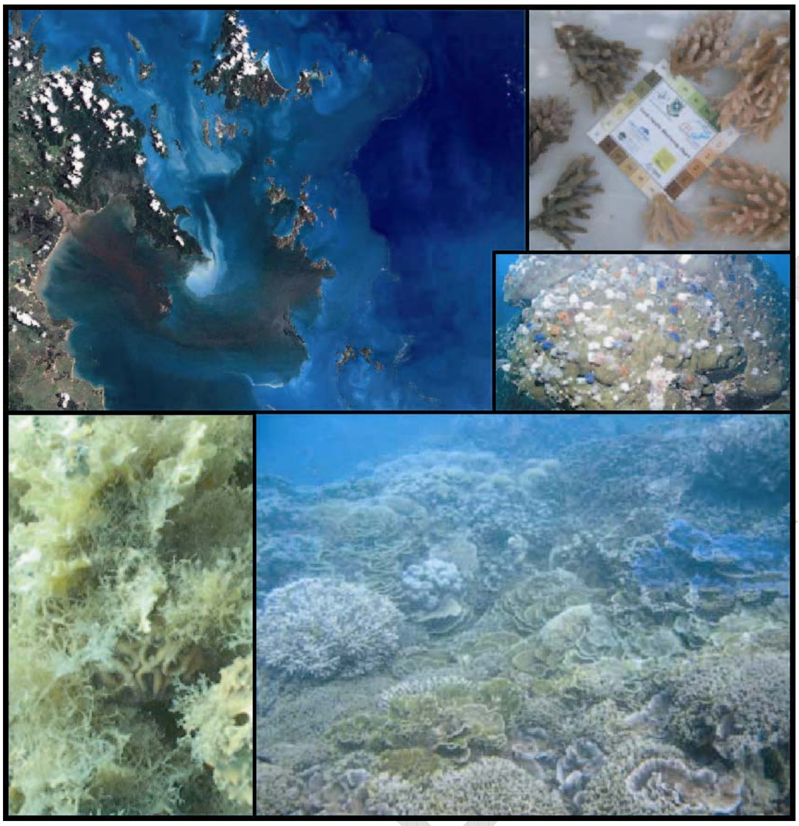
Coral-based Indicators of Changes in Water Quality on Nearshore Coral Reefs of the Great Barrier Reef



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Executive Summary

Halting and reversing the decline in water quality is a key priority to maintain the health and resilience of the Great Barrier Reef (GBR). To assess the effectiveness of land management strategies, indicator-based monitoring data are needed to predict and detect biological responses to changes in water quality. The aim of this report was to summarise research on a range of coral-based indicators at different spatial and temporal scales and identify those most suitable for inclusion into a 'toolbox' for monitoring the health of nearshore reefs on the GBR. The types of indicators investigated ranged from physiological responses to community-level measures in corals. We defined a set of selection criteria against which candidate indicators were assessed for their use to indicate changes in the key components of water quality (i.e. sedimentation, turbidity and light attenuation, and nutrients). Based on this matrix we identified seven coral-based indicators that could be incorporated into a monitoring toolbox. These were:

- Symbiont photo-physiology;
- Colony brightness of massive Porites;
- Tissue thickness of massive Porites;
- Density of macro-bioeroders in living Porites;
- Changes in coral juvenile densities;
- Changes in coral community structure; and
- The maximum depth of coral reef development.

Each of these measures has a different sensitivity and response time to changes in water quality. A combination of these measures, complemented by indicators based on biofilms and direct water quality measurements, is therefore recommended as a composite indicator system to assess changes in the exposure and condition of nearshore reefs on the GBR.

Contents

1.1 Background and Aims

There is considerable concern about the influence of runoff of nutrients, sediments and agrochemicals on the Great Barrier Reef (GBR). The coastal zone of the Great Barrier Reef World Heritage Area, with an area of 30,000 km2 and a water volume of 300 km3, receives an average annual input of water and sediment on the order of 66 km3 and 14-28 Mt, respectively (Furnas 2003). Nutrient and sediment input have increased several-fold since European settlement (Moss et al. 1992, McCulloch et al. 2003). Current estimates of annual inputs of nitrogen and phosphorus from land are 43,000 and 7,000-11,000 tonnes, respectively; a significant proportion of these nutrients are associated with particulate matter.

Halting and reversing the decline in water quality entering the lagoon is a key priority to maintain the health and resilience of the Great Barrier Reef. New management initiatives detailed in the 'Reef Water Quality Protection Plan' are now being implemented (Queensland Government & Commonwealth of Australia 2003). Such management relies on water quality specific and cost effective monitoring of the status and trends in the condition of inshore coral reefs and of water quality. Our research has aimed at developing coral-based indicators to assess the condition of inshore coral reefs of the GBR.

Numerous studies have developed and applied indicators as measure of coral health in the past, however, with some exceptions, few studies have aimed at comparing proposed indicator measures against each other. The exceptions include Risk et al. (2001) who highlighted the need for early warning, cost-effective indicators that can be used at large spatial scales. They proposed a toolbox comprising assessments of the diversity of stomatopods, amphipods and other invertebrate, and the measurements of bioerosion and geochemical markers to identify intensity and origin of stress. Using a rapid assessment method, DeVantier et al. (1998) showed that a two-tiered examination of ecological indicators (benthic cover and taxonomic composition of scleractinian corals) could discriminate sites with high conservation value in the Whitsunday Region of the GBR. Jameson et al. (2001) described the value of using a multimetric index to assess ecosystem health and developed the Index of Biotic Integrity (IBI), combining measures such as sessile epibenthos, benthic macroinvertebrates, fish, marine vegetation, phytoplankton and zooplankton, to produce an environmental score of the condition of coral reefs.

The aim of this report was to summarise research that has assessed a range of coral-based indicators at different spatial and temporal scales and identify those most suitable for inclusion into a 'toolbox' for monitoring the health of nearshore reefs on the GBR. The types of indicators investigated ranged from physiological responses to community-level measures in corals. At the physiological level, thickness of the tissue layer, coral growth rates, concentrations of chlorophyll a and lipid content as well as colony brightness and the photo-physiology of the dinoflagellate symbionts (Symbiodinium) were tested as proxies of environmental condition. At the population and community level, we tested changes in coral cover, community structure, the density of macro-boring bioeroders in living massive Porites, partial mortality and coral demography of massive Porites along environmental gradients. The study was carried out along a water quality gradient in the Whitsunday Islands of the GBR (Cooper et al. in press). To test causal effects of increased nutrient supply and decreased irradiance from suspended particulate matter on the physiological indicators, controlled experiments were carried out in tanks and with in situ manipulative experiments.

This report includes a brief summary of some of the main effects of three key components of water quality: sedimentation, turbidity and light attenuation, and nutrients, on corals to provide a context against which the proposed indicators can be assessed. A matrix of five criteria that characterise a useful indicator was developed and used to rank potential indicators. Finally, a discussion on future research directions highlights issues arising from the work undertaken here that warrant further investigation.

1.2 The Main Effects of Water Quality on Corals

1.2.1 Sedimentation

Sedimentation is defined as the deposition of particulate material onto the benthos, with the origin of the particles either resuspension from the seafloor or new imports through terrestrial runoff (Rogers 1990, Wolanski et al. 2005). Levels of sedimentation on coral reefs vary widely with differing spatial and temporal scales. Rates of sedimentation are usually greatest near the coast where wind waves can re-suspend old seafloor sediments, and near river mouths, and decrease with distance from the shore (Rogers 1990, Todd et al. 2001, Lirman et al. 2003). At smaller scales, sedimentation is usually greatest in sheltered, wave-protected lagoons, bays, or deeper reef slopes, and lowest in shallow wave-exposed areas (Wolanski et al. 2005). Sedimentation rates also vary temporally, and are high after periods of strong winds, waves and terrestrial runoff (Wolanski et al. 2005).

Increased concentrations of particulate materials can have contrasting effects on corals. Feeding on fine sediment particles may enhance coral growth in some species (Anthony 1999). However, the ability of corals to utilise particulate organic matter as a source of nutrition varies among species and types of sediment (Anthony & Fabricius 2000). In general, however, settling particulate matter represents a stress to corals. Energy investment into sediment rejection stresses corals in a variety of ways including down-regulation of photosynthesis and increasing their rates of respiration and mucus production (Riegl 1995, Telesnicki & Goldberg 1995, Yentsch et al. 2002, Philipp & Fabricius 2003). Photo-physiological stress occurs within hours of exposure to sedimentation (Philipp & Fabricius 2003) and is strongly related to the quality of the sediment (Weber et al. 2006), and is thus considered a useful sublethal indicator of changes in water quality. Accumulation of sediment on corals may ultimately result in tissue necrosis leading to injury and partial mortality (Lasker 1980, Rogers 1983, Peters & Pilson 1985, Gilmour 2002, Bak, 1978 #2302), which can lead to whole-colony mortality thereby altering the demography, percentage cover and community structure on coral reefs. Changes in community structure occur because susceptibility to sedimentation varies among coral species according to tissue thickness, polyp sizes and growth forms (Abdel-Salam et al. 1988, Stafford-Smith 1993, Riegl 1995, Wesseling et al. 1999).

1.2.2 Turbidity and light attenuation

Turbidity refers to the amount of suspended particulate matter (SPM) in the water column (and to a lesser extent some dissolved organic compounds) and their effect on light attenuation (Te 1997, Fabricius 2005). Suspended particles include both inorganic and organic matter (bacteria, phytoplankton, zooplankton and detritus), or inorganic particles with organic coating. Turbidity and thus light attenuation may vary over small spatial and temporal scales depending on the proximity of sources of terrestrial runoff (Fabricius 2005) as well as changes in local weather conditions (Larcombe et al. 1995, Orpin et al. 2004, Wolanski et al. 2005).

Turbidity and light attenuation can have contrasting effects on corals. Some species gain a substantial proportion of their energy budgets from heterotrophic feeding on SPM, while others obtain most of their nutrition from phototrophy regardless of the availability of particulate matter (Anthony & Fabricius 2000). At deeper depths, the energy gained from utilising SPM are most likely offset by the energy lost from reduced light availability (Fabricius 2005). Corals are able to photo-acclimatise to changes in light levels by adjusting the concentration of photosynthetic pigments and/or the density of their symbionts. The coral-symbiont association can adapt to low irradiance by increasing concentrations of photosynthetic pigments and/or the density of the symbionts (Falkowski & Dubinsky 1981, Dubinsky et al. 1984, McCloskey & Muscatine 1984, Porter et al. 1984, Chapter X). Symbionts adapted to high irradiance have less photosynthetic pigments and/or occur at lower cell density and thus exhibit lower light absorption characteristics (e.g. PAR-absorptivity; Ralph et al. 2005, Chapter X). The latter may increase with increasing contents of photosynthetically active pigments (Ralph et al. 2005). Further, maximal photosynthetic rate and minimum saturation irradiance (E_k) are higher whereas light utilisation efficiency (α) is low (White & Critchley 1999, Ralph & Gademann 2005, Ulstrup et al. 2006a). In contrast, symbionts adapted to low irradiance are characterised by low maximal photosynthetic rate and E_k, and high α (White & Critchley 1999, Ralph & Gademann 2005, Chapter X). Corals which are not able to compensate energetically from reduced light availability may experience decreased rates of calcification and thinner tissue in the coral host (Rogers 1979, Telesnicki & Goldberg 1995, Anthony & Hoegh-Guldberg 2003a). Due to variable abilities of corals in deeper water to compensate for low light, increased turbidity may lead to reduced density and diversity of corals, thus reducing the limit of depth distribution in coral communities (Birkeland 1987, Yentsch et al. 2002, Cooper et al. in press).

1.2.3 Nutrients

The main sources of new nutrients (N and P) in the GBR are upwelling from the Coral Sea and terrestrial runoff (Furnas 2003, McKergow et al. 2005). Corals are exposed to nutrients in a variety of forms that include particulate matter, and dissolved inorganic and organic nutrients (DIN and DON). Since dissolved inorganic nutrients (both N and P) are assimilated rapidly by phytoplankton, only a fraction of DON is bio-available, and the majority of nutrients are discharged in terrestrial runoff as particulate matter, particulate nutrients are the most common bio-available form of nutrients for corals in the coastal zone (Furnas 2003). Concentrations of nutrients on coral reefs vary widely with differing spatial and temporal scales. For example, nutrient concentrations are generally higher on coastal than offshore reefs (Brodie et al. 2007, Cooper et al. in press), and higher in summer (December to May) than in winter (Brodie et al. 2007).

As with sedimentation, turbidity and light attenuation, the effects of exposure to nutrients on corals depend on their concentration. Moderate levels of dissolved inorganic nutrients and particulate nutrients can enhance rates of gross photosynthesis (Kinsey & Davies 1979, Hoegh-Guldberg & Smith 1989, Ferrier-Pages et al. 2000), increases in symbiont density (e.g. Hoegh-Guldberg & Smith 1989, Muscatine et al. 1989) and tissue thickness (Barnes & Lough 1992, Lough & Barnes 2000), but reduce rates of calcification (Kinsey & Davies 1979). At higher concentrations, however, light attenuation negates the advantages of heterotrophic nutrition due to down-regulation of photosynthesis and reduced rates of calcification (Marubini 1996), which may alter reef metabolic processes leading to changes in community structure and diversity (Fabricius 2005).

1.3 Selecting Indicators

Monitoring programs examine biological responses to determine the status, trends and the effects of specific stressors on ecological systems. Bioindicators and/or biomarkers are often used to detect such responses. A biomarker refers to measures at the biomolecular or biochemical level (McCarty et al. 2002), whereas a bioindicator refers to those at higher physiological, population and/or community levels. Here, we focused on assessments of physiological to community level indicators, as assessment of biomarker tools such as

RNA/DNA ratio and genetic responses in corals to changes in water quality forms the basis of other studies (C. Humphrey, in prep). The use of biological indicators provides a number of significant advantages over direct measurements of water quality. For example, a direct measurement of water quality provides information about the condition of the water column at that particular point in time only. Moreover, if sampling is weather-dependant and constrained by safety considerations, then important information on the effects of episodic events, e.g. terrestrial discharges during floods or the resuspension of sediments during strong winds, may be missed. These issues are overcome, however, with the use of biological indicators that can provide a time-integrated measure (from time periods of days to years) of the effects of changes in water quality on coral reefs. Indictors that respond rapidly to a stressor can be used to detect sublethal effects, while indicators with high specificity can provide ecologically relevant information about the exposure particularly if the stressors are unable to be quantified. Given the wide variety of natural and anthropogenic factors that can influence a complex ecosystem such as a coral reef, it is unlikely that a single indicator exists that could sufficiently describe the condition of a coral reef (Erdmann & Caldwell 1997, Jameson et al. 1998). Rather, a composite of indicators (*sensu* Risk et al. 2001) incorporating responses from different ecological levels of organisation (i.e. physiological to communities) that can be combined to form an index (e.g. Jameson et al. 2001) has greater potential for success in assessments of the health of coral reefs.

To select a biological indicator objectively, however, requires a set of selection criteria. Here, we defined five key criteria (Table 1) modified from Jones & Kaly (1996), Erdmann & Caldwell (1997) and Jameson et al. (1998) that were considered to characterise desirable features of indicators necessary for assessing the condition of nearshore reefs of the GBR. An important criterion in the selection of any indicator is the response time over which the biological response is manifest in the individual, population or community. Both the times for the onset of a response and the period until full recovery of a response can range from near-instantaneous to decades. An important distinction, therefore, is to differentiate between methods suitable for detecting effects during or shortly after exposure to the stressor (rapid, with onset of response and recovery from an event within hours to weeks), and those better suited to detecting cumulative effects over prolonged periods of time (slow: onset and recovery taking months to years). An example of a method providing an immediate indication of stress is a change in the photo-physiology of *Symbiodinium* (Jones et al. 1999, Philipp & Fabricius 2003), whereas variation in the density and composition of macro-bioeroders due to changes in water quality may occur on a time-scale of years (Hutchings & Peyrot-Clausade 2002). Both types of indicators have advantages and disadvantages. A rapid response following exposure to a stressor is considered a desirable feature of an indicator as the response could be used as a sub-lethal indicator particularly for acute disturbances such as episodic runoff events. This is offset, however, by the high level of sampling intensity and replication required in monitoring programs to obtain accurate estimates of a response that could change on a time-scale of days to weeks; important events may be missed if recovery is too quick. Equally, whilst an indicator responding on a slower time-scale may not provide an early warning of change, they are still considered useful particularly for monitoring of chronic effects, as these types of indicators are likely to have low natural variability, and require lower sampling intensity to detect ecological change. Thus, in addition to response time, the importance of which will depend on the question being addressed, outlined below are five criteria that can be used to select indicators for assessments of the condition of coral reefs:

(1) ***Response specificity*** is the extent to which the biological response is specific to the stressor (either chronic or acute) of interest, and not to variation due to other causes. For example, the maximal depth of zooxanthellate corals was strongly related to a water quality gradient in the Whitsunday Islands and is considered highly specific to changes in water quality, particularly light attenuation associated with turbidity, but is unlikely to respond to other stressors, e.g. warming sea temperatures. The photo-physiological

parameter PAR-absorptivity, which indicates a more densely pigmented coral tissue layer possibly due to greater density of symbionts and/or concentration of chlorophyll (Ralph et al. 2005), was also strongly related to differences in water quality. However, symbiont loss is a well known response to warming sea temperatures (e.g. Glynn & D'Croz 1990, Hoegh-Guldberg 1999), thus changes in PAR-absorptivity due to changing water quality can at times be confounded by bleaching stress.

(2) ***Monotonic*** refers to the shape of the dose-response relationship, in which the magnitude of the response reflects the intensity (and/or duration) of the stress. A decrease in the photosynthetic yield (F_v/F_m) of *Symbiodinium* exposed to increasing levels of a stressor (Jones et al. 1999, Philipp & Fabricius 2003, Negri et al. 2005) is an example of a monotonic response indictor.

(3) ***Variability*** refers to indicators that demonstrate patterns of low variation in the absence of the stressor. An indicator that displays patterns of seasonal or temporal variability such as symbiont density (Fitt et al. 2000) or lipid content (Leuzinger et al. 2003) might still be suitable for inclusion into an indictor system provided that the variability is known and can be controlled for.

(4) ***Practicality*** refers to indicators that are easily quantified, are low in cost, require a low level of expertise and are applicable over a range of spatial and temporal scales (e.g. Risk et al. 2001). The cost factor includes consideration of the amount of labour required to collect data in the field and for laboratory analyses, and the cost of equipment and reagents required to process the samples. The colour chart developed by Siebeck et al. (2006) is an example of an economic, simple tool that can be used by a range of end-users.

(5) ***Relevant*** refers to indicators that are both ecologically relevant and also important in the public perception. Relevance assists in the communication of the results to a wide range of end-users. Measures such as the shift from a diverse hard coral to a macroalgal dominated reef community, are readily communicated to the public (e.g. Hughes 1994).

1.4 Recommended Indicators

To aid selection of the most appropriate indicators for changes in water quality on nearshore corals, all candidate indicators were assessed against the selection criteria in Table 1, and ranked at a scale of 1 to 5 determined from the sum of positive scores for each of the five criterion described above (following Fabricius & De'ath 2004, Table 2). Response time was excluded from the scores as both rapid and slower responding indicators can provide useful information in monitoring programs, depending on the question. An indicator with a slow response time would be inappropriate for monitoring short-term disturbances, e.g. dredging operations, whereas one with a fast response time may have reverted to background levels if a monitoring site is visited months after the event. Indicators with a score of 5 were 'highly recommended' for use in programmes to monitor changes in coral communities in response to changing water quality. An indicator for nutrient, light attenuation or sedimentation stress that responds rapidly and remains at an altered level for some time after exposure , is specific to the cause, demonstrates a monotonic response during the exposure, has low background variability, is practical to implement and has ecological and public relevance would receive a maximum score. Scores of 4 to 5 were assigned a 'high' recommendation, and seven indicators fell into this category. An example of an indicator that scored a 'high' recommendation was symbiont photo-physiology. Photo-physiological responses of *Symbiodinium* are known to be rapid and monotonic with increasing exposure to sedimentation and pollutants (Philipp & Fabricius 2003, Negri et al. 2005, Weber et al. 2006), can be measured economically once the initial set-up costs have been covered, but have only medium specificity to changes in water quality (discussed below). Indicators that ranked 3 had a ‘medium’ level of recommendation due to satisfying only some of the selection criteria. For example, lipid content provides valuable information on the energetic reserves of a coral that are fundamental for processes such as growth and reproduction (Anthony et al. 2002). However, lipid content varies naturally with reproductive cycles (Leuzinger et al. 2003), which has the potential to obscure physiological responses to changing water quality. Indicators that ranked 2 or lower may provide useful, often complimentary, information about the responses of corals to key stressors, but have a ‘low’ level of recommendation. The indicators that were highly recommended were symbiont photo-physiology, colony brightness of massive *Porites*, tissue thickness of massive *Porites*, density of bioeroders in living *Porites,* changes in coral juvenile densities, changes in community structure, and maximum depth of coral reef development. Here, we briefly summarise the properties, advantages and disadvantages of these seven measures.

1.4.1 Photo-physiology

Supporting data

Spatial variation in the photo-physiology of symbiotic dinoflagellates (Symbiodinium) of the scleractinian coral Pocillopora damicornis was examined along a water quality gradient in the Whitsunday Islands on the Great GBR. Chlorophyll a fluorescence of Photosystem II (PSII) and PAR-absorptivity were measured using an Imaging-PAM (pulse-amplitude-modulation) fluorometer. Imaging-PAM measurements included PAR-absorptivity, minimum fluorescence (F0), maximum quantum yield (Fv/Fm), quantitative parameters of rapid light curves (RLCs) (apparent photosynthetic rate, PSmax; light utilisation coefficient, α; minimum saturating irradiance, Ek) as well as non-photochemical quenching (NPQ241) and excitation pressure over PSII (Q241) determined at 241 μmol photons m-2 s-1 along the RLCs. Most parameters correlated with a water quality index (WQI) developed for the Whitsunday Islands. The direction of change varied depending on the depth of sampling, suggesting two contrasting mechanisms of photo-adaptation in shallow and deep corals. In shallow water, heat dissipation (NPQ241) was elevated at outer islands possibly in response to high irradiance, and low at nearshore reefs, which combined with high excitation pressure over PSII (Q241), may suggest potential effects of sedimentation and/or pollutants rather than irradiance. In contrast, at the deep depth, photo-physiological patterns were consistent with patterns of light/shade-adaptation (Falkowski & Dubinsky 1981, Kühl et al. 1995, Ralph et al. 2002, Anthony & Hoegh-Guldberg 2003b, Ulstrup et al. 2006a) suggesting that deep corals on nearshore reefs in the Whitsunday Islands are light-limited. This study provided the first evidence of photo-physiological responses related to in situ gradients of irradiance and water quality at mesoscales (i.e. 10s km).

Recommendation and methods

Cooper and Ulstrup (in prep) and previous studies demonstrate that measures of symbiont photo-physiology, i.e. chlorophyll a fluorescence of PSII and PAR-absorptivity, should be a component of ‘coral health’ monitoring programmes. PAM techniques provide a direct and rapid measure of sublethal stress in corals. If long-term water quality monitoring data were available for selected study areas, changes in water quality could be quantified by responses in photo-physiological parameters of corals sensu Chapter X. Few studies have examined the influence of nutrients on maximum quantum yield (Fv/Fm) (but see Hoegh-Guldberg and Smith 1989 for study of nitrogen limitation on photosynthesis) and controlled dose-response experiments are required to validate results based on field associations. Moreover, seasonal and temporal variability of symbiont photo-physiology on nearshore reefs of the GBR are not understood and need to be investigated further. Although photo-physiological measures may vary naturally, chlorophyll a fluorescence is a powerful tool to assess the status of the symbionts within their coral host. The response time of changes in photo-physiology is low, i.e. changes can occur on a time-scale of hours to days, suggesting a moderate to high sampling intensity (e.g. multiple times per year) would be required to obtain accurate estimates of these measures.

1.4.2 Colony brightness of massive Porites

Supporting data

A total of six physiological measures were investigated in two scleractinian corals (P.damicornis and massive Porites) in the field along a water quality gradient followed by a series of experiments manipulating water quality to validate patterns recorded in the field. The physiological measures included concentration of chlorophyll a, the density of symbionts, determinations of protein content and skeletal density in P.damicornis, and colony brightness and tissue thickness of massive Porites. In the field study, most of these measures showed significant relationships with water quality in both species. For P. damicornis, concentrations of chlorophyll a and symbiont density increased approximately 2.5-fold, but the density of the skeleton decreased 1.2-fold, along the gradient as nutrient and sediment levels increased from outer islands toward the nearshore reefs. In massive Porites, the colonies became progressively darker in colour along the water quality gradient.

In the laboratory experiments, Porites lobata showed a rapid physiological response in colony brightness following long-term exposure to suspended particulate matter. Corals were up to 2 colour chart scores darker after 20 days of exposure to suspended particulate matter and nutrients, and reduced irradiance, whereas corals in control treatments (i.e. filtered seawater and no shade) maintained consistent colony brightness throughout the experiment.

The response of colony brightness to differences in water quality in the laboratory was further tested in a transplantation experiment in the field. Nubbins of P. lobata transplanted from outer, shallow locations (low nutrients, high irradiance) to inner, deep locations (elevated nutrients, low irradiance) were noticeably darker as measured by colour chart and spectral reflectance, and had higher concentrations of chlorophyll a. This result was consistent with other studies of photo-acclimatisation to enhanced nutrients (Hoegh-Guldberg & Smith 1989, Muscatine et al. 1989) and light limitation (Falkowski & Dubinsky 1981, Dubinsky et al. 1984).

Recommendation and methods

On the basis of the field and manipulative studies and existing data on the acclimatisation of corals to altered regimes of nutrients and irradiance, colony brightness of massive Porites demonstrates potential as a useful indicator for incorporation into a monitoring toolbox. Colony brightness can be measured with a range of different tools, the simplest being a coral colour chart (Siebeck et al. 2006), and an alternative being reflectance spectrometry. Importantly, our study is the first to show that coral pigmentation can be used to quantify changes in water quality in situ on scleractinian corals. Changes in coral colour due to adaptation to altered irradiance or nutrient availability occur within a period of several weeks. However, coral colour can vary naturally in response to the physical environment (e.g. light and temperature; Hoegh-Guldberg 1999), and seasonally (Brown et al. 1999, Fitt et al. 2000, Chapter X) and these factors have to be controlled for when using colony brightness as an indicator of changing water quality.

1.4.3 Tissue thickness of massive Porites

Supporting data

The thickness of the tissue layer of massive Porites was also investigated along a water quality gradient and with a series of experiments manipulating water quality to validate patterns recorded in the field. As with P. damicornis, most of the measures for massive Porites showed significant relationships with water quality including a decrease in tissue thickness along the gradient as nutrient and sediment levels increased from outer islands toward the nearshore reefs. In the laboratory experiments, the thickness of the tissue layer, which has been reported to decrease in response to high levels of sedimentation (Barnes & Lough 1999), increased when exposed to suspended particulate matter most likely due to increased heterotrophy (Anthony 1999, Anthony & Fabricius 2000).

Recommendation and methods

On the basis of the field and manipulative studies and existing data (Barnes & Lough 1992), tissue thickness of massive Porites also demonstrates potential as an appropriate indicator for incorporation into a monitoring toolbox. Tissue thickness of massive Porites can be measured using simple tools such as vernier calipers and samples can be collected using a hand-drill. The thickness of the tissue layer can vary within a colony (Barnes & Lough 1992), so sampling must be standardised and replicates should be collected from the upper surfaces of colonies. The response time of changes in the thickness of the tissue layer to changes in water quality (particularly changes in irradiance) are considered to be in the order of 2-3 months (D. Barnes, AIMS, pers. comm), which suggests a moderate sampling intensity (e.g. every year) would be appropriate for this measure. However, the process is destructive and consideration should be given to procedures that mitigate the effects of the sampling process on the source colony.

1.4.4 Density of macro-bioeroders in living Porites

Supporting data

Spatial variation in the density of macro-bioeroders in living colonies of massive Porites was examined along a water quality gradient in the Whitsunday Islands on the Great GBR. The rationale is that macro-bioeroders (especially polychaetes, bivalvia and barnacles) are filter feeders that flourish at high particle loads. The study found that there was a 50-fold increase in the density of boring macro-bioeroders at the shallow depth (~3 m) along the gradient from mid-shelf to nearshore reefs in the coastal zone. Obtaining estimates of macro-bioeroder densities and species composition on coral reefs has been suggested previously as a potential indicator of changes in water quality (Hutchings & Peyrot-Clausade 2002). In French Polynesia, there were more deposit-feeding polychaetes on eutrophic fringing reefs, which were subject to terrestrial runoff, compared with oligotrophic atolls suggesting changes in feeding-guilds of macro-boring polychaetes may provide an indicator of particulate food availability in the water column. Similarly, Sammarco & Risk (1990) attributed greater intensity of internal bioerosion of Porites lobata on nearshore compared with offshore reefs of the GBR to greater nearshore productivity coupled with more grazing fish on offshore reefs, although this was not formally tested with any water quality data from their study sites. Chapter X examined spatial variation (10’s km) in the density of macro-bioeroders in massive Porites, respectively, but further work is required to examine the extent of variation in this measure at larger spatial scales, i.e. among regions of the GBR.

Recommendation and methods

Our study and existing data (e.g. Sammarco & Risk 1990, Hutchings & Peyrot-Clausade 2002) demonstrate that densities of macro-bioeroders in massive Porites are indeed related to water quality gradients, and on this basis, this measure is recommended as an appropriate indicator for inclusion into a monitoring toolbox. The relationship between density of macro-bioeroders and water quality in the Whitsunday Islands was depth-dependant indicating that depth has to be controlled for if this measure is to be used. Obtaining estimates of bioeroders density is a cost effective and low-technology measure that provides a time-integrated estimate of the effects of changes in water quality on corals. The relationship between density of bioeroders and changes in water quality is ecologically relevant, particularly if rates of erosion exceed that of carbonate accretion (Hutchings 1986). The response time of abundances of bioeroders is likely to be slow (months to years; Hutchings & Peyrot-Clausade 2002), thus indicating a low sampling intensity (e.g. every 2 – 3 years) would be appropriate for this measure.

1.4.5 Coral juvenile densities

Supporting data

Reef community characteristics, including the densities and taxonomic richness of coral juveniles strongly decline along water quality gradients. Juvenile densities in hard corals on reefs in the most turbid waters were around a quarter of those in cleaner water, and in octocorals less than a tenth of those in cleaner waters along the Whitsundays water quality gradient (Fabricius et al. 2007). Similarly, the taxonomic richness in hard coral and octocoral juveniles in the most turbid waters were around half to a third of those in cleaner water. This study shows that the ability of reefs to recover from disturbances is severely compromised, with reefs potentially taking twice to four times as long to re-establish cover, and resulting in a lower taxonomic richness than on reefs in consistently cleaner waters. This finding is consistent with results from other studies that have shown reduced coral recruitment success at declining water quality conditions (reviewed in Fabricius 2005).

Recommendation and methods

Changes in the density and taxonomic richness of coral juveniles are strong, ecologically relevant and consistent across regions. Their specificity for prolonged exposure to water quality conditions is relatively high, although data need to be assessed in the context of the broader ecological condition of reefs (connectivity etc). Changes in juvenile densities are likely to change before changes in community structure can be detected, because coral juveniles have a greater sensitivity to sedimentation than adult corals, and coral larvae choose their settlement site depending on the suitability of substratum and light. Juvenile densities are assessed within belt transects. Growth rates in corals are species-specific and though massive corals are older than small branching colonies. For the sake of convenience all colonies of 5 cm or less in diameter are being included, as the susceptibility to sedimentation and other changes in water quality depends on colony size rather than colony age.

1.4.6 Community structure

Supporting data

Reef community characteristics, including the cover of the main benthos groups and the taxonomic richness of hard corals and octocorals, changed along water quality gradients in three independent inshore regions of the Great GBR (DeVantier et al. 1998, van Woesik et al. 1999, Fabricius et al. 2005, DeVantier et al. 2006, Fabricius et al. 2007). These studies showed that along water quality gradients, the cover and taxonomic richness of both hard corals and octocorals declined several-fold, from clear to turbid sites, while macroalgal cover strongly increased along the same water quality gradient. This finding is consistent with results from around the world that have documented shifts from coral to algal dominated communities where water quality changed (reviewed in (Fabricius 2005).

Recommendation and methods

Responses in the taxonomic richness of hard corals and octocorals, macroalgal cover are strong, ecologically relevant and consistent across regions. A combination of these measures, when interpreted correctly, can represent relatively robust and relevant indicators to monitor changes in water quality conditions. The methods to monitor these measures are established (English et al. 1997, Abdo et al. 2003), and much of the information is acquired on a routine basis by standard reef monitoring programs. Macroalgae can establish within seasons to years, and are therefore more responsive than the more long-lived coral communities as long as herbivore densities do not change. Juvenile densities and macroalgal abundances are therefore likely to both change before changes in community structure can be detected, and efforts may therefore be prioritised to quantify these two measures.

1.4.7 Maximum depth of coral reef development

Supporting data

The lowest depth limit of coral reef development, i.e. that coinciding with the zone of transition from zooxanthellate hard corals to azooxanthellate octocorals, was investigated along a water quality gradient in the Whitsunday Islands on the Great GBR (Cooper et al. in press). The study showed that the maximum depth of zooxanthellate corals decreased five-fold along the gradient from outer to coastal locations and was related significantly to a water quality index based on thirteen irradiance and water column nutrient variables. This finding was consistent with previous study that found a negative correlation between the maximal depth of corals and levels of suspended particulate matter and turbidity (van Woesik et al. 1999, Yentsch et al. 2002) and suggests that the lower edge of coral distribution in the Whitsunday region is determined by light availability, and possibly sedimentation. The lower depth distribution in corals may, therefore, be used as an indicator for changes in water column light properties, similar to the use of the lower distribution limits of seagrasses in assessments of estuarine ecosystem health (e.g. Abal & Dennison 1996, Dennison & Abal 1999).

Recommendation and methods

The findings of van Woesik et al. (1999), Yentsch et al. (2002) and Cooper et al. (in press) suggest that the maximal depth distribution of coral reef development is a useful measure that should be included into a toolbox for monitoring the condition of nearshore coral reefs. Whilst this indicator showed strong relationships with changes in water quality in the Whitsunday Islands, further work is required to examine the extent of variation in this measure at larger spatial scales, i.e. among regions of the GBR. The methods for determining the maximal depth of coral reef development need further refinement, e.g. comparing quantitative methods (e.g. transects, quadrats) to identify the zone of transition from zooxanthellate hard corals to azooxanthellate octocorals, wherever hard substratum is available. Nevertheless, this measure has high specificity, is economic and a practical indicator that provides a time-integrated estimate of the effects of water quality on coral reefs. Moreover, understanding the relationship between the maximal depth of coral reef development and changes in water quality is ecologically relevant to the condition of coral reefs. The response time of changes in the maximal depth distribution of zooxanthellate corals is unknown and warrants further investigation. Notwithstanding this, it is considered that the response time would be in the order of years suggesting a moderate sampling intensity (e.g. every two to three years) would be appropriate for this measure.

1.5 Synthesis and Future Research Directions

Our systematic assessment of research presented here and in Fabricius et al. (2007) has resulted in the recommendation of seven coral-based measures to indicate changes in levels of sedimentation, turbidity and light attenuation, and nutrients on nearshore coral reefs. These are symbiont photo-physiology, colony brightness of massive *Porites*, tissue thickness of massive *Porites*, density of bioeroders in living *Porites*, changes in coral juvenile densities, changes in coral community structure, and the maximal depth of coral reef development. Of the investigated candidate measures to indicate stress, some have been shown to respond to a range of stressors, including unusual levels of temperature and salinity. For example, maximum quantum yield (F_v/F_m) decreases in response to sedimentation (Philipp & Fabricius 2003, Weber et al. 2006) but also following exposure to low salinity (Kerswell & Jones 2003) and elevated sea temperatures (Ulstrup et al. 2006b). Among the water quality specific indicators, few were found to be specific for either sedimentation or turbidity or nutrients, and further work is needed to identify indicators for each of specific water quality conditions. Since elevated levels of sedimentation, turbidity and nutrients tend to co-occur in many nearshore environments, such greater specificity was considered secondary compared with identifying indicators that are specific for water quality.

Each of the coral-based measures proposed here has a different level of sensitivity and response time, and hence combinations of these measures may serve to indicate relative levels of exposure, and short-lived episodic vs chronic exposure (Fig. 1). Our indicator measures were plotted against increasing levels of stressors in ascending order, from sublethal stress to mortality. These responses vary according to the magnitude and duration of exposure to the stressors. Similar responses to those presented in the short-term may occur following exposure to lower levels of stress over longer (months to years) periods of time but this remains to be determined. Exposure to the key components contributing to decreased water quality (i.e. elevated sediments, turbidity and nutrients, and reduced irradiance) will first invoke a response at the physiological level (i.e. the early warning indicators). At increasing exposure (either longer duration or higher levels), responses at the population and community level will become evident.

Symbiont photo-physiology, colony brightness and tissue thickness of massive *Porites* have a relative high level of specificity for water quality if depth is controlled for and in the absence of bleaching conditions. Maximum quantum yield (F_v/F_m) decreases following exposure to sedimentation (Philipp & Fabricius 2003) and low irradiance (Anthony & Hoegh-Guldberg 2003b). PAR-absorptivity and quantitative parameters of rapid light curves (RLCs) including apparent photosynthetic rate (PS_{max}), light utilisation coefficient (α) and minimum saturating irradiance (E_k) correlated strongly with water quality and/or light limitation (Hoegh-Guldberg & Smith 1989, Anthony & Hoegh-Guldberg 2003b, Uthicke 2006). Importantly, photo-physiological stress to changes in water quality occurs on time-scales of hours to days (Philipp & Fabricius 2003, Negri et al. 2005, Weber et al. 2006) and on this basis, it is likely to be the most appropriate ‘early warning’ indicator capable of quantifying a response to changes in water quality.

Maximal depth of coral reef development can serve as quite specific indicator of longer-term exposure (chronic) water quality conditions on coral reefs (Titlyanov & Latypov 1991, van Woesik et al. 1999, Cooper et al. in press). Similarly, densities of macro-bioeroders measured in living massive *Porites* are known to proliferate at locations where particulate organic matter are not limiting (Sammarco & Risk 1990, Hutchings & Peyrot-Clausade 2002). These two measures are likely the most specific indicators for chronic changes in water quality conditions. Similarly, continued exposure high levels of sedimentation and poor water quality may lead to reduced juvenile densities, and changes in the community structure through the loss of susceptible species, resulting in decreased species richness and shifts to communities dominated by resilient coral species and macroalgae (van Woesik et al. 1999, Fabricius et al. 2005, DeVantier et al. 2006).

The focus of this report has been on identification and selection of coral-based responses to changes in water quality. The challenge ahead will be to improve the understanding of patterns of variation and defining thresholds for the suite of indicators identified here. For example, further work is required to provide estimates of seasonal and temporal variability in symbiont photo-physiology on nearshore coral reefs of the GBR. The relationship between the maximal depth of coral reef development and water quality requires further investigation because if deep corals on nearshore reefs are indeed light limited, then simple tools such as Secchi depth and monitoring coral reef depth may provide time-integrated information on strategies to improve water quality on the GBR. It has been beyond the scope of this report to examine and identify 'thresholds of concern', but clearly future research should focus on understanding the physiological, ecological and community responses to differing loads and duration of the key components of water quality. Moreover, priority should be given to studies that investigate the responses, adaptation and consequences of changes in water quality on corals and coral reefs that are exposed to a changing environment of temperatures and water carbonate saturation.

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Table 1. Criteria for selection of indicators to assess effects of key stressors on corals and coral communities.

Attribute	Criteria
Specificity	Indicator should be specific to the cause (the stressor of interest), hence clearly attributable to that stressor.
Monotonic	The relationship between the disturbance intensity and the response size should be monotonic (rather than modal).
Variability	Indicator should be consistent at a range of scales, i.e. time and space. Ideally, there should be low background variability.
Practicality	Indicator should be cost effective, easy to measure, and a proxy for another, more complicated or costly measure. Measurements should be observer-independent and carried out by a range of users, ideally requiring a low level of expertise.
Relevance	Indicator should be ecologically relevant, and ideally important in public perception to assist communication.

Table 2. Matrix for identifying indicators of the effects of changes in water quality on nearshore corals of the GBR. Indicators are assessed against the criteria defined in Section 1.3. Rank denotes the sum of positive scores when assessed against each criterion, and determines the level of recommendation. Abbreviation, Med. = Medium, Rec. = Recommendation.

Response	Method	Response time	(1) Specificity	(2) Monotonic	(3) Variability	(4) Practicality	(5) Relevance	Advantages	Disadvantages	Rank	Rec.
Behavioural and physiological											
Polyp activity, tissue expansion and mesenterial extrusion	Visual, descriptive estimate. (Telesnicki & Goldberg 1995)	Immediate to weeks	Low (-)	No (-)	High (-)	Yes (+)	Low (-)	Simple indicator of stress. Supporting evidence for use with other quantitative methods.	Not easily quantified, variation among species, colonies and diurnally; low specificity.	1	Low
Photo-physiology	PAM fluorometry (Ralph et al. 2005, Chapter X)	Immediate to days	Med. (+)	Yes (+)	High (-)	Yes (+)	High (+)	Provides a measure of sublethal stress.	Specialised tool, initial cost of equipment high but cost of measurements is low.	4	High
Colour brightness	Colour charts, spectrometry. (Siebeck et al. 2006, Chapter X)	Weeks	Med. (+)	Yes (+)	High (-)	Yes (+)	High (+)	Simple method to quantify changes in pigment content and density of symbionts.	Background spatial and temporal variation in colour brightness needs to be determined.	4	High
	Chlorophyll *a* extraction, fluorometry. (Hoegh-Guldberg & Smith 1989)	Weeks	Med. (+)	Yes (+)	High (-)	No (-)	Low (-)	Direct quantification of the concentration of photosynthetic pigment.	Natural variation, requires specialised equipment.	2	Low

Response	Method	Response time	(1) Specificity	(2) Monotonic	(3) Variability	(4) Practicality	(5) Relevance	Advantages	Disadvantages	Rank	Rec.
	Counts of symbiont density. (Hoegh-Guldberg & Smith 1989)	Weeks	Med. (+)	Yes (+)	High (-)	No (-)	Low (-)	Direct quantification of the number of symbionts within the coral.	Natural variation, method is time consuming.	2	Low
Tissue thickness of *Porites*	Calipers (Barnes & Lough 1992)	Weeks to months	Med. (+)	No (-)	Low (+)	Yes (+)	High (+)	Sublethal indicator of stress.	Natural variation, method is destructive.	4	High
Lipid content	Extraction and gravimetric determination of lipids. (Harland et al. 1992)	Weeks to Months	Med. (+)	No (-)	High (-)	Yes (+)	High (+)	Energy reserves are relevant for reproduction and growth.	Seasonal and intra-colonial variation, sampling is destructive method time consuming.	3	Med.
Coral diseases	Visual estimate. (Bruno et al. 2003)	Weeks	Low (-)	Yes (+)	High (-)	No (-)	High (+)	Increased incidence of disease reflects levels of stress to corals.	Varies according to presence of pathogens. Low specificity, expertise required.	2	Low
Population											
Population size structure	Quantify colony size. (Meesters et al. 2001)	Months to years	Med. (+)	Yes (+)	High (-)	Yes (+)	Low (-)	Provides information on processes, e.g. reproduction, that are related to size.	Method may be time consuming.	3	Med.
Partial mortality	Visual estimate. (Ginsburg et al. 2001, Nugues & Roberts 2003)	Days to months	Low (-)	Yes (+)	High (-)	Yes (+)	High (+)	Indicates stressors such as sediment accumulation.	Low specificity due to other factors such as predation by *Acanthaster planci*, feeding scars from fishes.	3	Med.

Response	Method	Response time	(1) Specificity	(2) Monotonic	(3) Variability	(4) Practicality	(5) Relevance	Advantages	Disadvantages	Rank	Rec.
Macro-bioeroder density in living massive *Porites*	Quantify and identify the density of macro-bioeroders in living *Porites* colonies. (Hutchings & Peyrot-Clausade 2002)	Weeks to years	High (+)	Yes (+)	High (-)	Yes (+)	High (+)	Density of filter-feeding macro-bioeroders may reflect long-term changes in the load of suspended particles.	Experimental research is needed to test links between densities of specific macro-bioeroders groups and environmental conditions.	4	High
Community											
Changes in the cover of main benthic groups	Line/point intercept transects. (English et al. 1997, Abdo et al. 2003)	Months to years	Low (-)	Yes (+)	High (-)	Yes (+)	High (+)	Traditional component of reef monitoring programs. Simple method, requires low skills base.	Low specificity.	3	Med.
Taxonomic richness, abundances of indicator species, and community structure in corals	Surveys, taxonomic inventories. (van Woesik et al. 1999, Fabricius et al. 2005, DeVantier et al. 2006)	Months to years	High (+)	Yes (+)	Low (+)	Yes (+)	High (+)	Provides indication of mortality of the corals that are most susceptible, which may pre-empt mortality of other corals.	Requires considerable replication. Reflects mortality of corals rather than sublethal stress. Need to identify species of various susceptibilities to the stressors, which may change in space and time.	5	High

Response	Method	Response time	(1) Specificity	(2) Monotonic	(3) Variability	(4) Practicality	(5) Relevance	Advantages	Disadvantages	Rank	Rec.
Larval supply	Quantify rates of larval settlement using settlement tiles. (Babcock & Davies 1991)	Days to weeks	Low (-)	No (-)	High (-)	No (+)	Low (-)	Changes in larval supply provide insight to the resilience and recovery potential of coral reefs.	Local patterns of reproduction in corals must be known. Background variation in larval supply is variable, and may not reflect condition at settlement site.	1	Low
Coral recruitment	Quantify juvenile densities. (Smith et al. 2005)	Months to years	High (+)	Yes (+)	High (-)	Yes (+)	High (+)	High specificity	Time consuming	4	High
Indicator organisms other than corals	Changes in the relative abundances or cover of organisms associated with coral reefs. (Fabricius et al. 2005)	Months to years	High (+)	Yes (+)	High (-)	Yes (+)	Low (-)	Changes in indicator species may pre-empt mortality of corals but only if indicator species is more sensitive to disturbance than sensitive corals.	Method to be developed.	3	Med.
Maximum depth coral reef development	Quantify transition zone of zooxanthellate to azooxanthellate community. (Cooper et al. in press)	Years	High (+)	Yes (+)	Low (+)	Yes (+)	High (+)	Provides an indirect measure of the effects of components of water quality that influence water clarity and hence lead to light limitation in zooxanthellate corals.	Method under development.	5	High

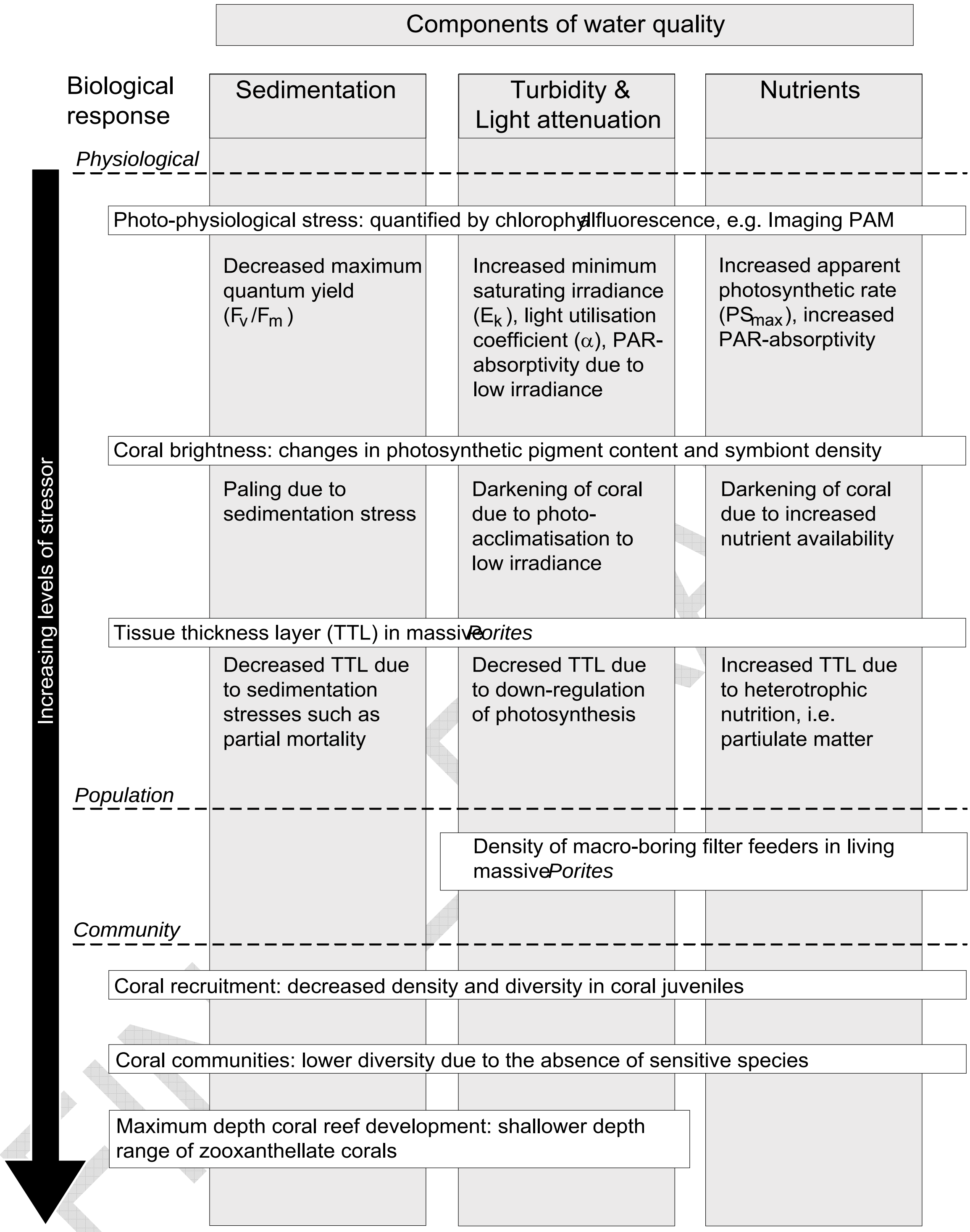

Figure 1. Biological measures to indicate increasing exposure to the key components of water quality. Indicator measures that can be used to assess all three stressors are displayed at the level of exposure at which the measure is useful. The grey boxes indicate cases where the indicator values differ depending on the type of stressor.