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Viewpoint

Shifting the paradigm of coral-reef health assessment

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Abstract

Coral reefs are in crisis. Globally, our reefs are degrading at an accelerating rate and present methodologies for coral-reef health assessment, although providing important information in describing these global declines, have been unable to halt these declines. These assessments are usually employed with no clear purpose and using uncorrelated methods resulting in a failure to prevent or mitigate coral reef deterioration. If we are to ever successfully intervene, we must move beyond the current paradigm, where assessments and intervention decisions are based primarily on descriptive science and embrace a paradigm that promotes both descriptive and mechanistic science to recognize a problem, and recognize it before it becomes a crisis. The primary methodology in this alternative paradigm is analogous to the clinical and diagnostic methodologies of evidence-based medicine. Adopting this new paradigm can provide the evidence to target management actions on those stressors currently impacting reef ecosystems as well as providing a means for proactive management actions to avert irreversible habitat decline.

Keywords: Coral reef; Monitoring and assessment; Diagnostics; Paradigm

"He that will not apply new remedies must expect new evils; for time is the greatest innovator."—Francis Bacon

1. Introduction—the current paradigm

Coral reefs are among the worlds failing ecosystems and one of the most persuasive examples of the effects of global environmental damage. Found in over 100 countries, coral reefs cover an estimated 284,300 km^2 (ICRIN, 2002). Per unit area, they are one of the Worlds most valuable ecosystems in terms of ecological, economic and cultural capital, yet we are losing them at an accelerating rate (Wilkinson, 2002). Recent reports indicate that 58–70% of coral reefs globally are directly threatened by human-associated activities (Bryant et al., 1998; Wilkinson, 1999; Hoegh-Guldberg, 1999; Goreau et al., 2000), while over 80% of the Caribbean coral-reef cover has disappeared in the last 30 years (Gardner et al., 2003). According to other estimates, 27% of the worlds coral reefs have already been substantially degraded while another 31% are forecast to be lost by 2030 (Wilkinson, 2000).

The major stressors responsible for coral-reef decline have been attributed to coastal urban and industrial development, agricultural activity, sedimentation, overharvesting, marine pollution, disease and climate change

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(Walker and Ormond, 1982; Bryant et al., 1998; Risk, 1999; Turgeon et al., 2002; Bellwood et al., 2004). Reef species experiencing persistent environmental disturbances (e.g., coastal development and land-based pollution) may exhibit acute mortality leading to a seemingly rapid loss of coral-reef diversity and abundance, but may also display non-acute, sub-lethal effects. These effects are often present as increased incidence of disease, altered growth and regeneration rates, reduced reproductive effort and recruitment which can ultimately result in a cascading effect of ecosystem deterioration (Richmond, 1993; Hoegh-Guldberg, 1999; Nystrom et al., 2000; Knowlton, 2001; Porter and Tougas, 2001; CRMP, 2001; Patterson et al., 2002). Attempts have been made to arrest and reverse these declines by establishing global monitoring networks, marine protected areas, and implementing conservation and management programs at international, national, regional and local levels. Although there are exceptions in some locales where success in reducing human-induced decline has been demonstrated (Smith et al., 1981; Hunter and Evans, 1995; Loya, 2004), overall, attempts to arrest coral reef decline on a global basis have failed and the steadily increasing rate of reef degradation from the direct and indirect effects of anthropogenic stressors, including global climate change, continues (Wilkinson, 2002; Jameson et al., 2002; Bellwood et al., 2004). The paramount questions are: Why are we failing to stop these declines and what can we do to change this?

The reasons for our failure to stop the global demise of our reefs are likely to be many and include socioeconomic and political factors. As stakeholders, scientists and environmental resource managers, one key issue is the need to provide evidence that clearly links declines to specific anthropogenic pressures at local, regional and global scales. Addressing this issue first requires examining how we currently differentiate and assess the status of coral reefs (Risk, 1999).

Over the last 30 years, coral-reef assessment has provided an extensive description of certain responses at the population and community levels in terms of coral cover, diversity and population dynamics of other reef species (usually fish abundance and diversity) (Risk et al., 2001). There have been modifications to the original methodology described by Risk (1972) to include protocols that focus on land-sea interactions and productivity, like CARICOMP (Caribbean Coastal Marine Productivity Programme, 1997), which attempts to integrate measurements in mangrove, sea-grass and coralreef communities. Other assessment methods provide a regional perspective, like the AGRRA (Atlantic and Gulf Rapid Reef Assessment) protocol, which looks for patterns of change in the community by evaluating assemblages of coral, fish and algae (Ginsburg et al., 2000), assuming that changes in one of these major groups will precipitate changes in the others. The Florida Keys Coral Reef Monitoring Program (CRMP) is designed to determine benthic cover of scleractinian corals, their size, mortality and recruitment and develop species inventories. Companion projects to CRMP examine water quality, coral disease, and seagrass communities (Eaken et al., 1996; Wheaton et al., 1998; Santavy et al., 2001). Volunteer programs like RECON (Reef Ecosystem Condition) (Lang et al., 2000) and ReefCheck (Hodgson, 2000) also contribute data on coral species, coral colony size, coral disease incidence as well as quantifying fish and invertebrate species. It is data from programs like these that support efforts such as the global coral reef monitoring network (GCRMN), which provides bi-annual reports on the world-wide status of coral reefs (Wilkinson, 1998, 2000, 2002). These extensive monitoring and assessment networks have provided valuable, detailed, concordant descriptions of global reef status—coral reefs are in critical decline (Wilkinson, 2002; Bellwood et al., 2004).

Similarly, documentation of decline in other, valued, ecological assets (e.g., top predatory birds) has historically also provided vital information of an emerging ecological crisis (Risk, 1999). But here the emphasis changed from observation and documentation of decline to investigation of the causes of decline (e.g., bioaccumulation of certain persistent organic pollutants such as DDT; acid rain), followed by mitigatory action underpinned by robust scientific evidence. In coral-reef assessment, this first critical step from observation to investigation has not yet been achieved. If we are to prevent the further demise of our global coral reef habitats, we must move from this current paradigm to an alternative paradigm for coral reef monitoring and assessment.

2. Shifting the paradigm: acknowledging the limitations of classical environmental risk/impact assessment strategies

Coral-reef resource management and assessment continues to rely heavily, if not solely, on assessment activities which have no clear objectives or coherent context, where the data generated provide little value in developing recommendations to guide management strategies and policy formulation regarding reefs (Risk, 1999). These coral-reef assessments may provide data indicating changes in characteristics including abundance and diversity of reef biota, but unfortunately, most often cannot separate natural variability from the effects of anthropogenic disturbance. Few, if any, of the major monitoring programs have attempted to uncover mechanistic processes by quantifying putative reef-deterioration factors (e.g., pesticide run-off, siltation, fresh-water input) in conjunction with monitoring ecological responses; thus there is little correlative data to connect putative stressors with the observed ecological effects (Peters et al., 1997). The descriptive nature of current monitoring and assessment approaches focuses on documenting a change, though few studies actually try to document an effect. If used alone, these descriptive approaches are incapable of identifying the causes of deterioration or the etiology of the degenerative processes that lead to the visible and often irreversible changes in reef community structure and function. Without the forensic data linking biological change to causative agents, resource managers and scientists are only able to say that the ''reefs are ill'' or the ''reefs are dying'', but are impotent in being able to rectify the situation.

Tissue, water and sediment analyses of specific pollutants have been used in assessments to characterize reef condition. These types of measures may be able to document the quality and quantity of a contaminant in the environment, but cannot readily describe nor predict biotic responses to that contaminant. Presence of a toxicant or environmental agent (e.g., high or low temperatures) does not necessitate a stressed condition for an organism (e.g., diseased state; Downs et al., 2002; Downs, 2005). Biological systems, in general, are complex and hierarchal, possessing a number of different compensatory mechanisms which operate at multiple levels (e.g., molecular, genetic, cellular, tissue, behavioral and anatomical). These compensatory mechanisms may ameliorate adverse effects before the pollutant or environmental agent (e.g., high-temperature) reduces the fitness of an individual organism or alters its functional role in the community (Allen and Starr, 1982). Determining the condition of a population or a coralreef community solely by measuring pollutants as a risk approximation is a crude exercise that at times produces information that is ambiguous, controversial and ineffective, or worse, abides false conclusions. Simply stated, biological responses to exposure are more appropriate measures of effect than chemical criteria. Often, while chemical standards can be met for water or sediment quality (e.g., less than several ppb for lead, cadmium and copper), it is the combination of toxicants that results in mortality or reduced biological function. Thus, the evaluation of environmental effects on biological systems associated with anthropogenic pressures, such as pollutants, must begin with understanding of dose–effect relationships, in the context of documented information of exposure. Clearly this necessitates monitoring and assessment tools that provide quantitative information on both the structural, metabolic and functional aspects of the biological system under evaluation, as well as measurement of known pressures, such as environmental and contaminant factors.

Current coral-reef assessment approaches are also limited in their ability to provide evidence for causation of reef declines because often there is no context in which these descriptive methodologies are to be applied.

In other words, the user of such methodologies rarely has an identified and cogent conceptual framework or strategy in which the descriptive technique can validly and adequately be used to help achieve clearly identified goals (i.e., establishing both the nature and causes of declines to underpin mitigation strategies, or assessing the effectiveness of policy and management). This is clearly illustrated in the Survey Manual for Tropical Marine Resources (English et al., 1997) when it states, ‘‘The first action in developing a long-term monitoring programme is to state the objectives. This will guide the selection of methods, sites, and times of sampling’’. However, it does not state what those objectives might be, why you should employ a certain method, or how the results might be interpreted or used within a particular context. On the contrary, it only states that these methods should be employed, ‘‘because they are important to the health of the reef...’’ providing no definition of health or how these methods contribute to a diagnosis of the nature of the condition of the reef. The crucial fault here is not the methods, but a lack of context in which the methods are applied. In many cases, application of these methods by resource-management programs is analogous to taking a persons pulse, but not knowing what that pulse rate means (no context or definition) and therefore unable to determine if the patient is well or critically ill or whether to advocate a therapeutic intervention.

Once clearly identified goals have been established, an ensuing issue is to define and state specific objectives with specific endpoints for assessment that are linked to these goals; end-points that are realistically measurable and whose measurement has meaning in defining the condition of the reef. Closer inspection suggests this inability is rooted in the ambiguity of a poorly defined conceptual system for reef assessment. Concepts such as ‘‘ecosystem health’’ or ‘‘coral-reef health’’ have been espoused by both scientists and environmental managers as an operational property that can be assessed and acted upon. Some of the conceptual systems for assessing ecosystem health include Karrs Index for Biotic Integrity (Karr and Chu, 1997; Jameson et al., 2001) and Costanzas Ecosystem Health Index (Costanza and Mageau, 1999). Unfortunately, these conceptual systems of Health Indexing are faulty in that their conceptual and operational use of the word health is improperly defined and improperly applied (health is not an operational or real property, but an abstraction). This also includes other operational terms for assessment (e.g., resilience) whose meaning has become ambiguous with improper use. An exhaustive critique of current Ecosystem Health Index conceptual systems is beyond the scope of this paper, although an exceptional critique by Suter (1993) on Ecosystem Health Indices provides cogent arguments and explanations of why some of these conceptual systems fail. However, it is noteworthy that the proponents of Ecosystem Health Indices recognize that current methodologies used in coral-reef and environmental surveillance and monitoring lack context (goals/objectives); they are attempting to provide a context for such methods, but unfortunately, fall short. The Ecosystem Health Index concept suffers in part from trying to create a conceptual system of assessment using pre-existing survey tools and methods, rather than first creating a conceptual system for assessment, then designing or recruiting tools and methods that will meet the requirements (operational objectives) of that conceptual system.

3. Shifting the paradigm: identifying the goals of monitoring and assessment for coral reefs and a methodology to meet those goals

If we are to ever halt coral-reef degradation and reverse the losses that have been set in motion, we must recognize ‘‘that existing institutions have ceased adequately to meet the problems posed by an environment that they have in part created’’ (Kuhn, 1996) and recognize the necessity for a shift or change in the paradigm and approaches that currently dictate how the welfare of coral reefs is assessed. The crisis is that coral reefs are degrading, and we currently lack the understanding and the ability to mitigate the problem. Rejection of one paradigm necessitates adoption or substitution of another (Kuhn, 1996). Any new paradigm erected for coral-reef monitoring and assessment must be able to provide the types of knowledge and technologies that can fulfill the requirements resource managers have to (a) demonstrate and determine the extent of resource injury/condition, (this is in part fulfilled by current monitoring activity), (b) forensically link the injured resource to causal factors (this is not currently fulfilled), (c) conduct the overall monitoring activity in the context of clear and measurable goals and, (d) provide a cohesive set of methods and tools to routinely and consistently meet these management goals and that are able to evaluate the effectiveness of the management response and in so doing, enhance resource protection (Boehm et al., 1995a,b).

One framework, we argue, that would be effective in providing the information necessary to meet the environmental management objectives mentioned above is analogous to the clinical and diagnostic methodologies of evidence-based medicine (Fig. 1). The methodology of a clinical examination of a coral reef would include an anamnesis or historical review, as well as a current examination, akin to the concept expounded by Schaeffer et al. (1988). The purpose of this examination is to detect overt changes in carefully chosen assessment end-points with known reference values. These parameters may be chosen across the hierarchy of biological organization and include molecular/biochemical (e.g., DNA lesions, lipid peroxidation), cellular/tissue-level phenomena (e.g., concentration of vitellogenin in male fish livers, pathological lesions), population metrics (e.g., sex ratio, average size of adults, coral cover, recruitment density), species diversity and abundance.

Geochemical, atmospheric and oceanographic endpoints must also be included in the anamnesis, as well as an understanding of nearby human demography and social practices (Risk, 1999). The goal is to establish whether a quantifiable or qualitative change in the condition of a specific coral reef exists is evident from the profile of one or more of these parameters (i.e., an altered condition). From this, a rational basis for targeted investigation can be established by the investigator to further investigate the causes and consequences of that change (EPA, 2000). For example, if there is an acute decrease in crab or shrimp populations on a coral reef with no associated decrease in fish or cnidarian population density, insecticides or an infectious virus or bacterium could be tested to confirm or refute these possibilities (Richmond, 1996).

Central to an evidence-based approach is the ability to understand the nature of an altered condition (EPA, 2000). Once an altered state is detected, the Diagnostic Method prescribes developing diagnostic hypotheses and associating probabilities to each of the hypotheses, based on the anamnesis (past history of the subject) and current examination of the subject (Black et al., 1999). It is important to point out that the term subject has a hierarchical connotation and may be used to imply a group of cells, organs, organ systems, or organisms (population of a given species), but not ecosystems. This is because these entities have identities that have defined boundaries; while ecosystems “do not have clear boundaries like the skin or cortex of an organism, they do not have consistent structures from one individual example to the next, and they do not have mechanisms like the neural and

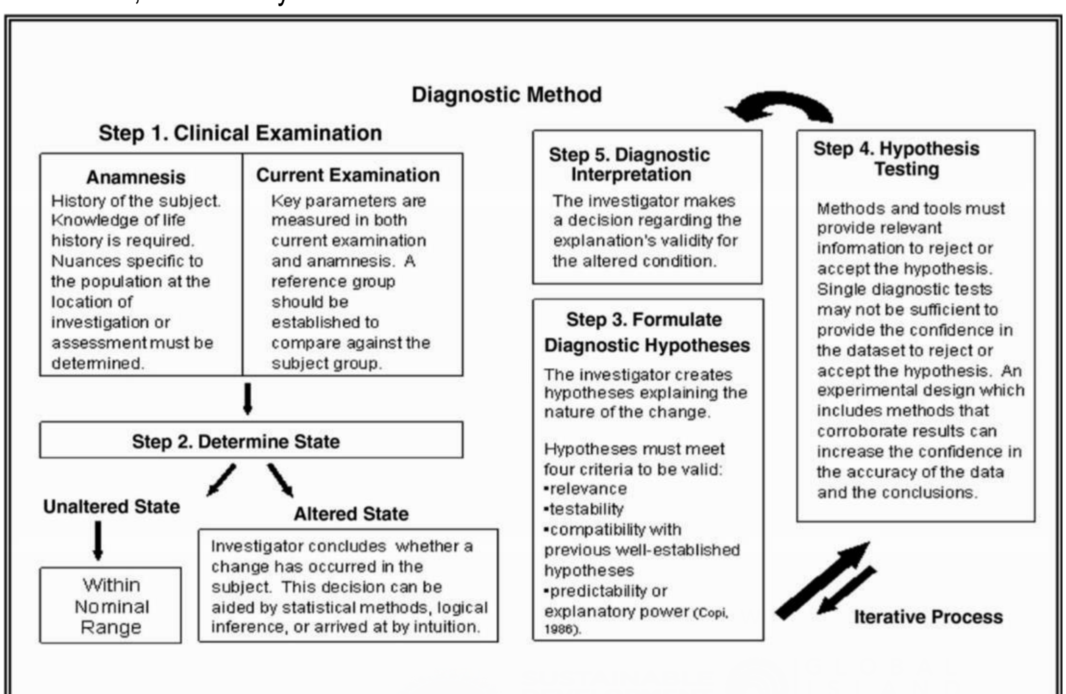

Fig. 1. Diagnostic Method.

hormonal systems of organisms to maintain homeostasis'' (Suter, 1993). Nor do ecosystems have mechanistic processes with clearly defined structural components (defined and well-described relationships; Whittaker, 1957). To make a valid diagnostic hypothesis, the subject must have an identity and not be an ambiguous reference or connotation (Mill, 1874; Frege, 1892). The requirement of identity for valid diagnostic hypotheses thus limits the application of the Diagnostic Method to populations of a species and lower levels of the biological hierarchy. This does not prevent implying or insinuating changes in subjective qualities of higher-order pseudo-systems (e.g., the community concept in ecology) in the biological hierarchy from the perceived mechanistic processes that occur at lower-level processes, but it does present some difficulties in making valid logical inferences about the higher-order pseudo-system from premises that are rooted in lower-level processes (Method of Residues, Mill, 1874). In other words, it may be suggested or inferred that changes in mechanistic processes (e.g., reduced reproductive capacity in a keystone species) interpolate into higher-order changes (e.g., population collapse), but caution should be exercised before deriving those conclusions merely by knowing, for example, that a given process in an individual species is malfunctioning.

As valid diagnostic hypotheses are erected, the Diagnostic Method stipulates testing the validity of the most probable diagnostic hypotheses by the use of information gleaned from the anamnesis and current examination (Hilborn and Mangel, 1997). The purpose of a diagnostic test is to confirm or disprove a hypothesis (Popper, 1959). For example, a stand of Acropora is observed to be experiencing wide-spread and rapid loss of coral tissue. The pattern of tissue loss is similar to that which has been seen in other species infected by a Vibrio sp. bacterium. A polymerase chain-reaction assay is used to test for the presence of the Vibrio shiloi bacterium in coral that are exhibiting symptoms of acute necrosis (Hypothesis 1: V. shiloi is present and responsible for the disease signs). An ELISA-based assay against the Vibrio endotoxin is used to test for pathogenicity of the Vibrio (Hypothesis 2: V. shiloi is present and producing endotoxin, a pathogenic factor). The original diagnostic hypothesis was that V. shiloi is present on the dying coral and is responsible for the tissue loss. In this case, negative results of the first test indicate that specifically V. shiloi is not infecting the acroporids, but it does not rule out that a different species of Vibrio (e.g., Vibrio coralliilyticus) is present or responsible for the symptoms. Even if the tests for both diagnostic hypotheses do not refute the hypotheses, confidence in the explanation (mechanism) for the symptomology can be increased (or decreased) by further corroborative diagnostic tests (Popper, 1959). The purpose of the hypothesis testing step in the Diagnostic Method is to provide the investigator with evidence for the greatest likelihood of an explanation for the nature of the phenomenon observed.

The final step in the Diagnostic Method is the conclusion(s) and decision(s) reached by the investigator explaining the nature of the phenomenon. The system of argumentation used to infer a conclusion should be based on sound logical principles (Copi, 1986; EPA, 2000). Not all arguments, however, will have the certainty or confidence that is associated with a pure syllogistic deductive argument or a Sherlock Holmes inference-of-elimination of all alternative hypotheses (''When you have eliminated the impossible, whatever remains, however improbably, must be the truth'' (Doyle, 1892)). Many final arguments for a causal stressor or stressors will be based on arguments of analogy and probable inference (inductive argumentation) or arguments based on a system of weight of evidence. These types of arguments should not be disregarded, since many cases of a natural resource damage event are often based on such argumentation (Hill, 1965; Boehm et al., 1995a,b; EPA, 2000).

Ultimately, the goal of the Diagnostic Method is to discern a mechanistic relationship between the putative stressor and the effect; in other words, an explanation for the nature of the phenomenon. Defining a mechanistic relationship creates a model describing the chain of events that are initiated by the causal entity and it allows the testing for the validity of any aspect of the model. Hence, the Diagnostic Method is an iterative and interactive process, requiring re-evaluation and organization of data and hypothesis testing (EPA, 2000).

Needless to say, there are challenges in implementing this methodology within the current reef monitoring and assessment frameworks. Coral-reef assessments are currently handicapped by the rampant use of ill-defined terminology, which can lead to ambiguity, a scarcity of diagnostic tools and standardized protocols, and stockpiles of data with limited use-because much of it was collected without the clear purpose of a diagnostic application. Diagnostic assessments require an explicit study design and careful synthesis of objective and subjective knowledge using inductive and deductive reasoning. Implementing the Diagnostic Method requires clearly defining the objectives of the diagnostic investigation with precise, unambiguous definitions and concepts (EPA, 2000). Positing of clear objectives will aid in specifying what data are required to erect testable hypotheses. This, in turn, guides the selection of appropriate standardized protocols and techniques or the creation or adaptation of technologies that together can provide an understanding of the biological mechanisms responding to the variety of pressures that modulate function at each level of biological organization (molecular/biochemical, cellular, tissue, individual, population).

The optimal power and precision of the Diagnostic Method can only be achieved if reference values for each endpoint in the analysis have been determined and validated. These are ranges which result from assaying specimens from individuals that meet carefully defined criteria (reference group). In most cases, reference groups are composed of healthy individuals, but may also be defined by individuals with specified diseases or conditions. Regardless, reference values are critical to diagnosing or screening populations and in certain situations, changes in the values of particular parameters may become more important than absolute values with the patient becoming their own reference (Henny and Hyltoft Petersen, 2004; Ritchie and Palomaki, 2004; Petitclerc, 2004; Grasbeck, 2004). We should also note that reference values can be influenced by factors such as differences in genetics, sex, spatial or temporal scales (e.g., normal ranges for blood pressure differ among age groups and gender). Hence, recognizing and applying the appropriate reference values can allow the investigator to discriminate among subtle distinctions that are crucial to developing a definitive diagnosis. Ignoring them can result in erroneous conclusions when trying to distinguish whether the observed altered condition is within a nominal range or not. Once reference ranges are established, the investigator has a gauge for systematically documenting alterations from nominal ranges and describing what that may mean; thus developing relationships between signs and diseases that are necessary to distinguish whether the organism is experiencing merely an altered condition or has moved into a pathological state, denoted by a decrease in performance of a given function (Schaeffer, 1996; Moore, 2002; Downs, 2005).

Fortunately, recent advances in fields such as medicine, biotechnology, environmental chemistry, satellite imagery analysis (i.e., temporal texture) and biogeochemistry are translatable to coral-reef assessment. Our abilities to probe cellular physiological, biochemical, evolutionary genetic, and biogeochemical processes provides a unique and timely path to understanding the underlying mechanisms that govern organismal responses to different pressures in recognizable patterns and, in turn, help create causal linkages. In terms of coral reefs, molecular, cellular and physiological diagnostic biomarkers provide a means of assessing both qualitative and quantitative responses of coral reef organisms to a variety of pressures individually and collectively. The ability to detect changes at a level where pressures are directly affecting an organism (i.e., molecular/cellular) may allow for early detection and development of prognostic indicators of higher-order effects, for example, population effects (i.e., reduced growth, compromised defense systems and diminished reproduction) that, in turn, can influence community and ecosystem dynamics (Moore, 2002; Fauth et al., 2003; Downs, 2005).

Advancing a new paradigm for assessing coral-reef condition that includes organismal- and environmental-based metrics will require progress in three areas: (1) knowledge of fundamental processes, (2) technology development and application, and (3) validation of the concepts and technologies (i.e., an applied method of investigation) for real world situations. Research into the mechanisms of cellular and physiological processes, their behavior in response to specific stressors and understanding how these processes relate to each other and to higher-order phenomena is paramount. As with medicine, successful treatments arise only as a result of an astute understanding of the nature of the ailment and physiological condition of the organism. This can best be achieved through studying, in part, these processes in model organisms (similar to the Drosophila, Arabidopsis, Aplysia, and even sea urchin model systems) under controlled laboratory and field conditions. The critical element is having a model, recognizing that any model chosen will have associated caveats. Knowledge of these limitations is not a drawback, but is in fact an advantage because the purpose of a model is to act as a ''strawman'' to test the validity of hypotheses. If data support the hypothesis, then there is support for the model; if not, then the true value of a model is exposed and we learn something new (Allen and Starr, 1982).

Ultimately, we must establish the causal links between stressors and organismal and ecological change (e.g., diversity, percent coral cover). Using molecular, cellular and patho-physiological parameters has a major advantage of being able to create profiles that may reflect specific types of stressors. Stress signatures observed in the field can then be used to focus more detailed analytical analyses. For example, high resolution chemical analysis efforts in combination with biomarker data can be used to provide evidence of exposure and effect that can lead to targeted policy decisions. Ultimately, understanding changes that occur within genomes, proteomes and metabolomes provides great potential in this regard (Moore, 2003; Downs, 2005).

Using only a single end-point for assessment, whether it be a biomarker such as acetylcholinesterase activity or a change in population density, provides only part of the linkage between stressors and higher-order ecological consequences. Drawing on multiple assessment endpoints across hierarchical levels will be the only means of providing a fuller, mechanistic understanding of the causes of reef deterioration. The collective findings of each method however cannot remain as isolated bits of data, but must be integrated and statistically evaluated in an appropriate manner to provide a profile consistent with a given stressor-specific response. These profiles can then be used to characterize and distinguish between conditions such as whether there is a sub-lethal impact or whether corals and other coral reef organisms are being exposed to individual chemicals or mixtures of pollutants, regardless of whether the condition has manifested as a pathological or community consequences (Downs, 2005). This integrated approach is critical for establishing cause-and-effect relationships, in some cases before outward visible changes are manifested and prior to late-stage, irreversible responses. The integration of methods across disciplines and biological hierarchies however, will only be effective if we can manage data, not in static storage, but in a dynamic architecture in which the data are transformed into information, which is then synthesized into knowledge—and that knowledge is then acted on.

4. Conclusions

Within the management framework, confrontations among stakeholders and resource users often arise. For example, developers may blame reef decline on over-fishing, while fishermen point to runoff and sedimentation as the key problem. Classical coral-reef assessment approaches are unable to recognize causal links or partition responsibility in such cases. In the face of such uncertainty, inaction is often the path followed, with the continued loss of reef resources as the only predictable result. A claimed lack of specific proof on the issue has led to a policy of no response. As such, ''science'' is used as an excuse to postpone management and mitigation responses (Pelley, 2004).

We must come to understand that it is not coral reefs that need to be managed, but rather, it is the human activities affecting reefs that are the true target for management programs. Proper management programs need to be based on good scientific evidence, clearly identified goals and objectives, and include efforts that can be evaluated in terms of measurable outcomes and deliverables. Both adequate and accurate data are critical to the management process.

The top three causes of coral reef decline identified through a broad consensus before the Pew Oceans Commission and the US Commission on Ocean policy are over-fishing of coral reef resources, reductions in water and substratum quality due to sedimentation, runoff and pollution from land-based and marine sources and massive bleaching events tied to global climate change. These major categories of stressors rarely occur individually, and there are well-recognized synergisms. For example, nutrients from agricultural runoff, sewage outfalls and sediment inputs coupled with over-fishing of herbivorous fishes can lead to an alternate stable state of algal dominance. Classical reef-monitoring and assessment practices cannot determine the exact causes or the relative contributions of multiple stressors responsible for such major changes. We do not advocate the dismissal of these classical assessment techniques, but instead advocate for the proper application of these techniques in a coherent and goal-oriented context. The diagnostic tools and models presented in this and accompanying papers within this Special Issue provide a starting point to develop a different paradigm of coral-reef monitoring and assessment and identifies some of the available and emerging methods that could be used to establish causality.

The possibilities of understanding the forces that affect a coral reef and its response to a changing environment provides new opportunities for a more efficient allocation of management-directed resources. Providing a context and methodology for coral-reef assessment facilitates the wise selection of the best management options. Without a change in how we assess coral-reef condition, the identification and implementation of effective management-directed activities is simply not going to happen, now or in the future. The proper application of environmental forensic and monitoring assessment methodologies within a cogent management framework is essential if coral reefs are to survive as a legacy for future generations.

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