Coral reef health indicators and thresholds of concern

Hugh Sweatman

Australian Institute of Marine Science

Australian Government | Australian Institute of Marine Science

Australian Government

Department of the Environment and Water Resources

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Acronyms Used In This Report

ABS.................... Australian Bureau of Statistics
AGRRA .... Atlantic and Gulf Rapid Reef Assessment
AIMS .... Australian Institute of Marine Science
ANZECC .... Australia and New Zealand Environment and Conservation Council
AQIS................... Australian Quarantine and Inspection Service
BHR.................... Biological Health Rating
CARICOMP......... Caribbean Coastal Marine Productivity Program
CCA.................... Crustose coralline algae
CRAMP .... Coral Reef Assessment and Monitoring Program
CRC.................... Cooperative Research Centre
CSIRO .... Commonwealth Scientific and Industrial Research Organisation
DDM .... Day to day management
EHMP .... Ecosystem Health Monitoring Program
EnTox .... The National Research Centre for Environmental Toxicology
EoLF .... Effects of Line Fishing experiment
GBR .... Great Barrier Reef
GBRMPA .... Great Barrier Reef Marine Park Authority
IBI....................... Index of Biological Integrity
IRC .... Intergated Report Card
JCU .... James Cook University
KNP.................... Kruger National Park
LIT .... Line intercept transect
LTMP.................. Long-term Monitoring Program
MA .... Macroalgae
MAR .... Mesoamerican Reef Program
MTSRF............... Marine and Tropical Sciences Research Facility
PCQ.................... Ports Corporation of Queensland
PET .... Plecoptera, Ephemeroptera and Trichoptera taxon richness
QDNRW .... Queensland Department of Natural Resources and Water
QDPI&F.............. Queensland Department of Primary Industries and Fisheries
QEPA .... Queensland Environmental Protection Agency
QFMA................. Queensland Fisheries Management Authority
QPWS .... Queensland Parks and Wildlife Service
SIGNAL.............. Stream Invertebrate Grade Number – Average Level
SLATS................ Statewide Landcover and Trees Study
TPC .... Threshold of Potential Concern
TUMRA .... Traditional Use of Marine Resources Agreement
UQ .... The University of Queensland
WQ .... Water quality

Abbreviations Used In This Report

diam................... diameter
O/E .... Observed value / Expected value
Is .... Island

Summary

This report looks at components and measures of ecosystem health and practicalities of applying the approach to marine systems and to the Great Barrier Reef (GBR) in particular, with reference to incorporating measures of reef health into the Marine and Tropical Sciences Research Facility (MTSRF) Integrated Report Card.

In assessing ecosystem health it is important to include indicators or metrics that can be related to processes that maintain populations and ecosystems as well as those that relate to current status. Measuring indicators of processes is usually more resource-intensive than measuring indicators of state, so the former are less commonly included in monitoring protocols for large scale monitoring programs.

The interpretation of indicators most commonly involves comparison with values from reference sites: sites in similar bio-physical setting that are relatively free from of human disturbance. In the context of the GBR province, the large area includes many types of reefs, so regionalization of survey and reference sites will be critical. Secondly, the effects of natural disturbances such as crown-of-thorns starfish outbreaks and cyclones are obvious on GBR reefs, but it is much less clear which reefs have also suffered from anthropogenic disturbances that could be ameliorated by management intervention and which have not, so the identification of reference sites is uncertain.

In terms of inclusion of indicators of coral reef health into the MTSRF Integrated Report Card, the report lists many potential indicators that have been surveyed at varying spatial scales on the GBR. Their usefulness to the Report Card depends on the scale of reporting that evolves; data of many kinds are available, but only for limited areas of the GBR. Carefully standardized measures of diversity of key groups (benthic organisms and reef fishes) are metrics that are widely used in reporting environmental health and are available for many sites.

In the absence of clear reference values for interpretation of indicators, the best strategy must be to use the distributions of observed indicator values (appropriately regionalized), in combination with rigorous expert review and, where appropriate, backed by focused research programs.

Introduction

The stated aim of the Marine and Tropical Sciences Research Facility (MTSRF) is to ensure the health of North Queensland's public environmental assets through the generation and transfer of research and sharing knowledge. The research programs address questions being posed by government, industry and the public by applying knowledge from a range of disciplines and strives to maximize the adoption of the results by end-users and to communicate them to the public To this end, all research themes feed into Theme 5: *Enhancing Delivery*, whose objective is to develop knowledge products that will be useful to the major end-users of the MTSRF program such as government agencies, industry and community sectors. Among the key products for Theme 5 is an Integrated Report Card on the status and trends of North Queensland's natural assets.

As part of a program concerning Status and trends of species and ecosystems in the Great Barrier Reef (Theme 1) this report looks first at the subject of ecosystem health and how it could be assessed. Then the types of data that are available for reefs of the Great Barrier Reef (GBR) are considered with a view to the selection of indicators of reef health and their interpretation for incorporation into the MTSRF Integrated Report Card.

Ecosystem Health

References to "health" of natural systems abound in the media and in policy documents, so the idea of ecosystem health is clearly a resonant analogy for communicating information about the status of natural systems. Similarly, references to health of natural systems and parallels between such systems and organisms that have vital properties go back centuries but the last thirty years have seen several attempts to identify a scientific basis of ecosystem health and to measure it in natural systems.

History

Some of the first quantitative attempts to assess the condition of natural systems in the spirit of "Ecosystem Health" were by James Karr and co-workers who developed Indices of Biological Integrity (IBI) in the 1980s, initially for freshwater systems in response to the 1972 amendments to the US Federal Water Pollution Control Act, precursor to the Clean Water Act, which mandated protection of "the physical, chemical, and biological integrity of the Nation's waters." The emphasis on "integrity" has been adopted in the definition of healthy ecosystems in the Australian guidelines for water quality (allowing the maintenance of biodiversity and ecosystem integrity (ANZECC, 2000)).

IBIs are multimetric indices, that is: they integrate a number of independent metrics (equivalent to indicators) that reflect different aspects of the functioning of the system or are sensitive to different kinds of stress. Karr emphasised (e.g. Karr and Chu, 1997) that the best metrics both reflected and were specific to human impacts on the ecosystem and so could be used to identify such impacts against the background natural variation. In practice, the multimetric indices of the IBI approach are generally dominated by metrics of taxonomic richness (number of taxa) because a biota's structure, including which taxa are present and their relative abundance, generally changes at lower levels of stress than do ecological processes (Karr and Chu 1997). Across diverse taxa and regions, similar biological attributes (e.g., taxonomic richness, the relative abundance of tolerant and intolerant species or guilds of species and trophic structure in terms of the proportion of herbivores or carnivores etc) are consistent and reliable indicators of site condition (Karr 1997a, Jameson et al. 2001).

Interpretation of IBIs depends on comparison of values from survey sites with values from reference sites that have suffered minimal human disturbance: sites that retain their biological integrity. Indicators and metrics of health or integrity do not have the same value at all places; both survey sites and reference sites clearly need to be grouped into comparable sets based on physical setting (regionalized) for the interpretation to be valid. Nor do does overall biological integrity correspond to maximum values for any single biological attribute such as biodiversity or primary production; the number and identity of species, productivity etc will depend on environmental setting (climate etc) and site history.

Over the same period that saw the development of IBIs, and by no means in isolation from that process, a number of researchers such as DJ Rapport and J Costanza worked to provide a scientific basis for the term “Ecosystem Health”. Rapport (1998 a,b) provided an overview of the scientific concept, and was at pains to stress the limits to the metaphor. The scientific version of ecosystem health does not imply that ecosystems are super-organisms. Ecosystems differ from organisms in numerous important characteristics, for instance they have diffuse boundaries, they do not reproduce and are not subject to genetic selection. The scientific concept of ecosystem health owes more to Leopold’s (1941) concept of “land health”. Leopold was concerned to “determine the ecological parameters within which land may be humanly occupied without making it dysfunctional”. As with IBIs, the focus has been on human interaction with ecosystems and particularly on sustainable human use: the sustained provision of the diversity of ecosystem services. The scientific concept of ecosystem health is intimately involved with management of natural systems for human benefit, rather than an inherent biological reality. Leopold himself noted early on that it was easier to identify dysfunctional systems than to define the characteristics of healthy ones.

Drawing together the work of several authors, Rapport (1998a) listed eight variables that define ecosystem health:

1. **Vigour**, which corresponds loosely to nutrient cycling and productivity. This does not imply that more cycling or more productivity is necessarily better, the appropriate comparison is with reference sites.
2. **Resilience** the capacity of a system to cope with stress and to bounce back when stress decreases. This property of natural systems has intuitive appeal to resource managers and a large literature has accumulated quite independently from any scientific basis for ecosystem health. Discussions of components of resilience are often accompanied by diagrams of balls in cups of various shapes (eg Gunderson 2000, Bellwood et al. 2004). In the analogy, the bottom of the cup represents a stable state for the system (ball) which can be displaced by disturbance, but either returns to the bottom at a rate dependent on the steepness of the walls of the cup (“engineering resilience” (Holling 1996) or “stability” (Gunderson 2000)) or flips over the rim into an adjacent cup (an alternate stable state). The disturbance required to displace the system to an adjacent stable state is a measure of “ecological resilience” (Holling 1996). Gunderson (2000) considered that the existence of a single equilibrium state was not the general case for ecological systems and so shortened the term to “resilience”). If resilience is an aspect of system dynamics, then it can in principle be measured after disturbance, but potential resilience seems much harder to assess in anticipation of disturbance.
3. **Organisation** concerns ecosystem complexity, both diversity and the extent of interdependence (symbioses, mutualism, competition), which generally increase with perceived health of the ecosystem, and the proportion of opportunistic species, which shows an inverse relationship.
4. **Maintenance of ecosystem services**. Healthy ecosystems are able to provide a full range of ecosystem services.

5. **Diversity of management options**, meaning that healthy ecosystems can support many potential human uses (This would seem to be a component of maintenance of ecosystem services, above)
6. **Reduced subsidies**. This refers to input of energy or chemicals or human labour necessary to maintain productivity in agricultural use of ecosystems
7. **Damage to neighbouring systems**. This includes such processes as runoff damaging downstream habitats, which are low in healthy ecosystems.
8. **Human health effects**: the ability of an ecosystem to sustain healthy human populations.

The first three variables: vigour, resilience and organization (originally proposed by Mageau et al. 1995), are included in most discussions of the science of ecosystem health; the other five variables seem to be less generally accepted among proponents of the subject. As with IBIs, estimates of these values of these variables have no absolute interpretability, but need to be compared with values from reference sites in equivalent ecosystems that are not dysfunctional.

Rapport (1998a) contended that the scientific concept of ecosystem health is a useful well beyond its power as a device for communication; medical analogies can be extended to preventative measures, diagnosis and cures.

Both the evolved concept of ecosystem health and IBIs measure status relative to that of ecosystems that suffer minimal human impact, and refer to the integrity and functionality of processes that return the system to such a state after disturbances that are part of the natural dynamics of ecosystems, and so make the system self sustaining. Dennison and Abal (1999) add an extra component of practicality to the definition of ecosystem health for a system that is subject to considerable human impacts, Moreton Bay in Queensland, defining a healthy ecosystem as one “in which: key processes operate to maintain stable and sustainable ecosystems, zones of anthropogenic impacts do not deteriorate and critical habitats remain intact.”

Application of ecosystem health concepts to marine systems

While descriptions of many reef management programs use the term “ecosystem health”, not many have explicitly considered the more formal definition in the design of monitoring programs or have reported quantitative differences in “health” among sites. As an example, Kramer (2003) summarised data collected under the Atlantic and Gulf Rapid Reef Assessment (AGRRA) program between 1998 and 2000 from varying numbers of sites within 20 regions of the Caribbean. Local mean values for the indicators were presented with the overall means as a reference. The “health” of reefs in the regions was assessed by cluster analysis based on the scores for 13 AGRRA indicators from sites in each region that were >5m deep. Groups of regions were identified as “Better”, “Average” or “Worse” based on the first three splits in the analysis. This interprets the status of individual sites by comparison with the current status of other survey sites rather than in relation to pristine or historical condition.

The Mesoamerican Reef (MAR) program has embarked on development of a report card for the environmental health of the reefs of the Mesoamerican Barrier Reef. The program involves institutions across several Central American countries that have established reef monitoring programs using a combination of the AGRRA and the CARICOMP protocols. The planned report card is a reporting mechanism for the established program. The extensive website (www.healthyreefs.org) identifies groups of structural, functional, threats and social indicators, ranks their functionality and, in a very few cases, identifies target values. The report card itself is stated to be “in development”.

Jameson et al. (2001) laid out a strategy for the application of IBI to coral reefs, focussed on the Caribbean. Their comprehensive lists of potential metrics and recommendations of the numbers of metrics that would be required show how remote the full implementation of such an approach is on the GBR. Jameson et al. (2001) suggest that metrics for six components of reef biota: sessile epibenthos, benthic macro-invertebrates, fish, macrophytes, phytoplankton and zooplankton, should be included in the IBI. The authors propose a large number of potential metrics to contribute to a coral reef IBI including taxon richness of many groups (sometimes phyla or classes, but families in the case of reef fishes) fecundity, growth rates, proportional representation of trophic categories, size distributions, incidence of disease and deformities.

Fairweather (1999) discussed the application of the science of ecosystem health in estuaries. He was concerned to identify indicators of ecosystem processes as well as structure. He suggested some strategies for the development of such indicators and reported results of some pilot studies in mangroves of the Sydney region.

The South East Queensland Ecosystem Health Monitoring Program (EHMP) spans freshwater, estuarine and marine environments in the Brisbane area. The program arose from extensive studies in the region's catchments (Smith and Storey 2001) and the Moreton Bay Study (Dennison and Abal 1999). The monitoring results from the EHMP are published as a report card built on the general principles of Ecosystem Health and IBIs. The health of aquatic ecosystems in the various sub-regions is expressed in terms of the extent that values of indicators recorded in the waterways deviate (in standardised units) from an appropriate reference condition of minimal human impact.

Indicators

Desirable features of indicators

There are many expressions of the desirable qualities of indicators variables, e.g. Soule 1988, Karr and Chu (1997), Harwell et al. (1999), Jameson et al. (2001), Scheltinga et al. (2004). Idealised indicators would have the following characteristics:

1. Specificity – the indicator changes in response to an identifiable stressor
2. Short response time – lag between onset of stress and detectable change is short
3. Monotonic response to levels of stress
4. Practical – economical and easy to use

Indicators and ecosystem health

The concept of ecosystem health stresses the maintenance of ecosystems in some desirable state, usually characterised by minimal human impact. In the context of estuaries, Fairweather (1999) pointed out that most indicators concern structure of assemblages and so give a static view of the state of the system, rather than capturing the dynamic processes that would maintain the system. Structural indicators can be made more process-orientated by considering reproductive condition to show potential for breeding or size-frequencies to indicate potential for recruitment. Fairweather proposed the term "ecoassay" to describe measures of ecological processes and suggested some possible approaches (Table 1). It is unfortunate that many indicators that give information about ecosystem processes and functional capacity are slow and complicated to sample, and so are not easily included in large-scale monitoring programs. For instance, coral larvae of various species will settle on terracotta tiles. Availability of propagules is fundamental to the recovery and maintenance of populations, but spawning of many species is highly seasonal, so timing of deployment is critical and logistically complicated, requiring simultaneous deployment at many widely spread sites. The deployment period must also be similar in all sites if data are to be comparable, because early post settlement mortality is high, so the longer the tiles are left after the settlement pulse, the fewer colonies survive. Finally, counting and identifying newly settled corals is very laborious and taxonomic resolution is usually only possible to genus level. Finding, identifying and recording juvenile coral colonies in the field are also slow and require observers to have good taxonomic knowledge. The same is largely true for reef fishes: recruitment is also seasonal, so the timing of surveys is critical for comparability, and may require near-simultaneous, labour intensive surveys of sites that are hundreds of kilometres apart.

Table 1: Examples of ecological processes in mangrove habitats that could potentially be assessed by ecoassays (modified from Fairweather 1999)

Process types	Examples of possible “ecoassay” indicators
Nutrient cycles	Litterfall, decomposition, nutrient release
Recolonization	Recruitment, immigration
Infestations	Parasites, disease, bioeroders
Herbivory	Defoliation rates
Carnivory	Loss of prey individuals
Mutualisms	Presence of both partners
Competition	Guild analyses
Bioaccumulation	Enrichment ratios

Many survey protocols take a “snapshot” approach and aim to base any assessments of dynamics on single surveys of community structure (plus a raft of assumptions). On the other hand, monitoring programs that have been established for several sampling cycles have the potential to provide estimates of trajectories of change in attributes of communities. In the coral reef context, most monitoring programs estimate coral cover, but rate of change in coral cover, particularly with a correction for the potential for increase, would be much more pertinent than an absolute cover value to the persistence of coral communities at the site over the longer term. A coral community where coral cover drops to 15% but is increasing at 3% (absolute) per year five years later is more likely to persist than a reef where the same reduction occurs but cover has barely changed after five years. The latter could indicate a stressor that is depressing juvenile survival (among many other possibilities). At the same time, coral cover cannot increase indefinitely; average coral cover on the fronts of reefs on the GBR is about 30%, so reef fronts where coral cover is already well above the average may be expected to show smaller rates of increase than sites with lower cover and more colonisable space. On the other hand, rapid increases in coral cover are usually due to growth in size of established colonies, rather than recruitment of small colonies, so rate of growth may increase up to the point where colonies become vulnerable to wave action or water movement (Madin and Connolly 2006). The development of such indicators involving trajectories is an opportunity for innovation.

Indicator sets

There is a good deal of convergence in the variables that are included in the various protocols for monitoring coral reefs around the world (Table 2) reflecting the kinds of data that can be collected by programs that must monitor a relatively large number of sites using scuba. There is a variety of kinds of information that are potentially useful for assessing the health of coral reef assemblages: measures of productivity, numbers of coral propagules and fish larvae that reach each site, growth rates and survivorship of various organisms. These are directly related to the maintenance of communities, but are slow to collect in the field and/or laborious to process in the laboratory, which makes them impractical for long term monitoring programs that cover many sites.

Other indicators are being developed for assessing one particular impact on reefs of the GBR. In the particular the CRC Reef Healthy Country Healthy Reef project C7.2 aimed to identify characteristics of coral reefs that vary with gradients in water quality away from rivers and so could be indicators of changes in water quality in the absence of direct measurements. These indicators are still being developed and have not yet been integrated into any broad program of data collection.

Potential indicators relevant to coral reef health on the GBR

In November 2006 a group of scientists and managers met at AIMS to consider potential indicators of reef health and their interpretation as part of the genesis of the MTSRF Integrated Report Card. Apart from general discussion about approaches to the report card and about environmental indicators and their interpretation, the meeting considered an extensive list of variables that could be relevant to the condition of reefs, based on the list of indicators chosen by the MAR program for their coral reef report card (www.healthyreefs.org). Since this report concerns indicators of reef health, MAR indicators concerned with social well-being and governance were not considered. Some potential indicators such as *Acanthaster planci*, which occurs on the GBR but not in the Caribbean, have been added. The resulting list of potential indicators is presented in Table A2 (Appendix 1). The list includes indicators of the state of reef communities and indicators of pressures (stressors).

Ideally an assessment of the health of reefs would be based on indicators related to processes that maintain reef communities (settlement, recruitment, growth rates) as well as indicators of structure (species diversity, trophic structure) involving a range of taxonomic groups. The format of the Integrated Report Card is still in development and details of the scales for reporting were undecided at least until early 2007. Scales of reporting will determine the range of indicators that can be used. In general the data on reef communities are so sparse when considering the whole GBR that only those data collected by the largest programs such as the AIMS LTMP and the Reef Plan Marine Monitoring Program will be available at the largest scale. The possible range indicators will be severely constrained by availability of data.

Table 2: Variables recorded by selected monitoring programs outside Australia. Reef Check is an international program for community monitoring of reefs that has an Australian presence.

	AGGRA	CRAMP Hawaii	MAR	CARICOMP	Reef Check
BENTHOS CORALS	• Total coral cover • Coral colony vitality (Dustan 1987) • Colony size and height • Incidence of disease • Incidence of bleaching • Cause of death • No of damselfishes • Partial mortality – new and old • Agents of partial mortality	• Percent cover, richness and diversity of corals • On fixed quadrats: • Recruitment: - Growth • Mortality of individuals	• Percentage coral cover (genera or spp) • Coral mortality index and condition (as AGGRA) • Recently dead coral: - very recent - recent - older recent - long dead • Coral recruitment on tiles	• Hard coral life forms, soft corals, gorgonians, zooanthids, (all broad categories) • Separate survey of gorgonians (to species if possible)	• Broad categories: hard coral, soft coral, recently killed coral, rock, rubble sand, silt, other • Extent of bleaching • Presence of: - coral disease - coral damage - recently killed coral
BENTHOS ALGAE	• Macro-algae (MA) • Crustose coralline algae (CCA) • (MA:CCA ratio)	• Algal cover by functional groups	• Percentage algal cover • CCA, turf, • Algal production (growth - a proxy for nutrient availability)	• Line Intercept Transects: Algal groups	• On LIT: cover of macro-algae (*Ulva*, blue-greens) that respond to nutrient enrichment (see above), NOT *Halimeda* and *Sargassum*
OTHER INVERTEBRATES	• Abundance of *Diadema*		• Abundance of: - *Diadema* - Sponges - Gorgonians	• Sponges • Ascidians	• Cover of sponges • Abundance of exploited spp. Sea urchins, lobster, giant clam, banded coral shrimp, holothurians, *Acanthaster,* Triton shell (species vary with region)

	AGGRA	CRAMP Hawaii	MAR	CARICOMP	Reef Check
REEF FISHES	• Abundance and size of selected: - herbivores - predators - indicator spp?	• Abundance and length (all spp) gives biomass	• Abundance of selected reef fish: all Acanthuridae, Chaetodontidae, Haemulidae, Lutjanidae, Scaridae, Serranid genera Mycteroperca and Epinephelus; selected Balistidae and 5 miscellaneous • Abundances of newly settled juveniles of selected species of fish from Acanthuridae, Chaetodontidae, Pomacentridae, Grammatidae, Labridae, Scaridae • Also Rover diver surveys in same area, 30 min timed swim, log 10 categories		• Abundance of selected target spp for fishers (minimum size for snappers and groupers) and aquarium collectors (species vary with region)
STRUCTURE		• Rugosity			
PRODUCTIVITY				• Emphasis on simple measures of growth and productivity of seagrass and Mangroves	
PHYSICO-CHEMICAL		• Sediment grain size	• Sedimentation (settlement traps) • Water chemistry		

Interpretation of indicators, metrics and indices of reef health – targets, critical values and thresholds of potential concern

In order to interpret indicators, metrics or indices, the observed values must be compared with standards. These standards are of various types:

1. The IBI and ecosystem health frameworks recommended calibration of metrics across many sites subject to a range of human impacts (to demonstrate sensitivity), including sites with minimal human impact (as reference points).
2. Interpretation of the number of Plecoptera, Ephemeroptera and Trichoptera families (PET richness) and Stream Invertebrate Grade Number – Average Level (SIGNAL) scores (a measure of sensitivity to disturbance) for freshwater invertebrates used in the EHMP (2007) also depends on comparison with “ecosystem health guidelines” based on 80th or 20th percentile values of empirical data from sites in streams of the appropriate type that have been only minimally disturbed by human activity.
3. The indices “native fish species richness” and “native fish assemblage O/E” of the EHMP involves comparison with expected values for fish diversity in streams with varying biophysical characteristics and levels of human disturbance based on extensive studies in the region followed by statistical modelling (Kennard et al 2001, 2006).
4. In order to incorporate indices that do not have target values specified in “ecosystem health guidelines” into Ecosystem Health report card grades for the EHMP, each site is allocated a “Biological Health Rating” on a 4-point scale, with high values associated with healthy status. This general approach is also used by the AGGRA program in the Caribbean (Kramer 2003) where local results are compared with regional norms, which are unweighted means for the variable in question. The same approach was used for an index of relative condition for inshore reefs of the GBR (Sweatman et al. 2007).
5. In the absence of formal studies values can be set based on the opinions of experts, preferably combined with explicit conceptual models of the functioning of ecosystems of interest.

When applying such methods to the GBR it is difficult to identify reef areas that have experienced a range of levels of human disturbance among GBR reefs with any certainty. Any effects of human disturbance are likely to be subtle compared with the impacts of arguably natural disturbances, such as cyclones and predation of corals by *Acanthaster planci*, the crown-of-thorns starfish. For instance, the effects of runoff on coral reefs have been a long-term concern and there are clear gradients in water quality (suspended sediment, dissolved nutrients) with distance from shore and distance from rivers (Van Woesik et al. 1999, Fabricius and De’ath 2004). These gradients differ among regions and there are some differences in coral communities associated with the gradients (Fabricius et al. 2005). However, it seems certain that there have always been gradients of some kind in water quality between river mouths and the ocean; the question of how those gradients have changed with changes in land use is as yet unanswered. Coring to reconstruct past coral communities from fossil evidence is one possible approach to this particular question, but information is very limited at present. A modification of the FORAM index (Hallock et al. 2003), which relates the ratio of autotrophic to heterotrophic groups of Foraminifera to turbidity, could potentially be applied to fossil foram communities on the GBR and so used to reconstruct the nature and date of changes in water quality in the past. The method is still being developed for application on the GBR (S Uthicke, pers comm.).

Another area that needs to be developed is regionalization of the reef into areas that support comparable communities. A basic component of the Marine Park Authority's Representative Areas Program was to divide the GBR Marine Park into homogeneous regions using a combination of the available data and expert opinion. The resulting bio-regionalization identified 30 coral reef regions as well as 34 inter-reefal regions within the marine park (Fernandes et al. 2005). While these bioregions were not intended to define reporting units, the number of regions highlights the diversity of the GBR region. Data on most aspects of reef communities on the GBR are sparse in comparison with such diversity, meaning that empirical data for each region will be limited so distributions of values of indicators will be poorly represented and specifications of the types of community that would be expected at a site (the third type of reference value) will be very imprecise. Some of the most broad scale data sets concern the distribution of hard and soft corals based on rapid assessments from many sites (DeVantier et al. 2006, Fabricius and De'ath 2001). These data have been analysed for biogeographical patterns of diversity, but they would need to be re-analysed for the purpose of predicting regional patterns of community structure.

A simple approach to assessing the condition of coral reef communities in the absence of background information

In 2004, the CRC Reef Research Centre funded a survey of 33 sites on nearshore reefs of the GBR between Cape Tribulation and Keppel Bay. Nearshore reefs are most likely to be at risk of exposure to runoff, a major management issue for the region, yet there was relatively little information about the coral communities on nearshore reefs. The study provided a snapshot of the condition of a number of such reefs spanning the most modified regions of the GBR coast in 2004, and a baseline for assessing subsequent changes. Because of the normally turbid conditions on nearshore reefs, surveys did not record fish communities but concentrated on sessile benthic organisms. Surveys recorded cover of benthic organisms, diversity of hard corals and size frequency of coral colonies. Many of the sites were subsequently incorporated into the Reef Water Quality Protection Plan Marine Monitoring Programme.

In order to draw the extensive information together in the final report (Sweatman et al. 2007), an index of relative reef health was calculated using values for four variables from surveys at two depths at each location. Estimates of coral cover, species richness, density of juvenile corals (<10cm maximum dimension) and the density of large coral colonies were ranked across all sites, then sorted and assigned to quartiles of the population and given values between 0 and 3. The lowest 25% were assigned a value of 0 and the highest 25% were given a value of 3. These values where then summed for each location, giving an index of relative status with a possible range from 0, if values for all variables at a particular location were within the lowest quartile of recorded values, through to 12 if values for all variables were in the highest quartile of observations. Scoring the values for each variable involved judgment as to what is "good" or "bad" in terms of the status of a coral community. Higher values of each variable were considered to be better than lower values. The results represent a simplified estimate of relative status as no attempt was made to weight the four variables. For example, high cover of hard corals may indicate a positive state, but low cover may simply reflect a recent disturbance and so should perhaps not carry the same weighting as the density of recruits, if these reflect the recovery potential of the community. While the survey reefs were all nearshore reefs, no correction was made for natural regional differences among community types (regionalization). Another logical weakness of this approach is that each component variable was scaled to the range of values that were recorded in the 2004 surveys; how these values compare with the range of possible values, or with pristine values from 150 years ago, is unknown; there is certainly scope for "shifting baselines" (Sheppard 1995). Nor is it certain that high values of the index do actually correlate with community persistence, or that low values do indicate stress; this would need to be confirmed by monitoring the dynamics of communities over appropriate time scales.

Thresholds of concern

Thresholds of concern have gained currency as a result of an adaptive management framework developed in the Kruger National Park (KNP) in South Africa (Biggs and Rogers 2003). An overarching “vision” for the park that is refined by extensive consultation with all stakeholders leads to a series of “objectives” for management of the park. These objectives are expressed in various levels of detail, options for implementation are considered in depth and the best option is implemented, along with a monitoring program and a schedule for formal audit and review of effectiveness of all components. Part of the refinement of the objectives involves identifying monitoring end-points: “thresholds of potential concern” (originally “thresholds of probable concern” (Rogers and Biggs 1999)) or TPCs that define the limits of acceptable change in the indicators related to each objective. In effect, these are levels at which stakeholders agree to become concerned about ecosystem change. In some cases TPCs may initially be educated guesses, but the formalised review process means that they will be scrutinised and refined.

TPCs provide a focus for all park management related activities: the identification of useful TPCs is a valued outcome and hence a focus for research activities by park staff and their collaborators, clarity of objectives and immediate input into park management gives monitoring activities an enhanced relevance and the capacity of the day to day managers to implement measures to turn components of the natural system back within widely respected limits gives a sense of achievement. TPCs draw on and give relevance to surprising kinds of research, for instance, one TPC concerning woody vegetation cover would be exceeded when woody cover for any of the landscape types within the park drops by more than 80% of the highest value ever recorded (Biggs and Rogers 2003). Gillson and Duffin (2007) used fossil pollen records for the KNP region to construct estimates for woody cover over the past 5,000 years and concluded that the TPC had not been exceeded in that time.

While TPCs appear to be very successful in the tightly integrated adaptive management regime of the Kruger National Park, the broad management of the coral reefs of the GBR is principally through zoning plans and responses occur on a timescale of several years. The processes linking management action in the coastal catchments to coral reef health are also likely to operate on a similarly long timescale. While TPCs represent a possible framework for interpreting indicators related to reef health, the main advantages of the KNP framework seem to be organisational, lying in the close integration and focus of the adaptive management system, rather than in an enhanced assessment of ecosystem health. In the context of Queensland and the GBR, many of the organisational advantages are likely to be diluted by long lag between management interventions and changes on coral reefs and by the multi-institutional involvement in management, monitoring and research.

TPCs differ fundamentally from the standards for interpreting values of other indicators that have been discussed so far. While interpretation of indicators by comparison with a reference site or prescribed standard gives aspirational targets for natural resource managers, TPCs relate to setting lower bounds for the condition of the ecosystem. This acknowledges that ecosystems change with natural cycles of disturbance and recovery as well as with human impacts. In the literature about KNP, TPCs seem simply to represent values on a continuous scale at which management intervention is mandated. In other contexts, the threshold of concern appears to be related to an ecological threshold – a set of conditions at which the ecosystem changes to an alternative stable state. The other side of the KNP approach is that no change in management activities is required until the indicators approach the TPC value. In the context of KNP, TPCs are set so as to minimise constraints on the dynamics of the ecosystem (risk tolerance) because theories of resilience (Holling 2001) suggest that constraining a system within narrow bounds results in reduced long term resilience, though no empirical evidence is given to support this.

“Limits of acceptable change” have been proposed in the context of coral reefs: Oliver (1999) described their use in adaptive management of a dredging program near Townsville that had the potential to cause unusually high sedimentation on some highly valued reefs. The values for the rates of bleaching and partial mortality of coral on the reefs downstream that would cause dredging to be suspended were initially based on expert opinion, but these were reviewed and refined, then formalised and agreed to by all stakeholders.

In some cases experimental work may provide a basis for setting thresholds for the lower bounds of ecosystem condition. For instance, Markey et al. (2007) tested five insecticides for their effects on larvae of one species of coral, *Acropora millepora*, and found that concentrations as low as $1\mu g.l^{-1}$ caused decreases in settlement and metamorphosis of 50-100%. Experimentally determined values need to be evaluated critically and confirmed for local species and conditions. As an example, Pastorok and Bilyard (1985) suggested that sedimentation rates $>50mg.cm^{-2}.day^{-1}$ were likely to cause catastrophic damage to coral communities, based on studies of reefs in some areas of the Caribbean. When Hopley et al. (1990) studied coastal fringing reefs north of Cairns, they found that sedimentation rates $>50mg.cm^{-2}.day^{-1}$ occurred regularly during the frequent windy periods, yet these reefs supported more than 140 species of hard corals, many of which were clearly adapted to the turbid conditions.

There are no agreed thresholds of concern for most of the commonly recorded variables relating to the health of coral reefs. Coral reefs are dynamic systems and reefs that are remote from direct human influence still show cycles of disturbance and recovery that can involve major disturbances from arguably natural causes. As an extreme example, low coral cover might suggest degradation, but Colgan (1987) reported that reefs in Guam where coral cover had fallen below 1% following a severe outbreak of in 1968-69 recovered to have an average cover of 65% by 1981. Coral cover on reefs in the Capricorn-Bunker group on the GBR showed a similar pattern following storm damage in 1988 (Halford et al. 2004). There is an issue of scale that will be important to the MTSRF IRC: coral cover can drop to very low levels on individual reefs, but *Acanthaster planci* outbreaks do not usually affect every reef in a region at the same time. Thus the threshold of concern depends on the scale of the reporting area.

In the general absence of logical thresholds, thresholds should be based on extreme values (for instance, 90th percentiles) of the distribution of recorded indicator values (suitably regionalized), with scheduled reviews by a panel of reef scientists who should also identify opportunities for experimental work to assist setting thresholds of concern or with interpreting monitoring results in other formats.

Recommendations – indicators for the Integrated Report Card

Table A2 lists many variables that are collected in some areas of the GBR, but their usefulness to the IRC depends on the evolving scales of reporting. Most indicators that are more closely related to population and ecosystem processes are only available at a limited number of sites. Measures of diversity of important groups of reef organisms (sessile benthic animals and reef fishes) are commonly used in assessments of environmental health, but data from different monitoring programs will need to be carefully standardized.

Development of practical indicators of ecological processes on coral reefs, along the lines of Fairweather's (1999) eco-assays would be very desirable. Indicators based on population trajectories of key groups of organisms from long-term programs are another possible new development.

In the absence of easily identified reference sites, values from the distributions of recorded values for indicators (appropriately regionalized) must be used for interpretation. This should be backed up by rigorous expert review and targeted research to refine the identification of critical values.

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Appendix 1

Table A1: Legend for Table A2.

Column heading	Notes
Coverage: cross and along shelf	Spatial coverage of relevant area of the GBR
Coverage: resolution	Spatial resolution
Coverage (interval)	Time between samples
Coverage (duration)	Length of record
Ecological relevance	Do the data provide a true indication of reef health, given their utility as a proxy for the main attribute/stressor?
Responsiveness	Is the indicator 'sensitive' to human stress or human intervention?

Sources	
1	AIMS LTMP 47 core reefs surveyed annually since 1992 and in alternate years since 2006
2	AIMS LTMP manta tow reefs surveyed haphazardly since 1985
3	AIMS LTMP 56 reefs monitored for effects of 2004 rezoning

Table A2: Potential indicators related to health of coral reefs. This table was based on the Heathy Reefs Program indicators as they apply to the GBR, with the main focus being spatial and temporal coverage. The table came out of a workshop on indicators and thresholds of concern held at AIMS in November 2006.

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
REEF STRUCTURE								
Biodiversity and Community Structure								
Hard coral cover (total)	H(1, 2)	H(1, 2)	H(1, 2)	H(1, 2)	H(1, 2)	L?	From AIMS LTMP	Major structural component of reefs
Hard coral cover (diversity)	H(1)	H(1)	H(1)	H(1)	H(1)	H?	From AIMS LTMP (limited taxonomic resolution)	Spp have different tolerances of stressors
Soft coral cover (total)	H(1)	H(1)	H(1)	H(1)	H(1)	L?	From AIMS LTMP	Major benthic group
Macroalgae	H(4)	H(4)	H(4)	H(4)	H	H?	From AIMS LTMP	Major benthic group, competitors of corals, complex relation to nutrients
Coral fish abundance	H(1)	H(1)	H(1)	H	H(1)	M	From AIMS LTMP, Time lags in some responses	Major benthic group
Coral fish diversity	H(1)	H(1)	H(1)	H	H(1)	H?	From AIMS LTMP, Prescribed list of 200 spp.	Have different tolerances of stressors
Rugosity	-	-	-	-	-	L	Very limited index may be possible from laborious re-analysis of videos of LTMP sites. Subjective assessment for some inshore sites (JCU)	Important for fish and invertebrate diversity

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
Focal spp. (Iconic / long replacement time)								
Large *Porites*	-	-	-	-	-	-		Very long lived
Dugong	H	H	H	M	H	H?	JCU surveys every 5 yrs	
Turtles	-	H	H	H	H	M?	Nesting site surveys QPWS	
Barramundi cod	-	-	-	-	-	H?		Susceptible to spear fishing
Maori wrasse	H(1)	H(1)	H(1)	H(1)	H(1)	H?	Very rarely recorded	Iconic sp, target for fishers
Sharks	-	-	-	-	-	H?		Top predators, susceptible to fishing
Bolbometopon	H(1)	H(1)	H(1)	H(1)	H(1)	L?	Very rarely recorded	
Abiotic Factors								
SST	H		H	H	M	-	CSIRO/GBRMPA ReefTemp	
Salinity	L	L	L	M	M	-	AIMS surveys and ships of opportunity	Flood plumes, upwelling
Chlorophyll a / Ocean colour	H?	H	H?	H	Potentially long	H?	From CSIRO - under development for RWQPP MMP	Indicator for nutrients
Turbidity	H?	H	H?	H	Potentially long	L?	From CSIRO - under development for Reef Plan Marine Monitoring Program	Affects photosynthetic organisms
Sedimentation	-	-	-	-	-	H?		Deleterious to many corals

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
Pesticides	L strategic	M	L	H	L	H	Entox RWQPP MMP	Affect coral reproduction, inter alia
Year of last cyclone	H	H	H	H	H	-	BoM records	
Habitat Extent								
Area of coral reef	H	M?	H	L	L	-	From GBRMPA GIS / A Lewis benthic elevation model	
Area of Mangroves	H	H	H	L	?	M?	EPA Wetland Mapping Project	
Seagrass (extent & density)	L	H	M	H	M	H?	From QDPI	Sensitive to WATER QUALITY, turbidity
REEF FUNCTION								
Reproduction & Recruitment								
Coral size frequency (inshore to genus, 5 size categories)	L	M	L	L?	L	H?	Monitored by AIMS on inshore reefs (Reef Plan Marine monitoring) to be discontinued.	Indicative of pop dynamics
Coral settlement	L	L	L	L?	L	H	On some inshore reefs by AIMS Reef Plan Marine monitoring - VERY laborious, requires very careful timing wrt spawning for comparability between sites and / or years	Susceptible to sediments / pollutants
Coral recruitment (juveniles)	L	M	L	L?	L	H?	Monitored by AIMS on inshore reefs (Reef Plan Marine monitoring) to genus.	Indicative of pop dynamics

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
Fish size frequency	M	M	M	H	M	H	(QDPI&F monitoring program, JCU - G Russ et al)	Indicative of pop dynamics
Fish recruitment	L	L	L	L	H	H	AIMS (D. Williams) Long time series for small fishes on 2? Reefs - discontinued	Indicative of pop dynamics
Coral Mortality								
Recent partial mortality (esp. massives)	-	-	-	-	-	-		
Coral disease prevalence	H(1, 2)	H(1, 2)	H(1, 2)	H(1, 2)	H(1, 2)	M?	AIMS LTMP / JCU (B. Willis), Lizard Is and Heron Is regions only	Caused major shifts in Caribbean reef communities
Bleaching prevalence	H	H	H		H		GBRMPA bleaching surveys / BleachWatch / Eye on the Reef	Major coral mortality
Time since last bleaching	H	H	H		H	-		
Crown-of-thorns starfish (COTS)	H(2)	H(2)	H(2)	H(2)	H(2)	-	AIMS LTMP / Reef Check at tourism sites	Major agent of coral mortality, tenuously linked to runoff
COTS outbreak status	H(2)	H(2)	H(2)	H(2)	H(2)	-	AIMS LTMP	
Time since COTS outbreak	H(2)	H(2)	H(2)	H(2)	H(2)	-	AIMS LTMP	

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
Herbivory								
Herbivorous fish abundance & composition	H(1)	H(1)	H(1)	H(1)	H(1)	L	AIMS LTMP for selected spp only	Complex interaction with algae
INTERACTIONS & RISK								
Tourism/Coastal Development								
Human sewage biomarkers	H	L	H	L	L	?	Many coastal sites - Kelly Lobb, UQ/GBRMPA, - baseline	
Coral damage Index eg ship grounding, anchor damage	L	M	L	?	H	H	(Eye on the Reef, DDM - focussed on tourism sites)	
Tourism index (EMC)	L	L	L	L	L	L	GBRMPA	
Coastal Development index (remote sensing, popn, marina approvals)	H	H	H	H	H	?	DNRW / GBRMPA?	
Recreation (boat registrations, diver days)							GBRMPA / Coastwatch?	
Agriculture & Island Runoff								
Pollutant accumulation (passive sampling, estuarine fish biomarkers)	L	H	H	H	L	H	Entox Reef Plan Marine monitoring	
Coral physiological indicators (eg coral colour)	L	M	?	L	L	?	AIMS Developmental at present	related to WQ

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
Modified FoRAM index	L	M	?	L	L	?	AIMS in development- laborious, initial survey only	Related to WQ
Land use change (clearing, fertiliser & pesticide use, wetland areas)	-	H	H	H	H?	?	DNRW - SLATS program/ EPA Wetland Mapping Project/ Agrochemical usage - ABS?	Related to WQ
Fishing								
Abundance & size of targeted finfish spp (incl Harvest spp)	H	H	H	H	H		QDPI&F LTM program / EoLF/ Some from AIMS LTMP	
Red throat emperor density & biomass	M	H	H	H	H		QDPI&F LTM program / EoLF/ JCU (G Russ) / Some from AIMS LTMP	Major target sp.
Coral trout density & biomass	H	H	H	H	H		QDPI&F LTM program / EoLF/ JCU (G Russ) / Some from AIMS LTMP	Major target sp.
Trochus	?	?	?	?	?	?	QFMA	Minor fisheries
Beche-de-mer	?	?	?	?	?	?	QFMA	Minor fisheries
Trop Rock Lobster	?	?	?	?	?	?	QFMA	
No of Recreational fishers								
Catch & effort (incl trawl & recreational)	?	?	?	?	?	?	QFMA	
Spawning aggregations	L	L	L	L	L	?	JCU / QDPI&F	
By-catch	L	L	L	L	L	?	QDPI&F By-catch study	

Indicator variable	Coverage: across shelf	Coverage: along shelf	Coverage: resolution	Coverage (interval)	Coverage (duration)	Respon-siveness	Source	Comments
Indigenous Use								
Number of indigenous agreements/TUMRAs	?	?	?	?	?	?	GBRMPA / QPWS	[Only one so far]
Climate Change								
GBRMPA Reef Temp heat stress predictions	H	H	H	H	L	H	GBRMPA / CSIRO	
Bleaching surveys	H	H	H	H	H	H	GBRMPA / AIMS	
Introduced Marine Pests								
Distribution, abundance & risk	L	M	L	H	M	?	(PCQ, QDPI&F, JCU, AQIS)	