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

S6. Novel technologies in coral reef monitoring

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Glossary of technical terms

Artificial intelligence (AI) is a broad concept, in computer science, of machines being able to carry out tasks in a way that we would consider “smart”. In AI, intelligence is demonstrated by machines, in contrast to the natural intelligence (NI) displayed by humans and other animals. In computer science AI research is defined as the study of "intelligent agents": any device that perceives its environment and takes actions that maximize its chance of successfully achieving its goals. Colloquially, the term "artificial intelligence" is applied when a machine mimics "cognitive" functions that humans associate with other human minds, such as "learning" and "problem solving”.

Automated image annotation is an application of machine learning defined as a process by which a computer system automatically assigns metadata in the form of labels or keywords to a digital image. The main idea of automated image annotation techniques in coral reefs is to automatically learn to identify corals and other organisms from a large number of images to develop concept models than can automatically label elements in new images to quantify their abundance.

Autonomous Underwater Vehicle (AUV) is a robot that travels underwater without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles, a classification that includes non-autonomous remotely operated underwater vehicles (ROVs).

Deep learning is part of a broader family of machine learning methods based on learning data representations, as opposed to task-specific algorithms. Deep learning models are loosely related to information processing and communication patterns in a biological nervous system, such as neural coding that attempts to define a relationship between various stimuli and associated neuronal responses in the brain. In coral reefs, deep learning architectures such as deep neural network has specific applications to pattern recognitions from images, as an automated image annotation system that has proven to be far superior than other approaches.

Machine learning is a field of computer science that gives computer systems the ability to "learn" (i.e. progressively improve performance on a specific task) with data, without being explicitly programmed. Therefore, machine learning is a current application of AI based around the idea that we should really just be able to give machines access to data and let them learn for themselves.

Object-based analysis is here particularly referred to Object-Based Image Analysis (OBIA), defined as a method for automated image annotation employing two main processes, segmentation and classification. Traditional image segmentation is on a per-pixel basis. However, OBIA groups pixels into homogeneous objects. These objects can have different shapes and scale. Objects also have statistics associated with them which can be used to classify objects. Statistics can include geometry, context and texture of image objects. The analyst defines statistics in the classification process to generate for example coral cover.

Remotely Operated Vehicle (ROV) is a tethered underwater mobile device. This meaning is different from remote control vehicles operating on land or in the air. ROVs are unoccupied, highly maneuverable, and operated by a crew aboard a vessel.

Robot is a machine—especially one programmable by a computer— capable of carrying out a complex series of actions automatically. Robots can be guided by an external control device (e.g. ROV) or the control may be embedded within (e.g. AUV).

Sensor is a device, module, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor. A sensor is always used with other electronics, whether as simple as a light or as complex as a computer.

Remote sensing is the acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to on-site observation. In current usage, the term "remote sensing" generally refers to the use of satellite or aircraft-based sensor technologies to detect and classify objects on Earth, including on the surface and in the atmosphere and oceans, based on propagated signals (e.g. sunlight reflection).

Unmanned Aerial Vehicle, commonly known as a **drone**, is an aircraft without a human pilot aboard. UAVs are a component of an unmanned aircraft system (UAS) which include a UAV, a ground-based controller, and a system of communications between the two. The flight of UAVs may operate with various degrees of autonomy: either under remote control by a human operator or autonomously by onboard computers.

1.0 Executive Summary

This report summarises a review of current technological advances applicable to coral reef monitoring, with a focus on the Great Barrier Reef Marine Park (the Marine Park). The potential of novel technologies to support coral reef monitoring within the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) framework was evaluated based on their performance, operational maturity and compatibility with traditional methods. Given the complexity of this evaluation, this exercise was systematically structured to address the capabilities of technologies in terms of spatial scales and ecological indicators, using a ranking system to classify expert recommendations.

The main logistical limitations for translating knowledge from coral reef monitoring into management and policy making are: i) time required to complete analyses, reporting and making data and information available and ii) spatio-temporal representation. Reporting time can be disproportionally larger than the timeframe within which the advice is expected. Spatial and temporal coverage of monitoring programs can be limited in very large jurisdictions, such as the Marine Park. The integration of traditional monitoring techniques and novel technological solutions can offer solutions to decrease reporting times and increase spatio-temporal representation of monitoring.

Overall, we recommend a staged implementation of current technological advances for coral reef monitoring. A suite of technological tools is currently available that could support coral reef monitoring, some of which are already being implemented in monitoring and assessments. Other technologies are evolving rapidly, and their maturation and readiness for implementation in coral reef monitoring will be demand-driven. Given the fast pace of technology development, this report provides recommendations at two temporal scales: immediate and near-future (2-5 years) implementation.

Underwater and above-water vehicles or platforms are now operationally mature and sufficiently reliable to support observations of key ecological attributes at reef-wide scales (Fig 1). Autonomous platforms, such as underwater robots (AUV, ROV), are also available and would be offering access to habitats that pose risks to divers but represent keys gap in existing monitoring programs, such as deep reefs and coastal habitats inhabited by saltwater crocodiles.

Analyses methods such as artificial intelligence and pattern recognition from images have evolved rapidly, to the point that measurements of key ecological attributes (e.g. composition and abundance of benthos, structural complexity) can now be collected with high precision and several hundred times faster than manual expert analyses. As the development of sensors (e.g. underwater hyperspectral sensors) and software (e.g. complex machine learning algorithms) will advance over the next 2-5 years, the capabilities of automated image annotation and 3D habitat reconstructions to contribute to coral reef monitoring are also growing rapidly.

Remote sensing is reaching a maturity to be implemented for monitoring of shallow coral reef systems. Accessibility of satellite-based sensors with higher temporal repetition (daily instead of weekly) and coverage (e.g. the Great Barrier Reef) is now allowing to evaluate the status and trends of reef systems at intermediate and broad scales (e.g. area and cover of dominant habitats and substrate types, extent of coral bleaching). In the medium-term, access to easy-to-

operate drones, high-quality sensors (increased in radiometric quality and high resolution) and a development of advanced processing techniques (online processing of large data sets, object-based analysis or machine learning routines) will enable the extraction of a higher level of detail at reef scales.

A key recommendation from this review is that technology can at present not replace traditional ecological monitoring methods, because solutions offered by technology do not cover the entire spectrum of capabilities traditional methods can reliably achieve. Rather, technological advances offer solutions to maximise the spatial and temporal coverage of current monitoring, and increase the speed of data analysis. For example, autonomous vehicles now offer the possibility of surveying reefs over scales of kilometres across multiple depths gradients, and in habitats that pose a risk to divers. However, assessments of fish communities as well as patterns of mortality and disease in corals, for example, cannot currently be measured accurately using any of the available technologies. The implementation of technological solutions should, therefore, integrate traditional and next-generation approaches. Importantly, such integration can only be achieved if data standardisation and compatibility among methods is assured.

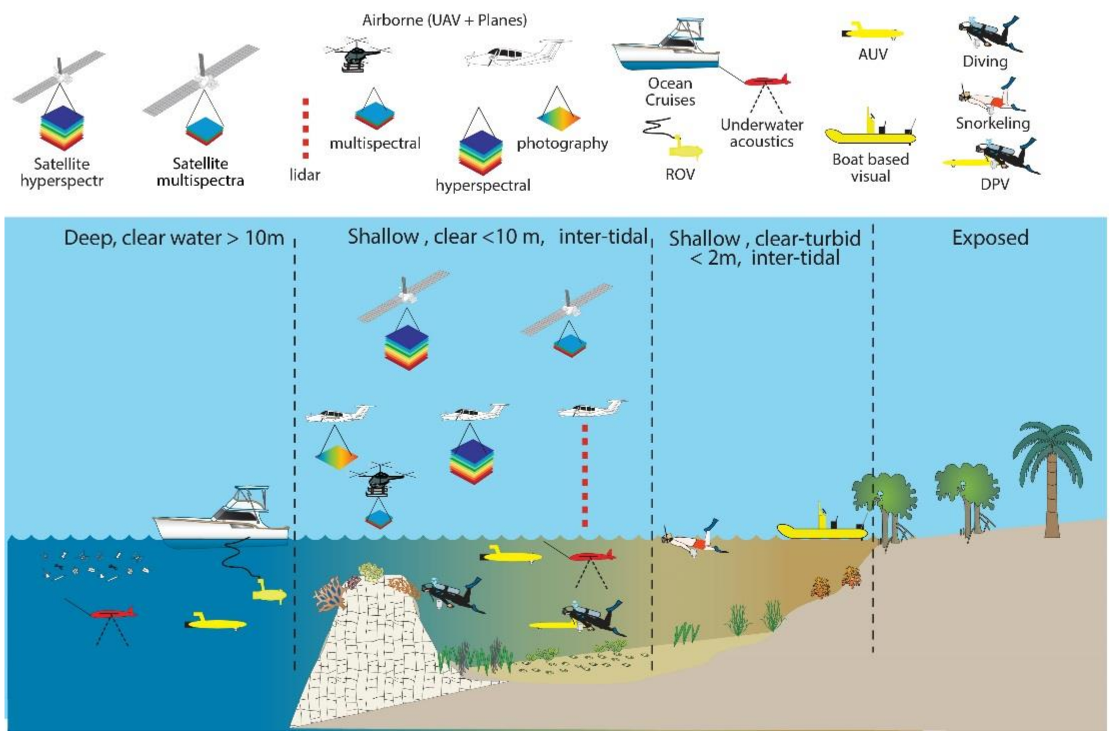

Figure 1. Conceptual diagram of integrated technologies, including variety of platforms and sensor types, that could be combined and implemented for the RIMReP (adapted from Goodman, Purkis & Phinn 2013)

2.0 Introduction

Under the increasing pressure from more intense and recurrent anthropogenic disturbance, global ecosystems are degrading rapidly (Pandolfi *et al.* 2003; Ellis 2011). Based on these accelerated patterns of change, it is commonly agreed that a sound ecological knowledge on the patterns of change and plausible management scenarios is required to undertake informed decisions to avoid or mitigate the functional collapse of these ecosystems (Lindenmayer & Likens 2010; Hughes *et al.* 2013a; Hughes *et al.* 2013b). While it is well established that hypothesis-driven and adaptive management should lead to substantial increases in the efficiency of monitoring in conservation (Nichols & Williams 2006), that paucity and scarcity of ecological monitoring data can inhibit active conservation (Caughlan & Oakley 2001; Lindenmayer & Likens 2010).

On coral reefs, the availability of monitoring data can strongly influence policy implementation and management actions (Ban *et al.* 2009; McCook *et al.* 2010; Mills *et al.* 2010). Although considerable effort is already in place to survey or monitor coral reefs in some regions, high costs and limited accessibility to survey sites combined with a vast spatial and temporal extent of most reef systems often results in patchy or spatially limited biophysical data (Udy *et al.* 2005; Phinn, Roelfsema & Stumpf 2010; Madin & Madin 2015). In addition, the information gathered by coral reef surveys often takes a considerable amount of time and resources to be extracted and synthesised in order to inform decision-making, contributing to an increasing paucity in management actions.

In response to the escalating challenges facing the Great Barrier Reef (the Reef), a *Reef 2050 Long-Term Sustainability Plan* (LTSP) was released in early 2015 (Commonwealth of Australia 2015). The specification of targets, objectives and outcomes in this sustainability plan clearly elevate the importance of monitoring and calls for a Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) to assess the Plan's overall effectiveness. The RIMReP is intended to integrate existing programs, fill critical information gaps and align reporting and modelling to provide the most comprehensive and up-to-date understanding of the Reef, its values, the processes that support it and the pressures that affect it (Addison *et al.* 2015). As such, advances in technology prominently feature as potential tools to be implemented within the RIMReP design in order to help fast-track, scale up and integrate assessments of coral reef condition.

In the current decade, the fast evolution of technology in engineering (from robotics to sensor design), computer vision and storage and processing capacity has empowered modern society in many aspects from navigation systems and biomedical sciences to real-time data analytics in e-commerce. Many technological advances are becoming more applicable and available to marine sciences; for example, underwater robotics are now widely used and more accessible, artificial intelligence is proving very successful in data mining, and satellites are increasing sensor resolution and frequency of data capture across the oceans.

Given the rapidly increasing availability of a range of technology that could potentially facilitate and scale up coral reef monitoring, here we present the results from a desktop study aimed at reviewing the capabilities of modern technologies to support coral reef monitoring in the Great

Barrier Reef Marine Park (the Marine Park) under the RIMReP program. To achieve this aim, capability matrices were derived from expert opinions and peer-reviewed literature that evaluate existing technologies in terms of their performance, operational maturity, expected costs of deployment and capacity to guarantee data continuity from existing and long-term coral reef monitoring. Based on this assessment, this report provides an expert-based recommendation on the suite of technologies that can be implemented now and in the near future to monitor specific properties or indicators of the reef condition.

3.0 Scope and Approach

3.1 Overview

A generic evaluation of suitable technologies for coral reef monitoring is a complex task because of the multiple dimensions on which to evaluate technological implementation (Table 1). For example, different technologies may be better suited to specific environmental conditions (e.g. shallow clear water vs deep turbid, etc.). In addition, the type of parameters to monitor will require different resolutions in terms of spatial detail, spatial extent, temporal and taxonomical resolution or even chemical composition. Finally, providing a suite of available technological tools, specific combinations of sensors (e.g. hyperspectral), platforms (e.g. Satellites, Underwater Robots), logistics and infrastructure requirements may be differentially suited to each ecological parameter (Table 1).

Table 1: Dimensions affecting the suitability of technological solutions for coral reef monitoring. This table lists examples of different conditions or scenarios on which coral reef monitoring often requires different approaches, and therefore technological solutions.

Dimensions	Details	Examples
Environmental condition where monitoring takes place	Depth	High water depths limit the use of diver-based technological solutions and will require using platforms such as underwater robotics. Similarly, data reliability from satellite and airborne technologies is limited to specific depth to still be able to differentiate specific features.
	Water clarity	Data reliability from satellite and airborne technologies is limited to specific optical properties to still be able to differentiate specific features.
	Habitat type	Mesophotic reefs (a.k.a. deep reefs) will have different environmental conditions than reefs flats of exposed reef fronts, and therefore technologies need to accommodate to such conditions.
Candidate Parameters to monitor	Spatial detail and Temporal Resolution	Corals are only bleached for an approximate four-week period, and it could be limited to only a colony or to whole geomorphic zones.
	Taxonomical complexity	Taxonomic definition can influence the capacity of observers to extract information from images in comparison to field and laboratory identification. Species, genera or functional groups will pose different challenges for technology to accurately identify organisms within

		each taxonomical tier. Therefore, some technology may be better suited than others depending of the desired taxonomic definition.
	Desired spatial extent	Coverage of the entire Reef will require remote sensing techniques, but detailed surveying underwater, and at depth, will require different tools.
	Data continuity	Implementation of technological advances should guarantee compatibility and continuity of data with traditional methods, in order to maximise the long-term datasets where available.
Technological tools available	Diversity of tools and combinations to address specific objectives	A diversity of tools is available from recent advances in technologies, ranging from autonomous vehicles to diver operated sensors and their applications will depend on the problem needing to be solved.
	Range of sensor resolutions	Sensors can vary in the spatial resolution they can produce, and normally there is a trade-off between spatial resolution extent of area covered.
	Operational maturity and costs	Science and technology are rapidly evolving fields. While some studies may indicate that certain technologies offer a promising avenue for coral reef monitoring, not all technologies have been fully implemented and will require maturing their operations to make their implementation in field surveys feasible.
Logistics and infrastructure	FTE required	Amount of personnel required to implement each technology will be different in case-by-case scenarios. For example, Unmanned Aerial Vehicles may require a dedicated and qualified person to design and execute surveys, wereas diving operations will required a team of qualified personnel.
	Skills and knowledge required	Unmanned Aerial Vehicles and Autonomous Underwater Vehicles will require technical personnel for their deployment, maintenance and troubleshooting.
	Transport	Engineering technologies such as Unmanned Aerial Vehicles, Remotely Operated Vehicles and Autonomous Underwater Vehicles will require different vessel specifications to be deployed. UAVs can be deployed from land and boats, but they can only operate within a range from the receiver. AUVs may operate within a larger range from the vessel, but accurate geo-location may be more attainable using a tender boat in the vicinity. While ROVs can be deployed from tenders, certain specifications will be required to keep the above water equipment safe as the boat stability can affect underwater navigation of the unit.

To address the complexity of evaluating technologies within a range of different scenarios, this review has been systematically structured to evaluate technologies within three main dimensions against each other, keeping logistical and infrastructure considerations in mind:

1. **Candidate monitoring parameters**, that have been identified by the RIMReP Expert Group for coral reefs. Here, we used a synthesised version from this list on which to

evaluate the performance of technologies. Note that these parameters are relevant to monitoring of biological communities and attributes. Environmental monitoring parameters are not considered in this review.

2. **Desired spatial and temporal scales** for coral reef assessment has been divided into three main categories: fine, intermediate and broad-scale.
3. **Available technologies** have different outputs and applicability depending how they are combined. Here we aggregate technologies within different combinations of:
    a. **Sensors**, which refers to the devices which detect or measures a particular property (e.g. camera).
    b. **Platforms**, defined as the units which carry the sensors (e.g. divers, robots, satellites).
    c. **Processing tools**, which convert raw data into meaningful ecological information.

To evaluate these three conditions/dimensions, a capability matrix was created to contrast monitoring parameters against the desired spatial and temporal scale and the available technologies based on assessment of the literature, existing remote sensing capability assessments, advice of expert collaborators, and expert knowledge of the report authors.

The valuation of technologies in this review was challenged by defining the boundaries of the study and the level of detail on which to assess the technology capability. In regards of boundaries, we focussed on 1) the candidate monitoring parameters, considered in their broad definition and not in the individual detail (e.g. bleaching in general, not the different colours or stages); and 2) desired spatial and temporal scales were discretised in a spectrum from metres to thousands of kilometres, and days to years. However, for simplicity, this review does not consider local environmental conditions (e.g. depth, water clarity or sea surface roughness), which should be accounted for when determining how these technologies can be implemented. Similarly, within the range of technological tools available, this review is centred on those already in place and which have been proven to a certain extent. Potential ideas of how technology can evolve to support marine monitoring are excluded for the purpose of this review.

Given that technological tools will have different outputs and applicability depending how they are combined, here we aggregate technologies within different combinations of sensors, platforms and processing tool onto a category defined as technological solutions, on which we evaluated their capability of implementation on coral reef monitoring.

Within the aforementioned dimensions, the capability of a given technological solution was classified within a five tier classification system: Highly Recommended, Recommended, Potential, Uncertain and Not Feasible (Table 2). Classes were differentiated on the following criteria: 1) Evidence of good performance, in terms of accuracy or precision, repeatability and efficiency, 2) Operational Maturity, which defines whether an integration of technologies, at a given scale, has been implemented for the monitoring of given parameters, and 3) Capacity to guarantee data continuity where previous data is available.

Table 2. Classification scheme used to evaluate the capability of technological solutions to contribute to coral reef monitoring for each candidate parameter and desired scale.

Capability classification	Evidence of good performance	Operationally mature	Data continuity	Description
Highly Recommended	Yes	Yes	Yes	Evidenced in peer-reviewed literature and implemented as a monitoring tool
Recommended	Yes	No	Yes	Evidenced in peer-reviewed literature but need evidence of implementation
Potential	Some	No	Yes	Potential capability based on expert knowledge but requires research and development
Uncertain	Unknown	No	Unknown	No evidence or information available
Not Feasible	No	No	No	Not feasible at this stage

The thinking process described in this report was based on the evaluation conducted to create the remote sensing toolkit capability matrix (http://ww2.sees.uq.edu.au/rsrc/rstoolkit/assets/pdfs/mapping-capabilities_marine.pdf). In the remote sensing toolkit exercise, the remote sensing technologies specifically were evaluated for a suit of variables that are required for terrestrial, atmospheric and marine environment (Roelfsema *et al.* 2017), and offer an user interface to help assess the suitable remote sensing approach for specific environmental conditions and parameters (www.rsrc.org.au/rstoolkit/).

The remote sensing technologies evaluation included in this report is based on the evaluation conducted for the remote sensing toolkit, with additional updates from recent literature. In contrast, non-remote sensing-based technologies were newly assessed.

3.2 Candidate Parameters to monitor

Table 3. Summary parameters pre-selected by the RIMReP Coral Expert Group as candidate attributes to monitor. The list of parameters has been classified by groups (e.g. Hard Corals, Algae), ecological categories (e.g. Taxonomic and Functional) and type (e.g. Abundance, Size Structure).

Group	Category	Parameter type	Parameter detail
Hard and Soft Corals	Taxonomic and Functional	Abundance	Total
			Genus
			Functional groups
			Juveniles
	Population and community structure	Size Structure	Functional groups or genus
	Agents of Health and Disease	Bleaching	Incidence and Severity
		Disease	Incidence
		Partial mortality	Proportion of mortality within a colony (Hard corals)
Algae	Taxonomic and Functional	Abundance	Total
			Genus
			Growth Forms
	Agents of Health and Disease	Disease (CLOD)	Incidence
Fish	Taxonomic and Functional	Abundance	Total
			Species
	Population and community structure	Size Structure	Species
Other Benthos	Taxonomic and Functional	Abundance	Crown-of-thorn starfish
			Drupella spp
	Population and community structure	Size Structure	Crown-of-thorns starfish
Ecosystem	Attributes	Structure	Structural Complexity
	Processes	Growth Rate	Corals and Soft Corals

3.3 Spatial Scales

The spatial characteristics of parameters to be monitored significantly influences whether and how they are monitored. Spatial scales are determined by two components:

- Areal extent to be represented for the monitoring (e.g. a zone on a reef vs all the reefs on the Reef); and
- Spatial detail to be monitored (e.g. dominant benthic cover type vs per cent of coral present).

In this review, we defined three distinct monitoring scales (Table 4 and Figure 2) that coincide with monitoring requirements laid out by Udy et al (2005), which included focussing monitoring on processes, resilience, condition and overall status. These scales were chosen to allow the technology assessment in that context.

Table 4. Classification of Spatial scales used in this review to evaluate the capabilities of technological advances for coral reef monitoring.

Scale	Spatial extent	Spatial detail	Examples
In-depth	Path of Coral - Geomorphic Zone	0.1-10s m	Community composition. Juvenile abundance and diversity. Agents of mortality and health (Disease, predation).
Intermediate	Geomorphic zone to full extent of one reef	10-1000s m	Reef wide trends in composition and abundance.
Broad	One reef to 1000s of reef.	1000-10000's of m	Habitat mapping

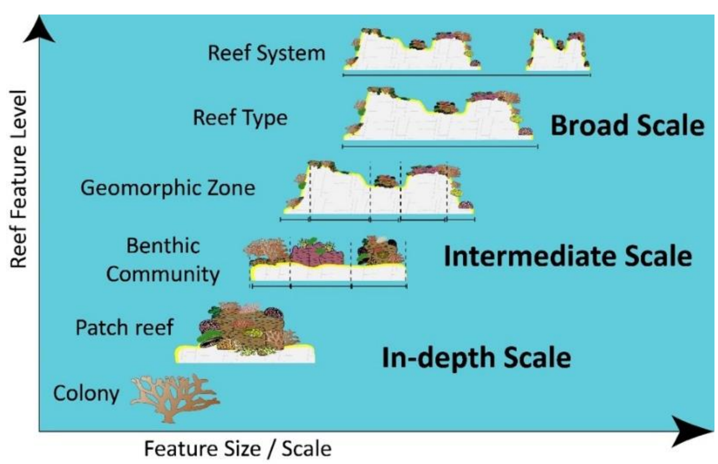

Figure 1. Classification of spatial scales used in this review to evaluate the capabilities of technological advances for coral reef monitoring (derived from (addapted from Phinn, Roelfsema & Mumby 2012).

4.0 Summary of technologies applicable to coral reef monitoring

4.1 Passive sensors

4.1.1 Definitions

Passive sensors measure a signal (e.g. light reflected from earth surface) without actively sending out signals. For example, imagery/photos rely on a light source that could be strobe or the reflected sunlight or emitted thermal energy regardless of whether they are collected by diver or satellite. These sensors are usually unable to be penetrate through turbid water, smoke, clouds or at night. The amount of light reflected, absorbed or transmitted by a feature is highly dependent, for instance, on the incoming light, for instance pigments, canopy structure and biomass.

Each pixel in an image contains information on the light reflected at specific sensitive wave length for a feature on the ground, which is often represented by a spectral reflectance signature. This signature is a record of how much sunlight interacted with the feature and was reflected back to the sensor in an aircraft or satellite.

Multispectral or hyperspectral signatures vary depending on the type of sensor. A multispectral sensor records less than 10 wave length bands to record reflected light and produces simple spectral signatures. A hyperspectral system can measure over 1000 wave length bands light and produce highly detailed signatures. The advantage of hyperspectral systems is that they produce more detailed spectral signatures, which enables more detailed and accurate mapping of water column and benthic attributes. Multi and hyperspectral sensors are commonly found on air or space-borne sensors for far-range imaging from hundreds of meters (e.g. airborne drone) to thousands of kilometers (e.g. satellites).

RGB sensors, on the other hand, use a model that interprets monochrome values between pixels to recreate a red, green and blue color composite, and do not measure individual reflectance for each sensitive band in each pixel. As a result, spectral characteristics of features (e.g. absorption of light by chlorophyll pigments) cannot be determined from RGB imagery. However, spectral characteristics of features can be measured from multi or hyperspectral sensors. RGB sensors are commonly found in standard cameras used above and underwater for so-called close range photography ranging from several centimeters (e.g. diver) to hundreds of meters (e.g. airborne drone).

4.1.2 Applications

Multi and hyperspectral sensors are commonly used for mapping physical and biological attributes in coral reef environments at intermediate to broad scales (Mumby *et al.* 2004; Hedley *et al.* 2016). Multispectral, high spatial resolution sensors (pixels < 5 m) are commonly used to map benthic properties of individual reefs (Andréfouët *et al.* 2003; Phinn, Roelfsema & Mumby 2012) or larger reef systems (Rowlands *et al.* 2012; Roelfsema *et al.* 2013). Multispectral moderate spatial resolution sensors are commonly used to map geomorphic properties at large spatial extent (Andréfouët 2004; Andréfouët *et al.* 2006). Hyperspectral high spatial resolution sensors (pixels < 5 m) are commonly captured from airborne platforms, in contrast to multispectral high spatial resolution sensors. Due to their extended hyperspectral range and small pixel size, they have improved capability to differentiate benthic features (Dekker *et al.* 2011; Leiper *et al.* 2014). However, their capacity to delineate coral species is often limited (Hochberg & Atkinson 2000). Only a few studies have mapped benthic composition using hyperspectral high spatial resolution imagery, but they suggest the technique can be implemented across large reef systems such as Ningaloo Reef (Kobryn *et al.* 2013).

Close range hyperspectral benthic data has commonly been collected using underwater spectrometry (Dekker *et al.* 2010), and just recently underwater imaging spectrometry was successfully implemented underwater to differentiate coral species (Chennu *et al.* 2017) and to map small areas underwater (Caras, Hedley & Karnieli 2017).

RGB sensors are commonly used on sensors for snorkeling or diving photo surveys (Roelfsema & Phinn 2010; González-Rivero *et al.* 2016), underwater AUV (Roelfsema *et al.* 2015) and also UAV-based surveys (Casella *et al.* 2017). Due to their high pixel resolution, RGB sensors are able to differentiate a variety of bottom features (Beijbom *et al.* 2015) and with the increase in data storage capability, kilometers of photos can be collected in the field (González-Rivero *et al.* 2014b). RGB sensors are also used increasingly for determining rugosity based on structure from motion photogrammetry (Figueira *et al.* 2015b; Leon *et al.* 2015a).

4.1.3 Recent developments

In remote sensing, the main development in regards to passive sensors is the increased radiometric quality, such as that of Landsat 8 OLI vs Landsat 7 ETM, and Worldview 3 vs Quickbird sensors. Due to the increased capability to launch very small platforms in space, the number of satellites launched and decommissioned is increasing, and as a result satellite sensors can be updated and improved more rapidly. In addition, there has been an increasing demand for very small sensors that can be deployed on drones above and underwater, planes and satellites to provide greater spectral, spatial and/or temporal resolution at the scale at which these different sensors are deployed.

5.0 Active sensors

5.1 Definitions

Active sensors transmit a signal that, when reflected off an object, provides information about the environment, such as water depth or mangrove canopy composition. Depending on their radiometric characteristics, active sensors can penetrate clouds and are unaffected by water clarity and could be used at night.

Acoustic sensors are commonly used to measure distance from sensor to the seafloor. Acoustic sensors include both single-beam, which measure depth at a single point on the seafloor, and multi-beam which can send out beams in a fanned arc to create a 3D image of the seafloor.

5.2 Applications

In addition to mapping the topography of the seafloor, acoustic sensors can also be used to quantify seabed hardness and therefore to delineate between hard and soft sediments (Walker, Riegl & Dodge 2008). In archeological underwater studies, laser imaging, using airborne or underwater sensors, can provide very high resolution (<1mm) 3D mapping of large areas (Roman, Inglis & Rutter 2010; Doneus *et al.* 2013). While their applications in archeology could be translated to coral reef ecology, the feasibilities and operationalisation of these technologies are yet to be evaluated.

6.0 Platforms

6.1 Definition

Platforms on which sensors are located can vary in type and usage and can be classified into several groups: snorkeler or diver operated, snorkeler or diver with propulsion operated, Underwater Tethered Drone (ROV), Underwater Autonomous Vehicle (AUV), Unmanned Airborne Vehicles (UAV), aircraft, and satellites (Table 5). Advantages and limitations for each of these platforms are primarily influenced by the application and environmental conditions on which to deploy them (Table 6).

Table 5. Summary characteristics of technological platforms evaluated in this review for their potential implementation in coral reef monitoring.

Platforms	Distance to seafloor	Extent covered	Limitation	Strength
Snorkeler or diver operated	10s cm	10s-1000s m	Snorkelling limited to max 3 m in depth. Occupational diving limited to about 40 m and constrained to about an hour of survey.	Flexible. Adaptable to weather conditions within safety.
Diver propulsion Vehicles (DPV)	10s cm	1000s – 5000s m	Snorkelling limited to max 3 m in depth. Occupational diving limited to about 40 m and constrained to about an hour of survey.	Large area coverage at close range.
Remotely Operated Vehicle (ROV)	10s cm	10s - 100s m, limited to distance from the vessel	Tethered to the surface. Limited by the distance from vessel. High tech	Can operate under for dangerous conditions for divers.
Autonomous Underwater Vehicle (AUV)	10s cm	10s - 100s km	Battery power and object avoidance, high tech	Safe and large area coverage

Unmanned Airborne Vehicles (UAV)	100s cm	10s -100s km	Battery power and regulations, and requires water column correction, high tech	Cover large area in very high detail
Air planes	100s m	100s-1000s km	Regulations, and water column correction, high tech	Cover larger area in relative high detail
Satellites	1000s km	1000s – 10000s km	Level of detail and requires water column correction, and clouds, high tech	Cover very larger area in moderate detail

6.2 Applications

Snorkelers and divers have functioned as ‘platforms’ for decades to gather information of the ecological communities at a high level of detail using various methods (English, Wilkinson & Baker 1997; Hill & Wilkinson 2004; Roelfsema, Phinn & Joyce 2004). Data collection and interpretation has traditionally relied on expertise of the diver collecting the data. However, the introduction of digital underwater photography has allowed image-based monitoring information to be collected by a snorkeler or diver without expert knowledge of the ecosystem, as the analysis of the imagery is carried out afterwards by experts or automated methods.

Diver propulsion vehicle (DPV), provide the advantage of integrating additional sensors to the traditional diver-based platform, and also enable much greater spatial coverage (González-Rivero *et al.* 2014b; González-Rivero *et al.* 2016).

Underwater Tethered Drone or Remotely Operated Vehicle (ROV) can be used to survey virtually any habitat. Smaller ROVs are cheaper and can be deployed from smaller vessels, but are generally limited to shallower depths. ROVs allow real-time interpretation of the environment, making them ideal for site surveys and activities such as specimen collection from deep habitats inaccessible to divers.

Table 6. Summary of pros and cons of implementing each platform in coral reef monitoring as well as their ideal scenario where they are recommended to be used.

Platform	Pros	Cons	Ideal Usage
Snorkeler / Diver	Diver-based surveys are the traditional method for surveying coral reefs. Therefore, divers have the advantage of having established SOPs, and with sufficient expertise can conduct surveys of fish and benthic communities with higher taxonomic resolution than any other platform.	Divers are limited in both the spatial extent and habitats that they can survey. In terms of spatial coverage, divers can only cover a distance of a few hundred metres in any one survey. More importantly, divers are strongly limited to shallow habitats, leaving 'deep, dark and dangerous' habitats unsurveyed	Surveys requiring expert knowledge or experimental research
DPV	Allows for diver-based observations while increasing the spatial coverage of surveys	Ability to survey deep, dark, dangerous habitats still limited for a diver. DPVs generally collect digital imagery, so generally result in loss of taxonomic resolution	Ecological surveys at intermediate scales with intermediate taxonomic resolution
AUV	Autonomous so can survey virtually any habitat or depth. Spatial coverage much greater than ROVs or diver-based methods. Geo-referencing allows for accurate, repeatable surveys across time and space	Taxonomic resolution limited by image quality. Potential for mechanical problems. Currently need to be deployed from a vessel, although increased range and coordination with autonomous surface vehicles (ASVs) is improving rapidly. Currently available AUVs not designed to survey steep reef walls. Deployment and data post-processing requires specific expertise	Intermediate to broad-scale habitat surveys across a wide range of reef habitats.
ROV	Enables visual surveys of virtually any habitat. Can be fitted to collect specimens/samples. Generally smaller and lighter than AUVs, allowing deployment from smaller vessels	Limited in spatial scale and taxonomic resolution possible. Requires expert pilot and mechanical expertise to fix problems. Need to be deployed from a relatively large vessel with appropriate power supply.	Preliminary surveys of unexplored habitats, collection of specific taxa
Airborne (UAV)	Large spatial coverage, flexibility to mount different sensor payloads	Limited to surveying very shallow waters, although methods for increasing depth range are improving. Most UAVs still have short flight times, limiting the amount that	Surveying shallow habitats at low tide - potentially complementing AUVs for very shallow habitats

		can be done by any one single UAV	
Satellite	Very large spatial coverage. Ability to collect wide range of environmental data through time	Low spatial resolution, potentially high cost for acquiring data from commercial entities	Broad-scale environmental data

Autonomous Underwater Vehicles (AUV) have been used to gather detailed information about seafloor composition in shallow waters (Roelfsema *et al.* 2015) and in deep waters (Armstrong *et al.* 2006; Bridge *et al.* 2011; Friedman *et al.* 2012) AUVs allow collection of visual images and associated environmental data over large spatial and temporal scales (up to 10-15 km per day, depending on the vehicle), making them an ideal habitat mapping tool, particularly in conjunction with broad-scale environmental data such as multi-beam bathymetry. However, there is no capacity to see the data being collected in real time, so it is useful to have some prior knowledge of the study site (i.e. multi-beam bathymetry).

Unmanned Airborne Vehicles (UAV) have been used on coral reef environments to map high level benthic detail (Casella *et al.* 2017).

Planes have been used in combination with hyperspectral image sensors to map benthic composition (Kobryn *et al.* 2013; Leiper *et al.* 2014) or water depth for large areas (Hedley, Roelfsema & Phinn 2009). Airborne visual assessments such as the monitoring the mass bleaching events in 1998, 2016 and 2017 (Berkelmans & Oliver 1999; Hughes *et al.* 2017). Where in the most recent assessment RGB oblique imagery were acquired of the reefs for the purpose of visual analysis.

Satellites are the ideal platform to capture imagery over large spatial scales on a regular basis, exemplified by the freely available multispectral moderate resolution satellites of the Landsat and Sentinel series (Hedley *et al.* 2016). These sensors have a revisit time of 5 days to 16 days, however current cube satellites such as the Planet Dove have a revisit time of 1 day, and are equipped with multispectral high spatial resolution sensors (Asner, Martin & Mascaro 2017).

6.3 Recent developments

Snorkeler or Diver: Closed circuit rebreathers (CCR) increase bottom time available to divers, and are therefore useful for deep dives requiring long decompression stops. Improved technology in both the CCR sensors and associated dive computers has dramatically increased the safety of rebreathers even for very deep diving, and CCRs are now commonly used for scientific research in many countries, including the United States and United Kingdom. Training programs are easily accessible and can even be tailored to scientific divers, making them more applicable to scientific research.

Autonomous Underwater Vehicle (AUV): Smaller platforms can be deployed from smaller vessels, longer battery power, improved obstacle avoidance systems for surveying unknown terrain, user friendly and commercial off the shelf.

Airborne platforms (UAV, aircraft): Ongoing improvement of not only technology but also in regards to permits, makes these platforms easier to use or to access for monitoring purpose. Airborne platforms allow the complex integration of a number of sensors to provide a very light level of detail of the reef and, because these platforms have been widely used for decades, their applications for long-term changes are becoming increasingly robust (Purkis 2018).

Satellite: So-called cube satellites are the size of a microwave and are only a few kilograms in weight, making them cheap to build and launch and providing increased capability to launch very small platforms into space. Similar new approaches are improving launching capability, such as the recently-launched battery driven satellites and launch platforms that can return to earth. On-board processing and data storage capability is also increasing rapidly. Current developments in onboard processing are designed to correct imagery as it is taken, also offering thematic or continuous data products. As a result, on-board processing will make the turn-around time faster to provide consistent products. However, the application for coral reef monitoring is still poorly understood.

7.0 Processing Tools

7.1 Benthic Information extraction

7.1.1 *Definition*

Various approaches are available to turn images of the seafloor into valuable and ecologically relevant information. Two types of imagery sources are identified: 1) Field-based and close-range photography captured through snorkelling, diver, AUV or ROV and covering up to several square meters and 2) Far-range imagery or remote sensing imagery (UAV, Plane, Satellite) covering an extent of several hundreds of meters to thousands of kilometres. Information extraction techniques used include pixels or object-based classifiers and neural networks.

7.1.2 *Application*

Close-range photography: Underwater photography has been widely used to rapidly capture information from coral reefs and measure relevant parameters (e.g. abundance and composition of benthos) by manually scoring a set of points on a photo (Kohler & Gill 2006). Although traditional photography and image analysis is still widely used, it is very time consuming and observer-dependent. The increasing capability of automated image recognition is now allowing analysis of thousands of images with high confidence (González-Rivero *et al.* 2014a; Beijbom *et al.* 2015; González-Rivero *et al.* 2016; Griffin *et al.* 2017). These automated approaches utilise a variety of techniques including deep learning, Support Vector Machine and Regression classifiers.

Remote sensing applications: Before any information can be extracted from remote sensing imagery, raw images must be corrected for atmospheric and water column effects. Various correction approaches can be effective, but are mostly applied to small reef areas using physics-based approaches (Lesser & Mobley 2007; Dekker *et al.* 2011). To date, corrections have yet to be applied to remotely-sensed imagery of coral reefs over large spatial scales and across a range of water depth and clarity. Physics-based approaches have the added bonus that they can be used to extract reliable estimates of water depth from multispectral high spatial resolution satellite imagery (Hamylton, Hedley & Beaman 2015), where previously this was largely restricted to hyperspectral applications (Stumpf, Holderied & Sinclair 2003; Hedley, Roelfsema & Phinn 2009). Fluid lensing is another approach that is revolutionising the applications of remote sensing data in long-term monitoring (Purkis 2018). Fluid lensing is an experimental technology that uses water-transmitting wavelengths to passively image underwater objects at high resolution by exploiting time-varying optical lensing events caused by surface waves (Chirayath & Earle 2016). Because of the increased spatial resolution imaging sensors, fluid lensing has the potential to deliver centimetre-resolution data at regional scales, unlocking the ability to resolve, for instance, individual coral colonies and perhaps even providing sufficient detail to identify these colonies (Chirayath & Earle 2016).

Extraction of thematic, benthic or geomorphic information has been achieved based on individual pixels or on groups of pixels represented by objects (Hedley *et al.* 2016). Pixel-based approaches are used to derive benthic information from moderate (Capolsini *et al.* 2003) to high spatial resolution imagery (Andréfouët *et al.* 2003; Andréfouët 2008; Hamylton 2017). Recently, object-based classifiers have been used increasingly (Hedley *et al.* 2016) in coral reef environments in combination with multispectral high spatial resolution imagery (Saul & Purkis 2015; Wahidin *et al.* 2015), or with hyperspectral high spatial resolution imagery (Zhang *et al.* 2013). Processing capability has improved, allowing automated assessment of changes in benthic composition. Until recently, this level of ecological information has required manual digitisation of high spatial resolution RGB imagery (Scopélitis *et al.* 2011), or pixel-based approaches using moderate spatial resolution multispectral imagery (Knudby *et al.* 2010) and recently also from an object-based approach (Saul & Purkis 2015; Roelfsema *et al.* 2018).

7.1.3 *Recent developments*

Close-range photography: The application of machine learning and image recognition to identify organisms from benthic imagery can be challenging for a number of reasons, including: 1) Phenotypic plasticity driven by environmental conditions leading to large variability in the form and appearance a single species; 2) Patchiness of clonal organisms (ill-defined edges), which presents a challenge of boundary detection in certain groups (e.g. algae); 3) taxonomic definition of labels, where functional groups can be composed of a large number of species and morphologies (e.g. algae in the Reef are known to comprise more than 600 species); 4) Different requirements of resolution and scale to detect patterns among taxonomic or functional groups (e.g. hard corals and algae). For these reasons, pre-defining the image attributes to feed machine learning algorithms has posed some barriers to the full applications of automated image annotations in benthic imagery (González-Rivero *et al.* 2016). However, deep learning shows promise as a more novel and organic framework for automated image annotation, where the visual attributes of images are defined by the machine as it learns from the dataset. For this reason, deep learning has proved the most effective method for automated image annotation (LeCun, Bengio & Hinton 2015), and has already been implemented in existing online image processing services (e.g. CoralNet www.coralnet.ucsd.edu and BenthoBox https://www.aims.gov.au/advanced-observation-technologies/image-analysis). Currently, deep learning has the capacity to estimate the abundance of broad functional groups of benthos (e.g. morphological and taxonomic definitions) and key species from benthic imagery with an estimation error below five per cent (Gonzalez-Rivero, unpublished). Further developments for integrating different learning models and sensor data is also providing promise for expanding the capabilities of automated image annotation in coral reef monitoring (Treibitz *et al.* 2015; Chennu *et al.* 2017; Szegedy *et al.* 2017; Zoph *et al.* 2017).

Remote sensing: An ongoing challenge in the marine environment is that only a few techniques have been proven to produce benthic information over large spatial scales such as the Reef. This is mostly likely due to the dynamic water column over the submerged seafloor that changes in depth and composition through currents and tides (Dekker *et al.* 2011; Zoffoli, Frouin & Kampel 2014), the need for correcting for sea surface roughness (Kay, Hedley & Lavender 2009) and the lack of a complete and high-resolution coverage at the right time in the tidal cycle (Asner, Martin & Mascaro 2017). New approaches combining physical attributes (e.g. depth, reef slope, consolidation, significant wave height) and seamless mosaics of multispectral moderate resolution satellite imagery with object-based analysis and ecologically-driven rule-sets have been used to create geomorphic and benthic maps of entire reefs (Roelfsema *et al.* 2018). This study demonstrated that there is now an ability to correct imagery for large reef extent and derive water depth (EOMAP 2016). Current increases in the quantity of imagery, accessibility of imagery and spectral and spatial resolution require higher levels of processing power. Open-source cloud processing is commonly applied in terrestrial environments (Wulder *et al.* 2012; Gorelick *et al.* 2017; Hird *et al.* 2017; Murray *et al.* 2017) and is now implemented for wetlands (Murray *et al.* 2012), so should also be available for marine habitat mapping.

7.2 Tri-dimensional Reconstructions:

7.2.1 *Definition:*

Structurally complex habitats support a larger number of species than less complex habitats provide by (Tews *et al.* 2004). This relationship occurs because the three-dimensional (3D) complexity of a habitat increases the availability of refuges and barriers that fragment the living space, resulting in more heterogeneous assemblages of reef-associated organisms (Sebens 1991). These multiple scales of structure lead to more complex coral reefs hosting a greater diversity, abundance and biomass of species (Jones & Syms 1998; Graham & Nash 2013). Due to the current and predicted decline in coral reef structural complexity and its consequences to the ecosystem functioning (Wild *et al.* 2011; Rogers, Blanchard & Mumby 2014; Alvarez-Filip *et al.* 2015; Bozec, Alvarez-Filip & Mumby 2015; Harborne *et al.* 2017), maintaining structurally complex reefs is considered a key management objective (Jones *et al.* 2004; Graham & Nash 2013; Anthony *et al.* 2015). However, methods for accurately and rapidly quantifying the multiple attributes of reef structural complexity are not widely available, or are limited by methodological constraints (de Boer 1978; Rilov *et al.* 2007; Harborne *et al.* 2011).

Advances in pattern recognition from images can go beyond classification by expanding into the reconstruction of 3D models of substrates (e.g. fine-scale bathymetrical representations). Photogrammetry has been a technique widely used in remote sensing imagery to recovery exact position of surface points, scaling and mosaicking images, and creating three-dimensional reconstructions from overlapping 2D images (Johnson-Roberson *et al.* 2010). In principle, photogrammetric analyses are based on deriving the locations in 3D space of points in a sequence of images using triangulation of sequential or paired images. Widely used in topographic mapping, deriving the structure of objects and terrains using photogrammetry is now being increasingly implemented in underwater surveys. Consequently, tri-dimensional reconstructions can quantify reef structural complexity in a non-invasive, fast and reliable way (Figueira *et al.* 2015a; Ferrari *et al.* 2016b; Pizarro *et al.* 2017). Furthermore, by creating repeatable models of the reef structure, photogrammetric analyses on images can also recreate scaled and georeferenced mosaics of images and compare 3D models over time.

7.2.2 *Applications:*

Compared to traditional approaches for high resolution bathymetrical surveys (e.g. laser bathymetry, such as LiDAR), more recently developed underwater photogrammetric techniques offer a simpler, faster, and more affordable alternative for high resolution topographic reconstruction (Westoby *et al.* 2012; Burns *et al.* 2015; Ferrari *et al.* 2016b). Furthermore, image-based reconstruction provides two elements associated with structural complexity: (1) the structural attributes *per se*, like LiDAR, but also (2) access to the spectral attributes of the imagery, which enables more detailed ecosystem observations, such as compositional structure and seasonal or phrenological changes (e.g. Dandois & Ellis 2013). Traditionally, techniques of underwater three-dimensional reconstructions have primarily been utilised for habitat classification, as well as archaeological surveys (Johnson-Roberson *et al.* 2010; Friedman *et al.* 2012; McCarthy & Benjamin 2014), but photogrammetry from underwater footage has recently been used to address ecological questions (Agudo-Adriani *et al.* 2016; Bennecke *et al.* 2016; Burns *et al.* 2016). On coral reefs, applications of tri-dimensional reconstructions have increased rapidly over the past few years for applications including: 1) large-scale assessments of structural complexity (Friedman *et al.* 2012; Figueira *et al.* 2015a; Leon *et al.* 2015b; Ferrari *et al.* 2016a; Storlazzi *et al.* 2016; Young *et al.* 2017); 2) monitoring of demographic data such as growth, erosion, morphometry (Bythell, Pan & Lee 2001; Ferrari *et al.* 2017); 3) Habitat selection and distribution (González-Rivero *et al.* 2017); and 4) mapping (Ventura *et al.* 2016; Casella *et al.* 2017; Palma *et al.* 2017).

7.2.3 *Recent developments*

In recent years, underwater photogrammetry has been widely used to recreate the 3D structure of coral reefs at multiple scales, and their importance for understanding the trends and status of key ecological attributes is continuously increasing (Friedman, Pizarro & Williams 2010; Agudo-Adriani *et al.* 2016; Bennecke *et al.* 2016; Ferrari *et al.* 2016a; González-Rivero *et al.* 2017). Such advances have been made possible because of the commercialisation and standardisation of software platforms that enable reliable, repeatable, cheap, and easy-to-use 3D reconstructions that are adaptable to specific needs (Figueira *et al.* 2015a; Ferrari *et al.* 2016a). Importantly, while the technological knowledge required to create 3D image mosaics is relatively low because of the commercial software available, their use for measuring and interpreting ecological metrics requires certain basic programming knowledge.

8.0 Recommendations

Having outlined the current state of technologies and their applications and limitations, recommendations on the suitability of technologies for measuring each parameter at different spatial scales were formulated based on expert opinion (Supplementary Material, SM1). The contribution of technologies is summarised here based on the integration of platforms, processing tools and sensors to aid traditional monitoring by scaling and speeding up observations and analysis across different spatial scales (Figure 1): in-depth (100s of meters representing a section of the reef); intermediate (1000s of metres representing an entire reef); and broad-scale (1000s of kilometres representing the Marine Park). Given that technology is rapidly evolving, recommendations were sub-divided into technologies available for immediate (Table 7) and near-future (2-5 years; Table 8) deployment based on their operational maturity.

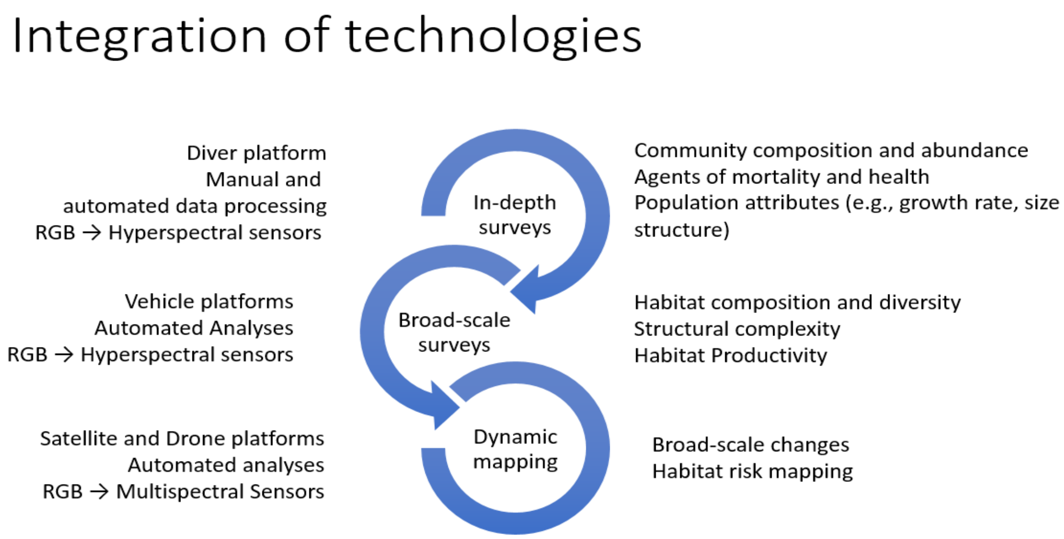

Figure 2. Schematic diagram showing the different spatial scales on which technological advances can be implemented and their proposed integration to enable a wider and more detailed understanding of the state and trends of coral reefs in the Great Barrier Reef under the RIMReP framework.

An important conclusion derived from this review is that current technological tools cannot be applied to the entire suit of candidate parameters (Table 2), but can enhance the capacity to assess a subset of parameters. Technological solutions can aid monitoring by increasing monitoring coverage and data analysis within a selection of parameters, and their integration with traditional expert observations is key to ensuring the success of the RIMReP objectives. The use of automated technologies to extract ecological information from reef surveys can be limited to a number of parameters. For example, measuring the abundance and composition of benthic communities is currently measured by existing long-term monitoring programs (e.g. the Australian Institufe of Marine Science monitoring programs) at high taxonomic resolution (e.g. species or genera for benthic and pelagic groups). Automated image analyses for close-range photography, on the other hand, can be limited to functional groups or key genera for benthic groups and, currently, there is not a robust method in place to automatically estimate abundance of fish species. As such, we recommend parameters associated with fish communities, diseases, coral juveniles and other small organisms (e.g. *Drupella* spp) to be measured by expert divers or snorkelers (Table 7). However, the development, adaptation and testing of wide-spectrum imaging sensors (e.g. Hyper- or Multi- spectral) or integrating processing approaches (3D reconstructions and Automated Image annotation) suggests that the applications of automated analyses can soon be expanded to cover a wider range of parameters, in particular benthic composition and detection of juveniles. Therefore, it is important to consider the constant evolution of technologies as demand drives their development (Table 8).

While technologies can be limited in the application to selection of monitoring parameters, another advantage of technologies emerges when evaluating their applications across "larger-than-usual" coverage. Traditional methodological approaches in monitoring by divers/snorkelers are often limited to a few hundreds of meters within a reef, and typically within shallow/safe environments. Automated survey platforms (AUVs, UAVs, Satellites) can rapidly expand the spatial coverage of traditional monitoring by expanding the depth range and spatial extent surveyed. These platforms allow the integration of highly advanced sensors (actives and passive), which, combined with automated data processing (image analyses and 3D reconstructions), can generate detailed information on the status and trends of coral reefs at spatial not previously achievable (e.g. whole reef, Mesophotic reefs). At these scales, the amount of data generated quickly surpasses the capacity of expert manual labour to measure ecological parameters. However, automated image processing provides a reliable method for fast processing of detailed, ecologically-relevant information, beyond simple metrics such as coral cover (Table 7). Therefore, at these scales (intermediate and broad-scale), a full implementation of technologies can automate the entire process from data collection to reporting is plausible and advised, at the expense trying to cover a greater range of parameters (SM1, Tables 10 and 11).

Table 7. Summary recommendations of technological tools which currently are operationally available and capable of aiding coral reefs monitoring within three main spatial scale categories: a) in-depth (site within a reef), b) intermediate (reef scale) and c) broad-scale (whole Reef). Technologies are aggregated in sensors, platforms and processing tools, and their integration is considered for each of the outputs or ecological parameters on which they can contribute to monitoring

Technology	In-Depth surveys	Intermediate surveys	Broad-scale surveys
Sensors	• RGB	• RGB + Multispectral	• Multispectral
Platforms	• Divers / Snorkelers • Digital Cameras • Autonomous vehicles (at Depth)	• Underwater vehicles (DPV, AUV) • Airborne drones	• Airborne drones • Satellites
Processing Tools	• Automated Image Annotation • 3D reconstructions • Manual observations	• Automated Image Annotation • 3D reconstructions	• Automated Image Annotation (object-based)

Outputs	• Detailed community composition (fish and benthos) • Agents of Mortality and health • Demographic attributes	• Functional community composition (benthos) • Structural complexity	• Habitat mapping at various information scales

Efficiency in data analyses, reporting and coverage are the most immediate and obvious advantages of the deployment of technologies for coral reef monitoring. However, the capacity to monitor previously unattained metrics in broad-scale monitoring programs is also highly valuable. One example of this is the use of 3D reconstructions, which are non-invasive and fast processing tools that use overlapping imagery (mainly RGB) to recreate the architectural structure of a coral reef. Measurements of key resilience attributes such as growth rate and rugosity can be easily quantified from 3D images and incorporated into monitoring programs to fill essential knowledge gaps. While these metrics can be measured without the use of novel technologies (e.g. chain-tape method for rugosity and buoyant weight for coral growth), their use is restricted to more academic exercises at a much restricted temporal and spatial scale because of the effort required to measure them in the field. 3D reconstructions offer the possibility of reliably and repeatable measuring of structural complexity and growth rates without significant additional effort in the field. Because 3D reconstructions are derived from imagery, they can be applied across all spatial scales (in-depth, intermediate and broad-scale) using a range of platforms (e.g. AUVs), adding a previously unattained dimension of ecological measurements in coral reef monitoring (Tables 7 and 8). A second example for advancing or extending the applications of ecological monitoring is the development of dynamic, region-wide habitat mapping derived from deployment of large-scale technologies. Currently, advances in data processing from remote sensing tools (e.g. Satellites, Droves, etc.) provide unique opportunities to extract habitat attributes of coral reef across large regions, such as the entire Marine Park (Table 7). As processing power and resolution continues to increase, recent advances suggest that high temporal resolution environmental data captured from satellites can add a dynamic dimension to habitat mapping, allowing attribution of the cause of ecological changes across hundreds to thousands of kilometres (e.g. bleaching impact, habitat loss).

Table 8. Summary recommendations of technological tools which have the potential to be available and operationally mature in a near-future (2-5 years) for their implementation in coral reefs monitoring. Technologies are grouped within three main spatial scale categories: a) in-depth (site within a reef), b) intermediate (reef scale) and c) broad-scale (whole Reef). Technologies are aggregated in sensors, platforms and processing tools, and their integration is considered for each of the outputs or ecological parameters on which they can contribute to monitoring

Technology	In-depth surveys	Intermediate surveys	Broad-scale surveys
Sensors	• Multi/Hyper-spectral	• Hyperspectral • Active Sensors	• Multispectral (High temporal resolution)
Platforms	• Divers / Snorkelers • Stereo-photography	• Underwater vehicles (AUV)	• Airborne drones • Satellites

Processing Tools	• Integrated automated image annotation aided by photogrammetry • Manual assessments	• Integrated automated image annotation aided by photogrammetry	• On-line and/or On-board automated image classification
Outputs	• Detailed community composition • Agents of Mortality and health • Demographic attributes	• Functional community composition (benthos) • Structural complexity	• Dynamic Habitat Mapping • Large-extent change detection

8.1 Moving forward in the implementation of technologies to fit objectives within the RIMReP framework

Implementing technological tools within coral reef monitoring requires a careful examination of the objectives and applications of each tool, as well as the overall view of how they integrate within the broader objectives of the program. Based on the reviewed technologies and recommendations, a careful planning and design should be considered in order to guarantee a seamless implementation of technologies for RIMReP. A few examples to consider are:

- **The various scales (e.g. In-depth, Intermediate and Broad scales)** can be multi-beneficial to the needs of those planning, processing, analysing and reporting on the data collected. Therefore, integrating these technologies requires an understanding of what is required from the data collected at each scale as well as across scales, as well as how the data could contribute to other RIMReP objectives.
- **Integration within survey scales:** Collecting fish parameters at intermediate scales will provide understanding of composition of fish communities, but explaining the observed patterns often also requires information at the same scale on the benthic composition and rugosity. Instead of gathering new datasets, RIMReP should ensure that data are aligned beneficially across monitoring objectives and components.
- **Integration among survey scales:** Collecting benthic information (e.g. crown-of-thorns starfish) at broad scales can be mutually beneficial if the data provides information that can be used to validate benthic mapping at broad scales. This also applies to the opposite case; benthic maps can help plan surveys for crown-of-thorns starfish control programs.
- **Communication to support integration:** Integration can only take place successfully if there is clear communication and open data sharing agreements between those involved in planning, collecting and analysing specific parameters. Practically, new RIMReP approaches could be integrated within and between scales, however integration could fail if there is no communication or data sharing agreement in place. In addition, there is a need for a centralised repository where data can be accessed in combination with metadata explaining the data sets and conditions of use.
- **Data management:** A system needs to be set in place as part of RIMReP. We envisage a user interface where the data for the different monitoring parameters can be accessed by those who require it. Furthermore, as technology is incorporated, data volume is only expected to increase considerably. Therefore, data management should be carefully planned to accommodate much larger requirements for storage and accessibility.
- **Expertise**: Technology is not a replacement for human labour but rather the means to scale up observations. Hence it is crucial that operators working with the new technologies are evolving their knowledge and expertise to the technological

developments and implementation, and that also those who analyse the data at different scales are aware of the strength and weakness of the data sets collected. The success of the combined integrated approaches depends not just on the technology but the associated human capacity to deploy and manage the technology.

9.0 Supplementary Material

9.1 SM1. Capability Matrices

Table 9. Capability metrics for implementing technologies, aggregated in terms of platforms, processing tools and sensors, at small spatial scales, here referred as the in-depth scale. Note that visual assessments by trained divers (i.e. unaided by technology) can be used for monitoring of all listed RIMReP candidate parameters.

Color code	Classification
(green)	Highly Recommended
(yellow-green)	Recommended
(orange)	Potential
(grey)	Uncertain
(red)	Not Feasible

Scale	**In-depth (site)**		
Spatial resolution	< 1 mm		
Platform	Diver		
Processing	Automated Image Classification		3D Reconstruction
Sensor	RGB	Hyper-spectral	RGB

Category	**RIMReP Candidate Parameter**	RGB (Automated Image Classification)	Hyper-spectral (Automated Image Classification)	RGB (3D Reconstruction)
Hard Corals	Total Abundance	Highly Recommended	Recommended	Not Feasible
	Abundance and Composition by Genus	Recommended	Recommended	Not Feasible
	Abundance and Composition by Functional Groups	Highly Recommended	Recommended	Not Feasible
	Abundance of Juveniles	Potential	Potential	Not Feasible
	Size Structure	Recommended	Potential	Not Feasible
Soft Corals	Total Abundance	Highly Recommended	Recommended	Not Feasible
	Abundance and Composition by Genus	Potential	Potential	Not Feasible
	Abundance and Composition by Functional Groups	Potential	Recommended	Not Feasible
	Abundance of Juveniles	Potential	Potential	Not Feasible
	Size Structure	Recommended	Potential	Not Feasible
Algae	Total Abundance	Highly Recommended	Recommended	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Uncertain	Not Feasible
	Abundance and Composition by Growth Form	Recommended	Recommended	Not Feasible
Other Benthos	Abundance of crown-of-thorns starfish	Highly Recommended	Recommended	Not Feasible
	Abundance of *Drupella* spp	Potential	Not Feasible	Not Feasible
	Size Structure of crown-of-thorns starfish	Potential	Potential	Not Feasible
Agents of Health	Partial mortality	Potential	Uncertain	Not Feasible
	Abundance of Disease	Potential	Uncertain	Not Feasible
	Severity of Coral Bleaching	Recommended	Uncertain	Not Feasible
Fish	Total Abundance	Potential	Potential	Not Feasible
	Abundance and Composition by Genus	Potential	Potential	Not Feasible
	Abundance and Composition by Functional Groups	Potential	Potential	Not Feasible
	Abundance of Juveniles	Potential	Potential	Not Feasible
	Size Structure	Potential	Potential	Not Feasible
Ecosystem	Structural Complexity	Not Feasible	Not Feasible	Highly Recommended
	Growth rates	Not Feasible	Not Feasible	Highly Recommended

Table 10. Capability metrics for implementing technologies, aggregated in terms of platforms, processing tools and sensors, at reef spatial scales, here referred as the intermediate scale

Color code	Classification
Green	Highly Recommended
Yellow-green	Recommended
Orange	Potential
Grey	Uncertain
Red	Not Feasible

	Scale	**Broad (reef)**					
	Spatial resolution	1 - 50 mm					
	Platform	Diver Propulsion Vehicles			Autonomous Underwater Vehicles		
	Processing	Automated Image Classification		3D Reconstruction	Automated Image Classification		3D Reconstruction
Category	**RIMReP Candidate Parameter** / **Sensor**	RGB	Hyper-spectral	RGB	RGB	Hyper-spectral	RGB
Hard Corals	Total Abundance	Highly Recommended	Highly Recommended	Not Feasible	Highly Recommended	Potential	Not Feasible
	Abundance and Composition by Genus	Recommended	Recommended	Not Feasible	Potential	Potential	Not Feasible
	Abundance and Composition by Functional Groups	Highly Recommended	Highly Recommended	Not Feasible	Highly Recommended	Potential	Not Feasible
	Abundance of Juveniles	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structure	Recommended	Recommended	Not Feasible	Potential	Potential	Not Feasible
Soft Corals	Total Abundance	Highly Recommended	Highly Recommended	Not Feasible	Potential	Potential	Not Feasible
	Abundance and Composition by Genus	Potential	Potential	Not Feasible	Potential	Potential	Not Feasible
	Abundance and Composition by Functional Groups	Potential	Potential	Not Feasible	Recommended	Potential	Not Feasible
	Abundance of Juveniles	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structure	Recommended	Recommended	Not Feasible	Potential	Potential	Not Feasible
Algae	Total Abundance	Highly Recommended	Highly Recommended	Not Feasible	Highly Recommended	Potential	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Abundance and Composition by Growth Form	Highly Recommended	Highly Recommended	Not Feasible	Potential	Potential	Not Feasible
Other Benthos	Abundance of crown-of-thorns starfish	Potential	Potential	Not Feasible	Highly Recommended	Potential	Not Feasible
	Abundance of *Drupella* spp	Potential	Potential	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structure of crown-of-thorns starfish	Potential	Potential	Not Feasible	Potential	Potential	Not Feasible
Agents of Health	Partial mortality	Uncertain	Uncertain	Not Feasible	Uncertain	Uncertain	Not Feasible
	Abundance of Disease	Uncertain	Uncertain	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Severity of Coral Bleaching	Recommended	Recommended	Not Feasible	Recommended	Potential	Not Feasible
Fish	Total Abundance	Not Feasible	Not Feasible	Not Feasible	Uncertain	Not Feasible	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Not Feasible	Not Feasible	Uncertain	Not Feasible	Not Feasible
	Abundance and Composition by Functional Groups	Not Feasible	Not Feasible	Not Feasible	Uncertain	Not Feasible	Not Feasible
	Abundance of Juveniles	Not Feasible	Not Feasible	Not Feasible	Uncertain	Not Feasible	Not Feasible
	Size Structure	Not Feasible	Not Feasible	Not Feasible	Uncertain	Not Feasible	Not Feasible
Ecosystem	Structural Complexity	Not Feasible	Uncertain	Highly Recommended	Not Feasible	Not Feasible	Highly Recommended
	Growth rates	Not Feasible	Uncertain	Recommended	Not Feasible	Not Feasible	Not Feasible

Table 11. Capability metrics for implementing technologies, aggregated in terms of platforms, processing tools and sensors, at regional spatial scales, here referred as the broad-scale

Color code	Classification
Green	Highly Recommended
Yellow-green	Recommended
Orange	Potential
Grey	Uncertain
Red	Not Feasible

Scale		Broad-scale (Reef)									
Spatial resolution		Very High (1-100 cm)			High (1- 5 m)				Medium (5-50 m)	Low (> 50m)	
Platform		Drones (100 m- 1000s m)									
		Planes (1 km - 100s km)									
					Satellites (1 km - 1000s km)						
Processing		Automated Image Classification									
Sensor		RGB	Multi-spectral	Hyper-spectral	RGB	Multi-spectral	Hyper-spectral	Multi-spectral	Hyper-spectral	Multi-spectral	Hyper-spectral
Category	**RIMReP Candidate Parameter**										
Hard Corals	Total Abundance	Recommended	Recommended	Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Recommended	Not Feasible	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Not Feasible	Recommended	Not Feasible	Not Feasible	Recommended	Not Feasible	Recommended	Not Feasible	Not Feasible
	Abundance and Composition by Functional Groups	Potential	Potential	Potential	Recommended	Recommended	Recommended	Recommended	Recommended	Not Feasible	Not Feasible
	Abundance of Juveniles	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structure	Potential	Potential	Potential	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
Soft Corals	Total Abundance	Recommended	Recommended	Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Recommended	Not Feasible	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Not Feasible	Recommended	Not Feasible	Not Feasible	Recommended	Not Feasible	Recommended	Not Feasible	Not Feasible
	Abundance and Composition by Functional Groups	Potential	Potential	Potential	Recommended	Recommended	Recommended	Recommended	Recommended	Not Feasible	Not Feasible
	Abundance of Juveniles	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structure	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
Algae	Total Abundance	Recommended	Recommended	Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Highly Recommended	Not Feasible	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Not Feasible	Recommended	Not Feasible	Not Feasible	Recommended	Not Feasible	Recommended	Not Feasible	Not Feasible
	Abundance and Composition by Growth Form	Potential	Potential	Potential	Recommended	Recommended	Recommended	Recommended	Recommended	Not Feasible	Not Feasible
Other Benthos	Abundance of crown-of-thorns starfish	Potential	Potential	Potential	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Abundance of Drupella spp	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structutre of crown-of-thorns starfish	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
Agents of Health	Partial mortality	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Abundance of Disease	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Severity of Coral Bleaching	Potential	Potential	Potential	Potential	Potential	Potential	Potential	Potential	Not Feasible	Not Feasible
Fish	Total Abundance	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Abundance and Composition by Genus	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Abundance and Composition by Functional Groups	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Abundance of Juveniles	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Size Structure	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible
Ecosystem	Structural Complexity	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Not Feasible	Not Feasible	Not Feasible	Not Feasible
	Growth rates	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible	Not Feasible

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