A COMPARISON OF SPECTRAL MEASUREMENT METHODS FOR SUBSTRATUM AND BENTHIC FEATURES IN SEAGRASS AND CORAL REEF ENVIRONMENTS

Arnold G. Dekker[1], Brando[1], V.E. , Janet M. Anstee[1], Elizabeth, J. Botha[1], Young Je Park[1], Paul Daniel[1], Malthus[1], T.J.M., Stuart R. Phinn[2], Chris M. Roelfsema[2], Ian A. Leiper[2], Sue Fyfe[3].

1 CSIRO Land & Water, Environmental Remote Sensing Group, Canberra, ACT, Australia
2 University of Queensland, Centre for Spatial Environmental Research, Brisbane, Australia
3 Geosciences Australia, Canberra, ACT, Australia

Abstract

Significant advances have been made in remote sensing methods that support accurate and repeatable methods for mapping the composition, structure and condition of submerged, coastal, coral reef and marine environments. One of the newer developments in substrate and benthic cover mapping are algorithms which have been developed using spectral reflectance libraries of the cover types composing the bottom of these environments. The spectral libraries are used either to constrain the approach taken or as an input parameterisation tool for mapping specific features. As a water column lies between the substratum, benthos and the air-water interface, any complete shallow aquatic water habitat spectral library for remote sensing purposes also needs to consider the apparent optical properties of the water column. Substratum mapping projects using these spectral data sets in a range of environments around the world demonstrate the necessity of appropriate spectral reflectance measurements.

In order to assess the estuarine, coastal, coral reef and marine environments extent from airborne or satellite imagery parameterized by *in situ* spectral reflectance libraries, a set of standards for the capture, storage and use of these spectral signature files needs to be established. The shallow water environment creates unique challenges for systematic and standardised underwater or above-water spectral reflectance measurements due to variations in solar angle, atmospheric conditions, sea surface conditions, currents, water column optical properties, etc. Globally useful spectral field data will need to include complete metadata (what is measured, how, by what instrument, where and by whom and under what conditions).

Introduction

Spectral measurements of intertidal to subtidal aquatic environments can be made in many different ways over a variety of biotic targets varying from seagrasses, macro-algae, micro-algae, turf-algae, corals, sponges, coralline algae to substratum types such as clay, mud, sand, detritus, pebbles, boulders, coral rubble and rocky reefs. Zimmerman & Dekker (2007) discuss the background optics necessary for accurate measurement of spectra in a benthic environment, Dekker et al. (2007) provide a concise description of remote and in situ sensing of spectra from optically shallow benthic seagrass systems; Phinn et al. (2008) were able to apply remote sensing to determine seagrass species, seagrass density and seagrass biomass; Zimmerman (2007) presents a thorough treatise on light and photosynthesis in seagrass canopies. Hochberg (2003) and Fyfe (2003) discuss the spectral severability of coral species and seagrass species, respectively.

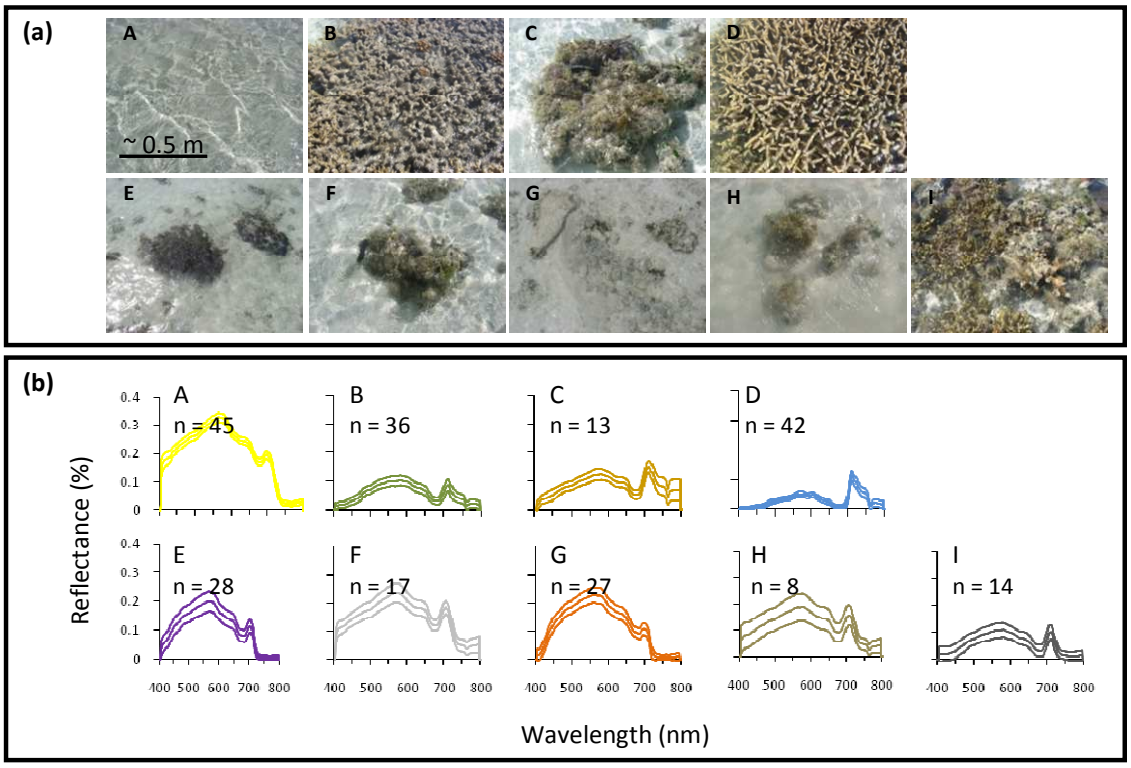

Figure 1. Photographs representing the bottom-type assemblages, taken from the point of view of the optical sensor (a), and associated mean spectral reflectance +/-SE (b). Letters A-I represent the coral reef assemblages which are described table 1.

Table 1. Coral reef assemblages defined on Heron Reef, and targeted for *in-situ* spectral reflectance measurements. Classes A-D are dominated by a single bottom-type (greater than 65% cover).

Class	Community
A	Sediment
B	Abiotic substrate with turf algae (abiotic TA)
C	Brown macroalgae
D	Live coral
E	Sediment and live coral
F	Sediment and brown macroalgae
G	Sediment and abiotic TA
H	Abiotic TA and brown macroalgae on sediment background
I	Abiotic TA with brown macroalgae and live coral

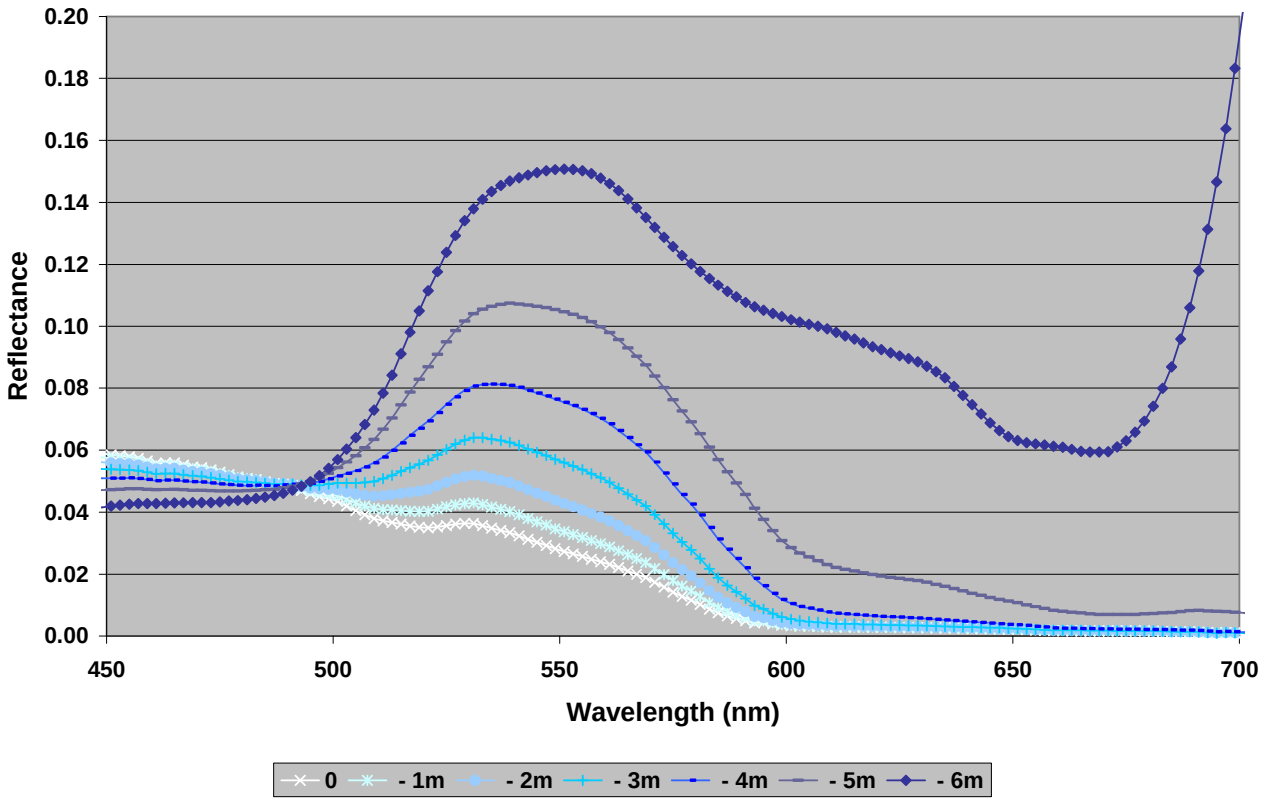

Figure 2. A Hydrolight (radiative transfer model) simulation of a measured *Zostera* spectrum (the pure Zostera end member spectrum with the spectrometer at a depth of 6 m at canopy level) and the at-surface reflectance (depth = 0 ; canopy is 6 m deep) and within intermediate depths of the water column for a typical Australian coastal water type with low chlorophyll, coloured dissolved organic matter and suspended matter.

The water columns covering these targets may be a few millimeters to 35 or 40 meters thick. Forty metres is approximately the depth in the clearest natural waters where a light signal reflected from the substratum ceases to have a measureable effect on water leaving radiance (Brando et al., 2009). For spectral measurements that are intended to be used in earth observation approaches an operationally relevant depth limit for measurements is between 10 to 15 metres. Beyond 15 metres, the spectral discrimination of any bottom feature becomes less likely as with increasing depth increasing light attenuation in both the blue and the red to nearby infrared wavelength regions reduces any spectral reflectance of the substratum being measureable in the water leaving signal. Figure 1 shows results of measurements at Heron Island (Australia) by one of the authors where coral and substratum types were spectrally measured in situ above water. Figure 2 shows simulated seagrass reflectance as the amount of water column distance to the *Zostera* canopy increases. The reduction in reflectance with increasing water column results in a spectral upwelling radiance from the benthos to be mainly confined to blue-green to green yellow wavelengths of 500 to 600 nm, (except for organic matter rich waters where a shift to yellow wavelengths may occur).

Towards a global spectral library

In Dekker et al. (2007) the following recommendation is made: "…..*in the coral reef community worldwide spectral library measurement programs [e.g. 13000 spectra collected see Hochberg et al. (2003)] have led to a demand for remote sensing of coral reef ecosystems. The seagrass community should also carry out a worldwide spectral library collection program (including the measurement of co-occurring benthic micro-algae, macro-algae, sediment and rock substratum), to mature the field of hyperspectral remote sensing (by standardizing processing methods) for use by seagrass biologists in their studies…..*"

The crucial phrase is "to carry out a worldwide spectral library collection program" as it implies standardized spectral measurement methods where spectra from habitats in different regions may be usefully compared. This manuscript attempts to summarize and critically evaluate seventeen existing methods for measuring seagrasses and macro-algae, corals and sponges and substratum types (tables 2, 3 and 4). Seven of these methods were used on seagrasses only; five methods on corals and sponges; and five methods on different types of substrata. Five of the seven methods are similar (but not identical covering two methods for above-water measurements of samples and three methods for underwater measurements of samples) between seagrass and macro-algae, corals and sponges and substratum types. Seagrasses and macro-algae have two additional methods related to above-water spectral measurements of samples of leaves or fronds.

These differences in spectral measurement methodology may have consequences for the intercomparison of the resultant spectra collected and deposited in any global spectral library. We will provide a brief discussion using tables 2 to 4 as a guide. A significant criterion for choosing to perform above-water spectral measurements is the relative ease of the measurements as compared to having to deploy submersible equipment using scuba divers with all the associated occupational health and safety issues. However, even for above-water measurements, underwater sampling is required of the targets before the above water measurements can be performed, which means there may be still the need for diving or snorkeling. It could also be possible to lower a spectrometer from the side of the boat onto the benthos or the substrate, but this requires target observations from a diver/snorkeler or a drop camera. A measurement with a spectroradiometer on board the boat but with the radiance/irradiance heads underwater attached with an optical fibre also fall under underwater measurements- as the sensor heads are underwater.

The advantage of underwater measurements are: that the targets (be it seagrasses, macro-algae, corals, sponges, encrusting algae, turf algae , benthic micro-algae, corals or other material) are measured in situ; any such spectra may be considered an end-member of that target as it occurs in nature, and the diver/snorkeler can verify what has been measured. Before discussing the main differences in methods we acknowledge that many other factors influence the reliability of spectral reflectance measurements such as the characteristics of the instrument [Instantaneous Field Of View (IFOV), spectral resolution (FWHM etc.) spectral intervals, radiometric sensitivity, spectral and radiometric stability as a function of light intensity, temperature of the spectrometer], Lambertian behavior of reference reflecting panels, flexing of optical fibre cables etc. However important these other factors are, they are part of every spectral reflectance measurement and are not unique to the aquatic environmental habitat measurements we are discussing here; the key is to

Seagrass & macro-algae										
Method	**Light field**	**E_d**	**L_u Sample**	**Sample orientation**	**Back-ground**	**Spectral range**	**Reflectance calibration**	**Reflectance calibration comments**	**Measurement comments**	**Additional error sources**
Surface 1	*Ambient*	Panel	Disturbed	Single leaves flat	White Grey Black	Limited by instrument specs	Panel calibration	Time lapse between panel and target	leaves transparent measurement is hybrid R Transmission	Sun and skyglint from wet leaf
Surface 2	*Ambient*	Panel	Disturbed	Leaves stacked till optically thick	White Grey Black	Limited by instrument specs	Panel calibration	Time lapse between panel and target		Sun and skyglint from wet leave surface
Surface 3	*Ambient*	HDDI	Disturbed	Single leaves flat	White Grey Black	Limited by instrument specs	Intercalibration L_u & E_d sensor	Simultaneous measurement L_u & E_d	If leaves transparent measurement is hybrid R Transmission	Sun and skyglint from wet leave surface
Surface 4	*Ambient*	HDDI	Disturbed	Leaves stacked till optically thick	White Grey Black	Limited by instrument specs	Intercalibration L_u & E_d sensor	Simultaneous measurement L_u & E_d		Sun and skyglint from wet leave surface
Underwater 1	*Ambient*	Panel	Natural in situ		Natural	Limited by K_d at measurement depth	Panel calibration in air and submerged	Time lapse between panel and target	Natural canopy structure and shading effects	Wave lensing + variable water column height
Underwater 2	*Ambient*	HDDI	Natural in situ		Natural	Limited by K_d at measurement depth	Intercalibration L_u & E_d sensor	Simultaneous measurement L_u & E_d	Natural canopy structure and shading effects	Wave lensing + variable water column height
Underwater 3	*Ambient + light source*	Panel	Natural in situ		Natural	limited by K_d light source spectrum target & panel	Panel calibration air & submerged intercalibration incl. light source	Time lapse between panel and target	Natural canopy structure and shading + artificial light canopy effects	Wave lensing + variable water column height

Table 2 Comparison of existing methods the authors have used for measuring spectral reflectance of seagrasses and macro-algae. HDDI = Cosine-corrected hemispherical diffuse downwelling irradiance sensor.

Corals & Sponges									
Method	**Light field**	**E_d**	**L_u Sample**	**Back-ground**	**Spectral range**	**Reflectance calibration**	**Reflectance calibration comments**	**Measurement comments**	**Additional error sources**
Surface 1	*Ambient*	Panel	Disturbed	White Grey Black	Limited by instrument specs	Panel calibration	Time lapse between panel and target	Disturbed canopy structure and shading effects	Sun and skyglint from wet surface
Surface 2	*Ambient*	HDDI	Disturbed	White Grey Black	Limited by instrument specs	Intercalibration E_d & L_u sensor	Simultaneous measurement L_u & E_d	Disturbed canopy structure and shading effects	Sun and skyglint from surface
Underwater 1	*Ambient*	Panel	Natural in situ	Natural	Limited by K_d at measurement depth	Panel calibration in air and submerged	Time lapse between panel and target	Natural canopy structure and shading effects	Wave lensing + variable water column height
Underwater 2	*Ambient*	HDDI	Natural in situ	Natural	Limited by K_d at measurement depth	Intercalibration E_d & L_u sensor	Simultaneous measurement L_u & E_d	Natural canopy structure and shading effects	Wave lensing + variable water column height
Underwater 3	*Ambient + light source*	Panel	Natural in situ	Natural	Possibly limited by K_d & light source spectrum & target and panel distance	Panel calibration in air & submerged + intercalibration incl. light source	Time lapse between panel and target	Natural canopy structure and shading + artifical light canopy effects	Wave lensing + variable water column height

Table 3 Comparison of existing methods the authors have used for measuring spectral reflectance of corals and sponges.

Substratum									
Method	**Light field**	**E_d**	**L_u Sample**	**Back-ground**	**Spectral range**	**Reflectance calibration**	**Reflectance calibration comments**	**Measurement comments**	**Additional error sources**
Surface 1	*Ambient*	Panel	Disturbed	White Grey Black	Limited by instrument specs	Panel calibration	Time lapse between panel and target	Disturbed sample-vertical mixing layers	Sun and skyglint from wet surface or if dry-unnatural condition
Surface 2	*Ambient*	HDDI	Disturbed	White Grey Black	Limited by instrument specs	Intercalibration E_d & L_u sensor	Simultaneous measurement L_u & E_d	Disturbed sample-vertical mixing layers	Sun and skyglint from wet surface or if dry-unnatural condition
Underwater 1	*Ambient*	Panel	Natural in situ	Natural	Limited by K_d at measurement depth	Panel calibration in air and submerged	Time lapse between panel and target		Wave lensing + variable water column height
Underwater 2	*Ambient*	HDDI	Natural in situ	Natural	Limited by K_d at measurement depth	Intercalibration E_d & L_u sensor	Simultaneous measurement L_u & E_d		Wave lensing + variable water column height
Underwater 3	*Ambient + light source*	Panel	Natural in situ	Natural	Possibly limited by K_d & light source spectrum & target and panel distance	Panel calibration in air & submerged + intercalibration incl. light source	Time lapse between panel and target		Wave lensing + variable water column height

Table 4 Comparison of existing methods the authors have used for measuring spectral reflectance of substratum. Note that substratum often contains benthic micro-algae, turf algae, or encrusting forms of coralline algae etc.

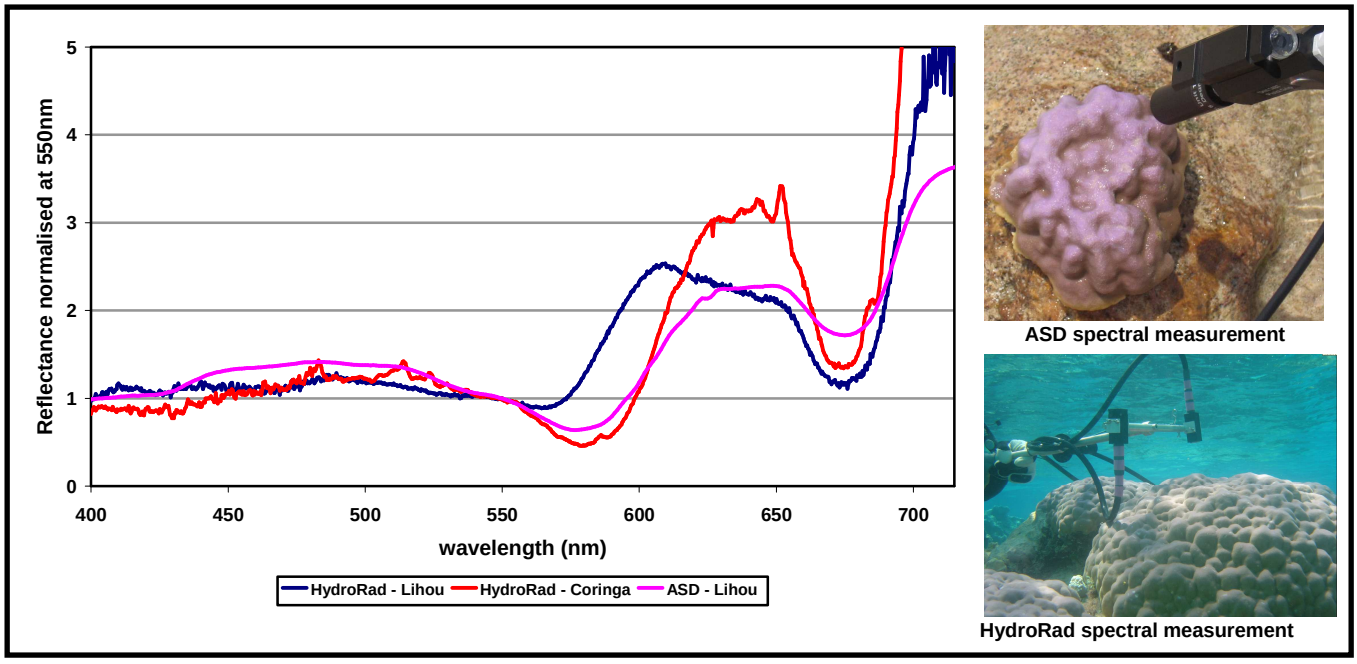

Figure 3 – underwater spectral measurements (normalized at 550 nm) using a HydroRad-4 (with an underwater L_{uw} and E_{dw} sensor) and an ASD above surface L_u measurement (using a Spectralon panel as reference) of similar coloured corals (the two Hydrorad-4 measurements were taken on two different reefs in the Coral Sea in 2006 and in 2008; the ASD measurement was taken in the same week as the HydroRad-4 Lihou measurement). The graph shows reasonable similarity in location of spectral features mainly caused by pigmentation absorption (local minima in reflectance) and local peaks in reflectance where minimal absorption occurs. The reasons for the variability need further research.

ensure that these characteristics are well documented such that important differences in set up between different measurements can be evaluated. Therefore, this paper focuses on understanding the unique aspects of methods related to spectral measurements of benthic habitats and its components.

For seagrasses and macro-algae there are four above-water spectral reflectance measurement types (see Table 2), and two main distinctions are made - each with two further distinctions:

1: how reflectance (either as E_u/E_d or as remote sensing reflectance L_u/E_d) is measured by measuring upwelling radiance L_{up} from a Lambertian reflecting panel and estimating downwelling irradiance E_d by multiplying L_{up} by PI and by the panel calibration factor or by measuring E_d using a hemispherical cosine corrected diffuser.

2: the manner of laying out the sample leaves or fronds on the background material (Figure 4).

Figure 4. Three examples of seagrass leave sampling for spectral measurements: left is Amphibolis with an epiphyte and in the middle Halophila leaves and on the right two seagrass cores with sediment. Note the transparency of the Halophila leaves where the neoprene is visible through the leaves. (Amphibolis and Halophila samples taken in West Australia; seagrass cores form Moreton Bay in Queensland).

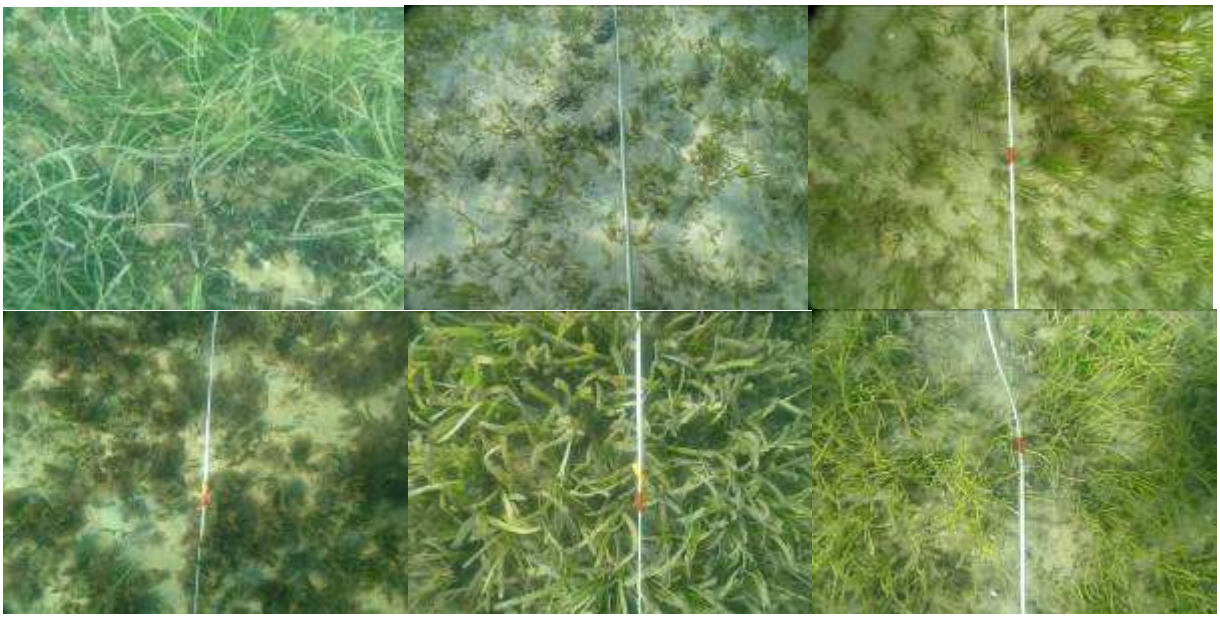

Figure 5 . An example of mixed seagrass and substratum compositions with canopy effects.

Many leaves and fronds are transparent to a degree (see Figure 4). If a measurement is made on different backgrounds then part of the signal in the spectral measurement may come from the background through the leaf or frond. Alternatively, leaves or fronds can be stacked over each other till they are optically thick - giving a pure end-member spectrum (Fyfe, 2003) . However, this pure endmember spectrum is not representative of the leaves in situ where they will have all the effects of a canopy underwater (leaf orientation due to waves and current, shading as shown in Figure 5). When measuring leaves or fronds lying flat, sun glint and sky glint from the wet layer on the surface of the leaves or fronds may occur depending on the illumination conditions (also the water layer on the leaves may change composition and thickness as the drying process starts) .

By measuring indoors in laboratory conditions some of these effects can be suppressed or controlled (e.g. by having a stable light source) although then an added source of uncertainty is change in the samples between times of sampling and measurements; these effects can be reduced by storing and transporting samples in the dark at temperature just above 0° C. This latter method has the advantage that personnel without spectral measurement expertise and with knowledge of the different bottom features, such as coastal management agency staff, could take care of the sample collection.

An added complication of taking samples to the surface may be that e.g. for long seagrass, the different parts of the leaves will have slightly different cell structure and physiology and colour, e.g. tops of leaves (dark green) versus bottom (bright yellow to light green) for *Posidonia* leaves that can be up to a metre long. When remote sensing or performing in situ measurements a spectral signal is normally measured from the leaf tops, while samples removed from their environment could be measured anywhere along the leaves. Additionally, epiphytic growth on leaf surfaces contain pigments and cell skeleton material that will change the spectral reflectance. If epiphytes occur the spectral measurements should be firstly of leaves with epiphytes, then scraped bare of epiphytes (the difference being the effect of epiphytes). Notes on type and density of epiphyte growth on samples should be made when taking spectral measurements.

For underwater spectral measurements three methods can be distinguished: these are 1) measurements of the target using a simultaneous measurement of either E_u/E_d or remote sensing reflectance L_u/E_d with a submersible spectroradiometric system (see Figure 3) (or a spectroradiometer on board the boat with optical fibres taken down to the substratum (see e.g. Karpouzli et al, 2004)-the essential issue is where the sensor heads that measure radiance and irradiance are located), consisting of a radiance measurement head or fibre and a hemispherical cosine corrected diffuser; 2) by measuring upwelling radiance underwater L_{upw} from a submerged Lambertian reflecting panel and estimating downwelling irradiance underwater E_{dw} by multiplying L_{upw} by π and by the underwater panel calibration factor; 3 as 2) however, a standard submersible light source is used to measure the submersible Lambertian surface and the bottom feature to compensate for the increasing loss of downwelling light (usually in the blue and on the red to nearby infrared regions) (Figure 6). In all underwater measurements light attenuation by the water between the sensor and the target (and in the case of an active light source the attenuation by the water between the light source and the target and the reflectance panel) plays a significant role (in above-water proximal measurements the effects of air are ignored).

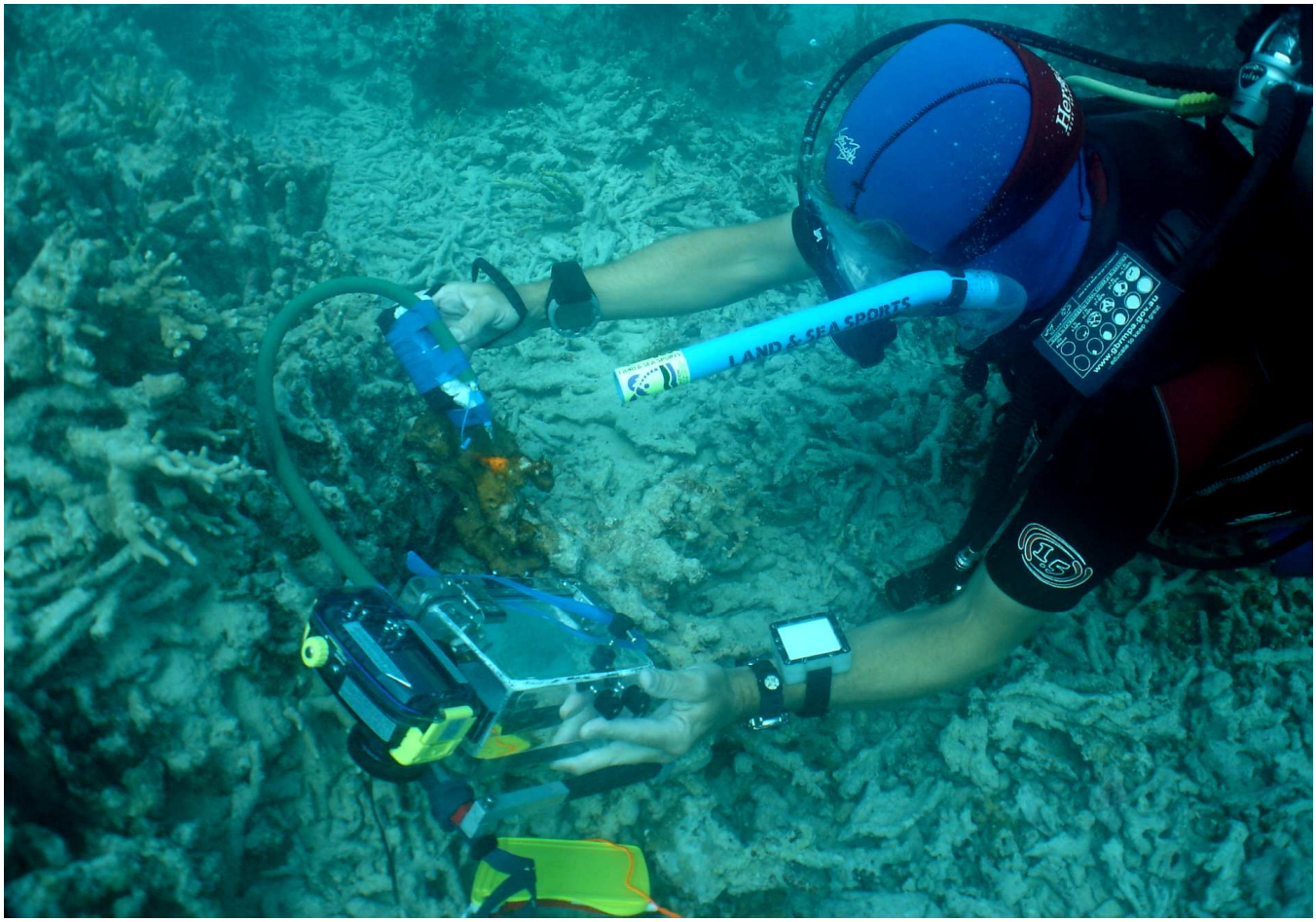

Figure 6: Example of underwater spectral measurement using a OceanOptics USB2000 and palm top computer in a custom build underwater housing which a diver operates on its own and therefore can unlimited move around. The diver can observe the spectral signature on the screen of the palm top while he/she points the optics with artificial light source (divers right hand) on the target material (e.g. branching coral.

In addition, underwater light measurements also are affected by air-water interface effects such as wave lensing of the downwelling light field causing rapid fluctuations of downwelling irradiance randomly distributed between the target, reflectance panel (if used) and the sensor and the water volume in between these three components.

Thus, although the underwater measurement has the advantage of measuring the target in situ in natural orientation there are several light field complexities added as well as the logistical complexity of needing multiple divers (although some underwater spectral measurement systems exist that only need one diver to operate the system, safety regulation often require an additional diver underwater to assist and a standby diver on the boat or on the shore for emergency management). Measuring the target in situ seems optimal. However, canopy effects can vary due to waves, currents, epiphytic growth etc., and the bottom (or substratum) can be detectable (in variable amounts) through the canopy, in which case the spectrum is a mixed target and substratum measurement. For these measurements over canopies with leaves and fronds

and possible visibility to the substratum as well as canopy shading effects the question becomes: what constitutes an endmember?

For corals and sponges (see Table 3) many of the same issues as mentioned for seagrasses and macro-algae occur, however some aspects are different. Corals are characterized by calcium carbonate skeleton with polyps in it, containing both animal and plant tissues. Coral samples taken to the surface do not change their coral skeleton and if measurements are taken rapidly (within minutes) after surfacing, the live coral polyp stays the same (see Figure 3 above and underwater images of a pink *Porites*). However, when the sample is not rapidly measured after sampling, changes in the sample may occurred as animal and plant cells will die, and plant pigments lose their capability to absorb light which will change the appearance of the coral. Corals appearance will also change when exposed to air: as the mucus layer normally present will disappear, and the coral tentacles will be retracted into the coral skeleton once exposed. Soft corals and sponges are filled with water which provide them their shape underwater, however once exposed to air the water will drain and thus this matrix-structure will invariably change. Coral and sponge samples are often optically thick relative to seagrasses and macro-algae which may be transparent. Underwater measurements of corals and sponges suffer much less from canopy illumination condition effects (as compared to seagrasses and macro-algae) but they do suffer from the same wave lensing effects.

Figure 7: Example of underwater spectral measurement using a HydroRad-4 spectroradiometer operated at the surface (left) while a long optical cable with up- and down welling sensor head is positioned by a diver above the target material(right). Through underwater communication devices the diver communicates with the spectrometer operator to inform each other about the status and the type of measurement..

For substratum measurements many of the same issues as mentioned for plants and animals (e.g. seagrasses, macro-algae, corals, sponges etc) are similar, but some aspects are different (see Table 4). The similarities occur as substratum is often mixed or covered with small plant material which varies types of light absorbing pigments: sand, silt and mud contain benthic micro-algae and or cyanobacteria; and coral rubble and rock can be covered by turf algae and cyanobacteria (Figure 7). Benthic micro-algae are mostly present on sand silt and mud as a thin surface layer and/or distributed within the top mm's to cm's. The spectral appearance can vary as the benthic micro algae can migrate vertical and horizontal according to their optimal desired location as a function of light, temperature and nutrients. Any sand, silt and mud sample taken to the surface is invariably disturbed by the time it is measured by a spectrometer, and in most cases, the benthic micro-algae spectral component of the sample will be (much) less than for an in situ measurement. The sand, silt and mud is also often disturbed during the sample collection as most grabs will overturn the material. When rubble with turf algae is exposed the plant material can change similar to seagrasses and macro algae, however the shape and structure of the rubble would not change.

For consolidated (hard) substratum types such as rock, rock reefs, boulders, dead coral an above or underwater measurement does not make much difference in regards to shape and structure. However, since turf-algae is present on most of these surfaces, and changes occur as plant tissue dies, pigment compositions will change and thus above water measurements will be affected. Although for above water measurements sun and sky glint effects may occur. Consolidated substratum is possible the hardest for gathering a representative sample as it will hard to retrieve a fixed sample. Thus, a dive or snorkel approach is required (whether for sampling or for spectral measurements).

Conclusions and recommendations

In order to create global spectral libraries of seagrasses, macro-algae, corals, sponges, encrusting algae, turf algae , benthic micro-algae, corals or other aquatic benthic material, the many existing methods may need some consolidation into a set of fewer standardised methods to ensure the resultant spectra acquired are more intercomparable. Because there is a significant difference in required infrastructure, training and occupational health and safety issues between spectral measurements that require target material to be extracted from its natural environment and measured in a controlled environment versus measurements where target material is measured in its natural environment (and, in the case of underwater measurements, differences between collecting a sample and using underwater spectral measurement equipment), the recommended protocol for a global spectral library may need to include both above and underwater measurement methods. If this is the way forward , it must be ensured that these measurements are as intercomparable as possible.

It is evident that in situ measurement where the target material is undisturbed capture the spectral reflectance of the target (be it a single species or an assembly of species and substratum types) in its natural condition. This measurement will in generally be conducted under water due to tides and water column depth, however some target material (e.g. exposed seagrass) could be measured above water while exposed at low tide.

The advantage of a measurement where the target material is extracted from its natural surrounding is that environmental factors that affect an in situ measurement are avoided: water depth, currents, light attenuation and wave lensing of surface downwelling light. This approach is needed when there is no opportunity to gather under water spectral reflectance due to spectrometer limitation or its operator cannot dive or snorkel. In both approaches there is still a need for snorkeling or SCUBA diving to or extract the target material from its natural surrounding unless a remote sampling device such as an Ekman grabber is used (risking severe disturbance of the sample). An additional advantage of measuring a sample at the

surface is that it enables natural resource management agencies to carry out the fieldwork rather than scientifically or professionally trained research dive teams.

Thus, from a research perspective underwater spectral measurements of substratum and benthos in situ are preferred, whereas operationally above-water measurements are preferred, in case the spectrometer and/or operator cannot operate underwater (although the requirement for underwater sampling still remains). In the case of extracting target material out of its natural surrounding permits may be required as it is intrusive to the sample, whereas spectral measurements underwater are non intrusive and therefore do not affect the underwater environment.

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These arguments lead to the conclusion that a comprehensive analysis of all existing methods is required in order to recommend the best way forward for global spectral library creation of aquatic benthic habitats. This analysis may start with a meta-analysis of all published methods and the results obtained until now, augmented by a dedicated comparative fieldwork effort involving multiple experts, capable of performing each of these spectral measurement methods. Radiative transfer modeling could also be used to account for how each of these spectral measurement methods affects the resulting reflectance spectra (see e.g. Hedley, 2008).

As this may take some time before being implemented, a further recommendation is that all spectral measurements must be thoroughly documented with all metadata relevant to the measurement included. In addition, any peer reviewed publication of aquatic benthic habitat mapping results should have sufficient information associated with the spectral measurement method to ensure the published spectral measurements are suitable to be included in a global spectral library.

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