of white patch, a disease that affects *Acropora palmata* (52). There is a very real risk, therefore, that human activities may inadvertently introduce environmental stressors and potential pathogens to marine communities, and will continue to do so unless our understanding of such dynamics improves.

1.6 What are the global patterns and where are the hotspots?

The Caribbean has been referred to as a "hot spot" for disease because of a rapid emergence of new, extremely virulent diseases, increased frequency of **epizootic** events, and rapid spread of emerging diseases among new species and regions. At least 82 percent of coral species in the Caribbean are host to at least one disease (21).

In the Pacific, the threat of coral diseases has been regarded as minor, due to the large distances between reefs and island nations, fewer potential sources of pathogens, a paucity of epizootiological studies and few recorded outbreaks. However, there were relatively few comprehensive detailed studies of coral disease in the Pacific prior to 2000, and most available information came from a handful of locations and researchers. As efforts increase to document coral diseases from more locations within the Pacific, the lists of species affected by disease, locations where diseases are reported, and **prevalence** of those diseases, are steadily increasing. It is now apparent that certain sites in the Pacific show a rather high prevalence of disease, and reports of outbreaks that kill a large number of colonies in a relatively short time suggest that the threat of disease impacts can no longer be considered minor.

1.7 What do we know about environmental drivers and stress?

An understanding of the influence that the environment plays in disease outbreaks could guide the development of useful management strategies (**Figure 1.6**). In this section, we summarize what is known about the relationship between particular environmental drivers and disease outbreaks. As with most aspects of the management of infectious disease in a marine setting, it is a work in progress and it is critical to keep in mind that all infectious syndromes are different and may respond in different ways to environmental change. However, identifying the factors that control the most important infectious syndromes is a key management strategy.

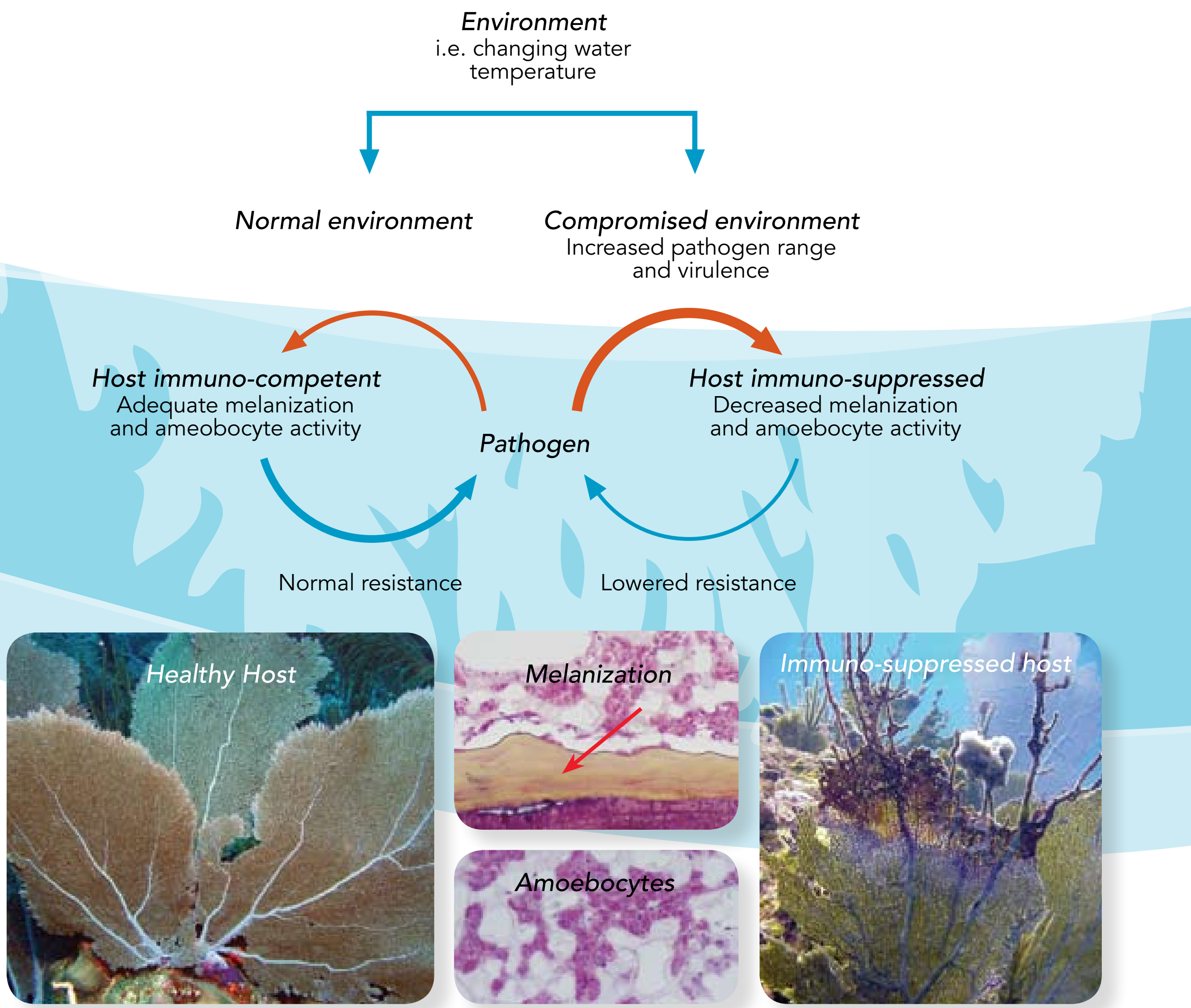

Figure 1.6 A schematic model showing the effect of an environmental impact – changing temperature – on a gorgonian coral infected by fungus. The healthy octocoral on the left is immuno-competent and is thus able to mount a normal immune response (melanization and amoebocyte activity). The diseased and dying octocoral on the right shows decreased melanization and suppressed amoebocyte activity, and is thus susceptible to attack by microorganisms. Modified from Mydlarz et al. (53). Photos by: C Couch and E. Weil.

Temperature

Outbreaks of some diseases are enhanced by ocean warming anomalies. An increase in disease following warming events may occur because corals are less able to fight disease while under temperature stress, or because pathogens are more virulent at higher temperatures. In three known cases where the pathogen can be cultured separately (*Aspergillus sydowii, Vibrio shiloi and Vibrio coralliilyticus*), pathogen growth and/or virulence increased with rising temperature, up to an optimal temperature (45,54-57).

Seasonal patterns in disease prevalence in the northeastern Caribbean provide further support for a link between warming ocean waters and disease outbreaks. Recurrent outbreaks of two virulent and damaging diseases, white plague and yellow band, have developed during seasons of highest water temperatures for the past four years on Puerto Rican reefs (Weil unpubl. data; Hernández-Delgado unpubl. data) and in the US Virgin Islands (42,58). Immediately following the peak of the 2005 bleaching event, the most devastating recorded in the North-eastern Caribbean, outbreaks of white plague, yellow band and white patch (32) were even more extensive in these areas and some outbreaks continued through 2007.

On the Great Barrier Reef, coral disease prevalence increased from winter to summer in all major families of coral (33). Prevalence increased fifteen-fold in acroporids, twelve-fold in faviids and doubled in pocilloporids in summer surveys. In addition, prevalence of three coral diseases increased significantly in summer surveys, with skeletal eroding band increasing more than two-fold, black band and other cyanobacterial infections more than three-fold, and white syndrome more than 50-fold.

Further work to document a link with temperature was carried out using disease prevalence surveys spanning 500 km of a latitudinal gradient along the Great Barrier Reef. In 1998, the Australian Institute of Marine Science's Long-Term Monitoring Program began to systematically monitor white syndrome (WS), which affects more than 15 coral species, including dominant plating acroporids. Divers conducted annual coral disease surveys on 47 reefs from 1998 to 2004 to quantify the number of cases of WS. Using a weekly four km data set of temperature values derived from the NOAA AVHRR Pathfinder (a radiation-detection imager that can determine sea surface temperature), a significant relationship was detected between the frequency of warm temperature anomalies and the **incidence** of white syndrome, indicating a relationship between temperature and disease. Interestingly, this relationship also depended on a high degree of coral cover, as would be expected for **transmission** of an infectious agent between hosts (23).

Links between outbreaks or increasing prevalence and warm temperature have thus been detected for black band disease, aspergillosis, yellow band disease, white patch disease and white syndrome. The list will likely grow as the data set expands. We still need to understand the mechanism operating in each syndrome: can we distinguish whether increased disease transmission during ocean warming is caused by compromised host **immunity** or the expansion of geographic range of microorganisms? Understanding these dynamics should aid in developing management strategies during periods of stressful temperatures.

Water Quality

As human populations continue to increase, nutrients, terrigenous silt, pollutants and even pathogens themselves can be released into nearshore benthic communities (59). While the link between anthropogenic stress and disease susceptibility is currently poorly understood, one hypothesis is that coral disease is facilitated by a decrease in water quality, particularly due to eutrophication and sedimentation. It is an urgent management priority to understand the link between water quality and infectious coral disease, because this is a local factor we can have some hope of managing.

Although corals are able to grow in high-nutrient water (60), recent evidence suggests a synergistic effect between elevated nutrients and disease. High nutrients (N, P) were associated with accelerated disease **signs** in both yellow band disease- and aspergillosis-infected corals in field manipulations (61), and in black band disease (62), although high nutrients alone were not associated with increased tissue loss in healthy corals. This is consistent with the findings of Kuntz et al. (63) who observed rapid tissue shedding in healthy corals exposed to elevated carbon sources, but little effect on corals of elevated N and P. Thus, corals seem to thrive under high nutrient conditions, but the combination of an active infection and elevated nutrients increases the disease **progression** rates of some syndromes. It is unclear whether this effect is due to an impact on host **resistance** or a positive effect on pathogen growth or virulence.

Figure 1.7 Tissue loss in a massive *Porites* in Palau caused by silt deposition. Photo: A. Croquer

Sedimentation offers yet another challenge to host disease resistance. The impacts of terrigenous sedimentation on nearshore communities are visible and well-documented; corals inhabiting silted reefs often possess large patches of dead, exposed skeleton bordered by apparently receding margins of healthy tissue (**Figure 1.7**). While coral tissue mortality was previously assumed to be the result of direct smothering, microbial agents may also contribute. Early work by Hodgson (64) identified silt-associated bacteria as a possible cause for **necrosis** in sediment-damaged corals, as antibiotic-treated water reduced the amount of tissue damage in experimentally-silted corals. More recently, opportunistic terrestrial pathogens (the soil fungus *Aspergillus sydowii* and the human enterobacterium *Serratia marcescens*) have been demonstrated as causal agents for two diseases currently impacting dominant corals in the Caribbean (52,65). Thus, terrigenous silt may not only cause physical stress for shallow, benthic organisms such as corals, but may also act as a pathogen **reservoir**.

This evidence suggests that anthropogenic stressors are linked with disease **severity** in complex ways. It is important to establish and quantify such linkages, as these factors may be possible to mitigate via improved reef management and land-use practices. The challenge lies in demonstrating these linkages in the complex system of diverse stressors acting upon the coral holobiont.

Box 1.1

Coral Reef Targeted Research: The Coral Disease Working Group

A Global Environment Facility/ World Bank initiative, the Coral Reef Targeted Research and Capacity Building for Management Program created six working groups to address the current alarming rate of reef decline by improving gaps in our knowledge of coral reef management (see www.gefcoral.org). As the Coral Disease Working Group for this project, the goals of our program are to fill critical information gaps about infectious coral reef disease, build capacity to study and monitor disease internationally, and help develop solutions for managing and conserving reef ecosystems. The cooperative research efforts are guided by our international team of microbiologists, ecologists and physiologists towards these ends. Working out of four Centers of Excellence, our research priorities include:

- assessing the global prevalence of coral disease;
- investigating the environmental drivers of disease;
- identifying the pathogens that cause disease; and
- understanding the coral's ability to resist disease.

We are also testing specific hypotheses about climate and anthropogenic changes that threaten coral reef sustainability. By building the capacity to manage these ecosystems, we hope to enhance reef resilience and recovery, worldwide.