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# Supplementary Report to the Final Report of the Coral Reef Expert Group:

## S2. Practical taxonomy for RIMReP Coral Reef Monitoring — Macroalgae

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# Executive Summary

This report reviews the benefits and limitations of seven assessment and classification schemes for macroalgae that have been applied in coral reef monitoring. It provides recommendations for a practical scheme of algae identification for use in the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP).

Ideally, one would monitor macroalgal abundance at the species level, as this would provide high value data to draw conclusions about coral reef ecosystem status and functioning. However, this scheme is impractical to implement given the taxonomic expertise required.

A practical scheme that includes a combination of different levels of taxonomic resolution is recommended for monitoring macroalgae for the RIMReP. Specifically, the scheme includes assessment of the per cent cover of the three major categories of algae, some functional form groups and key taxonomic genera:

1. Upright macroalgae (fleshy and calcareous macroalgae)
    - Fleshy macroalgae
        - Key genera, e.g. *Sargassum*, *Lobophora*, *Dictyota*, *Chlorodesmis, Caulerpa, Padina, Asparagopsis*
    - Calcareous macroalgae
        - Key genera, including for example *Halimeda* and *Amphiroa*
2. Algal turfs (includes canopy height measurements)
3. Crustose coralline algae (CCA)

This hybrid scheme has the benefit of the distinction of key algal groups that have important functional roles in reefs (e.g. upright macroalgae and turfs, and CCA), as well as macroalgal genera which may have beneficial or detrimental effects on coral population dynamics. For example, ratios of fleshy macroalgae vs. algal turfs vs. CCA can be easily calculated and will provide additional information on reef process. The scheme therefore provides insights into the potential drivers of community structure and change.

Similar schemes have been successfully used in coral reef algal studies in the central Pacific and at some reefs in the Great Barrier Reef (the Reef), including by some established Reef coral reef monitoring programs (e.g. Long-Term Monitoring Program (LTMP), Marine Monitoring Program-Inshore (MMP)). Finally, automated image classifying programs (e.g. CoralNet) can recognise some macroalgal genera, making this scheme compatible with future developments of such technologies.

Additionally recommended is the inclusion in the RIMReP coral reef monitoring of:

- In situ measurement of canopy height for the upright macroalgae and particularly for algal turfs as an indicator of shifts in the relative contribution of nutrient enrichment and herbivory controls of algae;
- Quantification of the rates of growth and calcium carbonate deposition by CCA, e.g. by using deployments of “calcification stations”.

# Introduction

## Definition of the term “macroalgae”

Macroalgae (or seaweeds) are a group of multicellular marine algae, mostly benthic and visible to the naked eye (Hurd et al. 2014). Macroalgae are taxonomically classified into four different Phyla: Rhodophyta (red algae), Ochrophyta (Class Phaeophyceae, brown algae), Chlorophyta (green algae) and Cyanobacteria (blue-green algae). This systematic classification is largely based on the composition of pigments involved in photosynthesis. Macroalgae are also classified based on their morphology and size, with three major categories being recognised: 1) macroalgae, usually refers to larger (canopy heights usually >10 mm), more rigid and anatomically complex algal forms (also called fleshy macroalgae or seaweeds); 2) algal turfs, refer to a group of filamentous algae of small size (1-10mm) and includes early or small-sized life history stages of 1); and 3) crustose coralline algae (CCA), refers to encrusting, calcified forms or red coralline algae. In the coral reef literature, however, different researchers use different terminologies to refer to macroalgae, for example, “macroalgae” has been used to refer to species of upright and fleshy forms, including calcified species such as *Halimeda*, but has also been used to include small filamentous forms such as algal turfs (e.g. Obura et al. 2017). In this report, the term macroalgae is used in a broader sense to include all three main categories, upright forms (fleshy and calcareous), algal turfs, and CCA.

## Abundance and importance of macroalgae in reefs

Recent surveys by the Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program (LTMP) show that macroalgae abundance on many reefs exceeds the cover of hard and soft corals in the Great Barrier Reef (the Reef) (Figure 1) (AIMS 2018). Similarly, surveys in the Central Pacific (Smith et al. 2016), Caribbean (Jackson et al. 2014) and Indian ocean (Obura et al. 2017) have concluded that macroalgae are the most abundant component of benthic reef communities in these regions. The relative abundance of the different macroalgal groups, i.e. upright macroalgae, algal turfs and CCA, however, has not been well documented in many instances (e.g. Bruno et al. 2014), yet these different groups play very different roles in coral reefs (Diaz-Pulido et al. 2007). Importantly, there is a perception that the abundance of upright fleshy macroalgae and algal turfs has increased in reefs worldwide, particularly due to increased mortality of hard corals (e.g. due to coral bleaching, crown-of-thorns starfish outbreaks, cyclones, etc.), reduced grazing rates (due to sea urchin disease and overfishing), increased nutrient supply and declining water quality (Hughes 1994, Lapointe 1997, McCook 1999, Fabricius et al. 2005), although the nature and magnitude of the increase in benthic macroalgae is still debatable (Bruno et al. 2009, Bruno et al. 2014). Providing detailed baselines and establishing accurate and precise monitoring programs that assess the macroalgal abundance at a practical and meaningful level is therefore critically important.

Macroalgae play fundamental roles in the ecology and functioning of coral reefs, although the different macroalgal groups (uprights, turfs and CCA) contribute differently to these roles. Algal turfs, for example, are significant primary producers (Adey and Goertemiller 1987, Klumpp and McKinnon 1992), converting solar energy and $CO_2$ in biomass and dissolved organic carbon that is consumed by a variety of micro and macro-organisms. CCA are important in reef building processes, including reef cementation and accretion, particularly in shallow reef habitats (Littler and Littler 1984). CCA are also important as inducers of coral larval settlement (Harrington et al. 2004), contributing to coral population recovery.

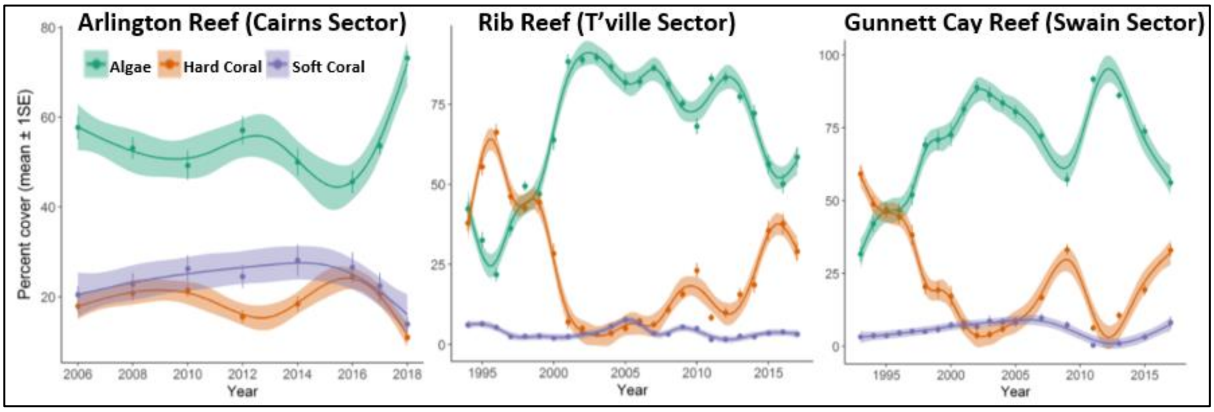

**Figure 1. Examples of macroalgal dominance in reefs on the Great Barrier Reef. Percent cover determined from fixed transects by the AIMS Long-Term Monitoring Program-LTMP (AIMS 2018)**

Many canopy-forming macroalgae, such as *Sargassum* and other Fucales form dense canopies that are used by a variety of invertebrates and fish as nursing and feeding grounds (Martin-Smith 1993, Tano et al. 2017). Some species of *Sargassum* can also produce associational refuges for corals that can considerably reduce their consumption by CoTS (Clements and Hay 2015). However, not all upright macroalgae are beneficial for reefs, as some are known to actively outcompete corals for space and light via a variety of competitive mechanisms, which would depend on the species of macroalgae (McCook et al. 2001, Del Monaco et al. 2017). As macroalgae colonise the space left by corals, their increasing abundance in turn limits coral larval settlement and recruitment, creating feedback loops that contribute to coral reef decline.

## Diversity and distribution of macroalgae

Macroalgae are biodiverse, with around 880 species reported for the Reef (Hurrey et al. 2013), although estimates of species richness are still uncertain and likely underestimated (McCook and Price 1997). Recent molecular studies of tropical macroalgal taxa have documented an astonishing cryptic diversity. For example, the brown fleshy macroalga *Lobophora* which a few years ago only comprised a handful of described species, now includes more than 100 taxa (Vieira et al. 2017). Many other reef genera are believed to have considerable cryptic diversity, too (e.g.the red alga *Portieria* (Payo et al. 2013)).

The spatial and temporal distribution of macroalgae in the Reef vary considerably depending on the location on the continental shelf, reef habitat, and season. Reefs closer to shore have abundant canopy-forming and fleshy seaweeds, while alga turfs and CCA are the dominant algal components in the outer reefs (McCook et al. 1997, Diaz-Pulido et al. 2007, Wismer et al. 2009). Macroalgae also experience seasonal variation in abundance, for example, canopy-forming macroalgae usually have high growth rates and biomass during the summer months and senesce during fall. Some fleshy brown macroalgae such as *Lobophora*, *Hydroclathrus* and *Chnoospora* are generally present year round but are more abundant during winter-to-spring seasons (Schaffelke and Klumpp 1997). The variability in space and time, as well as the diversity of forms and species needs to be taken into consideration when discussing monitoring programs aiming at understanding the dynamics of coral reef macroalgae.

## Objectives of this report

Given the importance of macroalgae in the ecology of reefs, and the varied contributions that the different forms and species make to reef functioning and reef status, understanding the causes and consequences of algal distributions is critical for reef conservation. This understanding may be facilitated by a monitoring system that goes beyond the simple inclusion of “macroalgae” as a group, to include an assessment of the abundance of key groups and genera of benthic macroalgae. Specifically, this report aims to provide an assessment of the different assessment and classification schemes of taxonomic resolution in macroalgae that have been used in reef monitoring. It provides recommendations for the level of taxonomic resolution that should be implemented in RIMReP for monitoring macroalgae in the Reef.

Coral reef monitoring programs in the Reef have used different algal categories and levels of taxonomic resolution (summarised in Cheal and Emslie (2017), including the single category “macroalgae”, or assessing macroalgae at genus (or species) level. These programs have also considered a variety of algal metrics including per cent cover, algal biomass, and canopy height. In this report the benefits and limitations of the different existing schemes are considered, and recommendations on a practical monitoring system to monitor the abundance of macroalgae in coral reefs, with emphasis on the Reef are provided. Finally, given the importance of CCA in reef accretion, reef building and carbon sequestration, as well as our recent studies on CCA (e.g. (Diaz-Pulido et al. 2014, Ordonez et al. 2017, Kennedy et al. 2017, Lewis et al. 2017a, Lewis et al. 2017b)), the use of “calcification stations” to monitor the abundance, growth and calcification of CCA in the Reef is discussed.

## General algal schemes used for monitoring purposes

There are a number of schemes or levels of taxonomic (or group) resolution for monitoring macroalgal abundance in coral reefs. These include:

- One grouping “Macroalgae”
- Major macroalgal categories: “Macroalgae”, “Algal turfs” and “CCA”
- Functional form group approach: Seven major groups
- Phylum, order or family level
- Genus-level
- Species-level
- Combination of schemes

## One grouping “Macroalgae”

This scheme uses only one category (or group), “macroalgae”, for assessing the abundance of macroalgae in coral reefs (Hughes 1994, Bruno et al. 2014). This category generally includes upright macroalgae, both fleshy and calcareous forms (e.g. *Halimeda*). However, in many instances, it is not clear whether the “macroalgal” category has incorporated other benthic algal groups such as algal turfs.

The benefits of using this level of resolution is that it provides a quick overview of the changes in dominance of benthic macroalgae (Figure 2), generally used in comparison to changes in hard coral cover. The use of this scheme provided sufficient resolution to identify the critical consequences of the mortality of herbivorous sea urchins in the Caribbean in the early 80s (Hughes et al. 1985) and facilitated comparisons of reef resilience and macroalgal roles across biogeographic regions (Roff and Mumby 2012). In the Reef, changes in macroalgal abundance have been useful to document phase shifts from coral to macroalgal dominance (Cheal et al. 2010). The use of this scheme requires no taxonomic expertise and because of its simplicity, many coral reef monitoring networks initially (i.e. decades ago) used this scheme to assess reef status, including Reef Check (e.g. Bruno et al. 2009), AIMS LTMP, the Great Barrier Reef Marine Park Authority’s rapid response team (Climate Change Group 2007), and Cinner et al (2013). This scheme therefore also provides access to global data sets.

The use of this approach, however, provides incomplete information on the processes driving change in macroalgal and coral abundance, and on the nature of the shifts in algal composition. As stated earlier, different groups and species of reef macroalgae have different functions and roles in reefs and the use of this scheme provides limited insights into the potential specific consequences of increased or decreased algal abundance in reefs and reef resilience.

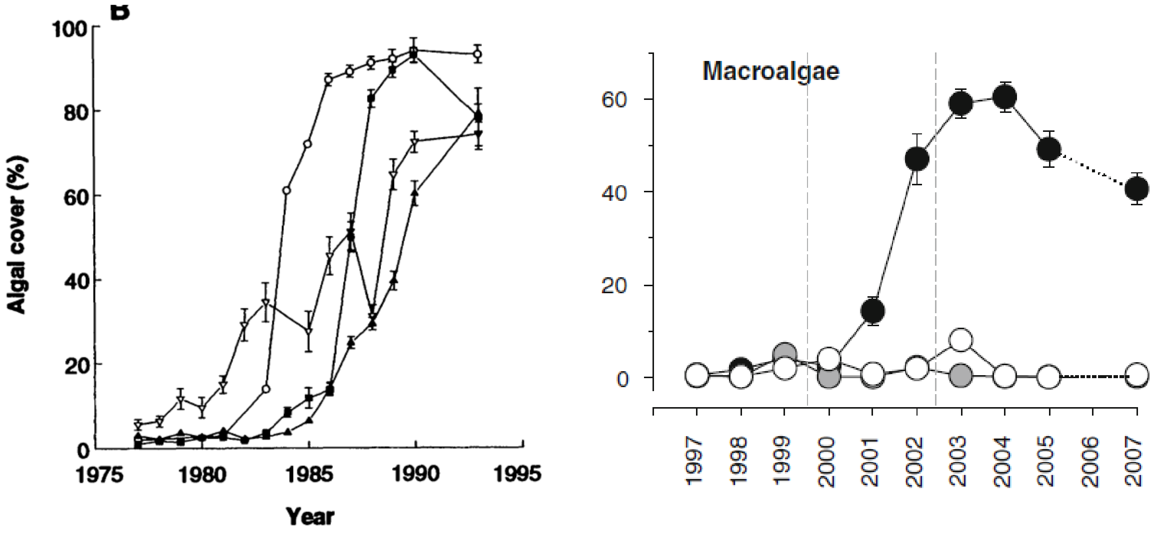

**Figure 2. Examples of studies that have used a single algal category to investigate changes in algal (= macroalgal) cover**. **Left panel**: Data from Jamaican coral reefs across four depths (Figure from Hughes 1994). **Right panel**: Data from three reefs in the Great Barrier Reef. Figure from Cheal et al. (2010).

## Major macroalgal categories: *Macroalgae*, *Algal turfs* and *CCA*

This scheme expands the macroalgae category to include three major categories, “macroalgae”, “algal turfs” and “CCA”. Here, “macroalgae” includes large algal forms (generally >10 mm height), more rigid and anatomically more complex than algal turfs. Some studies distinguish between “fleshy” and “calcareous” forms (Figure 3) (McClanahan et al. 2002, Smith et al. 2016), while others combine filamentous, fleshy and calcareous groups into the “macroalgae” assemblage (Obura et al. 2017). ‘Algal turfs’ includes assemblages or multispecies associations of minute filamentous algae and the early life stages of larger macroalgae. The terms ‘epilithic algal community’ (EAC) (Larkum et al. 2003) or “epilithic algal matrix” (EAM) (Wilson et al. 2003) are often used to refer collectively to the assemblage of minute filamentous algae, associated microalgae and bacteria, as well as the detritus component (mostly of algal origin) that grows and accumulates on the substrate. Finally, as detailed earlier, CCA refers to the group of encrusting calcified forms, mostly coralline algae (Corallinales *sensu lato*) and Peyssoneliales.

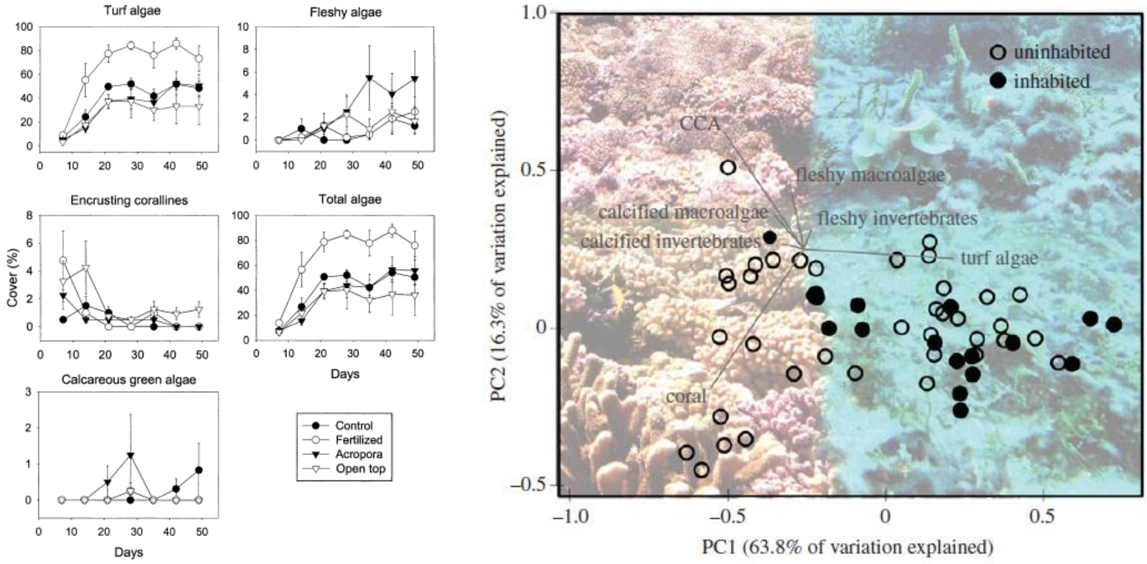

**Figure 3. Examples of studies that have used the major macroalgal categories for investigating changes in algal communities in reefs. Left panel**: Changes in major algal categories in response to herbivory reduction and nutrient addition in the Caribbean (Figure from McClanahan et al. 2002). **Right panel**: Principal component analyses of the per cent cover of major benthic algal categories in Pacific reefs (Figure from Smith et al. 2016).

This scheme is perhaps the most widely used to assess macroalgal abundance in coral reef monitoring programs globally (e.g. Atlantic (AGGRA (Kramer 2003, Ruttenberg et al. 2018); CARICOMP); the Reef (the AIMS LTMP adopted this scheme more recently; four monitoring programs use this scheme in the Reef according to (Cheal and Emslie 2017)(reviewed by (Lam et al. 2017)). The scheme provides much more detail and resolution in macroalgal monitoring than the previous algal scheme, contributing to a better understanding of coral reef algal dynamics. For example, distinction between macroalgae and algal turf categories, and inclusion of algal turfs allows inferences about coral-fish-algal dynamics (Bellwood et al. 2004, Wismer et al. 2009). Algal turfs are fundamental to reef ecology: they have high rates of primary productivity, growth and colonisation and usually quickly occupy the space left by corals following disturbances, e.g. coral bleaching (Diaz-Pulido and McCook 2002); turfs are usually the dominant benthic group in coral reefs (e.g. Figure 3, left panel; see also Pichon and Morrissey 1981, Morrissey 1980, Klumpp and McKinnon 1992, Vermeij et al. 2010, Ruttenberg et al. 2018). In general, reefs with high cover of low canopy algal turfs may indicate recent coral mortality and/or moderate herbivory intensity. Algal turfs are highly productive and produce significant amounts of dissolved organic carbon, therefore are a preferred grazing surface for many herbivorous reef fish (Wilson et al. 2003) having the potential to influence overall reef metabolism (Haas et al. 2013). When coral reef trajectories are analysed using the "upright macroalgae" group only (i.e. excluding the algal turfs), researchers have concluded that there is little evidence of transitions from coral to algal dominance (Bruno et al. 2009). However, inclusion of the algal turf category in coral reef trajectories provides a more realistic scenario of the true footprint of anthropogenic influences on reefs, and clear evidence of coral to algal phase shifts (Smith et al. 2016).

Distinction between fleshy and calcareous macroalgae is also important in this scheme, and particularly useful to identify the contribution of *Halimeda* to carbonate budgets, particularly relevant in some coral reef environments where *Halimeda* is the dominant component [e.g. bioherms in the northern Reef (McNeil et al. 2016)], or where the presence of fleshy macroalgae is associated with low rates of grazing by herbivorous fish (Hughes et al. 2007). Additionally, the inclusion of CCA is important as they are key contributors of the carbonate framework and their abundance and trajectories are usually opposite to those of upright fleshy macroalgae (Figure 2). This 'macroalgal categories' approach then provides a better understanding of the processes driving change in reef benthic communities than the previous 'macroalgae' scheme. However, it is still limited in the understanding of within-group variability, which is important as, for example, some groups of fleshy macroalgae play opposing roles in coral-algal competition (McCook et al. 2001).

Assessing the abundance of upright macroalgae (both fleshy and calcareous), algal turfs and CCA requires a basic level of expertise and can be conducted relatively quickly. Limitations of using this scheme include limited information on within group variability and incomplete knowledge of the processes driving change. For example, a recent analyses using the AGRRA monitoring data showed that the total cover of fleshy macroalgae was unrelated to the abundance of herbivorous fish in the Caribbean (Suchley et al. 2016). This suggests that there are other factors that are more important in regulating macroalgal abundance in coral reefs and /or that further detail is required when assessing the abundance of macroalgae in refs, specifically providing more detail in the way this category is assessed (Suchley et al. 2016).

## Functional form group approach: Seven major groups

This scheme is a much more detailed version of the previous scheme in which two of the major algal categories (algal turfs and macroalgae) are subdivided into various subgroups. The subgroups are established based on the functional morphology of the benthic algae and are arranged along a continuum of forms, anatomies, and sizes (Figure 4). For example, algal turfs are divided into two subgroups to differentiate between benthic microalgae with a single cell anatomy such as cyanobacteria, from larger forms such as filamentous algae (e.g. *Cladophora*, *Ceramium*). On the other hand, the "Macroalgae" (or upright macroalgae) group encompasses a number of functional subgroups ranked along a gradient of increasing anatomical complexity and size. For instance, “Foliose algae” have a simple anatomy, with a single layer of cells, while the “Leathery macrophytes” comprises genera such as *Sargassum*, with complex internal anatomy as well as larger size (up to several meters tall). Groups also have physiological (e.g. photosynthesis), structural (e.g. thallus toughness) and ecological (e.g. herbivore sensitivity) traits that are characteristic of each individual grouping (Littler 1980, Littler et al. 1983). The scheme was initially proposed by reef phycologists in the early 80s (Littler and Littler 1980, Littler et al. 1983), and subsequently refined by Steneck and Dethier (1994), and has been used in reef studies addressing coral-algal competition (McCook et al. 2001) and influences of anthropogenic activities in macroalgal assemblages (Duran et al. 2016). Although some coral reef monitoring programs such as NOAA (e.g. reviewed in Lam et al. 2017) differentiate between cyanobacteria and algal turfs, this level of resolution has not been widely used in monitoring programs to assess macroalgal abundance in reefs. In temperate ecosystems, a similar scheme has been designed to collect information from still images and video cameras [e.g. Collaborative and Automated Tools for Analysis of Marine Imagery (CATAMI) (Althaus et al. 2015)]. The CATAMI scheme proposes a number of functional form groups well aligned with the Littler’s and Steneck’s classification schemes.

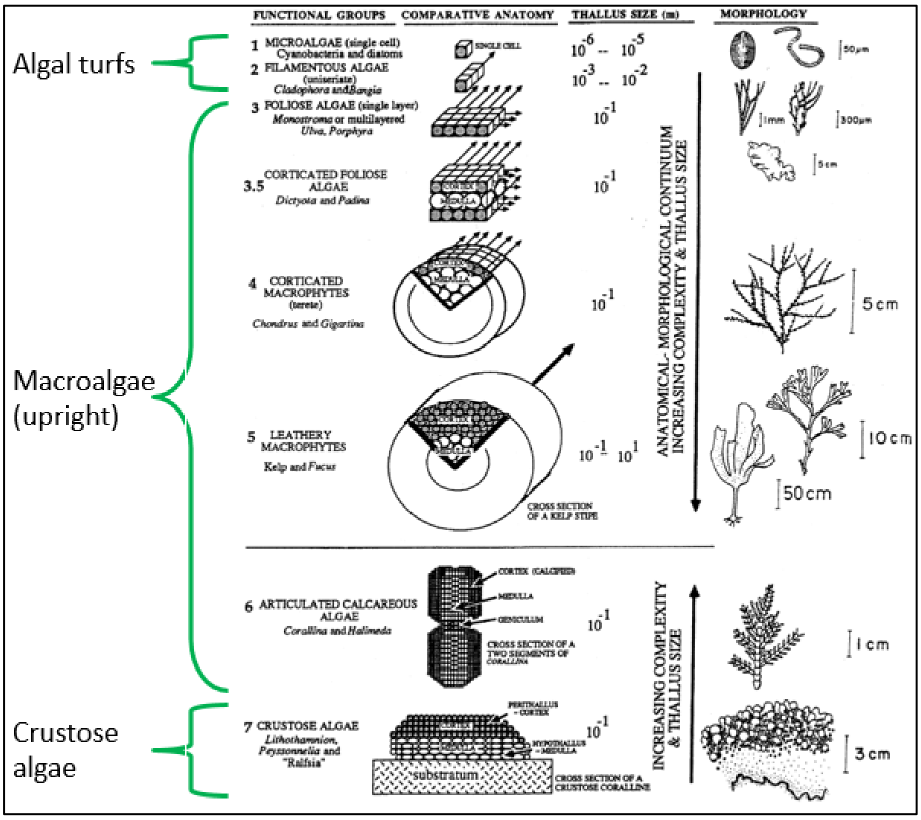

**Figure 4. Algal functional form groups (adapted from Steneck and Dethier (1994)** Major algal categories are subdivided into functional groups of increased anatomical complexity.

The benefits of using this scheme to monitor macroalgal abundance rest on its ability to predict physiological/ecological responses in macroalgal assemblages to environmental change by simply using a classification based on the algal forms (Figure 5). This scheme has been particularly useful in research to identify variability in the responses of macroalgae to herbivore reduction and nutrient effects. For example, in Florida, although the upright macroalgae group was more abundant in herbivore enclosures, the leathery macroalgae were exclusively found within herbivore enclosures cages. Identifying such subtleties in macroalgal responses to anthropogenic stressors may be important as different algal groups have different functional roles in reefs. In this particular example, leathery macrophytes such as *Sargassum* may also have the potential of providing refuge for corals from CoTS predation and from thermal bleaching (Jompa and McCook 1998, McCook et al. 2001). Although a classification using the functional-form scheme is much easier than using a phylogenetic / taxonomic approach, it nonetheless requires a level of expertise not always available in monitoring teams.

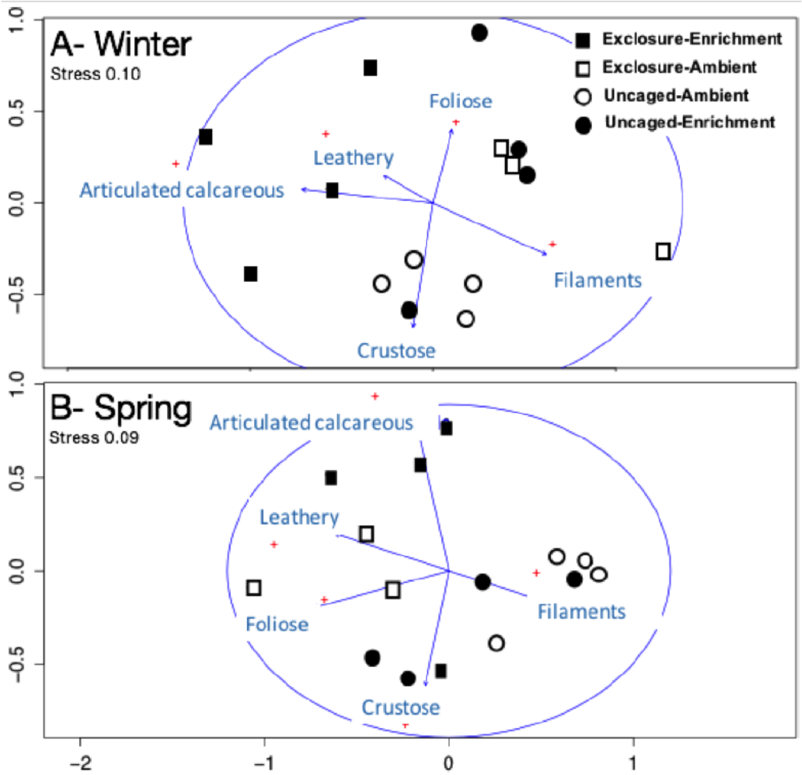

**Figure 5. Example of the use of the functional form groups approach to investigate responses of coral reef algal communities to environmental change, in this case, to herbivore reduction and nutrient enrichment.** Non-metric multidimensional scaling analysis of benthic algal communities on successional tiles in Florida in two climatic seasons (Figure from Duran et al. 2016).

## Phylogenetic / taxonomic approaches

The three previous schemes use the morphology and functional form of macroalgae as the basis to assess the abundance of macroalgae in coral reefs. Macroalgal abundance however, can also be assessed using phylogenetic / taxonomic approaches, which consider the phylogenetic relationships of the macroalgae and their taxonomic classification. Some studies have considered the different phyla (red (Rhodophyta), brown (Ochrophyta) and green (Chlorophyta)), order, family, genera, or species of benthic algae. The most common level of taxonomic resolution that is used in monitoring programs is the genus-level. In the following sections I discuss the use of phylum, order or family, and genus and species levels approaches for assessing algal abundance in reefs.

### Phyla, order or family

Assessments of the abundance of algae at the level of phylum, taxonomic order or family are rarely used in coral reef monitoring programs, perhaps because of the low resolution and variability within algal groups, and the difficulty in differentiating some algal phyla in some cases. For example, many species of the red alga *Gracilaria* can actually be yellow-brown under some light conditions or depending on the stage of senescence (pers. obs.). The corticated macroalga *Laurencia* (another red alga) can be green, brown or red. There are, however, a number of coral reef macroalgal studies which have used the phylum approach to explore the spatial distribution patterns of coral reef algae in the Reef (Figure 6) (Diaz-Pulido et al. 2016). In this instance, the phylogenetic scheme was successful in identifying clear difference in the abundance of algal phyla across the continental shelf and two depths (Figure 6). However, this assessment in itself provides no information on the nature of the differences across the shelf, limiting the utility of this scheme for monitoring purposes. Since macroalgae from the same phylum might play very different functional roles in reef ecology (e.g. coralline red algae and fleshy red macroalgae), the use of the phylogenetic approach (i.e. algal phyla) scheme provides limited resolution needed for coral reef monitoring (Fabricius et al. 2005), but see Hart and Klumpp 1996, for an example of the utility in exploring Crown-of-thorns starfish-fish-algae interactions). Notwithstanding, the phyla scheme is generally useful when assessing physiological responses of reef algae to environmental change.

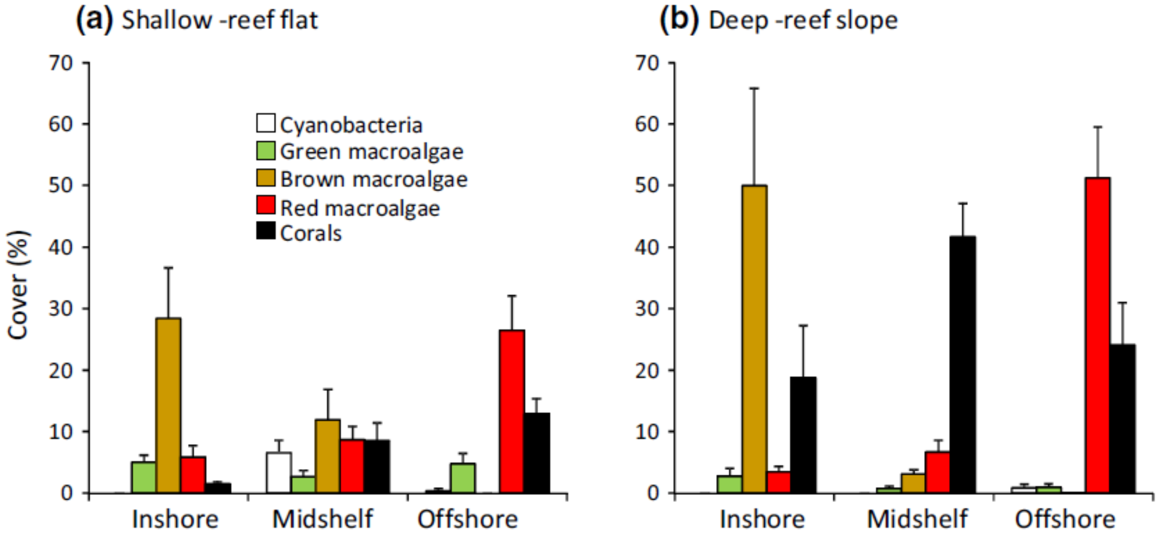

**Figure 6. Variability of the abundance of major benthic algal phyla [red (Rhodophyta), brown (Ochrophyta), green (Chlorophyta), and cyanobacteria] in shallow and deep coral reefs across a gradient of water quality and proximity to the coast in the Great Barrier Reef (Figure from Diaz-Pulido et al, 2016).**

The use of taxonomic orders or families for monitoring the abundance of reef macroalgae is primarily used for some groups of algae in which identification in the field to a finer taxonomic level is very difficult. For example, the order “Corallinales” can be applied to all encrusting (non-geniculate, i.e. CCA) and articulated (geniculate) coralline red algae, although in strict taxonomic terms, the order Corallinales has now been split into several orders including Hapalidiales, Corallinales, and Sporolithales, all including crustose coralline red algae. The order Dictyotales can also be used to include several genera with very similar morphologies that can only be differentiated under the microscope, for example the genera *Dictyota*, *Canistrocarpus*, *Dictyopteris*, and the *Vaughaniella* stage of *Padina*, which they all share a similar dichotomous ramification and ribbon-like appearance. However, the use of families is also limited because, for example, algae with different morphologies and ecological roles may be included within the same order or family. For instance, the brown alga *Lobophora* is a member of the order Dictyotales, a very distinct genus from *Dictyota*. Further, because the taxonomy of algae and their position within orders and families change continuously due to the development of new and more sophisticated molecular markers, the taxonomic resolution at the level of order and/or family for monitoring macroalgae in the Reef is not recommended.

### Genus-level

The approach using the taxonomic resolution at the level of genera is commonly employed in research programs to quantify the abundance of macroalgae in reefs and has been widely used in reefs across the Caribbean (Figure 7, right panel) (McClanahan et al. 1996, Mumby et al. 2005), Pacific (Tribollet and Vroom 2007, Tribollet et al. 2010) and the Reef (McCook et al. 1997, Fabricius et al. 2005). Five Reef monitoring programs use genus level to assess macroalgae, all coordinated by the AIMS LTMP or MMP (Marine Monitoring Program-Inshore) (Cheal and Emslie 2017). This approach has allowed a better understanding of the nature of the changes in macroalgal communities along environmental gradients and between reef habitats than previous approaches. There have been few studies exploring the temporal dynamics in macroalgal communities using this level of resolution (Tribollet and Vroom 2007), but when algal dynamics have been assessed though time, it has provided insights into population dynamics in relation to hurricane impacts, grazing and seasonality. For example, Mumby et al (Mumby et al. 2005) documented contrasting demographic trajectories in two dominant Dictyotalean species in the Caribbean, *Dictyota* and *Lobophora*, which were driven by significant variability in grazing susceptible and responses to seasonal changes in seawater temperature.

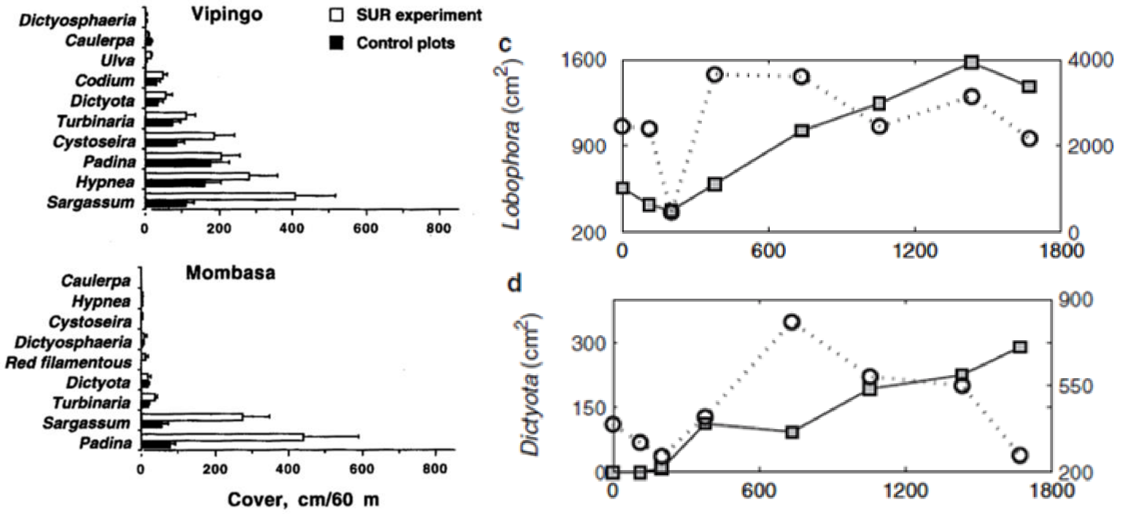

**Figure 7. Examples of studies using a taxonomic resolution at the level of general. Left panel**: Study examining the effects of sea-urchin removal on fleshy macroalgal communities in Kenya (Figure from McClanahan 1996). **Right panel**: Changes in area cover by two genera, *Lobophora* and *Dictyota* through time (days) in the Caribbean (Figure from Mumby et al. 2005).

Limitations of the use of this scheme include the need for intermediate level of taxonomic expertise for the identification of macroalgal genera and the increased amount of time in data analyses. However, recording the abundance of algal genera is possible with some training as the dominant macroalgal genera in reefs generally do not overpass 10 to 20 genera (McClanahan et al. 1996, Tribollet and Vroom 2007).

### Species level

The abundance of macroalgae in coral reefs is also assessed at the lowest taxonomic level, i.e. species level (Figure 8). This scheme has been employed in descriptive and experimental studies in coral reefs in the Caribbean (Hay 1981, Carpenter 1990, Diaz-Pulido and Díaz 1997, Diaz-Pulido and Garzón-Ferreira 2002), Florida (Duran et al. 2016), Pacific (Vroom et al. 2005, Vroom and Braun 2010, Smith et al. 2010) and the Reef (Hurrey et al. 2013, Diaz-Pulido et al. 2016). This approach is particularly useful to characterise macroalgal communities from different reef environments (e.g. shallow vs. deep reefs, inshore vs. offshore reefs, or reef flat vs. reef crest and slope habitats) (Morrissey 1980, Diaz-Pulido and Díaz 1997, Vroom et al. 2005) and to potentially identify habitats that support high species richness (Vroom et al. 2005, Hurrey et al. 2013). The latter may be important for reef conservation. The approach is unique in providing baselines of macroalgal abundance and species diversity so that the impacts of environmental change can be monitored. Temporal studies in Hawaii have been very useful in detecting species of macroalgae that have now become increasingly common in some reefs. For example, species of *Padina*, *Sargassum* and *Stypopodium* were minor components of benthic communities in the southern Hawaiian islands, but became dominant in reefs in the northern islands (Vroom and Braun 2010). A functional form approach would have classified *Padina* and *Stypopodium* under the same macroalgal category (foliose fleshy macroalgae), yet their dominance in these reefs varied considerably.

The approach is also valuable in determining the nature of the relationship between macroalgal communities and environmental factors and processes driving change in algal abundance, including nutrient and light limitation, hydrodynamics, herbivory, ocean acidification and warming. For example, detailed studies addressing the effect of reduction in grazing on algal community composition showed that many macroalgal species within a particular functional form group experience differential grazing pressure and were not consumed by herbivores, providing insights into coral reef metabolism (Sammarco 1983, Hatcher and Larkum 1983, Scott and Russ 1987, Carpenter 1990). A recent Reef study assessing macroalgal species cover across the continental shelf, identified species that are potentially more susceptible to increased $CO_2$ concentrations, extremely useful information for predicting the impacts of ocean acidification in reefs and coral-algal dynamics (Diaz-Pulido et al. 2016). A detailed assessment of the algal species composition has also been relevant in examining the trajectories of algal succession and identifying indicator species of the different stages of algal colonization of reef substrates (Diaz-Pulido and McCook 2002). Assessments of algal abundance at the finest level of identification also provide insights into the influences of climatic seasons and oceanographic conditions on algal species composition (Rogers 1996, Schaffelke and Klumpp 1997, Rogers 1997, Diaz-Pulido and Garzón-Ferreira 2002), patterns which may not be clearly identifiable if other approaches were used.

Similar to the scheme using genera to assess macroalgal abundance, the species-level approach has limitations due to the considerable expertise required to identify the macroalgae at this level of resolution. Considerable time is also required to process the quantitative data, particularly when communities are rich in species.

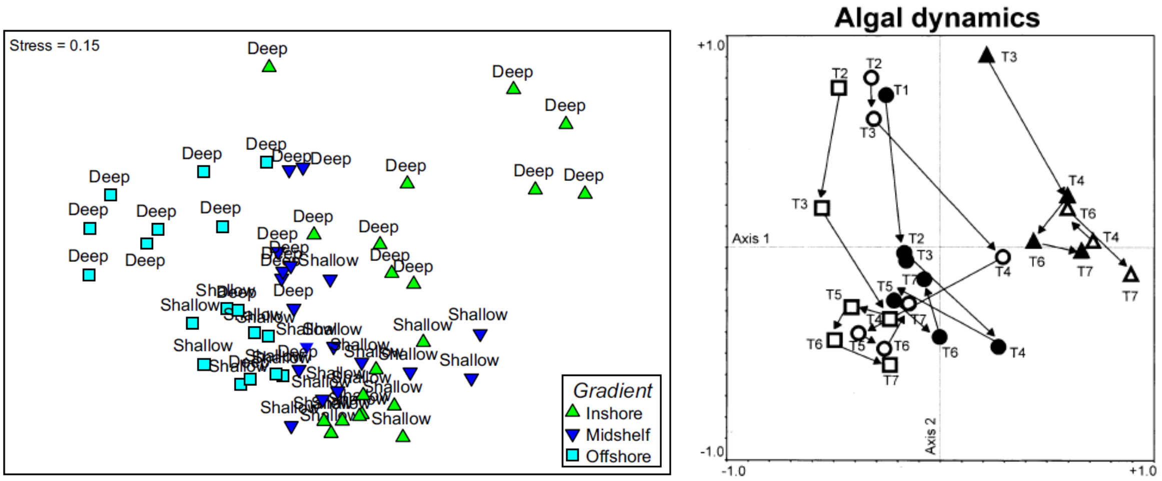

**Figure 8. Two studies showing the utility of assessing algal communities at species levels for identifying spatial (left panel, Diaz-Pulido et al. 2016) and temporal (right panel, Diaz-Pulido and McCook 2002) patterns.**

## Recommended classification scheme for monitoring macroalgae in the Great Barrier Reef

Each of the different schemes of taxonomic resolution used to monitor the abundance of macroalgae in reefs has its own advantages and limitations as discussed in this report and summarised in Table 1. Ideally, one would monitor macroalgal abundance at the species level, given the benefits of this scheme, however, this scheme is difficult to implement given the taxonomic expertise required to achieve this level of resolution. Algal taxonomists are rare and there is no current trend in marine (or biological) sciences education to encourage training of new generations in this discipline. At the other end of the spectrum is the approach of broadly classifying all “macroalgae” as one group, which requires minimum expertise and training, but considerably limits the potential to understand the nature and drivers of macroalgal community changes and coral-algal dynamics.

A practical scheme that includes a combination of different levels of taxonomic resolution is recommended for monitoring macroalgae for the RIMReP. Specifically, the scheme includes assessment of the per cent cover of the three major categories of algae, some functional form groups and key taxonomic genera.

**Proposed scheme**

- Upright macroalgae (fleshy and calcareous macroalgae)
    - Fleshy macroalgae
        - Key genera, e.g. *Sargassum*, *Lobophora*, *Dictyota*, *Chlorodesmis, Caulerpa, Padina, Asparagopsis*
    - Calcareous macroalgae
        - Key genera, including for example *Halimeda* and *Amphiroa*
- Algal turfs (includes canopy height measurements)
- Crustose coralline algae (CCA)

This hybrid scheme has the benefits of the distinction of key algal groups that have important functional roles in reefs (e.g. upright macroalgae and turfs, and CCA) as well as macroalgal genera which may have beneficial or detrimental effects on coral population dynamics (Figure 9). The scheme therefore provides insights into the potential drivers of community structure and change. Further, similar schemes have been successfully used in coral reef algal studies in the central Pacific (Hawaiian Islands, Mariana Islands, Line Islands, American Samoa, Wake and Johnston Atolls, and the Phoenix Islands (Tribollet and Vroom 2007, Tribollet et al. 2010, Smith et al. 2016)) and some reefs in the Reef (Diaz-Pulido et al. 2009) (Figure 9). Five well established reef monitoring programs use genus level to monitor macroalgae in the Reef (Cheal and Emslie 2017).

The hybrid scheme proposed here with the inclusion of key genera of upright (fleshy and calcareous) macroalgae allows aggregation of data at coarser levels for compatibility with databases used globally, maximising the benefits of this monitoring scheme (e.g. CATAMI databases). In doing so, this scheme becomes flexible and adjustable to the expertise available. The scheme does require expertise in genus-level identification, however, since the abundant genera of macroalgae on reefs are not so numerous, basic training can be provided to staff acquiring the data. When there are difficulties identifying the genera, the macroalgae can simply be classified under a higher category, e.g. fleshy macroalgae.

Finally, CoralNet automatic classifier (https://coralnet.ucsd.edu/) and other automated image recognition programs (e.g. from the XL Catlin Seaview Survey) can readily recognise some macroalgal genera, making this scheme compatible with future artificial intelligence technologies. Spectral signatures of macroalgal genera may also be useful for developing more automated monitoring in the future.

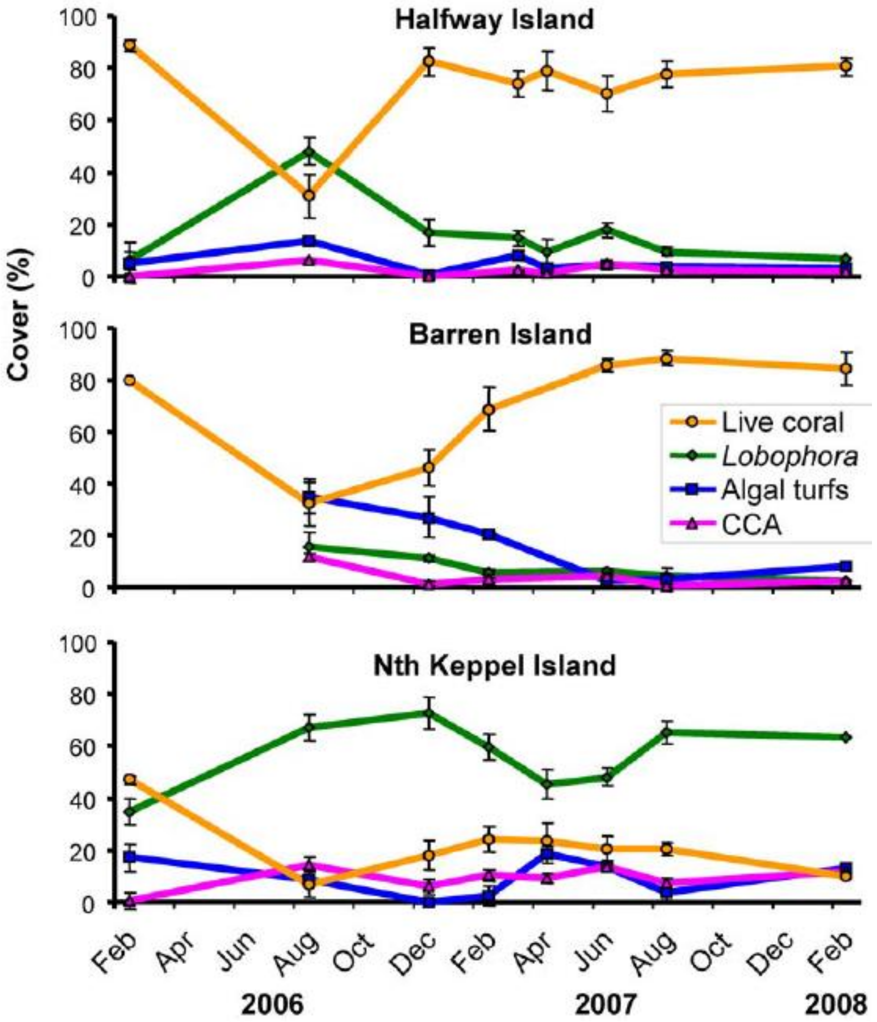

**Figure 9. Example of coral – macroalgal dynamics using a hybrid taxonomic – morphological approach** Key macroalgal genera are used (e.g. *Lobophora*), as well as functional form groups (e.g. CCA, algal turfs) (Figure from Diaz-Pulido et al, 2009).

The key metric to be assessed in the proposed monitoring of macroalgae is per cent cover of each of the macroalgal categories, groups and genera. Ratios of fleshy macroalgae vs. algal turfs vs. CCA can be easily calculated and will provide additional information on reef processes (e.g. Kramer 2003).

I further recommend the measurement of canopy height for the upright macroalgae and particularly for algal turfs. Because thicker algal turfs can often be deleterious to coral settlement, recruitment, and growth (Birrell et al. 2005, Birrell et al. 2008, Barott et al. 2009), inclusion of algal turf canopy height may be an indicator of shift in the relative contribution of nutrient enrichment and herbivory controls of algae (Flower et al. 2017). Measurements canopy height are easy to obtain in situ, however these can hardly be determined from still imagery.

**Table 1. Summary of benefits and limitations of different levels of taxonomic resolution used to monitor macroalgal abundance**

| Level of Resolution | Benefits | Limitations |
|---|---|---|
| One grouping “macroalgae” | Requires no expertise, quick, easy to implement, relatively expensive, access to large data sets. | Limited information on processes driving change, no resolution to distinguish between algal types [e.g. benign (e.g. protection from bleaching, Crown-of-thorns starfish) vs. harmful (e.g. coral competitors)].<br>No information on other groups, e.g. turfs. |
| Major macroalgal categories “macroalgae”, “algal turfs” and “CCA” | Relatively quick, not so expensive, little expertise required, includes key algal groups important for reef functioning:<br>•CCA: indictor of potential to build solid carbonate frameworks, accretion, settlement inducers.<br>•Algal turfs: highly productive, most abundant component, food for grazers & key in reef metabolism. | Limited info on processes driving change, some expertise required to assess categories, more time needed to analyse data.<br>No resolution to distinguish between types of macroalgae (e.g. benign vs. harmful). |
| Functional form group approach: Seven major groups | Includes key algal groups important for reef functioning (as above).<br>More resolution of the macroalgae category, e.g. differentiate leathery / canopy forming macroalgae, which are key for fish and inverts. | Few studies have used this approach, expertise required, more time required to analyse data.<br>Still provides limited info on processes. |
| Phylum, order or family | Useful in physiological studies and reef metabolism. | Not applied widely in reef algae, limited resolution in some groups, no distinction between benign and harmful species. Taxonomic expertise required. |
| Genus level | Provide insights into dynamics (e.g. differential effects of cyclones/hurricanes, grazing, nutrients, seasonality, etc.). | Taxonomic expertise required and training, time consuming. |
| Species level | Provides insights into drivers of community dynamics, estimates of species diversity (important for conservation). Differentiation between harmful and benign taxa.<br>Species can be grouped at different levels. | Considerable taxonomic expertise required and training, time consuming.<br>Increased time required to analyse data. |
| Recommended approach (hybrid of major algal categories and genera) | Provides potential insights into drivers of algal dynamics, used successfully in a number of studies, flexible, adjustable to expertise available. | Time consuming, requires expertise and training.<br>Suggested future improvements: CoralNet automatic classifier picks up some species effectively. |

## Crustose Coralline Algae blocks

As mentioned earlier in the introduction, macroalgae mediate many ecological and biogeochemical processes, including primary production, nutrient assimilation and recycling, and reef accretion among others. Monitoring key algal-mediated processes would therefore provide valuable insights into the changes in reef health and functioning in response to a changing environment. However, processes such as algal photosynthesis or nutrient assimilation are not considered here because there is no cost-effective way to monitor them at meaningful spatio-temporal scales. For instance, photosynthetic rates strongly depend on light levels and the latter vary considerably even within a day, making estimates of primary production difficult to use as a monitoring tool. The candidate indicators recommended by the CREG specifically identified reef accretion and the recommended approach described below will provide insights into the potential drivers of community structure and change.

Given the importance of Crustose Coralline Algae (CCA) for reefs, in particular for coral reef accretion, coral larval settlement and reef resilience, and their sensitivity to ocean acidification (e.g. (Diaz-Pulido et al. 2012),(Fabricius et al. 2015) it is crucial that monitoring programs include not only a detailed assessment of the abundance (per cent cover) of CCA in reefs, but also quantify the rates of growth and calcium carbonate deposition.

A prototype monitoring tool is available to measure rates of growth (vertical and marginal) and calcification of individual CCA crusts (e.g. Lewis et al. 2017a) and CCA community calcification *in situ* (Figure 10). This is similar to the “calcification stations” developed to monitor coral and CCA calcification by the National Oceanic and Atmospheric Administration (NOAA) in Florida (Morrison et al. 2013) and the central Pacific (Vargas-Angel et al. 2015), but modified to assess parameters of individual crusts of dominant reef building species in the Reef. The prototype was also modified to incorporate the best type of substrate material (recruitment tiles) to attract coralline algae recruitment and thus maximising the potential rates of CCA community calcification (Kennedy et al. 2017). Recruitment tiles can also be assessed for CCA community composition but this requires significant taxonomic expertise, although the use of molecular environmental sampling may prove useful in the near future. Presence of the Coralline Algae Lethal Disease (CLOD) (Littler and Littler 1995) and other CCA diseases (Vargas-Angel 2010) can also be monitored using the recruitment tiles. Our calcification stations have now been trialled in a number of reefs in the Reef (Kennedy and Diaz-Pulido 2017) and have the potential to be easily incorporated into RIMReP. Depending on the desired temporal resolution, the blocks can be replaced once or twice a year. Preliminary results indicate the calcification stations are suitable to obtain baseline information on CCA, critical to track the impacts of ocean acidification and warming on CCA, the cement of coral reefs.

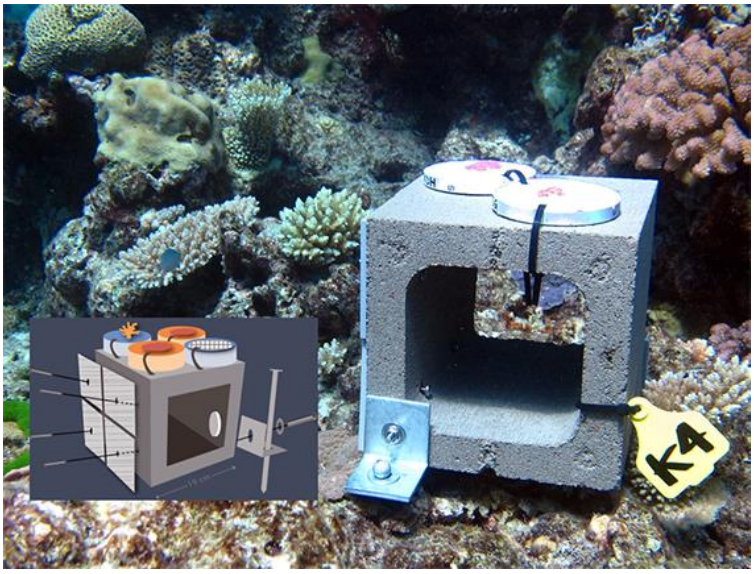

**Figure 10. Prototype of “calcification blocks” designed to monitor the growth and calcification of crustose coralline algae in the Great Barrier Reef.** The stations include crusts of dominant CCA embedded in resin on the top surface of the blocks to monitor individual rates of calcification, and plastic (or PVC) recruitment tiles on the side to assess community calcification. Blocks are anchored to the reef floor and replaced once (or twice) a year for monitoring CCA

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