DISEASE IN TROPICAL CORAL REEF ECOSYSTEMS

UNEP WCMC ICRI

Key Messages on Coral Disease

Disease in Tropical Coral Reef Ecosystems
ICRI Key Messages on Coral Disease

There is a clear consensus from the growing scientific literature that large-scale coral disease outbreaks represent a significant threat to the productivity and diversity of coral reef ecosystems. Global climate change has the potential to greatly increase the prevalence of coral disease worldwide, leading to a rise in associated coral mortality. This introductory guide aims to inform policy and decision-makers worldwide about the alarming emergence and progression of disease throughout coral reef ecosystems, the possible interactions of disease with other environmental influences causing stress to reef ecosystems, as well as appropriate management responses promoted by the international community.

UNEP WCMC

ICRI

CITATION
ICRI/UNEP-WCMC (2010). Disease in Tropical Coral Reef Ecosystems: ICRI Key Messages on Coral Disease. 11pp.

ONLINE GUIDE AND FURTHER INFORMATION
A copy of this guide, as well as further information on coral disease, can be found on the website of the Global Coral Disease Database (GCDD): **www.coraldisease.org**

CONTRIBUTORS
Produced by UNEP-WCMC, Cambridge, United Kingdom

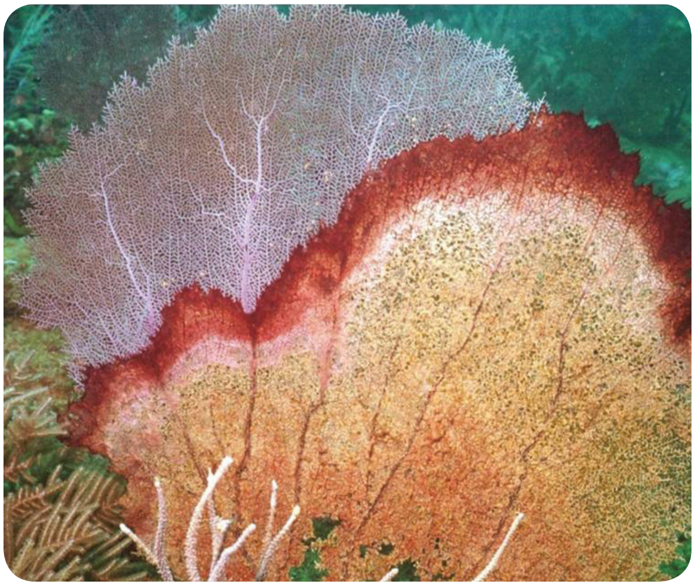
Prepared by Nicola Barnard and Christel Scheske, with generous support from the members of the ICRI *Ad Hoc* Committee on Coral Disease: Jan-Willem von Bochove, Angelique Brathwaite, Dave Gulko, Anthony Hooten, and Michael Schleyer. Additional inputs were provided by members of the GEF Coral Reef Targeted Research Disease Working Group: Laurie Raymundo and Ernesto Weil.

Design and layout by Dan Shurey

Quality Assurance
This guide has been produced with financial support from the US Department of State. It draws upon a body of work already available on coral disease, but is not a comprehensive review of the existing literature. Input was provided by leading researchers on the scientific content of the report. We wish to thank all those involved for taking the time to develop this guide.

1. INTRODUCTION

Tropical coral reef ecosystems around the world are increasingly at risk from numerous anthropogenic stresses and natural factors (Wilkinson, 2008). In particular, coral disease outbreaks are having a significant, negative impact on the structure and appearance of coral reefs, and have contributed to unprecedented declines in live coral cover and productivity of coral reef ecosystems upon which many millions of people depend (Galloway et al. 2009).



1. ©Bruckner AW: Sea fan with red band disease

What is coral disease?

Coral disease is defined as *an abnormal condition of an organism that impairs organism functions, associated with specific symptoms and signs* (adapted from Wobeser 1981). It may be caused by external factors, such as infectious disease (discussed here), or it may be caused by internal dysfunctions.

Why is coral disease important?

As a natural aspect of populations, background levels of disease exist in all healthy reef ecosystems. However, it is increasingly accepted that infectious diseases caused by microbial agents are a major contributor to coral reef decline, and an occurrence of disease greater than would be expected in a given time or place (an outbreak) presents serious concerns for managers and stewards of tropical marine ecosystems.

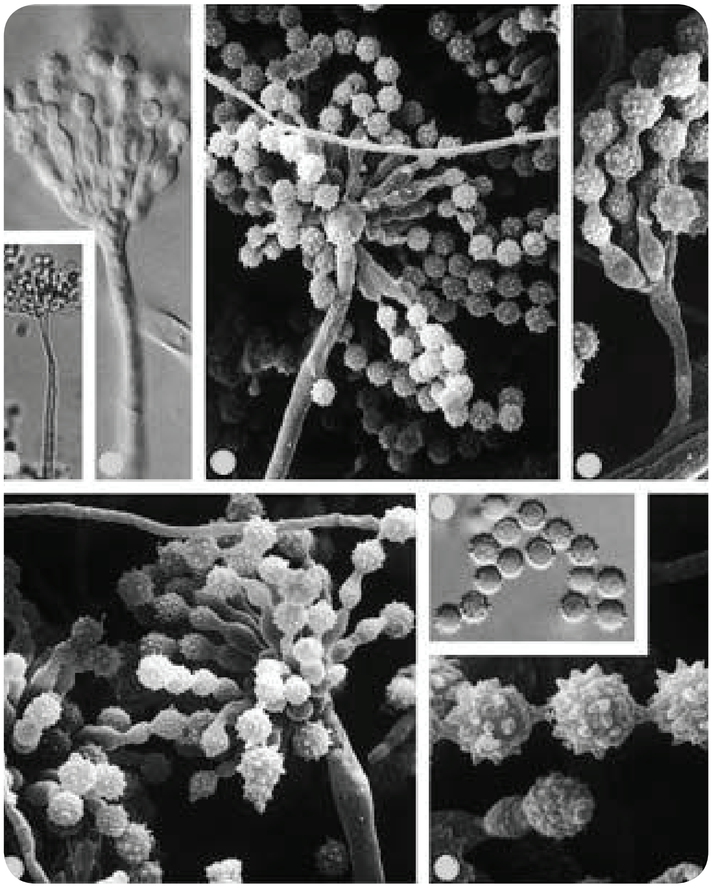
Several diseases are playing an increasingly important role in controlling coral population size, diversity and demographic characteristics (Galloway et al. 2009). Large scale disease outbreaks have already fundamentally altered the structure of reef communities in the Caribbean (Harvell et al. 2004). Critically, coral diseases threaten the major reef building coral species on which the structure and function of the reef ecosystem depends, with the potential to further reduce the productivity and diversity of vulnerable coral reef ecosystems. The number and distribution of tropical coral diseases appear to be on the rise (Sokolow, 2009). As such, coral disease is an increasingly important field of study from both a regional and international resource management perspective.

A growing body of research has moved studies of coral disease incidence, spread and prevalence towards more advanced assessments of the microbial characteristics of diseased corals and pathogens (Ainsworth et al. 2007). Further knowledge is being assimilated to better understand the inter-relationships of climate change, pervasive natural and man-made stressors and disease (Harvell et al. 2004; Harvell et al. 2002; Sokolow 2009). However, our ability to address the recent increases in coral disease is compromised by an incomplete understanding of the causal agents and mechanisms responsible for diseases and their consequences, and few diagnostic tools to help managers evaluate and manage diseases (Galloway et al. 2009).

2. WHAT DO WE KNOW ABOUT CORAL DISEASES?

2. ©Keshavmurthy S: Ciliates, having consumed zooxanthellae

3. ©Salvatorelli G: *Serratia marcescens*, associated with white patches disease



4. ©Hoog GS: *Aspergillus sydowii*, the fungus associated with aspergillosis

Research on the causes of coral disease has increased in recent years, especially in terms of identifying the pathogens involved (Harvell et al. 2007). Most biotic coral diseases are believed to be related to infection by one or a group of pathogens (Sokolow 2009). A host of contributing microorganisms (Richardson and Aronson 2000) and macroparasites such as ciliates (Cróquer et al. 2006) have been identified as possible causal agents. Little is currently known about the involvement of viruses (Sokolow 2009).

The causative pathogen-disease relationship has been identified for six of the coral diseases discovered so far (see Table 1). While the majority apply to diseases in the Caribbean or Red Sea, advances have been made to establish the role of ciliates as causative agents in skeletal eroding band (Winkler 2004) and some white syndromes in the Indo-Pacific.

Disease and location	Pathogen	Coral host
Bleaching (Eastern Mediterranean)	*Vibrio shiloi*	*Oculina patagonica*
Bleaching and lysis (Indian Ocean and Red Sea)	*Vibrio coralliilyticus*	*Pocillopora damicornis*
Aspergillosis (Caribbean)	*Aspergillus sydowii*	Gorgonians (sea fans)
White band disease (Caribbean)	*Vibrio carchariae*	*Acropora spp.*
White plague (Caribbean)	*Aurantimonas coralicida*	Several
White plague (Red Sea)	*Thalassomonas loyana*	Several
White patches (Caribbean)	*Serratia marcescens*	*Acropora palmata*
Yellow band disease (Caribbean and Red Sea)	Four *Vibrio spp.*	*Montastrea spp.*
Black band disease (widespread)	Consortium	Several

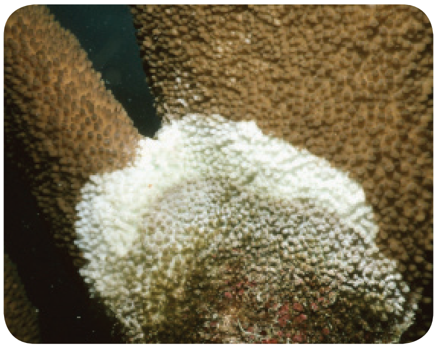
Table 1: Known coral pathogens (adapted from Rosenberg et al. 2007)

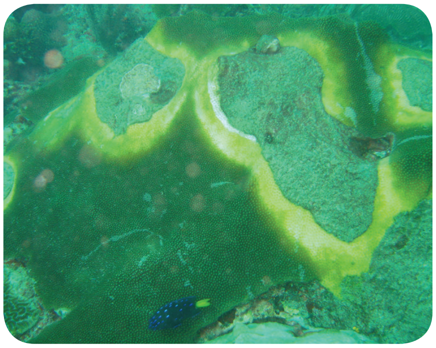
Vectors and pathways of coral disease

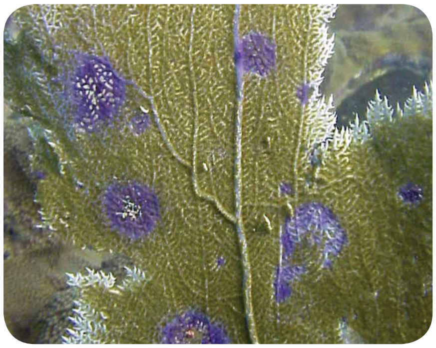
Knowledge of organisms that transmit pathogens from a reservoir to a host (vectors), the mechanisms by which coral disease is transmitted between organisms (vector pathways), and natural reservoirs of coral disease is far from complete. Terrestrial runoff, dust, waste-water, and ballast from ships may act as reservoirs for pathogens (Ritchie 2006). Studies indicate that dust originating from Africa may transport the fungus causing Aspergillosis in sea fans in the Caribbean (Ritchie 2006). Macroalgae have also been suggested as a possible reservoir of pathogens causing coral disease (Aronson and Precht, 2006). Corallivorous fish (Page et al. 2009), and other coral predators such as gastropods (Boyett et al. 2007; Weil 2004) have been suggested as common vectors of disease. A confirmed vector of coral disease, transmitting the bacterium associated with some types of coral bleaching, is the fireworm, *Hermodice carunculata* which feeds on coral tissues (Rosenberg et al. 2007).

5. ©Moya JA: The fireworm, *Hermodice carunculata*


6a. ©Evans D: BBD


6b. ©Bruckner AW: WBD


6c. ©Coral Cay Conservation: YBD


6d. ©Weil E: ASP


6e. ©Garrison G: WP


6f. ©Porter J: White patches

Diseases of particular concern in the Western Atlantic (Bruckner AW 2009): Black band disease (BBD, [6a]), white band disease (WBD, [6b]), yellow band disease (YBD, [6c]), aspergillosis (ASP, [6d]), white plague (WP, [6e]) and white patches ([6f]).

What is happening now?

Western Atlantic: In recent decades the Western Atlantic has become a 'hot spot' for coral disease (Weil 2004). Although only 8% of all coral reefs (by area) are found in the Caribbean, over 70% of all disease reports come from this region (Harvell et al. 2007). Remote reefs off southwest Puerto Rico for example, have experienced losses in live coral cover between 30-80% in the past decade, primarily due to the decline of dominant reef-building species (*Montastrea annularis* and *M. faveolata*) from disease and bleaching (Bruckner and Hill 2009). Similar alarming trends of coral mortality due to disease have been detected in Curacao (Bruckner AW and Bruckner RJ 2006). The recent discovery of diseases in the Caribbean previously thought to exist only in the Red Sea and Indo-Pacific regions, such as some diseases related to ciliates (Cróquer 2006), raises concerns of an increasing future threat from disease in this region.

Indo-Pacific: A number of studies indicate that disease prevalence in areas of the Indo-Pacific region, American Samoa (Aeby et al. 2009) and Hawaii (Aeby 2009) is currently quite low. However, reports of disease from new regions that were previously presumed to be unaffected (e.g. Solitary Islands, Australia), a higher percentage of reefs with disease, and recent increases in disease incidence in certain locations, indicate that across the region diseases appear to be exhibiting a rapid expansion in range and in types of disease since 2000 (Galloway et al. 2009). For instance, preliminary results of a large-scale assessment suggest that coral disease is now more widespread in the Great Barrier Reef than previously realized (Willis et al. 2009). In Indonesia, researchers observed that although total disease prevalence was low, disease progression rates were similar to those in the Caribbean, with the potential to undermine the reef framework in the isolated areas affected (Haapkylä et al. 2007; Haapkylä et al. 2009).

7. ©Spring S: Sewage outfall near a coral reef in Florida, severely decreasing water quality.

Based on the lessons learned from dealing with disease and the devastating effect disease has had in the Caribbean, coordinated and strategic preventative measures with a focus on maintaining overall ecosystem health need to be taken urgently in the Pacific region (Galloway et al. 2009). To achieve this, managers must engage more effectively with the active research community working to advance understanding of the regionally specific ecology, etiology, environmental stressors and epizootiology in relation to coral disease.

For a more in depth overview of global prevalence of coral disease by region, see Harvell et al. (2007).

What could happen in the future?

Non-infectious diseases caused by heat stress, toxins, toxicants and other agents can act in synergy with infectious diseases to further compromise coral reef health and threaten the longevity and productivity of vulnerable reef systems.

Several studies have shown that both corals and coral disease pathogens are sensitive to changes in ocean temperature. Warming sea surface temperatures encourage infectious disease by impairing the defense mechanisms of the coral host and by increasing the virulence or growth rate of disease-causing organisms (Boyett et al. 2007).

Seasonally warmer temperatures may also enable some diseases to expand their geographic ranges into previously unaffected reef areas. Global climate change therefore has the potential to greatly increase the prevalence of coral disease worldwide, leading to a rise in associated coral mortality.

Furthermore, degrading environmental quality and anthropogenic stress, for instance in the form of eutrophication and sedimentation, could potentially facilitate the spread and virulence of coral disease (Harvell et al. 2007). Regular monitoring of water quality parameters and environmental factors can indicate potential stressful conditions for corals and support the development of an early warning system for certain diseases (Raymundo et al. 2008).

The SYNERGISTIC Effects of Environmental Factors and Stress on Coral Disease

Growing evidence suggests that environmental and anthropogenic stressors are linked with coral disease and mortality in complex ways (Harvell et al. 2007) as described below.

Nutrient Enrichment: An overabundance of nutrients, particularly nitrogen and carbon compounds associated with terrestrial runoff and waste water, can enhance the progression of disease across a coral colony (Bruno et al 2003; Garren et al. 2008). Nutrient enrichment has been found to greatly increase the virulence of black band disease (Voss and Richardson 2006) and may similarly affect other coral diseases.

Ocean Acidification: Increased carbon dioxide concentrations in the atmosphere due to human activities cause a lowered seawater pH - an effect called ocean acidification. The change in the chemical makeup of the seawater is already impacting growth rates and calcification in some coral species, and is predicted to greatly increase stress on corals in the future, thereby making them more susceptible to disease (Sokolow 2009).

Algal Competition: There is evidence of widespread competition between algae and corals on reefs (McCook et al. 2001). Macroalgal overgrowth due to overfishing of herbivorous fish and a reduction in the numbers of echinoids, can suppress coral recruitment (e.g. Hughes et al. 2003), and some evidence suggests that macroalgae may harbor disease and thus act as disease reservoirs (Aronson and Precht 2006).

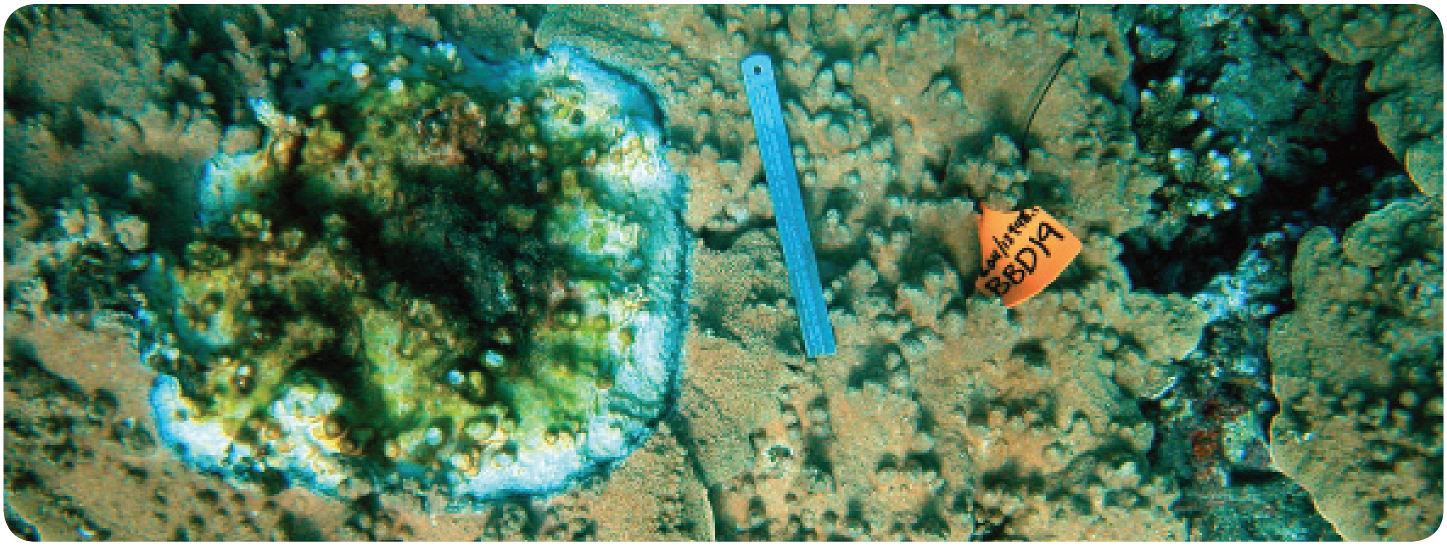
Irradiance: There are early indications that a complex combination of environmental factors, including irradiance levels and temperature, play key roles in the progression and transmission of disease. Boyett et al. (2007) suggest that high irradiance, in combination with elevated temperatures, may promote the progression of black band disease on the Staghorn coral, *Acropora muricata*, in the Great Barrier Reef.

Biodiversity: A mounting body of evidence indicates that the loss of biodiversity from an ecosystem tends to increase pathogen transmission and disease incidence by changing the abundance of the disease host or vector; the behavior of the host, vector or parasite; and/or the condition of the host or vector; thus giving weight to calls from the international community to increase the effectiveness of local, regional and global efforts to preserve natural ecosystems and the biodiversity they contain (Keesing et al. 2010).

Coral Disease and Marine Protected Areas

A study completed by the Coral Reef Targeted Research Disease Working Group has demonstrated a clear link between functionally diverse, species-rich fish communities and low coral disease prevalence. The study in the Philippines reveals that coral reefs within effectively-managed marine protected areas (where reef fish populations are protected from all harvesting and fishing activities) exhibit significantly lower levels of disease than adjacent coral reefs where fishing takes place. The study suggests that the reduction of fishing pressure on reef ecosystems, for example through the establishment and enforcement of marine protected areas, presents a promising approach to managing coral disease (Raymundo et al. 2009).

3. KNOWLEDGE GAPS



8. ©Weil E: Black band disease

Despite recognition of disease outbreaks as a major cause of mortality in reef-building corals worldwide, there are still considerable gaps in our knowledge and understanding of coral disease.

Naming disease

Researchers globally are working to create a common disease nomenclature system to allow for standardized naming of coral diseases. The uptake of agreed terms will facilitate collaboration between researchers, comparison between regions and the identification of disease causes. Much progress has been made in this area, and notable efforts include the *Coral Disease Handbook: Guidelines for assessment, monitoring & management* (Raymundo et al. 2008), as well as an overview of lesion identification by Work and Aeby (2006). Furthermore, simple field guides to common lesions in the Western Atlantic and Indo-Pacific and Red Sea regions detailing common lesion names, morphologic descriptions and representative photos are available from www.coraldisease.org.

Identifying disease

Coral disease identification is often based on visual cues observed in the field or from photographs. Such techniques have been shown to be insufficient for making accurate disease identifications (Ainsworth et al. 2007). This is because different causes of disease can result in similar obvious manifestations of disease, or progress from showing the signs of one disease to showing those of another (Ainsworth et al. 2007). Laboratory analyses of samples to identify the microbiological factors accompanying the disease manifestations, such as the presence or absence of certain pathogens, are therefore necessary to support accurate disease diagnosis.

Understanding pathogens and disease

There is limited knowledge of the cause of many diseases in coral, the origins of pathogens, life cycles, response to environmental factors such as temperature, or the range of coral species that they can infect (Harvell et al. 2004). To mitigate catastrophic and permanent loss of the dominant, slow-growing reef-building corals in the long-run, the causes and effects of diseases need to be

THE NEED FOR CAPACITY-BUILDING

A consensus among coral disease experts is that there is an urgent need for increased capacity-building in the area of coral disease research and monitoring, especially in the Indo-Pacific. Reef monitoring is both time and resource-intensive, and currently, the number of experts worldwide who have the necessary skills and knowledge to accurately identify coral disease is limited. Training modules and guidance tools, such as the *Coral Disease Handbook* (Raymundo et al. 2008), represent current efforts at disseminating such information. However, increased support for the development of workshops, training modules, and guidance tools would allow for a greater number of managers and researchers to contribute high-quality information to the field of coral pathology and disease management. This, in turn, is essential for a comprehensive, global monitoring system of coral disease, as well as the development and implementation of appropriate response and prevention measures.

better understood and communicated to resource managers, to support informed responses and the development of possible control mechanisms (Bruckner AW and Hill 2009).

Disease spread, vectors and vector pathways

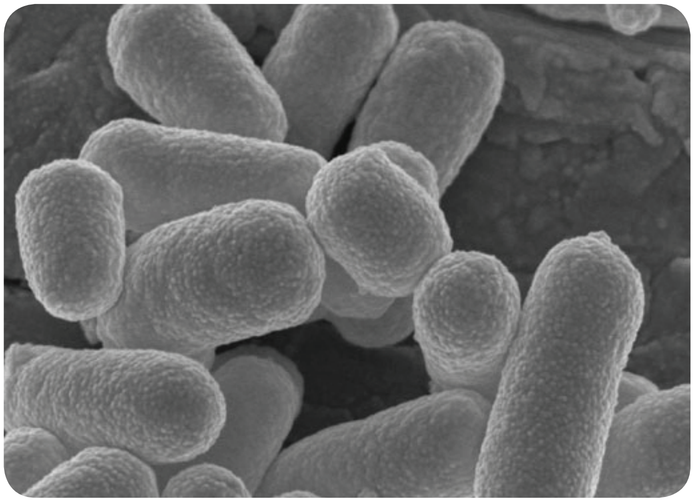
Although some possible origins and transmission modes of coral disease have been identified, this aspect of coral disease is poorly understood, and requires further research. The development of models to forecast the rate of spread of coral disease, and possible synergistic effects of environmental stressors, are vital for our understanding of the regional risks posed by a disease outbreak (Harvell et al. 2004).

Epidemiological models

There have been several recent attempts at creating spatial models of coral disease (e.g. Brandt and McManus, 2009; Sokolow et al. 2009; Williams et al. 2010). The results of these efforts indicate that environmental variables are crucial for a better understanding of coral disease, and that there is a highly variable response of diseases to these variables. There are fundamental differences between marine and terrestrial environments that make modeling of coral diseases particularly difficult. Compared to terrestrial environments, there is a greater diversity of hosts and pathogens in the ocean, the rates of transmission may be higher in marine systems, and marine hosts tend to be invertebrates with different immune system dynamics than vertebrates (Harvell et al. 2004).

Coral disease and human impacts on the environment

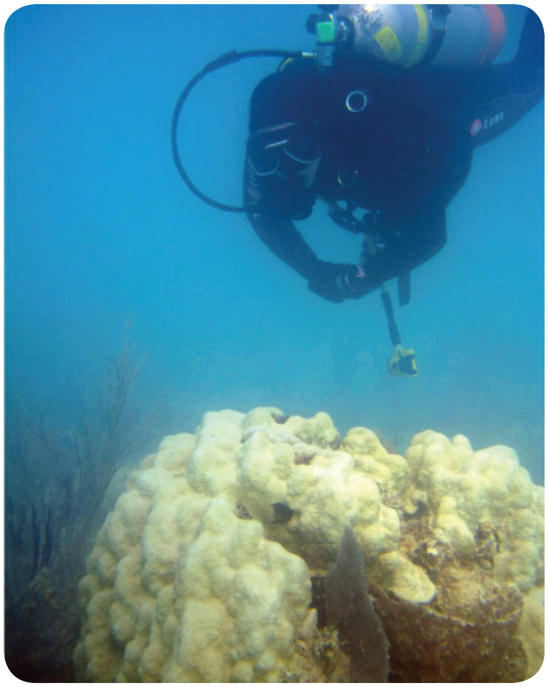
Knowledge of how anthropogenic impacts on the marine environment (e.g. climate change, pollution), influence coral disease dynamics is very limited. Available evidence points to a negative impact on the ability of corals to resist disease, and an increased virulence of disease pathogens as a result of human stressors. Management of coral disease requires increasing the resilience of coral reefs through improvements in water quality and biodiversity protection.



9. ©NOAA: A bacterial pathogen associated with white plague

4. MOVING FORWARD

Below are a series of actions increasingly called for by the management and research communities to respond more effectively to the growing issue of coral disease, build our collective understanding and reduce risk to coral reef ecosystems.


10. ©NOAA: Dead coral head

- Continue to support research efforts to determine causal agents, associated vectors and vector pathways, as well as the synergistic effects of environmental and human stressors on coral disease;

- Adopt and promote standardized protocols and metrics for the monitoring of coral health and disease, to enable greater interoperability and quality control of data and more accurate reporting on the global status of coral disease as a threat to critical ecosystems;

- Integrate coral disease observations into ongoing ecosystem monitoring efforts to establish scientifically robust baseline data on the background levels of coral disease within healthy ecosystems and to improve understanding of thresholds and triggers of disease outbreaks;

- Provide targeted training and long-term mentoring support for natural resource managers and researchers to improve in-situ observation of coral disease and data collection of critical characteristic signs and features;

- Implement steps to mitigate environmental and anthropogenic stressors that increase the spread and severity of disease, including improving sewage treatment, preventing soil erosion, and eliminating destructive fishing practices;

- Increase inter-disciplinary collaboration between key players such as research institutes, managers and modeling specialists, so as to maximally utilize different skill sets, develop better techniques for modeling and predicting coral disease outbreaks, and to improve access to facilities, technical knowledge and expertise;

- Maintain database/register of individuals and institutions working on coral diseases to facilitate interaction between these parties;

- Support regular reporting of coral disease data to the Global Coral Disease Database (GCDD), an online tool that allows users to collate, store, manage and view spatially explicit global coral disease data. Visit: www.coraldisease.org

5. REFERENCES

Aeby G (2009). Baseline levels of coral disease in the Northwestern Hawaiian Islands. In: Galloway SB, Bruckner AW, Woodley CM (eds). Coral health and disease in the Pacific: Vision for action. Silver Spring, MD: NOAA Technical Memorandum NOS NCOOS 97 and CRCP 7 National Oceanic and Atmospheric Administration, 168-188.

Aeby G, Work T, Didonato, E (2009). Coral and crustose coralline algae disease on the reefs of American Samoa. In: Galloway SB Bruckner AW, Woodley CM (eds). Coral health and disease in the Pacific: Vision for action. Silver Spring, MD: NOAA Technical Memorandum NOS NCOOS 97 and CRCP 7 National Oceanic and Atmospheric Administration, 190-213.

Ainsworth TD, Kramasky-Winter E, Loya Y, Hoegh-Guldberg O, Fine M (2007). Coral disease diagnostics: What's between a plague and a band? Appl Environ Microb, 73(3), 981-992.

Aronson RB, Precht WF (2006). Conservation, precaution, and Caribbean reefs. Coral reefs, 25(3), 441-450.

Boyett HV, Bourne DG, Willis BL (2007). Elevated temperature and light enhance progression and spread of black band disease on staghorn corals of the Great Barrier Reef. Mar Biol, 151(5), 1711-1720.

Brandt ME, McManus JW (2009). Dynamics and impact of the coral disease white plague: insights from a simulation model. Dis Aquat Organ, 87, 117-133.

Bruckner AW, Bruckner RJ (2006). The recent decline of Montastraea annularis (complex) coral populations in western Curacao: A cause for concern? Int J Trop Biol, 54(3), 45-58.

Bruckner AW (2009). The global perspective on incidence and prevalence of coral Diseases. In: Galloway SB, Bruckner AW, Woodley CM (eds). Coral health and disease in the Pacific: Vision for action. Silver Spring, MD: NOAA Technical Memorandum NOS NCOOS 97 and CRCP 7 National Oceanic and Atmospheric Administration, 90-121.

Bruckner AW, Hill RL (2009). Ten years of change to coral communities off Mona and Desecheo Islands, Puerto Rico, from disease and bleaching. Dis Aquat Organ, 87, 19-31.

Bruno JF, Petes LE, Harvell CD, Hettinger A (2003). Nutrient enrichment can increase severity of coral diseases. Ecol Lett, 6(12), 1056-1061.

Carpenter KE, Abrar M, Aeby GS, Aronson RB, Banks S, Bruckner AW et al. (2008). One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science, 321(5888), 560-3.

Cróquer A, Bastidas C, Lipscomp D, Rodriguez-Martinez RE, Jordan-Dahlgren E, Guzmán HM (2006). First report of folliculinid ciliates affecting Caribbean scleractinian corals. Coral Reefs, 25(2), 187-191.

Galloway SB, Bruckner AW, Woodley CM (eds) (2009). Coral health and disease in the Pacific: Vision for action. NOAA Technical Memorandum NOS NCCOS 97 and CRCP 7. National Oceanic and Atmospheric Administration, Silver Spring, MD, 314 pp.

Garren M, Smriga S, Azam F (2008). Gradients of coastal fish farm effluents and their effects on coral reef microbes. Environ Microb 1(9), 2299-2312.

Gawel MJ (2009). Overview of issues unique to the Pacific: Biological and social perspectives. In: Galloway SB, Bruckner AW, Woodley CM (eds). Coral health and disease in the Pacific: Vision for action. Silver Spring, MD: NOAA Technical Memorandum NOS NCOOS 97 and CRCP 7 National Oceanic and Atmospheric Administration, 162-167.

Haapkylä J, Seymour AS, Trebilco J, Smith D (2007). Coral disease prevalence and coral health in the Wakatobi Marine Park, south-east Sulawesi, Indonesia. J Mar Biol Assoc UK, 87(2), 403-414.

Haapkylä J et al. (2009). Spatio-temporal coral disease dynamics in the Wakatobi Marine National Park, South-East Sulawesi, Indonesia. Dis Aquat Organ, 87, 105-115.

Harvell, D Aronson RB, Baron N, Connell J, Dobson AP, Ellner S et al. (2004). The rising tide of ocean diseases: unsolved problems and research priorities. Fron Ecol Environ, 2(7), 375-382.

Harvell CD, Jordan-Dahlgren E, Merkel S, Rosenberg E, Raymundo L, Smith G, Weil E, Willis B (2007). Coral disease, environmental drivers and the balance between coral and microbial associates. Oceanography, 20(1), 173-195.

Harvell D, Mitchell CE, Ward JR, Altizer S, Dobson AP, Ostfeld RS et al. (2002). Climate warming and disease risks for terrestrial and marine biota. Science (New York, N.Y.), 296(5576), 2158-62.

Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C et al. (2003). Climate change, human impacts, and the resilience of coral reefs. Science, 301(5635), 929-933.

Keesing F, Belden LK, Daszak P, Dobson A, Harvell CD, Holt RD et al. (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. Nature, 468, 647-652.

McCook L, Jompa J, Diaz-Pulido G (2001). Competition between corals and algae on coral reefs: a review of evidence and mechanisms. Coral Reefs, 19(4), 400-417.

Page CA, Baker DN, Harvell D, Golbuu Y, Raymundo L, Neale SJ et al. (2009). Influence of marine reserves on coral disease prevalence. Dis Aquat Organ, 87, 135-150.

Raymundo LJ, Couch CS, Harvell CD (eds) 2008. Coral disease handbook: Guidelines for assessment, monitoring and management. Coral Reef Targeted Research and Capacity Building for Management Program. University of Queensland, Centre for Marine Studies, St Lucia QLD, Australia. www.gefcoral.org 121 pp.

Raymundo LJ, Halford AR, Maypa A, Kerr AM (2009). Functionally diverse reef-fish communities ameliorate coral disease. PNAS 106(40), 17067-17070.

Richardson LL, Aronson RB (2000). Infectious diseases of reef corals. Proceedings 9th International Coral Reef Symposium, Bali, Indonesia, 2, 6 pp.

Ritchie KB (2006). Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. Mar Ecol-Prog Ser, 322, 1-14.

Rosenberg E, Koren O, Reshef L, Efrony R, Zilber-Rosenberg I (2007). The role of microorganisms in coral health, disease and evolution. Nat Rev Microbiol, 5(5), 355-362.

Sokolow S (2009). Effects of a changing climate on the dynamics of coral infectious disease: a review of the evidence. Dis Aquat Organ, 87, 5-18.

Sokolow S, Foley P, Foley JE, Hastings A, Richardson LL (2009). Editor's choice: Disease dynamics in marine metapopulations: modelling infectious diseases on coral reefs. J Appl Ecol, 46(3), 621-631.

Voss JD, Richardson LL (2006). Nutrient enrichment enhances black band disease progression in corals. Coral Reefs, 25(4), 569-576.

Weil E (2004). Coral reef diseases in the wider Caribbean. In: Rosenberg E, Loya Y (Eds). Coral Health and Disease. Berlin: Springer-Verlag, 25-68.

Wilkinson C (2008). Status of coral reefs of the world: 2008. Townsville, Australia: Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre.

Williams GJ, Aeby GS, Cowie ROM, Davy SK (2010). Predictive modeling of coral disease distribution within a reef system. Plos One, 5(2).

Willis B, Page C, Bourne D et al. (2009). Coral disease on the Great Barrier Reef and in the Western Pacific. In: Galloway SB, Bruckner AW, Woodley CM (eds). Coral health and disease in the Pacific: Vision for action. Silver Spring, MD: NOAA Technical Memorandum NOS NCOOS 97 and CRCP 7 National Oceanic and Atmospheric Administration, 234-241.

Winkler R, Antonius A, Renegar DA (2004). The skeleton eroding band disease on coral reefs of Aqaba, Red Sea. Mar Ecol, 25, 129–144.

Wobeser GA (1981). Diseases of wild waterfowl. New York, NY: Plenum Press.

Work TM, Aeby GS (2006). Systematically describing gross lesions in corals. Dis Aquat Organ, 70, 155-160.

PHOTO CREDITS

Front cover, top: ©Dan Shurey; Front cover, bottom: ©NOAA