Supporting Material

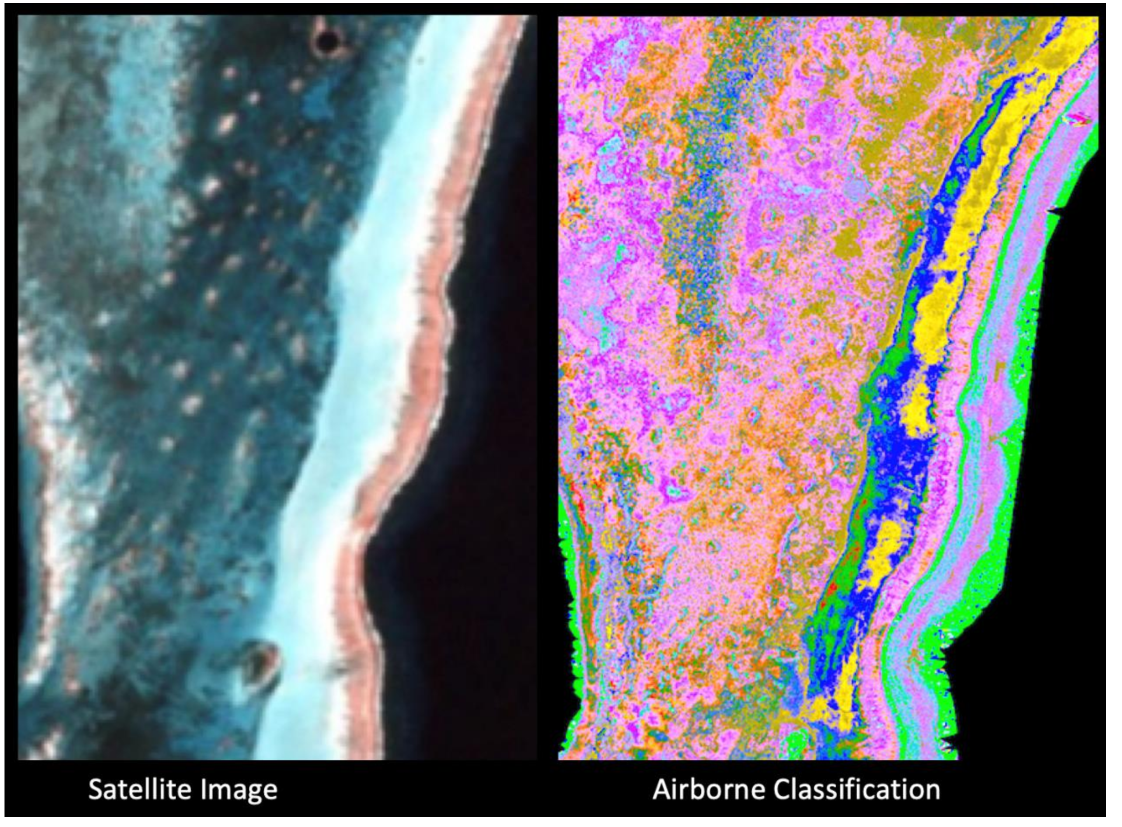

Figure S1. Remote sensing technologies provides an efficient way to monitor reefs with standardized measures allowing tracking of changes in a dynamic environment. The left panel is a three-channel (RGB) multispectral Planet Dove satellite image at 3.7 m resolution of a region of Lighthouse Reef Atoll, Belize. The right panel is a hyperspectral image at 2 m resolution by the Carnegie Airborne Observatory of the same region of reef, classifying data into 15 different benthic classes. Classified images such as these are useful in comparing reefs before and after environmental change.

Table S1. Currently available remote sensing technologies and their application to monitoring coral reefs.

Technology/Sensor type	Platform	Example	Application	Physical Parameters Measured	Resolution
Acoustic	AUV, Boat	RoxAnn, SONAR, ADPs	Fish presence/distribution; General reef habitat categories & distribution (> 50 m depth); Reef geomorphology (> 50 m depth); Structural complexity; Water properties	Bathymetry (> 50 m); Water velocity; Wind energy	1 – > 100 m
Hyperspectral	Aircraft, Satellite	AVIRIS, CAO, CASI, Hyperion	Accessibility; Coastal land use & change; Coral bleaching; Coral mortality; Reef geomorphology (< 20 m depth); Reef habitat categories & distribution (< 20 m depth); Structural complexity; Water properties (< 20 m)	Algal blooms; Bathymetry (< 20 m); Chlorophyll a concentration; Cloud cover; Light attenuation; PAR; Turbidity; Wind energy	0.05 – 30m
Laser	Aircraft, Boat	LADS, LiDAR	Coastal land use & change; Reef geomorphology (0 – 50 m depth); Reef habitat categories & distribution (0 – 50m depth); Structural complexity; Water properties (0 – 50m)	Bathymetry (0 – 50m); Wind energy	1 – 5m
Multispectral	Aircraft, Satellite	Planet Dove and Skysat (high res), Ikonos (high res), Landsat (med res), Quickbird (high res), MODIS (low res), SeaWiFS (low res)	Accessibility; Coastal land use & change (high & med res only); Coral bleaching; Reef geomorphology (high & med res only, < 20 m depth); Reef habitat categories & distribution (high & med res only, < 20 m depth); Structural complexity; Water properties	Algal blooms; Bathymetry (< 20 m); Coastal circulation (feature tracking); Chlorophyll a concentration; Cloud cover; Light attenuation; Ocean circulation; PAR; SST (MODIS); Turbidity	0.05 – 30 m
Photography	Aircraft	SLR camera	Accessibility;	Bathymetry	0.05 – 30 m

			Coastal land use & change; Coral bleaching; Reef geomorphology (< 20 m depth); Reef habitat categories & distribution (< 20 m depth); Water properties		
Radar	Ground station, Satellite	TRMM, Quik-SCAT	Water properties	Coastal circulation (feature tracking); Precipitation; Sea level/height; Sea surface roughness; Wind energy	25 m – > 1 km
Microwave	Aircraft	SLFMR	Water properties	Salinity	> 1 km
Thermal/Infrared Radiometer	Aircraft, Satellite	ATSR, GOES, TIRS	Coastal land use & change; Water properties	Cloud cover; Light attenuation; Ocean circulation; PAR; Salinity; Sea surface roughness; SST; Turbidity; UV; Wind energy	> 1 km

ADPs = Acoustic Doppler Profilers, ATSR = Along-Track Scanning Radiometer and Advanced Along-Track Scanning Radiometer, AUV = Autonomous Underwater Vehicle, AVIRIS = Airborne Visible/Infrared Imaging Spectrometer, CASI = Compact Airborne Spectrographic Imager, CAO = Carnegie Airborne Observatory, GOES = Geostationary Operational Environmental Satellite, LADS = Laser Airborne Depth Sounder, LiDAR = Light Detection and Ranging, MODIS = Moderate Resolution Imaging Spectroradiometer, Quik-SCAT = Quick Scatterometer, SeaWiFS = Sea Wide Field-of-view Sensor, SLR = Single Lens Reflex, SONAR = Sound Navigation and Ranging, SLFMR = Scanning Low Frequency Microwave Radiometer, TIRS = Thermal Infrared Sensor, TRMM = Tropical Rainfall Mapping Mission.

Table S2. Criteria considered by restoration practitioners when selecting reefs for coral outplanting, along with our assessment of the ability to apply remote sensing technologies to them. Remote sensing approaches are divided into four types or levels: diver, drone, airborne and satellite where drone covers boat, glider and AUV technologies. The diver-based term is only used when the remote sensing technology needs to be operated by a diver.

Criteria	**Ability to be Remotely Sensed**			**Application**	**Example of application/Case study**
	Platform	**Technology**	**Resolution required for outplanting**		
Coral fragment specific					
Origin of parent colonies	Airborne Drone	High resolution hyperspectral High resolution multispectral Photography	< 0.1 m	The origin of parent colonies can only be tracked by nursery practitioners however remote sensing methods could assist in identifying resilient parent colonies to harvest fragments from.	The application of remote sensing in identifying resilient coral colonies has not yet been demonstrated but is currently underway (C Drury, unpub.).
Condition/size of outplant	No, requires visual inspection				
Disease free	No, requires visual inspection				
Genotypic diversity	No, requires genotyping or knowledge of parent colonies				
Site specific					
Site selection	Airborne Satellite	Hyperspectral Laser Multispectral Photograph	< 30 m	Reef geomorphology and benthic habitat can be assessed to choose suitable reef site for outplanting.	Remote sensing technology has successfully been used to map coral reef geomorphology and benthic habitats at various spatial scales and detail (e.g. Roelfsema et al., 2013) which is useful in determining where to outplant.
Existing wild populations	Airborne Drone	Hyperspectral Laser Multispectral Photograph	< 30 m	Benthic types can provide details of where coral populations are present.	High spatial resolution remote sensing technology allows identification of benthic types with the capability to distinguish reef from adjacent habitat such as seagrass and sand (e.g. Hedley et al., 2016) allowing an identification of where coral populations exist.

Depth	Airborne Drone Satellite	Acoustic Hyperspectral Laser Multispectral Photography	< 40 m	Numerous ways to remotely sense water depth. LiDAR has been used to map depth up to 40 m and acoustic > 100 m depth.	Depth was traditionally obtained by acoustic sensing via boat however this is inaccurate in shallow water. LiDAR technology has been extensively applied to marine and coastal environments, and best in clear water (Gao et al., 2009), thus obtaining depth in both shallow and deep coastal environments is possible.
Water quality	Airborne Satellite	Hyperspectral Multispectral Photography Radiometer Thermal	< 30 m	Radiometer and thermal technologies can provide information on biophysical properties such as salinity. Hyperspectral, multispectral and photography can provide information on algal blooms and turbidity/sedimentation.	Remote sensing techniques are often used to monitor water quality, for example, river plumes and turbidity on the Great Barrier Reef (Devlin et al., 2015).
Size of the area	Airborne Satellite	Acoustic Hyperspectral Laser Multispectral Photography	< 50 m	Size of outplanting area can be inferred from general reef distribution and geomorphology.	In comparison to estimation by local managers, high resolution satellite imagery more accurately identified coral reef habitat area and connectivity (Selgrath et al., 2016) and thus remotely sensed maps provide the percentage cover of space available to transplant corals.
Bottom/substrate type and stability	Airborne Drone Satellite	Acoustic Hyperspectral Laser Multispectral Photography	0.05 – 50 m	Benthic habitat maps provide details on substrate type, with repeated measurements providing information on stability.	12 reef bottom-types, including fleshy algae, turf algae, hermatypic coral and seagrass, were found to possess characteristic spectral reflectance features ubiquitous through the world (Hochberg et al., 2003) and thus bottom-type can be easily distinguished by remote sensing.
Historical presence of coral species	No, requires practitioner knowledge				
Human activity and impact	Airborne Satellite	Hyperspectral Laser Multispectral Photography Radiometer	< 1 km	Maps provide information on coastal land use and change, distance to settlements and other human impact such as dynamite fishing.	The impact of three reef stressors; development, gas flaring and heavily lit fishing boat activity, were estimated through creating a global dataset of the distribution of night time lights and resulting light proximity index from satellite data (Aubrecht et al., 2007). Remote sensing can detect human impact on reefs through many pathways.
Protection status	Airborne Satellite	Hyperspectral Multispectral	< 1 km	With knowledge of delineations, protection zones can be mapped.	Remote sensing can create maps to visualise marine protected areas and can also help determine what

		Photography			areas are worth protecting. For example, Landsat imagery was used to create coastal habitat maps which were then used to develop a trans-frontier conservation area along the Tanzania/Mozambique coastline (Ferreira et al 2012).
Far from land-based pollution	Airborne Satellite	Hyperspectral Laser Multispectral Photography Radiometer	< 1 km	Maps provide information on coastal land use and change and distance to settlements. Water quality can be determined from various physical parameters measured by sensors.	Land-based pollution affects water quality with resulting impacts on reef health. A river plume risk map was created for the Great Barrier Reef through mapping river plumes with MODIS data (Petus et al., 2016).
How much to outplant/space to expand	Airborne Satellite	Hyperspectral Laser Multispectral Photography	< 50 m	Benthic habitat maps provide total available outplanting area.	Determination of the extent of benthic habitat is possible for spectrally unique types. For example, using nine sets of high-resolution satellite data to estimate the percentage cover of seagrass, a time series of seagrass dynamics was able to be derived (Roelfsema et al., 2014).
Number of outplanting sites	No, but could be optimized by using remotely sensed maps to provide total area available to outplant				
Disease absence/presence	Currently requires assessment by diver. Healthy and diseases corals could possess spectrally unique signatures. The technology is being developed; discrimination between healthy and unhealthy coral assemblages based on spectral information shows potential (Collin and Planes, 2012) .				
Site accessibility	Airborne Drone Satellite	Hyperspectral Laser Multispectral Photography	< 50 m	Accessibility of sites can be assessed through various remote sensing technologies.	Site accessibility can be inferred by distance to land. For example, distance to settlements and markets estimated with satellite data can help to predict fishing pressure on coral reefs (Rowlands et al., 2012).
Reef connectivity	Satellite	Hyperspectral Laser Multispectral Photography	< 1 km	This can be inferred by the distribution of benthic habitat/reef geomorphology as well as currents.	By integrating satellite observations, ship-borne sensing and particle dispersion models, predicted reef connectivity was very consistent with connectivity estimated through genetic population data of the anemonefish *Amphiprion bicinctus* (Raitsos et al., 2017).
Sedimentation loads	Airborne Satellite	Hyperspectral Multispectral Radiometer	< 1 km	Can be inferred by turbidity.	Using freely available satellite data, the influence of land-use change on water turbidity, quality and

					coral cover was investigated in Fiji (Brown et al., 2017).
Spurs and grooves to reduce predator migration	Airborne Satellite	Hyperspectral Multispectral Laser Photography	< 1 m	Structural complexity and benthic habitat distribution provide information on structures that can deter predators.	LiDAR derived rugosity of 4 m resolution was highly correlated with *in-situ* rugosity and a good predictor of fish biomass (Wedding et al., 2008) thus remote sensing technology is a good identifier of structures that reduce predator migration.
Abiotic factors					
Temperature and fluctuations	Airborne Satellite	Multispectral Radiometer Thermal	< 1 km	Radiometer, thermal and some multispectral technologies provide SST.	The measurement of SST has been long established and continues to increase in accuracy and resolution. Using satellite data, the probability of SSTs likely to cause mass coral bleaching can be predicted up to 4 months in advance (Liu et al., 2018).
Sufficient light for species and its productivity	Airborne Satellite	Hyperspectral Multispectral Radiometer	< 30 m	PAR can be detected by multiple sensors. Can also be inferred by bathymetry and calculation of light attenuation.	To help increase the accuracy of satellite-based bleaching products, temperature and light were combined to create the light stress damage algorithm which more accurately predicts the severity of bleaching events (Skirving et al., 2017).
Flow regime/wave exposure	Airborne Satellite	Acoustic Altimeter Laser Radar Radiometer Scatterometer	< 1 km	Wind energy, speed and currents are provided by many remote sensing technologies.	By merging altimeter derived sea surface velocities with sea surface temperature data, the estimate of global surface currents was improved (Rio and Santoleri, 2018).
Biotic factors					
Space competitors such as encrusting sponges	Drone	High resolution hyperspectral High resolution multispectral Photography	< 1 m	Requires high resolution technology to detect and classify very specific benthic types.	For example, a diver operated hyperspectral imaging system can provide percentage cover of benthic types including sponges, anemone and corals up to 1-2 cm (Chennu et al., 2017).
Predator abundance (particularly corallivorous snails,	No, requires diver to survey, however could be inferred if a connection between the predator and habitat type/extent exists				

fireworms and territorial damselfish					
Macroalgal cover	Airborne Drone	High resolution hyperspectral High resolution multispectral Photography	0.05 – 30 m	Determined through benthic habitat classification.	The classification of macroalgal benthic habitat has been well established. A study showed that three macroalgal species were able to be distinguished through hyperspectral sensing, and the ability to identify them was not affected by high concentrations of CDOM (Vahtmäe et al., 2006).
CCA cover	Drone	High resolution hyperspectral Photography	< 1 m	Hyperspectral technology still needs to be developed to more accurately distinguish CCA from other benthic types.	The percentage cover of crustose coralline algae was able to be determined using high resolution hyperspectral imaging with up to 65% accuracy (Leiper et al., 2014) however differentiating different species of coralline algae may be difficult as they have highly similar spectral characteristics (Mogstad and Johnsen, 2017).
Presence of *diadema*	No, requires diver to survey, however could be inferred by parameters such as reef complexity. Furthermore, sea urchin acoustics have been characterized for a temperate and tropical sea urchin (Soars et al., 2016) and therefore acoustic sensing could be further developed to document sea urchin abundance.				
Presence of parrot/surgeon fish	No, requires diver to survey, however could be inferred by parameters such as reef complexity. Furthermore, acoustic sensing could be developed to document fish presence and abundance.				

CCA = Crustose Coralline Algae, CDOM = coloured dissolved organic matter, LiDAR = Light Detection and Ranging, PAR = Photosynthetically active radiation, SST = Sea surface temperature

References

Aubrecht C, Elvidge CD, Longcore T, Rich C, Safran J, Strong AE, Eakin CM, Baugh KE, Tuttle BT, Howard AT and Erwin EH. 2008. A global inventory of coral reef stressors based on satellite observed nighttime lights. *Geocarto International* **23**: 467–479.

Brown CJ, Jupiter SD, Albert S, Klein CJ, Mangubhai S, Maina JM, Mumby P, Olley J, Steward-Koster B, Tulloch V and Wenger A. 2017. Tracing the influence of land-use change on water quality and coral reefs using a Bayesian model. *Scientific Reports* **7**: 4740.

Chennu A, Färber P, De'ath G, de Beer D and Fabricius KE. 2017. A diver-operated hyperspectral imaging and topographic surveying system for automated mapping of benthic habitats. *Scientific Reports* **7**: 7122.

Collin A and Planes S. 2012. Enhancing coral health detection using spectral diversity indices from WoldView-2 imagery and machine learners. *Remote Sensing* **4**: 3244–3264.

Devlin MJ, Petus C, Da Silva E, Tracey D, Wolff NH, Waterhouse J and Brodie J. 2015. Water quality and river plume monitoring in the Great Barrier Reef: An overview of methods based on ocean colour satellite data. *Remote Sensing* **7**: 12909–12941.

Ferreira MA, Andrade F, Mendes RN and Paula J. 2012. Use of satellite remote sensing for coastal conservation in the Eastern African Coast: advantages and shortcomings, *European Journal of Remote Sensing* **45**: 293–304.

Gao J. 2009. Bathymetric mapping by means of remote sensing: Methods, accuracy and limitations. *Progress in Physical Geography* **33**: 103–116.

Hedley JD, Roelfsema CM, Chollett I, *et al.* 2016. Remote sensing of coral reefs for monitoring and management: a review. *Remote Sens.* **8**: 118–157.

Hochberg EJ, Atkinson MJ and Andrefouet S. 2003. Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. *Remote Sensing of Environment* **85**: 159–173.

Leiper IA, Phinn SR, Roelfsema CM, Joyce KE and Dekker AG. 2014. Mapping coral reef benthos, substrates, and bathymetry, using Compact Airborne Spectrographic Imager (CASI) data. *Remote Sensing* **6**: 6423–6445.

Liu G, Eakin CM, Chen M, Kumar A, De La Cour JL, Heron SF, Geiger EF, Skirving WJ, Tirak KV and Strong AE. 2018. Predicting heat stress to inform reef management: NOAA Coral Reef Watch's 4-month coral bleaching outlook. *Frontiers in Marine Science* **5**: 57.

Mogstad AA and Johnsen G. 2017. Spectral characteristics of coralline algae: a multi-instrumental approach, with emphasis on underwater hyperspectral imaging. *Applied Optics* **56**: 9957–9974.

Petus C, Devlin M, Thompson A, McKenzie L, Teixeira da Silva E, Collier C, Tracey D and Martin K. 2016. Estimating the exposure of coral reefs and seagrass meadows to land-sourced contaminants in river flood plumes of the Great Barrier Reef: Validating a simple satellite risk framework with environmental data. *Remote Sensing* **8**: 210–240.

Raitsos D, Brewin RJW, Zhan P, Dreano D, Pradhan Y, Nanninga GB and Hoteit I. 2017.

Rio M-H and Santoleri R. 2018. Improved global surface currents from the merging of altimetry and Sea Surface Temperature data, *Remote Sensing of Environment* **216**: 770–785.

Roelfsema CM, Lyons M, Kovacs EM, Maxwell P, Saunders MI, Samper-Villarreal J and Phinn SR. 2014. Multi-temporal mapping of seagrass cover, species and biomass: A semi-automated object based image analysis approach. *Remote Sensing of Environment* **150**: 172–187.

Roelfsema C, Phinn S, Jupiter S, Comley J and Albert S. 2013. Mapping coral reefs at reef to reef-system scales, 10s–1000s km^2, using object based image analysis. *International Journal of Remote Sensing* **34**: 6367−6388.

Rowlands G, Purkis S, Riegl B, Metsamaa L, Bruckner A and Renaud P. 2012. Satellite imaging coral reef resilience at regional scale. A case-study from Saudi Arabia. *Mar. Pollut. Bull.* **64**: 1222–1237.

Selgrath JC, Roelfsema C, Gergel SE and Vincent ACG. 2016. Mapping for coral reef conservation: comparing the value of participatory and remote sensing approaches. *Ecosphere* **7**: e01325.

Skirving W, Enríquez S, Hedley JD, Dove S, Eakin CM, Mason RAB, De La Cour JL, Liu G, Hoegh-Guldberg O, Strong AE, Mumby PJ and Iglesias-Prieto R. 2017. Remote sensing of coral bleaching using temperature and light: Progress towards an operational algorithm. *Remote Sensing* **10**: 18.

Vahtmäe E, Kutser T, Martin G and Kotta J. 2006. Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters—a Baltic Sea case study. *Remote Sensing of Environment* **101**: 342–351.

Wedding LM, Friedlander AM, McGranaghan M, Yost RS and Monaco ME. 2008. Using bathymetric lidar to define nearshore benthic habitat complexity: Implications for management of reef fish assemblages in Hawaii. *Remote Sensing of Environment* **112**: 4159–4165.