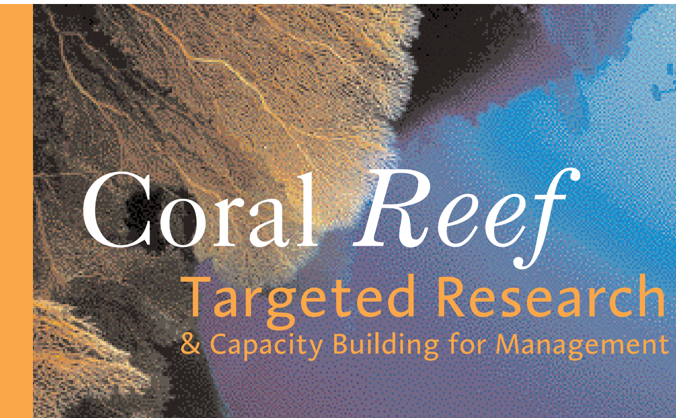

Distribution, causes and impacts of coral disease worldwide.

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Background

Over the last 20 years, coral reefs have been under increasing stress from natural and anthropogenic causes, including climate warming, poor water quality and over-fishing (Hoegh-Guldberg, 2003; Bryant, et al., 1998). Coral cover has declined significantly, particularly in the Caribbean (Green & Bruckner 2000, Richardson & Aronson 2002). Over this same period, an unprecedented increase in coral disease has contributed significantly to the loss of coral (Porter, et al., 2001; Harvell, et al., 2002). Disease outbreaks cause not only coral loss, but they can cause significant changes in community structure, species diversity and abundance of reef-associated organisms. While diseased-related damage of coral reefs has been well documented in the Caribbean (Jordan-Dahlgren & Rodriguez-Martinez 2003; Weil, 2003) the status of disease throughout the Indo-Pacific is largely unknown. Preliminary surveys in Australia (Willis, et al., 2004), the Philippines (Raymundo, et al., 2003), and E. Africa reveal significant and damaging new diseases in all locations surveyed.

What has prompted this rapid emergence of coral disease? Current research supports a connection between climate warming and increased incidence of disease (Harvell et al. 2001, 2002). Disease outbreaks are threshold phenomena associated with warming environments in many ecosystems, but coral reefs are among the most susceptible due to a very narrow thermal threshold for coral health (Harvell et al., 2002). The coral bleaching observed worldwide following the 1998 El Nino was the most massive and devastating ever recorded (Hoegh-Guldberg 1999). In this case, opportunistic pathogens may have accelerated the death of some coral.

Deteriorating environmental conditions could influence disease by altering host/pathogen interactions. For example, ocean warming could affect basic biological and physiological properties of coral, thus influencing the balance between opportunistic pathogens and the coral's ability to fight them (Harvell et al. 2002; Rosenberg & Ben-Haim, 2002, Ben-Haim et al. 2003).

Environmental factors could also alter the surface mucous layers (SML) of coral organisms (Ritchie & Smith 2003). These mucous layers harbor a normal microbial flora that protects the coral against pathogen invasion. Once disturbed, this layer may not protect as well. Other stresses include nutrient loading, which could enhance pathogen growth, and sedimentation, which could decrease coral resistance.

Little is known about the organisms that cause disease in coral. Of the 30 or so disease syndromes described, the infectious agent is known for only 5 (see Sutherland, et al. 2004). Reservoirs have only been identified for black band disease (Cooney, et al. 2002) and aspergilliosis (Shinn, et al. 2000). The only vector know is the fireworm (*Hermodice carunculata*) which harbors a bacterium that induces bleaching (Susman, et al. 2003).

As disease plays an increasing role in changing the structure and function of some coral reefs, we need to consider how management actions influence outbreaks. Exploring even basic questions is hampered by 1) the global nature of the problem; 2) overall lack of resources; and 3) a lack of expertise and technology in developing countries where many reefs are located. In response, the Coral Disease Working Group has been inaugurated as part of a World Bank/GEF global initiative. The goal of our program is to fill critical information gaps about coral reef disease to assist in the development of management and conservation strategies

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that protect reef ecosystems from damage due to disease.
This cooperative research effort is led by a team of internationally known microbiologists, ecologists and physiologists. We will test specific hypotheses regarding climate and anthropogenic changes threatening coral reef sustainability. By building the capacity to manage these ecosystems, we hope to enhance reef resilience and recovery, worldwide.

Major Areas of Research

The Global Assessment

The Global Assessment is designed to catalogue disease syndromes worldwide for the first time and reveal whether disease outbreaks are correlated with climate warming anomalies. There is evidence for this in the mass mortality of the gorgonian coral *Briareum asbestinium* following the 1998 El Nino event (Harvell et al. 2001). An increase in disease following warming events may be because corals are less able to fight disease while under temperature stress, or because bacteria are more virulent. In at least three cases, (*Aspergillus sydowii, Vibrio shiloi,* and *Vibrio corallilyticus*) pathogen growth and/or virulence factors increase to an optimal temperature (Alker et al. 2001; Isrealy-Tomar et al. 2001; Banin, et al. 2000).

While correlations between poor water quality (nutrient loading and sedimentation) and disease prevalence are of growing concern, evidence of direct links and synergistic effects are limited (Kuta and Richardson 2002; Porter et al., 2001; Bruno et al, 2003). This survey will explore the interactions between anthropogenic stressors and disease load.

Hypothesis 1: Coral disease prevalence correlates globally with warming trends.
Hypothesis 2: Coral disease prevalence correlates regionally with changes in climate and environmental quality.
Hypothesis 3: Disease prevalence and changes in coral mucous communities correlate locally with point source inputs.

RESEARCH STRATEGIES: At each site, we will measure nitrogen and sediment loading. We will compare sites with different nutrient and sediment loadings and will assess changes in microbial communities in healthy and diseased corals. Using molecular and enzymatic assays, we will assess differences among the microbial communities in coral mucus, water and sediment. Multiple regression analysis will allow us to then evaluate climate and anthropogenic influences on changes within microbial communities.

Global Impact of Coral Disease

Coral disease stands out as a primary factor in the deterioration of many Caribbean coral reefs. (Weil 2003). While the incidence and impact of disease on coral reefs in the Pacific remains unknown, our preliminary surveys in Australia and the Philippines reveal significant new diseases. Recently, Willis, et al., (2004) described brown band and white syndrome on the Great Barrier Reef and Raymundo, et al., (2003) described Porite's ulcerative white spots on the Philippine reefs. Widespread, intensive outbreaks may alter the composition, structure, and dynamics of coral populations and communities at local and geographic scales (Richardson 1998). Recent results show that surviving coral of some species affected by disease are non-reproductive, adding urgency to documenting direct impacts (Petes et al, 2003).

Hypothesis 1: Disease changes reproductive output and the dynamics of coral populations.
Hypothesis 2: Disease is changing the structure and composition of coral assemblages in all reef regions.
Hypothesis 3: Disease is changing coral reef biodiversity.

RESEARCH STRATEGIES: We propose an annual census at approximately 24 sites globally. At each location (e.g. Philippines, Palau, Australia, East Africa, Caribbean) we will measure disease prevalence to catalogue existing diseases and investigate impact of disease. We will work at 9 GIS registered sites per locale with both high and low water quality. Surveys are underway; team members have already collected initial data in the Caribbean, Australia, Palau and Hawaii.

The Causes, Reservoirs & Vectors of Coral Disease

Current research on disease reservoirs and vectors is hampered by lack of knowledge of the pathogens causing the majority of coral diseases. To date, there are only 5 coral diseases for which the microbial cause is known: black band disease (Cooney et al. 2002); white plague type II (Richardson et al. 1998), aspergilliosis (Nagelkerken et al. 1997; Smith et al. 1996), bleaching of *Oculina patagonica by Vibrio shilio* (Kushamaro et al., 1997; Rosenberg and Falkovitz 2004;) and white pox (Patterson et al. 2002). Disease reservoirs have only been identified for black band disease (biofilms in reef sediments, which contain non-pathogenic aggregates of the BBD; Carlton & Richardson, 1995) and possibly for aspergillosis (atmospheric African dust, which contains spores of the fungus, *Aspergillus sydowii*; Shinn et al., 2000). The only coral disease vector that has been identified is the fireworm, *Hermodice carunculata*, which has been found to harbor *Vibrio shiloi* (the pathogen inducing bacterial bleaching in a Mediterranean coral) in its guts (Sussman et al., 2003). Other good candidates include snails, parrot fish and damsel fish, which directly interact (predation, grazing, etc.) with coral colonies of the most important reef-building species.

Hypothesis 1: Specific coral predators and grazers act as vectors and/or reservoirs for coral diseases.
Hypothesis 2: Reef sediments are major reservoirs of coral pathogens.

Research strategies: We will first develop a suite of techniques to facilitate the identification of pathogens in coral. Because only a small percentage of bacteria in nature can be cultured, we will track the source of pathogens using various molecular fingerprinting techniques (such as 16S rRNA sequencing restriction fragment length polymorphism (RFLP), random amplification of polymorphic DNA (RAPD), and analysis of short sequence repeats). The development of genetic probes and pathogen-specific antibodies will also help verify the presence of pathogens. These probes will then be utilized to trace the route of pathogen transmission and identify vectors and reservoirs of infectious agents. Eventually a micro-array chip of global coral disease will be developed.

Coral Resistance to Disease

The microbial communities associated with corals are very complex (Rohwer et al. 2002), existing both inside the coral animal and in the surface mucous layers (SML). These normal communities, which may be specific to their host, protect the coral from disease. When the community structure changes, corals may become more susceptible to disease. Both bleaching and disease appear to change the microbial community profiles in the SML.

Mechanisms of inherent host resistance among corals are effectively a black box; we lack understanding of basic disease resistance mechanisms and their interaction with environmental stressors. While the first line of defense against pathogen invasion is probably the establishment of a healthy normal microbiota, some cellular defense mechanisms have been described. Both anti-bacterial and anti-fungal activities have been found in extracts from gorgonians (Jensen et al 1996; Kim et al. 2000a) and scleractinians (Koh and Sweatman, 2000) and in the case of sea fans, the response is inducible (Kim et al., 2000b). Petes et al. (2003), Mullen et al. (2003) report the production of chitinase, melanin and an inflammatory reaction in infected sea fans.

Hypothesis 1: Environmental stress can cause changes in mucous microbial communities.
Hypothesis 2: Changes in the mucous microbial community are correlated with disease.
Hypothesis 3: Climate and anthropogenic stress compromise coral immunity and facilitates disease outbreaks.

RESEARCH STRATEGIES: Various molecular approaches (such as 16S rRNA sequencing, restriction fragment length polymorphism, random amplified polymorphic DNA, and analysis of short sequence repeats) will be employed to assess changes within the microbial mucous communities in stressed, diseased and healthy corals.

The goals of the immunological work, starting with gorgonian seafans as a study system, are to develop assays for prophenyloxidase (PPO), chitinase and general antimicrobial activity. Once resistance compounds are identified, they will be incorporated into a chip of biomarkers for stress (through collaboration with the CDHC). Field sampling will eventually allow us to estimate clonal variation in sea fan resistance, quantify the response of corals to different experimental treatments of enhanced nutrients and temperature, and map spatial variation in resistance in the field.

The Link Between Science & Management

Because coral diseases may act synergistically with other stressors, there is reason to believe that management practices may be able to influence the impact of disease. However, strategies for dealing with disease outbreaks are currently nonexistent (Harvell 2004). The increasing frequency with which diseases influence and alter reef communities (Aronson and Precht 2001; Harvell et al., 1999, 2002; Weil et al. in 2002) necessitates their consideration and incorporation in management plans. The proposed study addresses this need by providing the scientific background to formulate recommendations for managers and policy makers. For instance, correlations between water quality and disease prevalence are of growing concern but evidence of direct links and synergistic effects are limited (Kuta and Richardson 2002; Porter et al., 2001; Bruno 2003). In addition, the role of coral community structure and diversity in maintaining productive fish and invertebrate populations is well documented, but links between these aspects and coral diseases are generally unstudied. As many MPAs are established specifically with the goal of protecting the fishery in mind, diseases that alter a reefs' ability to support a diverse fish population are of concern. Understanding the specific ways in which coral diseases can alter reef function will allow better predictive power for conditions under which outbreaks may occur, and the rationale to apply pressure to policy makers and local government to improve waste water treatment, solid waste disposal and land use practices.

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This project is part of a major initiative of the World Bank, with support of the Global Environmental Facility, to provide the best available scientific information on coral reef response to environmental disturbances and climate change. The "Coral Reef Targeted Research and Capacity Building for Management" project aims to conduct specific, targeted research to fill critically important information gaps in the fundamental understanding of coral reef ecosystems so that management and policy interventions can be strengthened globally.