

Review

A Review of Current Coral Monitoring Tools/ Diagnostic Methods & Introducing a New Tool to the Coral Health Toolkit

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Abstract: Rapidly and repeatedly ascertaining the health status of coral reefs is an ever more pressing issue as part of activities to understand and monitor the damaging impacts of climate change. A combination of increasing ocean temperatures, acidity and frequency of extreme storm events continues to alter the marine environment beyond what sensitive organisms, such as coral, can cope with. It is therefore vital to establish technologies and validated methods to provide a metric or indication into the health of these organisms. There are currently many surveys and techniques used by coral scientists to uncover insights into the status and assessment of coral reefs, from colour wheels to multispectral satellite surveys. Here we outline an array of current techniques and methods focused specifically on coral monitoring and health diagnosis, ranging across the length scales from simple diver-based surveyance to satellite remote sensing. The technique of using hyperspectral fluorescence imaging is also introduced as a viable novel addition to aid and extend the current toolbox of available technologies.

Keywords: Coral; Health; Bleaching; Review; Hyperspectral Imaging; Survey methods;

1. Introduction: Corals

Coral reefs are critically important for the ecosystem goods and services they provide, especially to coastal tropical and subtropical nations (Moberg and Folke, 1999). Corals are susceptible to a number of diseases as they have low tolerance to variations in environmental conditions including temperature, salinity, and solar radiation. Coral disease is one of the highest causes of reef degradation and has been increasing worldwide since first observed in the 1970s, particularly in the Caribbean, Red Sea and Indian Ocean. Coral disease has been linked to declines in water quality and fish stocks, heat stress and, more recently, to ocean acidification driven by anthropogenic activity (Bongiorni and Rinkevich, 2005; Ravindran and Raghukumar, 2006; Cervino *et al.*, 2008). Sustained periods of coral stress and disease can lead to colony-wide coral death, representing a significant concern for the 275 million people who live within 30 km of these ecosystems, and upon which livelihoods and food security is based (Lamb *et al.*, 2014). Coral reefs have an evidenced intrinsic value, provide an array of ecosystem services such as coastal defence, fisheries and a biomineralization sink for CO₂; for example one small reef (10 × 20 km) in the Philippines was calculated to have an estimated economic value of \$38 million USD/year (Cruz-Trinidad *et al.*, 2011). This monetary value, whilst impressive, does not accurately reflect the global importance of coral reefs as a major source of irreplaceable dietary protein and a vital form of coastal protection for many developing countries (Woodley *et al.*, 2015). Under the Intergovernmental Panel on Climate

Change (IPCC) representative Concentration Pathways (RCP) predictions both RCP4.5 & RCP8.5 show that increased coral host susceptibility will be reached at a minimum of 90% of global reef locations by this year (2020)(Maynard *et al.*, 2015), so especially now closer monitoring and protection of these extremely valuable natural assets is essential.

Generally accepted causes of coral bleaching are external factors or triggers (stressors) such as water temperature fluctuation, changes in carbon chemistry, pollution or bacterial/viral infection(Glynn, 1993). However, bleaching is most commonly associated with environmental fluctuations caused by global climate change and increasing ocean temperatures, with higher than average sea surface temperatures (SSTs) and high solar radiation being the primary factor of large-scale coral bleaching(Hoegh-Guldberg, 1999; Loya *et al.*, 2001). Bleaching is defined by the loss of colour in any symbiotic partnership between zooxanthellae and marine benthic animals. It should be noted that numerous other animals besides corals share this relationship with zooxanthellae from sponges to nudibranch molluscs(Sheppard *et al.*, 2017). The effects of bleaching is often evident with depressed growth and increased mortality in corals and is an adverse physiological response to the relatively extreme conditions being imposed by the surrounding environment(Douglas, 2003).

Mass bleaching events were first scientifically described in 1984 by Glynn, since then 4 global bleaching events have been described in 1998, 2010, 2015, 2016 (Queensland University of Technology (QUT), 2017).Recent mass bleaching events (2015-16) affected up to 75% of the globally distributed locations surveyed(Hughes *et al.*, 2017) and is comparable in scale with that of the 1997–1998 event, where 74% of the same 100 locations surveyed bleached again after recovering. Global climate-driven bleaching events are more frequently coinciding with El Niño–Southern Oscillation (ENSO) because average tropical sea surface temperatures (SST) increase, as an effect of global warming, La Niña conditions are becoming warmer than those observed during El Niño events 30 years ago(Hughes *et al.*, 2017). This means that as global climate continues to exert a greater warming influence on the oceans, SST will continue to rise along with the number and frequency of extreme heating events on coral reef systems. Coral bleaching is not necessarily a death sentence for the corals concerned, as colony recovery can occur if some individuals in the colony retain some symbionts within their cells not expelled during the bleaching process. From this small residual symbiont population, the coral can repopulate symbionts back to ‘normal’ levels once the stressor reduces or environmental conditions improve. However, corals in a bleached state are more susceptible to diseases and predation which is why mortality rates can be high(Castro and Huber, 2010).

Coral disease is an increasing cause for concern as a compound threat to already compromised coral reef communities and is primarily caused by infections from microbes such as viruses and bacteria sometimes introduced by pollutant marine plastics and with many of the causative pathogens currently undocumented. Coral disease is often conjunctive with a combination of factors, many of which are intricately linked with those that trigger the bleaching effect. Recent studies have suggested that ocean plastic pollution can help to promote microbial colonization of pathogens, with the likelihood of disease increasing from 4% to 89% when corals are in contact with plastics(Lamb *et al.*, 2018). This presents an especially urgent concern as estimates suggest that plastics comprise 50–80% of the litter in the oceans (an approximate total 12.7 million tonnes)(Cressey, 2016).

Distinguishing healthy from diseased coral is important for colony health monitoring. Diseased corals are frequently characterised by abnormal pigmentation of compromised tissue (Palmer, Modi and Mydlarz, 2009) versus healthy counterparts. A diversity of diseases have been observed (approximately 30 diseases and syndromes affecting 150 species worldwide(Green and Bruckner, 2000; Sutherland, Porter and Torres, 2004)) that affect the health of different corals, commonly referred to as ‘syndromes or ‘band/lines diseases’, with the term ‘disease’ used to describe

symptoms arising from a known pathogen, while 'syndrome' refers to effects displaying from an unknown causative agent, whether it be a pathogen, pollutant or climate condition such as warming (Sheppard *et al.*, 2017)

White, brown, pink, yellow and black line diseases are just some of these diseases that have been described in more detail (see Table 1 for examples) (Bongiorni and Rinkevich, 2005; Ravindran and Raghukumar, 2006; Cervino *et al.*, 2008; Muller and Van Woesik, 2012) and are distinguished on the basis of the alteration of colour that the disease invokes. The majority of banding diseases, excepting white and black, are usually specific to particular geographic regions or species (Table 1) (Galloway, Bruckner and Woodley, 2009). Many existing diver-based survey techniques already accommodate disease assessments as they are emerging as a major cause of reef degradation. The presence of the disease is often easily identifiable but large areas cannot be quickly or thoroughly covered by human divers, and a degree of subjectivity is imported to the survey results. Instead the use of automated Image-based techniques could also be utilised to more quantifiably observe and monitor diseased colonies on the basis of distinct optical measuring the differences between diseased and healthy coral tissue.

Table 1, Common Coral Diseases; description, location, species affected. Adapted from Bruckner, 2009 (Galloway, Bruckner and Woodley, 2009).

Condition	Location and Species affected	Description	Source
White band disease	Australia, Egypt, Guam, India, Mauritius, Oman, Papua New Guinea, Philippines, Saudi Arabia, United Arab Emirates 18 genera; 37 species	A distinct band of white demarking recently exposed skeleton between healthy tissue and skeleton. The white band forms a moving front that advances a few mm per day, the cause is not known but may be triggered by contact with cyanobacteria.	Antonius, 1981;1988; 1985a; 1987; 1995 Coles, 1994; Korrubel and Riegl, 1998; Riegl, 2002. (Antonius, 1981, 1985b, 1987, 1988; Coles, 1994; Korrubel and Riegl, 1998; Riegl, 2002)
Black band disease	Australia, Egypt, Fiji, India, Jordan, Papua New Guinea, Philippines, Saudi Arabia, Tonga, South Africa, Commonwealth of North Mariana Islands, Palau 19 genera, 49 species; <i>Pocillopora</i> and <i>Acropora</i> most frequently affected	A darkly pigmented mat/band 1-300 mm wide on the surface of the coral that separates healthy tissue from recently denuded white skeleton. Primarily caused by a bacterium called <i>Phormidium corallyticum</i> .	Antonius, 1985b; 1987; Chesher, 1985; Glazebrook and Steiner, 1994; Littler and Littler, 1996; Miller, 1996; Korrubel and Riegl, 1998; Cervino, 1998; Jordan and Samways, 2001; Dinesdale, 2000, Willis et al., 2004. (Antonius, 1985a; Chesher, 1985; Gates, Baghdasarian and Muscatine, 1992; Glazebrook and Streiner, 1994; Miller and others, 1996; Goreau et al., 1998; Korrubel and Riegl, 1998; Dinsdale, 2000; Jordan and Samways, 2001; Willis, Page and Dinsdale, 2013)
Brown band disease	Australia <i>Acropora Formosa</i>	A ciliate identified as a member of the subclass Scuticociliatia has been shown to ingest intact symbiotic algae and is responsible for the visible signs of this disease. (A variable brown band).	Dinsdale, 1994; Sweet and Bythell, 2012; Bourne et al., 2008.(Dinsdale, 2000)
Pink line disease	Papua New Guinea, Sri Lanka, Kavaratti Island, Indian Ocean <i>Porites compressa</i> , <i>P. lutea</i>	Band of pink pigmented tissue separating recently killed skeleton and normal tissue. Can begin as a small ring and progress outward. Associated with a cyanobacteria infection.	Ravindran et al., 2001; Goreau et al. 1998. (Goreau et al., 1998; Ravindran, Raghukumar and Raghukumar, 2001)
Yellow band disease	United Arab Emirates; Arabian Gulf; Iran 4 genera, 12 species	A broad band of denuded skeleton, yellow in colour, adjacent to decaying and sloughing tissue; the band advances 9-20 mm/week.	Korrubel and Riegl, 1998; Eghtesadi-Araghi, 2011.(Korrubel and Riegl, 1998; Eghtesadi-Araghi, 2011)

2. Current methods for Monitoring coral Health

Many reef monitoring programs do not prioritise coral bleaching and disease assessment due to the costly and time-consuming nature of in situ coral health surveys (Willis, Page and Dinsdale, 2002; Page *et al.*, 2009, 2017; Ruiz-Moreno *et al.*, 2012). Instead, monitoring programmes focus on population distribution and zonation which in many cases can be gained remotely using time-lapse satellite imagery, covering large areas. However, there are many factors that can be considered when looking at coral reef monitoring programs such as biological (percentage cover of corals, species composition and distribution), physical (Temperature, water quality) and socio-economic parameters (marine protected areas, fishing communities) (Hill and Wilkinson, 2004), this present study focuses on monitoring only biological parameters. Globally standardised assessments of coral health require detailed examination of all coral colonies within a designated survey area, which often involves lengthy person-intensive field time (Raymundo *et al.*, 2008). Accordingly, these types of survey do not occur with great frequency as this would be prohibitively expensive.

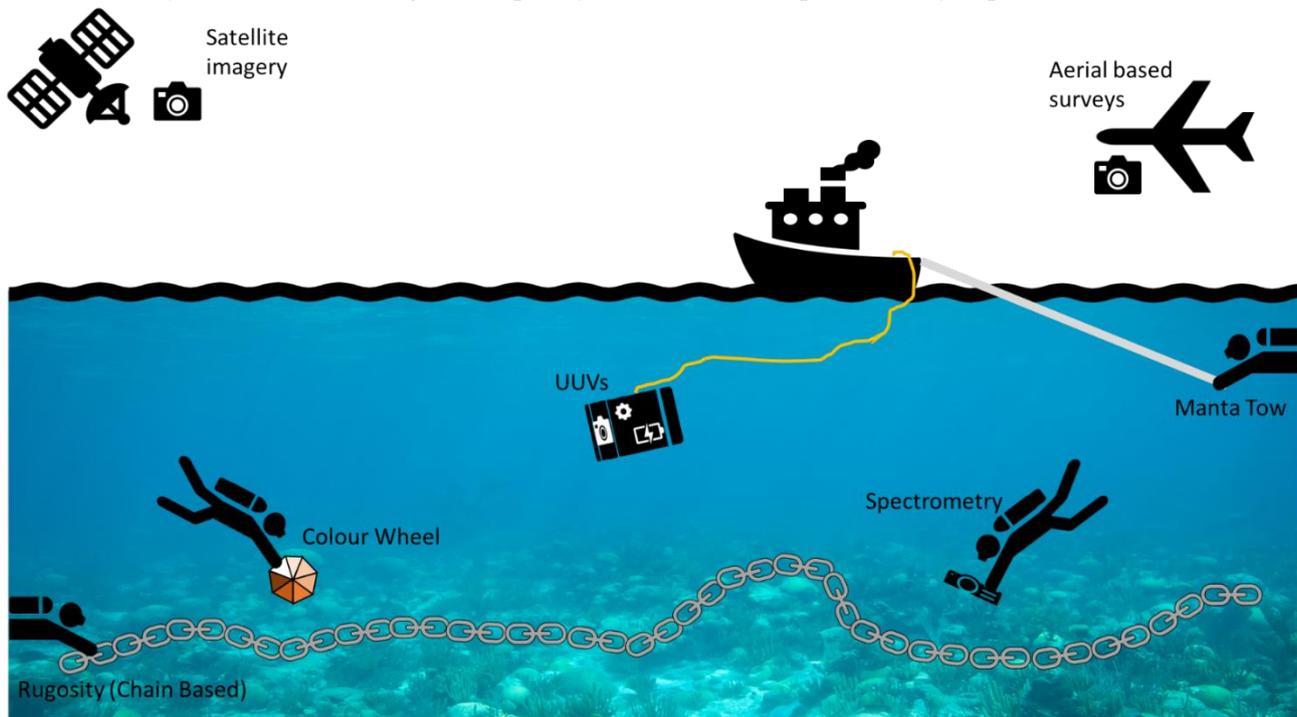


Figure 1, examples of some of the techniques used to determine coral 'health' from diver-based techniques to unmanned underwater vehicles (UUV's) to remote sensing.

The following sections describe diver-based survey techniques, where represent the 'classical' approach to coral surveyance.

2.1 Diver based Survey Techniques

Many coral health surveys utilise divers as 'Observers' recording data such as percentage cover of live coral which is a widely used metric of coral reef condition and utilised in studies that record coral reef decline and recovery across large spatial scales (Bruno and Selig, 2007). Divers offer a versatile set of tools for coral monitoring, being highly manoueverable, adaptable and able to deliver precise results (training permitting) conversely, divers are expensive from the standpoint of finances, logistics and time. There are a number of different survey techniques that divers can employ for assessing coral reef health which are as detailed as follows;

Manta Tow Method

The manta tow method provides a percentage estimate of living hard and soft coral, versus dead hard coral. The method involves towing a snorkelling diver (observer) at a constant speed behind a boat. The observer holds on to a manta board (a buoyant float with handles) attached to the boat by a length of rope. The observer makes a visual assessment of specific variables during each short pass of the manta tow and records this data on a data sheet (Hill and Wilkinson, 2004). One advantage of manta tow survey is that it is very simplistic requiring minimal equipment but allows large areas of reefs to be surveyed quickly. However, it requires multiple passes over a reef and a trained diver to be able to identify different coral species as well as the use of boat, which can't be deployed on very shallow reefs. The long-term effects of increased noise pollution from the boats engine also needs to be considered, with studies suggesting displacement of reef fish settlements (Simpson *et al.*, 2016) and potential disruption of coral larval settlements (Vermeij *et al.*, 2010).

Rugosity

Rugosity, which is the state of ruggedness or irregularity of a surface (Magno and Villanoy, 2006), is a commonly used measurement by coral reef biologists. It refers to areas of high substrate rugosity allowing coral attachment which are sufficiently high enough on the reef profile to be free from the influence of seafloor sediment movements. Marine ecologists can use this measurement to identifying areas of high rugosity on the reef which offer increased cover for reef fish from predation and more places for the attachment of sessile organisms such as invertebrates, algae and corals (Friedlander and Parrish, 1998; Mumby, 2006; Fuad, 2010).

Rugosity can be measured using a chain laid over the surface of the reef; a rugosity index, C , can be calculated as:

$$C=1-d/l$$

Where d is the horizontal distance covered by the chain that follows the contours of the reef and l is the length of the fully extended chain (Knudby and LeDrew, 2007; Fuad, 2010). Tin foil can also be employed to measure the surface area of individual coral colonies (Marsh Jr., 1970) by wrapping the colony in a known quantity of foil where the weight per unit area of the foil is known, where surface area can be calculated from amount of foil area and weight (Veal *et al.*, 2010). These are typically no longer performed in situ on reefs as it is potentially destructive and very time consuming. It is however sometimes deployed in laboratories for surface area calculations (wax dipping can also be used in labs but has no application in situ). These techniques give an idea of the reef topography, but it requires physical contact with the reef, making it an invasive method and potentially damaging to the reef. With the advances in camera photography and photogrammetry that have occurred within the last decade these in situ invasive techniques for rugosity measurements have now become outdated. Photogrammetry (outlined later) represents a more rapid and accurate method for rugosity calculations. Both techniques can be carried out far more accurately and non-invasively using underwater photogrammetric techniques.

Coral Recruitment

Recruitment is the process of larval settlement by new coral individuals becoming part of the adult population. The rate, scale, and spatial structure of larval dispersal drives population replenishment dynamics. Typically, plates of material (i.e. Limestone) are positioned around a reef, raised from the benthos, and left for recruitment to occur with periodic checking (Schmidt-Roach, Kunzmann and Martinez Arbizu, 2008). The plates can then be photographed in situ using a fluorescent light source in order to more easily observe coral juveniles than standard white light conditions (Piniak *et al.*, 2005). This is because fluorescence more easily identifies the juveniles with observed coral recruits 20–50% higher than under white light (Baird, Salih and Trevor-Jones, 2006). Fluorescence techniques rely on the naturally high abundance of fluorescent pigments found in

many corals (Papina *et al.*, 2002) but are only useful in regions where fluorescent taxa are dominant, such as most Indo-Pacific reefs (Baird, Salih and Trevor-Jones, 2006). At the end of the selected recruitment period the test plates are removed from the environment and treated with a chlorine solution to remove organic matter and left to air dry. Using a stereoscopic microscope, settled coral specimens are recorded by measuring the diameter of the pedal disc (part of the coral anatomy which it uses to attach to substrates) as well as the number and identity of primary corallites (Schmidt-Roach, Kunzmann and Martinez Arbizu, 2008). This survey gives an indication of the growth and recovery rates of corals and therefore reef resilience as the recruits represent the continuation of the reef lifecycle.

Transects

A transect is an arbitrary line across a whole or part of a habitat for the purpose of an ecological survey. Typical transect surveys record the percentage cover of different species to give an estimate of abundance. The transect is usually used in conjunction with Quadrats. A quadrat is typically a 1m x 1m square, often made from PVC pipe, that is placed in a habitat of interest and the species within those quadrats are identified and recorded. There are several different variants on the transect method outlined below;

Belt Transects (BT)

Belt transects consist of sampling quadrats all the way down the transect line usually at a predetermined interval such as the length of a quadrat. All corals within a predefined area are counted and the incidence of bleaching or disease is recorded. This method can provide detailed assessments on health status, with long term data (from repeated transects over months & years) providing information on colony fate (bleaching/recovery).

Line Intercept transects (LIT)

This method consists of a transect line running across a reef system and any corals interacting directly with the survey line being recorded. This can provide detailed data on species prevalence based on a whole colony assessment, population dynamics, and health status. Multiple transects through each zone is required to gather sufficient data. The general assumption of this type of data collection is that the size of coral colonies are relatively small in comparison to the transect line, and the transect itself is small compared to the whole reef system represented by the survey (English and Baker, 1994).

Point Count Transects (PCT)

Point count transects or 'intersects' are very similar to belt transects but the sampling is typically randomised by selecting random numbers along the transect to sample, for instance, if the transect is 30m sampled locations could be at 2m, 5m, 16m, 23m, 26m. The sampling only includes the randomly selected points along the transect, these can be varied depending on the research question or focus (Roberts *et al.*, 2016). These surveys are often used in conjunction with quadrat and are less time consuming than full LIT surveys. The survey requires multiple transects in each reef zone. With high diversity, high cover and abundant small corals, individual transects may require multiple dives to complete.

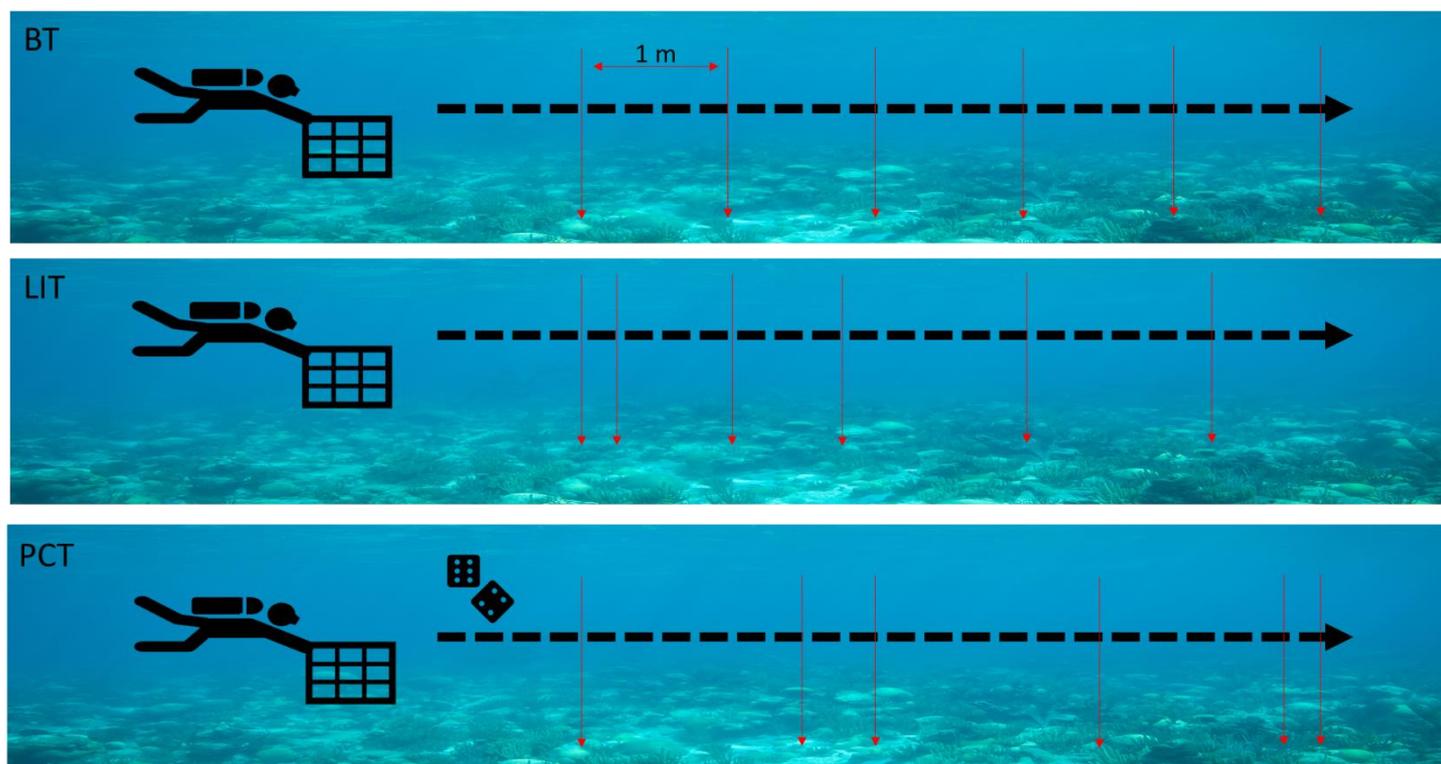


Figure 2, Diver Transect types; Belt Transects (BT), Line Intercept transects (LIT), Point Count intersects (PCT).

Colour charts/ wheels

The use of colour charts to quickly identify coral health is a commonly used survey methodology employed by divers. The technique involves a selection of colour hues on a card or dive slate that corresponds to a concentration of symbionts contained in coral tissue and to compare these two colours against one another. This requires bleaching experiments to be conducted to image corals at various states in the bleaching process and corresponding symbiont concentrations to be measured. One such study (Siebeck *et al.*, 2006) utilised photography to image the corals against a standard of known colours in order to generate a colour chart. A further selection of common colour variations are used to help differentiate between the most common coral colour types. This complete chart can be them employed by a diver to look and compare the coral colours by eye.

This technique represents a rapid low-cost approach for bleaching assessments but its subjective nature along with limitation of human eyesight mean that the results are qualitative at best. While performing such surveys using traditional digital camera images marks an improvement, the level of accuracy still remains an issue as only 3 broad colour bands are recorded (red, blue, green) by the camera sensor.

Pulse-amplitude modulation (PAM) Fluorometry and underwater spectrometers

Pulse amplitude modulation or PAM is a tool used to study photosynthesis in and under water. The device is a fluorometer which can be tuned to specifically look at chlorophyll fluorescence and electron transport rates (ETR) of photosynthetic organisms to provide a measurement of photosynthetic efficiency (Jones, Kildea and Hoegh-Guldberg, 1999). The diving PAM I & II (Walz) are the most commonly used devices in studies using this technique (Ralph, Gademann and Larkum, 2001; Chauka, Steinert and Mtolera, 2016; Kurihara *et al.*, 2018), although the device has limitations

with a maximum depth of 50m and a requirement to be held in near contact (<5 mm) to the sampled object for a set time in order to gain an accurate reading. Generally, the use of an irradiance sensor is used in conjunction with the sensor probe to obtain an incident light calculation. This, however, can be difficult to position on corals as well as the optical fibre use to measure the coral spectrum.

More general underwater spectrometry is also used usually by waterproofing spectrometers similar to the PAM and recording radiance reflectance measurements to gain spectral data. These spectrometers are required to be held in position up to 10 mm away from the sample (Leiper *et al.*, 2009) much like the PAM. An accompanying reference measurement is required which utilises a Lambertian reflectance standard target (commonly a Spectralon [varying reflectance values available from 2% to 99% reflectant]) in order to characterise solar irradiance to provide relative spectral measurements. Data is often limited by the spectral range and spatial resolution of the spectrometer.

In a marine setting both techniques are executed in a similar way. Data acquisition to cover a whole reef system is typically slow because of the sampling area of the probes. Often a random point sampling method is adopted in order to characterise large coral colonies in a more meaningful timescale.

2.2 Image based techniques

Underwater photographic surveys make up the bulk of modern reef monitoring and provide a means of rapidly surveying large reef areas (typically hundreds of m²). With the use of autonomous underwater vehicles this can be extended to cover many thousands of m² (Patterson and Relles, 2008; Williams *et al.*, 2012). A major advantage of image-based surveys is that the images created provide a permanent digital record of the habitat which reduces the dependency of infield coral experts and provides data that can be reanalysed or compared between repeat surveys.

Photo-quadrats

Surveys using photo-quadrats, imaged via high resolution digital cameras instead of manual counting and estimates provide a more accurate assessment of cover and can be archived for longevity (repeat) surveys. Using this technique also reduces diver 'bottom time', with data analysed in the laboratory rather than the field.

Photogrammetry

The use of underwater photogrammetric techniques is a rising field in coral health assessment as it is both quick and easy to conduct (Teague and Scott, 2017). The technique uses off the shelf cameras (either one or multiples depending on quality and use of the models), to take an array of overlapped images over a target area (60-80% overlap ideally) (Colomina and Molina, 2014). Images are run through structure from motion (SfM) software that stitches the images together and from "points of interest" creates 3D reconstructions (Teague and Scott, 2017). This technique can be applied to physical reef measurements such as rugosity as well as determining coral cover and distribution. Crucially, a wide variety of information can be extracted from the same data set, making it a very versatile technique which can be deployed by both divers and robots. With regards to mapping coral health, it is still limited by the use of traditional RGB cameras whereby the data that can be obtained from coral colour and fluorescence is limited by the three spectral recording bands of the device. This technique could however be combined with other visual data by creating/overlying layers of data using the 3D model as a topological base.

Hyperspectral imaging

Underwater Hyperspectral imaging (UHI) is a relatively new emerging technology with few instances of the application. Current diver operated hyperspectral systems such as the “HyperDiver” system, utilise hyperspectral and traditional imaging in combination to simultaneously capture high-resolution colour and hyperspectral images as well as provide topographic profiles of the benthos (Chennu *et al.*, 2017). This technique uses a push-broom hyperspectral imager (Pika 2, Resonon Inc.) with a spectral range of 400–900 nm sampled at ~1.5 nm resolution (480 fixed bands, 640 spatial pixels) (Chennu *et al.*, 2017). Some potential applications of the UHI-based ‘objects of interest’ (OOI) identification technique, as described by Johnsen (Johnsen *et al.*, 2016), include mapping and monitoring of seafloor habitats (minerals, soft versus hard bottom), seafloor pipeline inspections (type of material, cracks, rust and leakage), shipwrecks (type and state of wood, nails, rust and artefacts), deep-water coral reefs (species identification, area coverage and physiological state), deep water sponge fields (species identification, area coverage and physiological state), and kelp forests (species identification, area coverage, physiological state and growth rates of benthic organisms). This system is an improvement over traditional methods of monitoring, but the system is almost as large as the diver operating it. The system is roughly ~32 kg in air and is rated to a depth of 50m. Other lighter devices are available however these are mostly mounted on Underwater unmanned vehicles (UUV’s) and are often expensive and mainly used in oil and gas discovery.

Diver-based methods require a lot of diver ‘bottom time’, require multiple dives, significant infrastructure investment and are thus slow and expensive. However, by taking the diver out of the equation and using Robots i.e. (Remotely operated vehicle or ROV) as a platform for data capture removes the two very limiting operational constraints of depth and bottom time (Nornes *et al.*, 2015). This platform often means similar surveys require less time than a diver and do not require specific personnel, thus greatly reducing the expenses in a context where time and costs of intervention are extremely high (Drap, 2012; Teague and Scott, 2017). Such surveys also have an improved repeatability, which improves the quality of time-resolved (repeat-survey) data sets.

2.2 Discussion of diver-based techniques

Many of these surveys use a standardized sampling protocol so the data collected is comparable to other sites globally. Global standardised coral health surveys and assessments require thorough examination of all coral colonies within the survey area, which often involves large periods of survey data collection time (Hoegh-Guldberg *et al.*, 2007). For example, as outlined in a survey by Willis *et al.* 2002 (Willis, Page and Dinsdale, 2002), a 120-m² area could take two trained SCUBA divers up to 2.5 h to survey if the section of reef had a high coral colony density and diversity (Page *et al.*, 2017). This creates a high cost associated with collecting coral health data in situ and a reliance on skilled people with the experience to accurately and rapidly deliver a diagnosis. The use of SCUBA is often impractical or impossible for many surveys due largely in part to physical limitations (e.g. depth or currents) or the presence of unacceptable risks (e.g. hazards such as dangerous animals or environments). Diver based surveyance does not necessarily require much specialised equipment or post-survey data processing, but it does require that the diver has a highly specialised level of diagnostic expertise in coral taxonomy and disease identification (Page *et al.*, 2017).

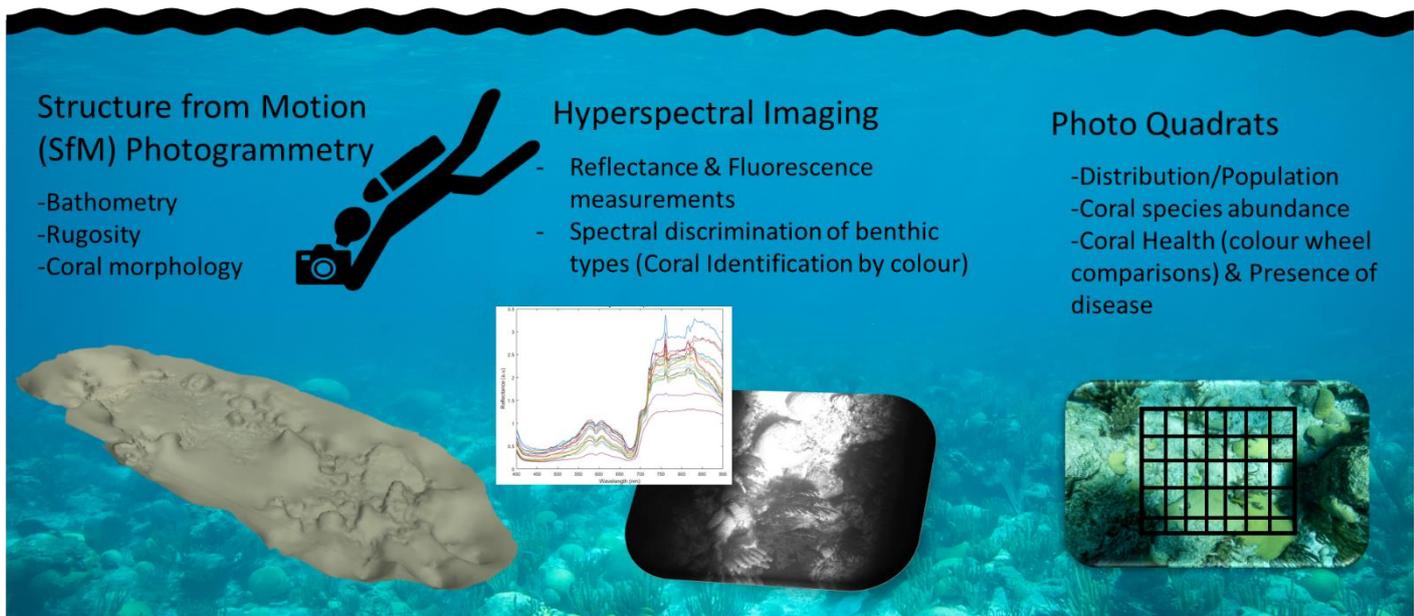


Figure 3, Image based techniques and examples of the type of data produced from the main techniques.

2.4 Remote Sensing Techniques

Satellites

The loss of pigmented zooxanthellae from corals during mass bleaching events results in an optical signal that can be strong enough for detection by remote sensing satellites in low Earth orbit. Satellite systems allow the surveys to cover vast areas quickly with the spatial resolution of the newest multi-spectral bands and panchromatic bands at 15-30 m. The data collectable is also limited by depth with satellite data only being able to generate accurate data to around 25m water depth.

Global programs such as the coral reef watch (NOAA) utilise satellite technology to observe and monitor coral health over vast areas. Techniques include the use of Satellite-derived sea surface temperatures (SSTs) to derive the spatial extent of coral reef bleaching. By using existing data to monitor SST anomalies that typically occur during the warmest months of the year, often a 1°C elevation above the monthly mean maximum can be observed to associate with bleaching (Strong *et al.*, 1997). Coral Reef Watch's HotSpot program utilises a newer technique that gives a "Satellite Bleaching Alert" or SBA. Based on satellite near-real-time HotSpot levels, Coral Reef Watch issues four levels of alerts for 24 reef sites in the tropics (Liu *et al.*, 2014). This gives an early warning system of vulnerable coral reef systems based on the change in SST from the norm, this technique however is largely speculative as there is no actual data taken directly from the corals themselves. It can therefore be considered a predictive tool for bleaching events.

Other satellites equipped with multispectral cameras can be used to monitor coral health such as the Landsat Thematic Mapper (TM) which has been used to map the geomorphology of Australia's Great Barrier Reef (Joyce *et al.*, 2004). The Landsat TM and Enhanced Thematic Mapper Plus (ETM+) have been used to generate data to monitor changes in groups of coral reefs (Palandro *et al.*, 2003) and more recently facilitated a detailed survey of the reefs in the Nansha Islands' using the Landsat 8 operational land imager (OLI) (Duan *et al.*, 2016). More specialised remote sensors such as the Hyperspectral Imager for the Coastal Ocean (HICO), a camera which was installed on the

International Space Station in 2015, selected coastal regions and imaged them with full spectral coverage (380 to 960 nm sampled at 5.7 nm intervals). During its five years in operation HICO collected over 10,000 scenes from around the world (University, 2015).

Accordingly, satellites can be a very useful tool for large area reconnaissance of coral reef health, albeit with a relatively poor spatial resolution and when cloud cover is limited.

Aerial

Another remote method for coral reef surveyance is the use of aerial surveys using light aircraft or a helicopter, flying at an elevation of approximately 150 m. In these surveys each reef is typically assigned a number by visual assessment from one of five categories associated with bleaching severity, using protocols set in aerial surveys conducted between 1998 and 2002 (Berkelmans *et al.*, 2004): 0, <1% of corals bleached; 1, 1–10%; 2, 10–30%; 3, 30–60%; and 4, >60% of corals bleached. The accuracy of this still method requires an underwater ground-truthing to compare against (Hughes *et al.*, 2017). Light aircraft can be used to image over large areas of coral reefs with higher resolution than satellites and flying below the cloud base.

The resolution and cost can be further improved upon by the use of Drones (UAVs) carrying miniaturized hyperspectral cameras which can produce images with a spatial resolution of 15 cm/pixel allowing for the identification and monitoring of individual corals. This method provides similarly large area cover with higher resolution than manned aircraft due to the lower flight altitude (30–100m). For example, a 2017 study by Queensland university of technology demonstrated that a UAV could photograph 40 ha of Reef in about 30 minutes to study coral bleaching (Queensland University of Technology (QUT), 2017).

Underwater unmanned vehicles (UUV's)

Underwater robotics can be used to replace the underwater human element of surveys thereby reducing cost and risk whilst also simultaneously improving repeatability. However, this is not yet routinely occurring. By replacing the human with a robot several limitations imposed by scuba reliance can be eliminated, for example, dive surveys require large amounts of time as there is a finite period a diver can spend underwater usually dependant on air tank capacity and depth (Standard air cylinder [12L/ 200 bar], lasts approximately 1 hour at 10m depth). The corresponding issue on UUV based surveys is battery life, of which multiple sets can be used to extend time. A UUV can also cover a larger distance in a shorter time, recording precise global position measurements as it does so. For example a 120-m² area (as described in Willis *et al.* 2004 (Willis, Page and Dinsdale, 2002)) may take two scuba divers up to 2.5 h giving the divers an average coverage of 0.13m²/s whilst a low cost remotely operated vehicle (ROV) at top speed can achieve 1m²/s (BlueROV2).

ROV have proved in principle to be a very effective tool to study, with a non-destructive approach, the conservation status of corals around the world. Allowing for a lot of data to be achieved through video data on coral occupancy, density, colony size, and damage caused by anthropogenic activities (Bavestrello *et al.*, 2014). With the emergence of the ever greater robotic autonomy and the ability to grid survey relatively large shallow marine areas with only limited supervision, enabled by various novel GPS solutions, the prospect for ever greater use of marine robotics for reef surveying looks strong.

Underwater Hyperspectral imaging (UHI) on UUV's

The use of UHI on UUV's is currently limited, very few studies have been conducted using this technique, one such study (Johnsen *et al.*, 2013), used a prototype UHI for mapping of objects of interest (OOI) on the seafloor. The main aims of this study were to develop the technique to identify

and map OOI on the seafloor for the ultimate aim of automated seabed, habitat and OOI identification which could be applied to coral habitats. Other studies (Hochberg and Atkinson, 2000) specifically using hyperspectral imaging with corals, have mainly focused on coverage and benthic discrimination for machine learning applications to automatically classify corals, not necessarily assess health or disease. Hence there exists an opportune sweet spot for technology development and application.

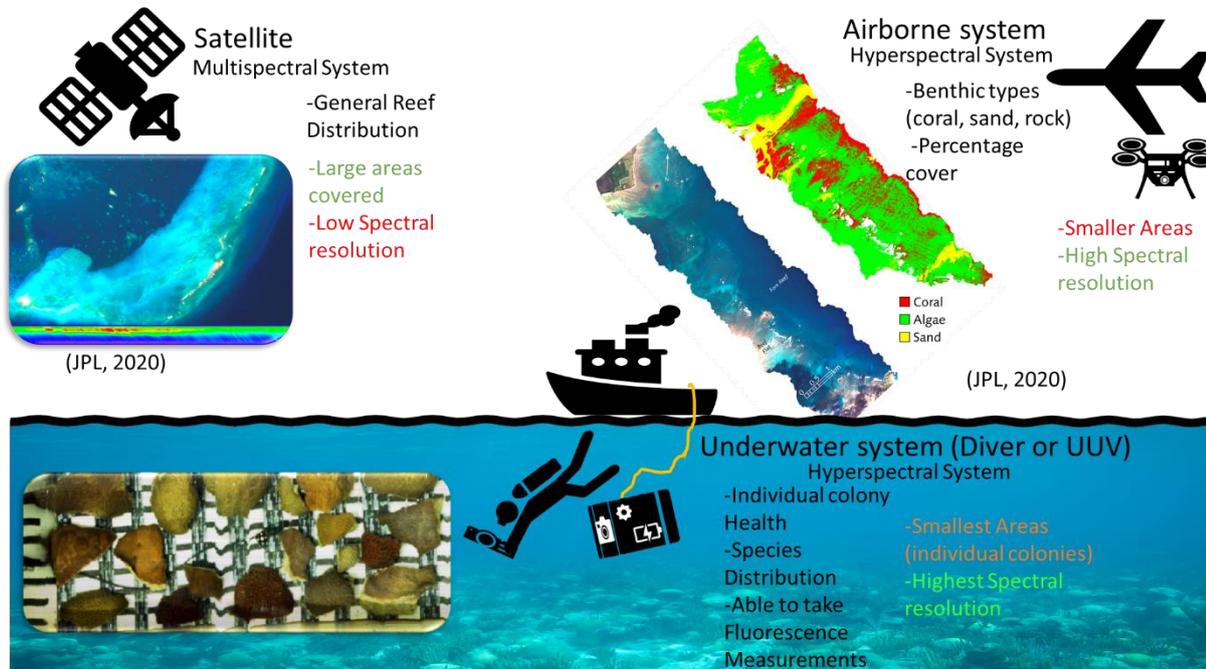


Figure 4, The types of data from each type of spectral system at the different levels from satellites to underwater systems. Images (Jet Propulsion Lab (JPL), 2020) & (Eric J. Hochberg, Bermuda Institute of Ocean Sciences).

2. The Future of Coral Monitoring? Hyperspectral Fluorescence imaging (HyFi)

Hyperspectral imaging has the potential to provide a new tool in rapidly assessing coral 'health'. Here we define health as the intensity of spectral peaks derived from key symbiont pigments (Chlorophyll, Diatoxanthin, green fluorescent protein (GFP) etc.). Hyperspectral imaging is able to categorise and quantify colour so the process of coral bleaching can be recorded. Visibly bleached coral as identified by the human eye or basic optical systems (RGB Camera) has expelled around 70% or more of its symbionts (Fitt *et al.*, 2000). By comparison hyperspectral can provide detection within the 0-70% range before it becomes visible to the eye as this is because the camera systems are far more sensitive to minute changes in colour (Teague, Willans, M. Allen, Scott, *et al.*, 2019).

To gain an even better assessment of coral health using UHI, a hyperspectral fluorescence imaging (HyFi) payload can be mounted onto an ROV system (or carried by a diver or mounted under a boat). The system utilises UV light emitting diodes (LEDs) to provide the illumination source to required to excite fluorescence of photosynthetic zooxanthellae and fluorescent proteins (FPs), these signals provide an insight into coral health (Teague, Willans, M. J. Allen, Scott, *et al.*, 2019). The system combines the new emerging technologies of low-cost underwater robotics and hyperspectral imaging optics. For example, fluorescence (FPs and chlorophyll) can successfully be excited using low power LEDs and coral bleaching can be detected using both hyperspectral reflectance and fluorescence measurements as markers for health (Teague, Scott, *et al.*, 2019). Crucially, this technique can look at coral disease with greater spatial resolution as compromised or damaged tissue synonymous with disease will be spectrally different from that of healthy tissue. Indeed,

hyperspectral fluorescence imagery can reveal this much earlier than traditional RGB imagery or by eye.

New techniques into hyperspectral imaging such as linear variable filter (LVF) technologies (Teague *et al.*, 2020) allow for lower cost imagers to be produced reducing the financial risk of submerging spectral imagers whilst simultaneously allowing multiple data sets to be generated in one data collection process. Hypercubes generated from LVF filters using photogrammetric software can also provide us with 3D models of the reef that provide an insight into reef structure/morphology and if done regularly will provide the ability to monitor changes to the reef, providing a quick and very visual data set that is easily understandable. Due to the imagers compact design and weight they can easily be mounted on ROV's or handheld by divers.

3. Health determination

From these different techniques/ methods coral health can be determined; derived from coral cover from diver or UUV surveys (image based or quadrat surveys) that gives an estimate of the distribution of the reef which can be useful when repeated regularly enabling population shifts and changes in distribution to be tracked. Previous work on this (Aronson *et al.*, 1994), suggests it could be an important tool for coral ecophysiology and a very generalised health indication.

In order to gauge the true extent of bleaching, an exact Symbiont density and chlorophyll-a content of individual coral samples needs to be quantified but this method is destructive, involving the removal of tissue. This is based on using the Johannes & Wiebe technique (Johannes and Wiebe, 1970) outlining the use of fine jets of water to remove tissue (commonly referred to as "water piking") and assessing coral health based on the composition of symbiodinium and chlorophyll content. This technique is not very practical in situ as it requires the removal of samples from the environment and is better suited to laboratory experiments to link effects of bleaching and pigment intensity. These experiments are valuable as they can help to link the levels of symbiont density to spectral peaks and approximate the stage of bleaching that can be determined using in situ hyperspectral imagery.

Using the physical colour of a coral is a rapid and non-invasive method for the assessment of bleaching and therefore 'health' (as defined previously). For divers, a colour card is made for a species that uses a 6-point brightness/saturation scale within four colour hues to record changes in bleaching state (Siebeck *et al.*, 2006). Colour wheels rely on bleaching experiments to gain the colours required to make the wheel and average colour hues linked to stages of bleaching, however this is not always straight forward as some coral species do exhibit colour variance. Hyperspectral imaging takes this similar concept but can more accurately record colour and minute variations in specific pigments not necessarily visible to traditional cameras (3 channel RGB) or the human eye. Satellites also use colour changes in the multispectral profiles to determine percentage bleaching and in the case of NOAA's Coral Reef Watch (CRW) this is combined with sea surface temperature (SST) to give predictions of bleaching risks. Satellite imagery requires a correction to account for the interaction of light with the atmosphere and water's surface. Any imaging method that is employed from above the water's surface requires ground truthing to verify and quantify exact levels of bleaching events. When this is done, the UAV (Drone) surveying potentially provides the best quality survey data and is also more affordable.

Hyperspectral Fluorescence imaging (HyFI) is a potentially invaluable new tool, capturing the characteristic of light signals emitted by fluorescent proteins (FPs). For laboratory pre-calibration, different coral species can be spectrally characterized and quantified non-invasively (Mazel, 1995; Myers *et al.*, 1999; Roth and Deheyn, 2013) to underpin field data. Similarly, with reflectance hyperspectral imaging fluorescence reveals spectral peaks that are derived from pigments that are expelled during the bleaching process. Chlorophyll fluorescence (685nm) provides a direct insight

into the symbiont density as chlorophyll is only contained within corals' symbiotic partner thus providing a direct bleaching metric.

GFP's fluorescence is another metric that can be used as it is highly responsive to changes in heat (Desalvo *et al.*, 2008; Rodriguez-Lanetty, Harii and Hoegh-Guldberg, 2009; Roth and Deheyn, 2013) and due to the vibrant colours stand out spectrally. These measurements also require a baseline calibration that can be achieved either by conducting laboratory based bleaching experiments or by surveying the same samples/locations over a time period to observe relative changes in the recorded spectrum.

4. Conclusion

Current marine monitoring practices and surveys have many different approaches to the question of is coral 'Healthy'? and many of these techniques complement each other as part of a large toolkit to help build a fuller picture of assessments into the condition of reefs. Due to the nature of coral reefs being such extraordinarily complex ecosystems, each different technique offers a different approach and piece of the puzzle shedding light on parameters pertaining to the overall system health.

HyFI could prove to be a powerful new tool in the diagnostic arsenal for coral health, with rapid non-destructive and repeatable measurements able to be taken across whole reef systems by the use of ROVs. The data obtained can be used in many different ways, making one tool capable of performing several diagnostic measurements from health to population surveys. Using the hyperspectral system in a number of different ways with little to no modification can potentially collect fluorescence data on coral host and symbionts, perform benthic mapping using 'optical fingerprint' analysis and identify ocean plastics to name just a few examples.

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