B. TOXICOLOGY & ECOLOGICAL EPIDEMIOLOGY

Identifying the Current State of Knowledge and Knowledge-gaps for Toxicological and Infectious Impacts on Coral using Ecological Epidemiology

Background

The deterioration of many coral reef ecosystems worldwide is a clear example of not only the effects global environmental damage can have on our oceans' health, but also damage from local sources of pollution. This damage is multi-factorial as are its consequences. Since the 1970's, mounting evidence has built a convincing argument that human activities are a prominent cause (e.g., coastal urban and industrial development, agricultural runoff, sedimentation, over-harvesting, marine pollution, disease and climate change) (Bellwood et al. 2004; Bryant et al. 1998; Risk 1999; Turgeon et al. 2002; Walker and Ormond 1982). Anthropogenic factors (i.e., physical, chemical and biological) can be exacerbated by natural factors (e.g., *climate:* water temperature, UV, weather pattern changes, volcanic/tectonic activity; *biological:* nutrient cycling, bioerosion, infectious disease) resulting in adverse health effects collectively recognized as disease (Wobeser 1981).

Reef species experiencing persistent environmental disturbances (e.g., coastal development and land-based pollution) may respond with acute mortality, resulting in rapid loss of diversity and abundance; but may also display non-acute, sub-lethal effects. These effects often present as increased incidence of disease (i.e., gross lesions), reduced growth, diminished reproductive effort and recruitment, and ultimately reef systems can cascade into irreversible deterioration (CRMP 2001; Downs et al. 2005c; Hoegh-Guldberg 1999; Knowlton 2001; Nystrom et al. 2000; Patterson et al. 2002; Porter and Tougas 2001; Richmond 1993). On a global basis, attempts to arrest overall coral reef decline have failed with reef degradation continuing (Bellwood et al. 2004; Jameson et al. 2002; Wilkinson 2002).

Why are we failing to stop the declines? How can we change this?

An examination of coral reef health assessments conducted over the last 30 years show detailed descriptions at the population and community levels in terms of coral cover, diversity and population dynamics of other reef species (usually fish abundance and diversity) but with little change in methodology (Downs et al. 2005c). Though necessary, these well-defined descriptions are not sufficient to answer *why* or *what* to do about the continuing decline of reef condition. Similarly, contaminant chemistry programs that detail the array of chemicals found at a site cannot answer whether these contaminants are benign or causal in disrupting coral health. A better understanding of the root cause of reef decline is necessary if mitigation decisions are to be successful. This requires integrating descriptive data with efforts to elucidate mechanisms of action and causal analyses to determine if there is an association between a biological response and a putative stressor, the nature of that association (e.g., impairment) (Boehm et al. 1995a;

Boehm et al. 1995b; Downs et al. 2005c; EPA 2000; Suter 2006) and in turn determine the associated ecological risk for better informed management options.

By its very nature, toxicology is an integrative science that is designed to uncover fundamental mechanisms of action governing chemical effects on biological systems. Drawing from the basic disciplines of molecular biology, biochemistry and physiology, toxicological principles and methods can be applied to subcellular systems and extended to ecosystems by evaluating ecological effects of chemicals or ecotoxicology (Hahn and Stegeman 1999; Suter 1993). With only a few studies recently published, toxicology and its relationship to infectious disease is only beginning to be applied to coral. It is however a critical underpinning for developing sound evidence that provides causal links between stressors and their biological effect(s) on corals and reef systems.

By merging toxicology, causal analysis and risk assessment information with measures of health condition (e.g., pathology, and health assessment), epidemiological methods can be used to understand disease incidence, distribution and causes while identifying and characterizing risk factors (predictors) that drive its occurrence, regardless of the root causation (biotic or abiotic). While classical epidemiology explores the statistical relationships between disease agents (both infectious and non-infectious), a related field, ecological epidemiology views disease as a result of the ecological interactions among populations of hosts and parasites (pathogens) and is concerned with the identification of critical parameters (e.g. the incubation period or latency) as well as the chemical and physical nature of the environment and how each contributes to the health of the organisms within the particular ecosystem (Cormier 2006; Suter 2006). Since most disease is multi-factorial, identification of risk factors for coral health can direct and prioritize management strategies toward risk reduction without requiring knowledge of specific etiologies.

Challenges and Recommendations:

The ultimate challenge is to move from a triage approach to coral reef decline to a state of knowledge where causal links can be determined and factors driving these system failures can be identified. This can then support ecological risk assessments that lead to the formulation of risk reduction strategies and mitigation actions. Developing this understanding can move us toward the ideal **goal of *health management and preventative care* for coral reefs.** To achieve a position of coral health management, however, will require recognizing that we currently lack the understanding and the ability to mitigate the problem and current approaches to environmental assessments for corals are not effective. The necessity for a change in the paradigm and approaches that currently dictate how the welfare of coral reefs is assessed must also be recognized. This requires a new approach to the science, new assessments and methodologies and a different focus of effort.

To effectively protect coral reef resources, resource managers need sound information that can clearly 1) characterize baseline health of coral reef communities, 2) demonstrate resource injury and determine its extent, 3) forensically link causal factors to the injured resource, and 4) routinely and consistently evaluate effectiveness of the management response and thus, enhance resource protection (Boehm et al. 1995a; Boehm et al. 1995b). A mechanistic understanding of modes of action, susceptibility differences among species, interaction between chemicals and environmental variables (e.g., temperature, salinity, light, pressure), and tools that allow monitoring for exposures and effects will enable causal and risk analyses to be used for coral reef assessments (Hahn and Stegeman 1999). Obviously not all human activities that cause environmental damage can be eliminated, however by adopting an environmental risk assessment strategy, decision-making can be improved to better protect coral reef resources by characterizing risks and quantifying them. Thus risk assessments enable prioritizing actions and provide quantitative measures for evaluating management actions and their consequences. While risk assessment is a process that assigns probabilities to adverse effects of human activities or natural damaging events, it does not address health assessment which is concerned with determining the occurrence and causes of impairments of non-human populations and communities, a field known as ecological epidemiology (Cormier 2006; Suter 2006). Thus integrating ecological epidemiology (biological assessment and causal analyses) with risk assessment (risk models that link alternative decisions to future conditions) provides a systematic means to improve understanding of the causal chain of events and the factors involved for informed management decisions (Suter 2006).

The Toxicology and Ecological Epidemiology working group (TEEWG) recognized the need to be able to *detect* change in coral health at the ecosystem, community and individual level *before* the system is damaged. Detecting change however requires establishing a baseline of health and disease indicators using standardized and accepted methodologies. The Group also emphasized that in order to determine the significance of the impacts that toxicants or pathogens have on coral ecosystems there is a greater need to track *biological responses* (i.e., health changes) than to measure the presence/absence of toxicants. The ability to discern biological consequences (direct and isolated effects) of toxicants will rely on the availability of laboratory studies. The integration of this process would call for adopting an epidemiological approach and then integrating it with ecological risk assessments for improving coral health and disease management options.

As a result of their deliberations, TEEWG recommended a systematic approach to begin the process (Fig. B.1). The first step is to adopt specific health indicators in field research and monitoring efforts to be able to detect change (i.e., condition assessment)(Cormier and Suter 2008) in coral health at the ecosystem, community, and individual organism levels; 2) conduct surveillance to determine baselines for health indicators and detect change resulting in impairment; 3) identify probable causes for impairment and (i.e., causal pathway analysis); 4) identify and assess risk factors as predictors of health effects (i.e., ecological risk assessment); 5) implement risk management decisions (i.e., management assessment); and 6) conduct outcome assessments to evaluate the success of the management decisions. The output of the Group provides a framework to move forward and a start at populating this framework with a) a list of predictors and outcomes; b) identification of data gaps and resources; c) a list of recommendations to enhance field monitoring efforts; d) a draft list of data variables and a standardized formaat for recording information; and e) specific recommendations to move forward.

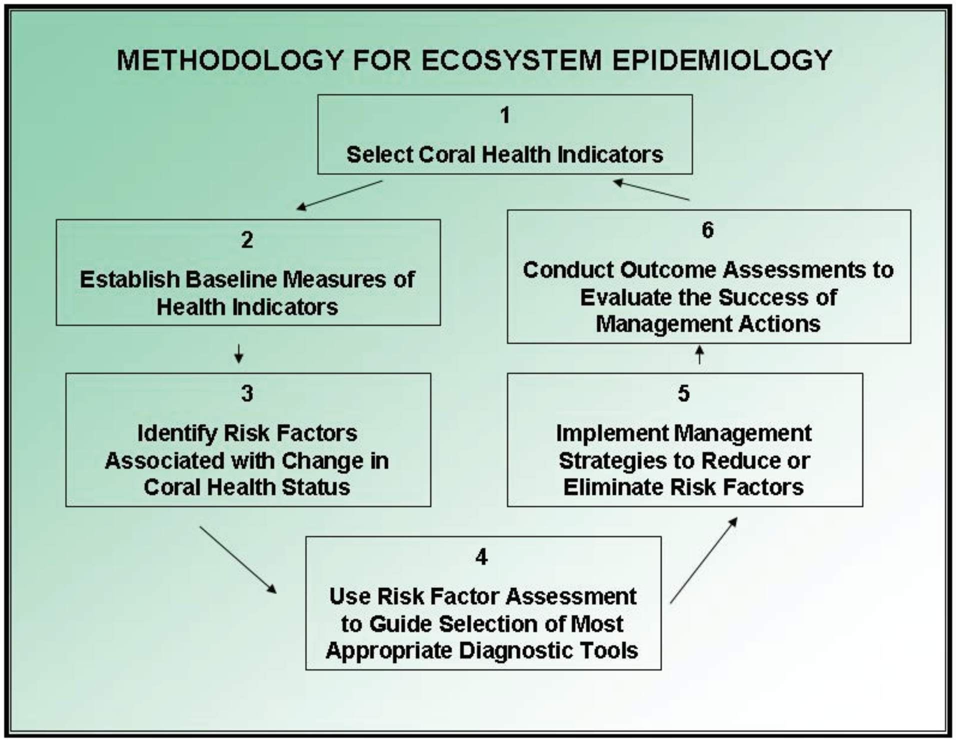

Figure B.1 Methodology for Ecosystem Epidemiology. A six step process that identifies Indicators and Risk Factors for Causal Assessment; Implements Management Strategy and Evaluates the effectiveness of management action.

B. Overall Strategic Objective: **Improve understanding of the causal links involved in coral reef decline to better inform decision makers for health management of reefs.**

B. Overall Recommendation: Adopt a formal environmental assessment framework that integrates ecological epidemiology with ecological risk assessment to provide decision makers with a coherent and consistent description of risks associated with management options that is transparent, reproducible and defensible.

In the following sections, the TEEWG identifies a series of key steps in the application of an integrated environmental assessment framework based on ecological epidemiology, that can help improve the detection, identification, and remediation (cure/management) of coral reef diseases and increase our understanding of the incidence, distribution and causes of harmful effects of chemical, physical, or biological agents (i.e., ecological epidemiology)(Suter 1993) on coral reef communities. The methodology involves:

1. Development and implementation of an ecological monitoring program to characterize coral community structure and function (Objective 1)
2. Establishment of baseline risk factors present at the site (Objective 2)

3. Use of epidemiology to identify potential risk factors associated with change (e.g., toxin, emerging disease) if a health change is detected, (Objective 3)
4. Use of these data to choose the most appropriate diagnostic tools to assess etiology, recognizing that the cause is likely multi-factorial (Objective 4)
5. Implementation of practical management strategies with the objective of reducing or eliminating risk factors associated with coral disease (Objective 5)
6. Conduct outcome assessments to evaluate the success of the management decisions (Objective 6)

Strategic Objective B.1 Identify and measure indicators of coral health and disease (morbidity) at the following levels: ecosystem, community, and individual for assessing condition and detecting impairments.

Recommendation B.1.1: Adopt a unified list of indicators of coral health and disease.

Indicators of health and disease are often referred to as bioindicators or biomarkers. There are three general classes defined as biomarkers of exposure, effect or susceptibility. Changes in these biomarkers are used to identify delayed or sublethal effects in individuals that survive an initial exposure to an adverse event. They can reveal exposures that result in compromised health as well as help define causal linkages and risk of adverse health effects. The most crucial characteristic of a health indicator is that it not only can detect biological changes but has diagnostic value in determining the nature of the change in association with a given stressor(s). Health indicators can range from remote satellite imagery to subcellular biochemical or cellular physiological endpoints. Integrating across levels of biological organization from cellular parameters to higher levels can help develop mechanistic profiles for certain cellular functions and disease states, and contribute to a suite of indicators for overall performance. The behavior of these indicators and the identification and quantification of pattern changes provides a basis for defining health status (i.e., diagnosis) and providing a prognosis.

Morbidity – the relative incidence of disease

Bioindicator / Biomarker – a distinctive biological or biologically derived indicator (as a metabolite) of a process, event, or condition (as aging, disease, or oil formation)

An initial list of biological indicators at the ecosystem, community and individual level is presented in Table B.1, and examples of the type of information they may produce.

Table B.1 CORAL HEALTH/DISEASE INDICATORS

	Indicator	Comments
ECOSYSTEM		
	Ecosystem structure and function	
	Calcification balance	
	Trophic level interactions	
	Ecosystem metabolism	
	Bioturbation	
	Changes in algal community composition and cover (abundance/biomass)	Increases in certain types of algae are indicative of impacts associated with increased nutrients and/or removal of herbivores.
	Bioindicators, e.g., foraminifora	
COMMUNITY		
	Species diversity and abundance	Identify organisms of special interest and their abundance: species of high commercial value, species of ecological importance, or pest species such as corallivores
	Bioerosion	
	Bleaching event	Extent of bleaching, species or genera affected,
	Rugosity/topographic analysis	Change on reef structure (topography or structural complexity) over time. Especially relevant for communities dominated by branching corals that may be detached and flattened during storms
	Bioindicators/symbionts: e.g. Butterfly fish (prevalence, feeding rates); stomatopods; sea cucumbers;	
	Catch per unit effort for reef fish.	

Table B.1 CORAL HEALTH/DISEASE INDICATORS (Cont')

	Indicator	Comments
POPULATION		
	Age (size)	Representation of different size classes
	Recruitment	Diversity and abundance of coral recruits, an indication of the potential for recovery and whether a reef is a source or sink.
	Intraspecific genetic diversity	
INDIVIDUAL		
	Bleaching	Amount of colony surface bleached, duration of bleaching, patterns of recovery and/or partial or total mortality
	Respiration/individual metabolism	
	Change in immune response	Susceptibility to disease
	Coral morphology	Growth form may be an alternate measure of species diversity
	Zooxanthellae content	
	Skeletal density/skeletal strength	
	Density banding.	
	Depth of tissue penetration	
	Abnormal growth/hyperplasia.	
	Growth/division rate of zooxanthellae vs coral growth rate. Growth rate; ratio; photosynthesis/respiration; proteins in PCP complex; photosynthetic efficiency	
	Autotrophic/heterotropic status of coral: C^{13} analysis, retrospective	
	Fecundity, gamete production. Changes in life history stages.	

Strategic Objective B.2: Establish a baseline of health and disease indicators

Recommendation B.2.1: Implement targeted surveillance programs for monitoring coral health and detecting biological change to develop a condition assessment.

The TEEWG identified examples (Table B.2 and Table B.3) of parameters, tools, and data that could provide detailed information on the structure, composition, functioning and health of the community. All of the variables identified may not be relevant to every region/location. For each location a detailed review of existing monitoring efforts, available baseline information and known threats should be undertaken to establish core baseline data variables. The TEEWG pointed out that the most prominent indicators in use today are associated with mortality and therefore identified a substantial need for more indicators of coral morbidity (rather than mortality). Examples include lesion regeneration rates, molecular indicators of stress, measures of genetic integrity, cellular physiological parameters indicative of immune status, detoxification, metabolism and various cellular and tissue-level processes. As new indicators for detecting biological change are identified, adopting a variable should be based on the criteria highlighted in the inset.

Criteria for Selecting a Biomarker

- **Relevant**
- **Measurable**
- **Easy to collect**
- **Cost-worthy**
- **Reliable & valid (trustworthy)**
- **Amenable to standardized collection protocols**
- **Comparable**

Table B.2 INDICATORS OF CORAL HEALTH & DISEASE: FIELD OBSERVATIONS: Variables are ranked in terms of difficulty in acquiring information and reliability of measurements with the minimum recommended frequency of monitoring. Difficulty of collecting: 1 = no training, no extra cost, less than 10 minutes during a survey; 5 = augmented funding, years of training, high cost, long time to collect). Reliability: is there an accepted protocol in place or standardized protocol that would be accepted? 1 = low trust in data; 5 = high trust, given that consortium has come up with an accepted protocol and data are collected using this protocol.

Variable	Difficulty	Reliability	Minimum Required Frequency of Monitoring
Species diversity	3	5	Annually
Trophic level interactions	2	3	Annually
Benthic community analysis	2	5	Annually
Remote sensing data	4.5	4	Annually
Population demographics • Age/size • Recruitment	 2 2	 2 5	Every 2 years
Bioerosion	1	5	Annually
Bioturbation (high, med, low: categorical designation)	1	5	Annually
Fish indicators: catch/unit effort; transects "fish counts"	2	5	1-4 times/year.
Bioindicators: sea cucumbers, butterfly fish.	1	3	At least annually
Algal blooms	1	5	Event driven/choice.
Rugosity	1	5	Every 2 years
Algal cover	2	5	Quarterly
Benthic algal community	2	5	Seasonal; 4 times a year.
Bleaching	1	4	Choice/ annual
Abnormal tissue growth	1	2.5	Annual
Fecundity assessment: Gamete presence/pigmentation	1	3.5	Seasonal
Human activity--use observations to guide further analysis.			
Natural: provide a list of potential risk factors.			

Table B.3 INDICATORS OF CORAL HEALTH & DISEASE: Laboratory Data (Definitions same as Table 2.2)

Variable	Difficulty	Reliability	Required frequency of monitoring
Calcification balance	3	5	Once
Life history stages; bioassays on different stages; controlled laboratory exposures	4	4	Most spawning events are annual.
Bioerosion--^{15}N isotope analysis.	1	5 (data) 3.5 (interpretation)	Once
Bioindicators: foraminifora	2	5	Annually; event driven
Algal blooms: algae characterization	2	5	Event driven/choice
Skeletal density.	1	5	once; opportunistic/event driven
Density banding	2	5	Once
Fecundity, gamete analysis (quantify, viability, fertilization study) Gamete histopathology	4	Annually or seasonally	
Sediment analysis: size, petrographic	1	4	Once
Water quality: pH, turbidity, salinity, temperature, wave action, e.g., routine YSI measurements.	1	4	Routinely
Tissue depth	ND	ND	RESEARCH NEED
Zooxanthellae: growth rates, ratio, photosynthesis/respiration; PCP complex. Normals yet to be established.	ND	ND	RESEARCH NEED
Autotrophic/heterotrophic balance. ^{13}C	Requires large sample size		RESEARCH NEED
Intraspecific genetic diversity	ND	ND	RESEARCH NEED
Contaminant chemical analyses: persistent organic pollutants (POPs). Water, tissue, skeletal.	1-5 metals: 1 persistent organics: 5	Variation--established methodology for some, not others.	RESEARCH NEED Testing based on probability; not shotgun contaminant analysis. Tends to be patchy in time and space.

Strategic Objective 3: Identify risk factors associated with a change in coral health status.

Recommendation 3.1 3.1: Establish site specific risk factors that may affect the location of interest and incorporate these into research and monitoring programs.

The TEEWG identified an initial list of possible risk factors (Table B.4) that may be associated with coral disease outbreaks. All categories of risk factors are not applicable to all situations. Potential risk factors must be measurable and quantifiable to allow detection of associations.

Many of the risk factors (i.e., causal factors) are anthropogenic in nature and affect water quality either from land-based sources of pollution or groundwater discharges. As these predictors of coral disease are more specifically characterized, the TEEWG identified types of anthropogenic and natural risk factors to consider in developing research and monitoring programs. These risk factors include:

- Anthropogenic (human activity)
  - Agricultural
  - Manufacturers / Industrial
  - Aquaculture
  - Fishing
  - Residential Activities
  - Recreational Activities
- Natural (general environmental)
  - Pathogens
  - Climate
  - Water Quality (temperature, salinity, turbidity, etc)

Strategic Objective B.4: Use risk factor assessments to choose the most appropriate diagnostic tools.

Recommendation B.4.1: Standardize methodologies for all variables.

The cause of most coral diseases are likely multi-factorial and investigations of these factors require a trans-disciplinary approach, drawing on many types of information to develop quantitative comparisons among groups and various factors. Adopting an Integrated Environmental Assessment (IEA) provides a logical, defensible and systematic approach to understand the complexities of disease. It blends concepts and methodologies of ecological epidemiology (i.e., biological assessment and causal analyses) with risk assessment (i.e., risk models that link alternative decisions to future conditions) to provide a systematic means to better identify causal factors and their path from source to impairment. A deliberate environmental assessment will provide a

Table B.4 IDENTIFICATION OF RISK FACTORS ASSOCIATED WITH A CHANGE IN CORAL HEALTH STATUS

PREDICTORS OF CORAL DISEASE (Risk Factors)	Measurement
Agriculture	
Sediment runoff	Measure: turbidity, sediment traps, YSI [*sediment--can be held by fleshy algae, re-release of metals/toxicants. Both measure of stress on reef and recorder of historical stress. Lead to causation.]*
Pesticides, herbicides	Measuare: quantify products. Separate water soluble and lipophilic--divide out risk, which associated with which disease processes. Also consider effects on different life history stages.
Fertilizer	Measure: Nitrogen, Phosphorus, Sulfur, heavy metals. Can fingerprint nitrogen (isotope suite); can tell fecal waste from industrial waste. Chlorophyll a: best measure of nutrient availability in the water
Salinity changes due to freshwater runoff	Measure: salinity
Animal waste	Measure: coliforms (total enterococci), antibiotics or other pharmaceuticals
Industrial/manufacturing:	
Oil/hard mineral extraction.	Measure: industrial solvents, processing waste, petroleum products, Inorganic waste: easy to monitor and use as diagnostic fingerprint (e.g. vanadium) Evolution of chemicals used in manufacturing. Testing done does not look at effect on coral reef organisms.
Mining coral, beach sand (destructive, but not toxic).	
Ore transport: potent source of nasty things. Measure: easy to monitor/identify--e.g. mussel shells.	
Perchlorates--present everywhere, in high levels in corals.	
Landfill runoff	
Mining tailings (sediment waste produced by mining).	
Marine transport/maritime activities	
Anti-fouling paints, copper used (processing waste). Diagnostic indicator of a certain type of activity	
Ballast water	
Oil spills/grounding	
Military activities	
Historical artifacts: bombs, sunken ships,	
Fishing activities	Measure: recreational, commercial, cultural, economic: fleshy algae dominate if consumers removed
Destructive fishing practices--dynamite fishing, may predispose to ciguatera, etc	
Overharvesting of large predators; effects on the food chain.	

Table B.4 IDENTIFICATION OF RISK FACTORS (Con't)

PREDICTORS OF CORAL DISEASE (Risk Factors)	Measurement
Mariculture/aquaculture	
Shrimp ponds: a major source of toxic materials, shoreline modification process. loss of mangrove ecosystem, biological filters. (Demonstrated human health impacts in Indonesia with shrimp ponds.)	Measure: presence or absence of aquaculture, distance, species cultured, type of aquaculture, pathogens
Escape of invasive species, predation	
Pond vs. cage: different downstream epidemiological implications	
Introduced pathogens	
Pharmaceutical/personal care products	
Endocrine disrupters	
Residential activity	
Household pesticide use: contributes to non-point source pollution.	
Chemical; pharmaceutical/personal care products	
Sewage	Organic: **Measure** coliforms (E.coli not a good measure in seawater) total enterococci; estrogen. Inorganic: **Measure** stable isotopes of nitrogen, caffeine--measures of human plumes
Polybromated diphenylethers: plasticizers, persistent. Industrial chemical, but also residential.	**Measure**: prevalence in water; if associated, look for primary source.
Recreational activity: water quality vs. direct impacts	
Water quality	
Hotel industry / golf courses / residential--sewage management.	Measure: Concentration of visitors/area as a risk factor for coral health.
Jet skis/waterskiing; pollution. Only burn about 80% of fuel.	
Divers as vectors of disease	
Direct impacts	
Water sports: anchoring dive boats, stepping on corals	Measure: number of snorkelers/divers in the area.
Jet skis: compression waves, effect of vibrations on fish.	Measure: compare management practices e.g. Palau vs. elsewhere. Presence of mooring buoys, controlled access. Jet ski rentals.
Anchor damage	
Invasive species--any maritime transport could vector. People or equipment. Algae, diseases, invasive species	

Table B.4 IDENTIFICATION OF RISK FACTORS (Con't)

PREDICTORS OF CORAL DISEASE (Risk Factors)	Measurement
Long range transport:	
Maritime: Ballast water	
Commercial: Transport of materials: e.g. sand	
Humans as fomites: wetsuit transport of disease	
Socioeconomical; ethics/values	
NATURAL	Consider with all risk factors that there are synergistic effects/multiple factors involved Measure: look at geological record for baseline. Case control: what could be the control time or location (place or time in which risk factor did not exist.)
Baseline processes	
Bioerosion	
Disease	
Climate:	
Water temperature	
UV	
Change in weather patterns	
Ocean level related to die-offs.	
Sea level fluctuations in geological time: big killers of reefs.	
Volcanoes/tectonic activity/volcanic ash	
Long range transport: Atmospheric transport--African dust	
Substratum/water quality Affected by runoff and sedimentation; heavy rainstorms, events occur naturally.	
Community	
Natural pathogens part of coral reef system	
Crown of thorn starfish, corallivorous gastropods and fishes	
HABs: cause of anoxia, coral damage. Natural vs. anthropogenic?	
Population	
Intraspecific variation/protection against population demise.	

quantitative basis for informed management decisions (Suter 2006). While relatively few diagnostic tools are available for corals, tools and approaches routinely applied to the study of other wildlife and human diseases are available to adapt for the study of coral diseases. These tools should be evaluated and tested on corals, with the goal of their application in a routine, standardized manner to Pacific coral disease and health studies. The TEEWG identified key actions that can help achieve standardized methodologies and integrate them into standard practices in the field of coral reef health assessments:

- Solicit standardized protocols from subject matter experts
- Publish selected protocols in peer-reviewed literature and central handbook (hard copies and web-based)
- Provide training for standardized protocols
- Educate users in the importance of standardized data to participants

Recommendation B.4.2: Develop and pilot a plug-and-play database

Standardized methods and protocols will help provide uniformity in data reporting and facilitate analyses and interpretation. However, the available data currently resides in a variety of databases and there is no integrated or centralized portal available to support the organization, analysis or interpretation of data that may be obtained through the IEAs outlined in Recommendation 4.1. The TEEWG recognizes that it is imperative to synchronize data from institutions to central location that is accessible, and is also equipped with computational tools to interrogate the data, conduct analyses and synthesize data into usable information for management decisions. To address this recommendation will require the creation of a sub-committee to develop such a database and agency support to house and maintain the database and develop analytical tools for end users. The TEEWG also pointed out that communication with participants and key stakeholders is critical and could be facilitated by providing an annual summary report, a valuable communication tool.

Recommendation B.4.3: Capacity building

The approach outlined by the TEEWG is not commonly used in the coral reef research and assessment community, yet it provides a valuable new thinking process for problem solving that logically organizes information, develops causal pathway models and builds weight of evidence arguments. This provides a transparent course of action to develop compelling information for causation and causal links that is vital for management decisions and selection of appropriate management actions. To successfully implement this integrated approach to environmental assessment will require education for the users. To this end, the TEEWG identified 7 key actions:

- Identify and acquire personnel (empower local resources & use traditional knowledge)
- Conduct training courses with subject matter experts
- Establish local infrastructure
- Ensure open communication / training among data collectors
- Address data sharing concerns regarding publication

- Assess potential reporting requirements with federal funds
- Consider using data routinely to:
  - Communicate with politicians, managers & legislators
  - Conduct long distance diagnostics with remote subject matter experts
  - Enable evidence-driven decisions
  - Identify risk factors (anthropogenic & natural)
  - Assess response to policy changes and other mitigation strategies

Strategic Objective B.5: Implement management strategies with the objective of reducing or eliminating risk factors associated with coral disease.

Recommendation B.5.1: Adopt an adaptive management approach whereby specific risk factors of concern are reduced or eliminated in certain areas.

To achieve a position of proactive coral health management requires being equipped to recognize new and reemerging infectious as well as non-infectious disease conditions, and understand the factors involved in disease emergence, prevention, and elimination. This requires:

- Adopting a methodology appropriate for assimilating and synthesizing numerous and diverse data points that encompasses the ability to detect chemical, physical and biological impairments; identify sources and pathways leading to the impairment; predictive capabilities to estimate risks (e.g., societal, economic, environmental) for different management options; and a means to evaluate the success of the management decisions.
- Providing training courses for equipping individuals to conduct risk analysis and ecological epidemiology and translate these analyses for decision making.

As Pacific Coral Reef Management evolves, it is critical to acknowledge, embrace and incorporate the traditional system of resource management into each of the steps in the process. A wealth of knowledge and success is espoused in these traditional methods that need to be incorporated into any contemporary coral reef management regime. Pacific Islanders are in tune with their local environment and are keenly aware of indicators of a healthy ecosystem as well as those that strike an alarm of impairment. Because of this knowledge and inherent value and respect this culture brings to coral reef management, it is important that it play a prominent role in developing a surveillance system to work with contemporary scholastic knowledge to understand and identify causes of ecosystem impairment and solutions. The Pacific Islander culture also provides a vital quality: once a problem is recognized they take local ownership and action to attain the solution, quickly before further harm is done to their resource. Given the vast area of Pacific coral reefs, and the limited capacity per area, training and capacity building efforts should empower local resources and take advantage of traditional knowledge.

Recommendation B.5.2: Identify a central facility to compile and share information in a timely manner with researchers, managers and other stakeholders, and to train local responders in risk factor assessments.

When conducting condition assessments, causal analyses, risk assessment or epidemiological investigations it is important to summarize the investigation in a report that includes the reason for the investigation; general summary characterizing the investigation, the clinical descriptions, results and possible source and conclusions on the nature of the disease, source of outbreak and method of transmission and any possible recommendations for control or management. These reports should be provided to relevant resource managers, researchers participating in the assessment, key stakeholders, and other decision makers in a timely manner to allow implementation of management responses, as necessary, as soon as possible after identification of the event. This will be best achieved through:

- Centralized facilities and web-accessible databases to compile, analyze and share data and information in a timely manner;
- Involving experts capable of conducting detailed analysis of these data, including local participants, with the goal of developing a hypothesis to explain the most likely cause, source and risk of distribution of the cases and suggest tools and strategies to mitigate the disease and or its impacts.

Because many Pacific communities still utilize traditional management systems it is important to ensure local ownership of the problem/solution and encourage local participation at every stage of the process while reaching resolution of the problem.

Strategic Objective B.6: Conduct outcome assessments to evaluate the success of the management decisions.

Recommendation B.6.1: Institute performance measures appropriate for evaluating the success or weakness of each component of the environmental assessment process, decisions and actions.

Once a problem has been detected, Resource Managers attempt to determine causes and evaluate solution options. Although their decisions are based on the 'best available science', it is essential to have a means to evaluate the performance of their actions, detect inadequacy in the evidence (i.e., science) used as a basis for their decisions or determine whether the action was effective. This may be accomplished by comparisons to similar areas without management intervention or through monitoring and surveillance to determine whether changes have occurred compared to baselines. This evaluation is key to identifying knowledge gaps and directing research and monitoring activities strategically in support of a successful adaptive management process.

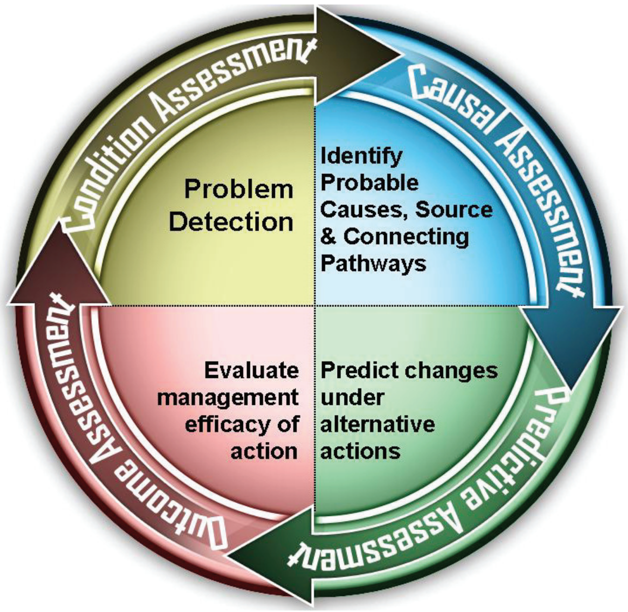

Figure B.2 Integrated Framework for Environmental Assessment. *Adapted from Cormier & Suter 2008.*

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