PROCESSING OF FIELD SPECTRORADIOMETRIC DATA FOR REMOTE SENSING MAPPING OF SUBMERGED VEGETATION IN COASTAL ZONES AND LAGOON ENVIRONMENTS

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ABSTRACT

Remote sensing techniques are applied to map submerged vegetation in coastal zones and lagoon environments. The lack of spectral signatures of submerged vegetation measured *in situ* and the uncertainties in water column attenuation characteristics often restrict the use of classification algorithms. In this paper, processing techniques for field measurements of spectral radiance on submerged vegetation are discussed and applied to show the usefulness and limits of this method for submerged vegetation mapping in shallow areas. A field campaign was carried out to quantify the spectral transparencies of two contrasting water bodies, measuring underwater downwelling irradiance at different depths. An accurate computation of the diffuse attenuation coefficient is therefore important; this study has shown that these are readily obtainable using *in situ* measurements of spectral irradiance. Our results show that spectral signatures for seagrass canopies can be derived from *in situ* measurements of spectral radiance. Although the spectral signature of the submerged vegetation is expected to vary with phenological period, a result of this research was the determination of typical spectral signatures of some of the most important Mediterranean submerged vegetation, during the most favourable period for optical remote sensing acquisitions.

INTRODUCTION

Seagrasses are marine flowering plants found in shallow coastal waters of all continents except Antarctica. They are the only rooted marine macrophytes and, as such, are crucial for coastal protection and biodiversity. The shoots emerge from rhizomes, which grow vertically and horizontally, and form extensive "meadows" which provide a habitat for many species of fish and invertebrates, and are significant contributors to water oxygenation (1). Seagrass meadows have been shown to influence water motion (2), velocity profiles and turbulent structures (3,4), all of which play an important role in sedimentation processes and in general water circulation (5).

Posidonia oceanica meadows are seriously threatened in the Mediterranean Basin today. Their location in shallow coastal waters makes them susceptible to environmental alterations resulting from human activities such as coastal development and subsequent alterations to localised hydrological influences, eutrophication, pollution, destructive fishing activities and anchorages (6). The current status of *P. oceanica* in the Mediterranean Sea is one of decline, with regressing beds recorded by countries which have undertaken surveys in their coastal waters. This pattern is typical of the world wide trend in all seagrass species (7).

Monitoring of marine benthic communities is considered to be an essential activity to increase our understanding of change in marine habitats and hence to ensure the best management of coastal areas (8). Traditional field-based monitoring methods are mainly based on underwater inspection using SCUBA diving (9) or remotely operated vehicles (ROVs) (10), interpretation of acoustic data (11) or by means of topographic instruments (12). However, such monitoring surveys can be problematic as they are time consuming and often expensive, requiring exhaustive field sampling and survey programmes. The use of multibeam acoustic data is also problematic in very shallow areas (less than 5 m) due to the very noisy signal and the more intensive survey required for complete coverage in shallow depths (13).

Remote sensing offers a solution for surveying the extent and development of *P. oceanica* and other macrophyte meadows in the Mediterranean Sea through being able to offer synoptic information over large spatial scales (14). Unlike optical remote sensing of terrestrial vegetation, for the technique to be applied successfully to submerged aquatic plants the reflected radiation from the plants must be detectable above the water surface (15,16,17). The spectral signature from the vegetation must also be sufficiently different from that of the surrounding bottom sediment and overlying water. The signal from the water will also be influenced by optically important constituents in the water column which include phytoplankton, inorganic suspended matter and dissolved aquatic humus (11). For clear waters the reflectance signal of benthic vegetation needs to be separated from that of the overlying water column, in order to distinguish different types of submerged vegetation (18).

The spectral signature of seagrasses is a fundamental tool for mapping submerged vegetation using optical remote sensing. The definition of these spectral signatures is necessary in order to apply classification algorithms over remotely sensed images of shallow water environments (e.g. lagoons and coastal areas). However, few papers have reported spectral libraries of different seagrass species (e.g. 19,20). The separation of different vegetation types in remotely sensed data needs to be addressed in order to understand the best wavebands to use. Measurements can be carried out either by measuring water leaving radiance and underwater downwelling irradiance (19), or by measuring the in-air optical properties of leaf samples collected *in situ* (20). The former measurements are strongly characterised by water column attenuation and temporal variability; they are also influenced by water reflected radiance; thus the spectral signatures of *in situ* vegetation are difficult to retrieve. The latter method requires the collection of leaves and needs to take into account the relationship between single leaf and canopy geometry in terms of reflected and transmitted light. To date, few comparisons between water column removal methods and actual measured leaf reflectances have been made in order to determine if they are representative of actual reflectances from seagrass canopies at depth (21).

The purpose of this paper is to investigate the most suitable methods for submerged marine vegetation reflectance retrieval from *in situ* measurements. Such a method requires the accurate characterisation of the optical properties of the overlying water column. Water column attenuation properties clearly vary spatially between lagoons and shallow coastal areas (22). They play an important role in the signal reaching a remote sensor. In this paper the attenuation properties of a shallow sheltered water column (a lagoon) have been compared to those of open clear water in a nearby site (a coastal bay) in order to quantify the difference in the attenuation phenomena.

BACKGROUND

There are about 60 seagrass species found worldwide, grouped in 13 genera and 5 families (23). These can be divided into temperate and tropical genera (24) but, among these, *Cymodocea nodosa*, considered a tropical genus, is commonly found in the Mediterranean Sea (25). Warmer temperate seas are dominated by the genus *Posidonia* (17). The *Posidonia* genus includes several species: *P. angustifolia*, *P. australis*, *P. sinuosa*, *P. ostenfeldii*, *P. coriacea*, *P. denhartogii*, *P. kirkmanii*, *P. robertsoniae* and *P. oceanica*. *P. oceanica (L.) Delile* is an endemic species of the Mediterranean Sea (26). All seagrass species are rhizomatous, clonal plants which colonise the seabed through shoot reiteration, in which leaves and roots are produced via rhizome extension (19). *C. nodosa* is a species that has seed banks: in favourable conditions it is capable of rapid recruitment into a disturbed patch. *P. oceanica*, lacking a seed bank, is capable of recruitment through vegetative fragments, with a $3 \cdot 10^{-4}$ ha^{-1} yr^{-1} rate of patch formation. *P. oceanica* seagrasses are ligulate (i.e. long, thin and flexible leaves) and colonises sandy bottoms in the Mediterranean Sea, with densities varying (27) from 1200 $shoots \cdot m^{-2}$ in shallow water (1-5 m) to 100 $shoots \cdot m^{-2}$ in deeper water (up to 40 m). Its shoots have 6-8 leaves, the outermost being oldest and longest, and the innermost youngest and shortest. The leaves are ~ 0.2 mm thick, ~ 1 cm wide and up to 1.5 m long.

Studies conducted on Mediterranean seagrass populations have highlighted an idealised successional sequence of species from initial colonisation by *C. nodosa* to a final dominance by *P. oceanica* (18). However, it appears that such a sequence is not always realised, and, in shallow water, the two species might co-exist (19).

The main factors influencing seagrass communities are light availability, temperature and salinity fluctuations, nutrient supply, current speeds, water exchange and sediment dynamics (28). Light penetration in the water is the most important factor regulating seagrass distributions and density. They may grow in up to 40 m of water depth (lower depth limit) where enough light is still available. There is also an upper depth limit for the species, as *P. oceanica* can not tolerate both long air exposure, desiccation and dynamic wave disturbance (29).

P. oceanica forms reef structures (*recife barrier*) in shallow water with leaves that lie flat on the surface, so retaining water (17). In an enclosed embayment, like a lagoon with low water exchange with the open sea, elevated temperatures may be common. Plant metabolism is improved with moderate temperature increases as a result of increased enzyme activity. Although most seagrasses tolerate a wide salinity range, *P. oceanica* is a stenohaline species and, therefore, cannot handle wide fluctuations in the salt content of water and freshwater inputs. The high productivity of seagrass ecosystems is largely dependent on the decomposition and remineralization of nutrients derived from detritus from the seagrass community (30).

THE STUDY AREA

The study area was the Stagnone di Marsala Lagoon, on the west coast of Sicily (Italy) (Figure 1). The lagoon is approximately 1800 ha in area, is about 10 km long and depth varies from 0.2 to 3 m. The lagoon is linked to the open sea by a narrow, shallow opening to the north (S.Teodoro mouth, 0.2-0.3 m depth, 450 m wide), and a wider opening to the south (between Punta dello Stagnone and Punta Alga, 1-3 m depth, 3200 m wide). For this reason, there are two sub-basins: a northern basin characterised by shallow water and low water exchange due to the restrictive nature of the northern opening; and a deeper southern basin characterised by higher water exchange rates. The morphology of the lagoon protects it from the high wave energy of the open sea, and therefore the water has very low turbidity. The warm, shallow water provides an ideal habitat for a variety of submerged vegetation, fish, molluscs, crustaceans and a wide range of bird life. There is a high species diversity and as such the lagoon is of great environmental importance; it has been designated as a nature reserve. Several types of vegetation thrive in the shallow water of the lagoon, and the dominating species are phanerogams (Alismatales) (31) including *P. oceanica* and *C. nodosa*. Where the environmental conditions are favourable, *C. nodosa* tends to form broad meadows, while *P. oceanica* appears in the form of reefs and atolls. The water is usually subjected to resuspension phenomena due to wind action. Water characteristics in terms of light attenuation have been compared with those of Mondello Bay, a small gulf located in the northern part of Sicily, and characterised by deeper and clearer water (Figure 1).

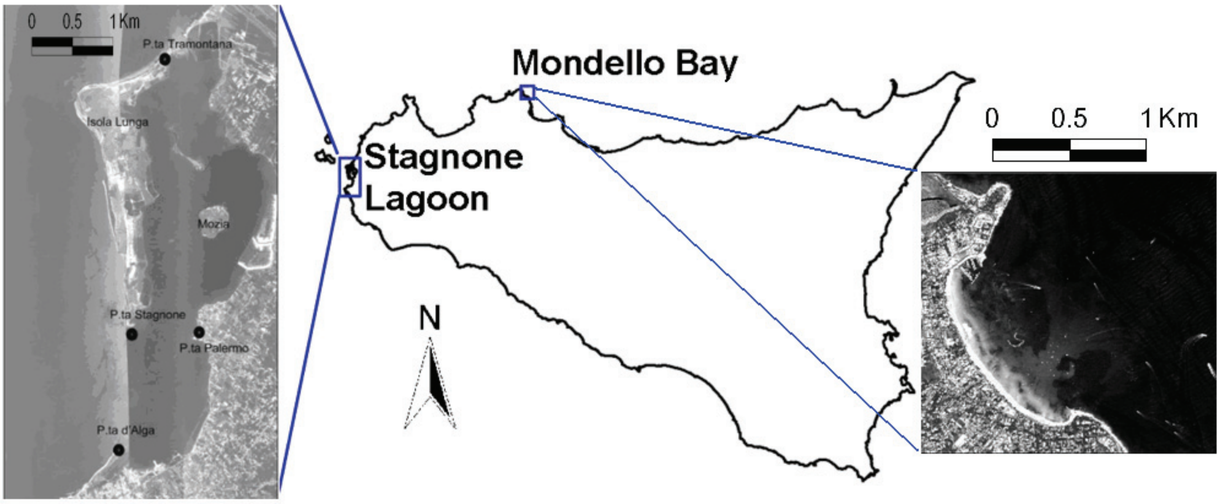

Figure 1: The location of the study areas in Sicily, with Stagnone Lagoon highlighted in the left image and Mondello Bay highlighted in the right image.

METHODS

Field campaigns were carried out in order to evaluate water attenuation parameters and spectral signatures of the submerged vegetation. Field measurements included: downwelling underwater and in air spectral irradiance, reflected spectral radiance on both submerged and emerged vegetation, and visual recognition of submerged vegetation using a bathyscope. The data collected have been processed in order to retrieve in-air spectral leaf optical properties, water column attenuation characteristics and underwater canopy reflectances.

Data acquisition - spectral measurements

All the data were positioned in UTM WGS84 zone 33 N using an EGNOS-enabled Magellan Meridian Platinum GPS unit. Visual observations of bottom type were made from the surface using a Cressi Sub bathyscope. Underwater and in-air downwelling spectral irradiances were acquired within the lagoon on 28th March 2007, using an Analytical Spectral Devices FieldSpec®ProFR spectroradiometer operating between 350 and 2500 nm with a spectral resolution of 3 nm for the region 350-1000 nm and 10 nm for the region 1000-2500 nm. A 10 metre long fibre optic cable fitted with a cosine diffuser was used to acquire underwater irradiances in the lagoon at depths between 0 and 1.2 m at 0.1 m intervals, in four well distributed regions of the study area, over vegetated bottom types. Water characteristics, in terms of light attenuation, are compared with those acquired in May 2005 in Mondello Bay which is characterised by deeper, clearer water.

To retrieve the optical properties of vegetation from the lagoon, measurements of the radiance of single layers of leaves were made using samples of the submerged vegetation spread out flat over white and dark reference panels in a single continuous layer. To calculate the spectral signatures (in terms of reflectance) of the submerged vegetation, spectral radiances of the vegetation and of a white reference panel are necessary. For this paper, spectral measurements acquired at the lagoon in September 2004 have also been used. Measurements were taken on *P. oceanica* and *C. nodosa* (5 scans each), with different water depths between 0.5 and 1.5 m at 0.5 m intervals, to take the influence of the water on spectral signatures into account. We are implicitly neglecting feasible differences due to different phenological periods. Furthermore, we are hypothesising that the spectral characteristics of the submerged vegetation in the neighbouring sites are similar, whereas water depth, turbidity, salinity, hydrodynamic and microclimatic conditions could actually influence both the leaf structure, and their contents in terms of photosynthetically active substances (e.g. chlorophyll and carotene).

The spectroradiometric measurements were carried out using a 25 degree optical lens and the distance from the target was approximately half a metre, measuring an area of ~ 0.5 m^2. In all cases reflectances were referenced to a calibrated white Labsphere Spectralon® reference panel.

Data processing - water column correction

To retrieve seabed reflectance, a correction for the effects of the overlying water column is necessary. To this aim, a simplified radiative transfer model of light in the water (21) was applied in which reflectance at the water surface is modelled as the sum of the contribution of the water column, plus the contribution of the bottom, Eq. (1):

$$R_{o^-}(\lambda_i) = R_\infty(\lambda_i)\cdot\left(1-\mathrm{e}^{(-2K_d z)}\right) + R_b(\lambda_i)\cdot\mathrm{e}^{(-2K_d z)} \tag{1}$$

where:

- $R_{0^-}(\lambda_i) = 0.545 \cdot R_{0^+}(\lambda_i)$ is the spectral reflectance just below the water surface (33);

- the factor 0.545 is the water-air transmission coefficient at the water surface;

- $R_{0^+}(\lambda_i)$ is spectral reflectance just above the water surface;

- $R_\infty(\lambda_i)$ is the spectral reflectance of an infinitely deep homogeneous water column;

- $R_b(\lambda_i)$ is bottom spectral reflectance;

- $K_d(\lambda_i)$ is the diffuse attenuation coefficient, and;

- z is the water depth.

The behaviour of the exponential terms in Eq. (1) model water column extinction; the greater the depth of the water the more negligible is the contribution of the bottom and the more the water column can be considered optically as infinitely deep. Similarly, the shallower the depth the greater is the contribution from bottom reflectance and the contribution of the water column becomes less important. The depth at which a water column can be considered as optically infinite depends on the wavelength as K_d is a spectral parameter. K_d can be calculated through the model of Sathyendranath and Platt (32) as a function of the absorption (a) and backscattering (b_b) coefficients, Eq. (2):

$$K_d(\lambda) = \left(a(\lambda_i)^2 + 2a(\lambda)b_b(\lambda_i)\right)^{0.5} \tag{2}$$

since $a(\lambda_i) >> b_b(\lambda_i)$ for most clear waters $K_d(\lambda)$ is largely determined by the absorption properties of the water (33). In this study we evaluated K_d directly from underwater measurements of spectral irradiance (34) as we measured downwelling spectral irradiance, Eq. (3):

$$K_d(\lambda, z) = \frac{\ln \dfrac{E_d(\lambda, z_1)}{E_d(\lambda, z_2)}}{z_2 - z_1} \tag{3}$$

where $E_d(\lambda, z_1)$ and $E_d(\lambda, z_2)$ are the *in situ* downwelling spectral irradiance at depths z_1 and z_2 below the water surface, respectively.

Assuming z_1 is equal to 0, we obtain:

$$E(z, \lambda) = E_{0^-}(\lambda) \cdot e^{-K_d(\lambda) \cdot z} \tag{4}$$

where E_0- represents the irradiance just below the water surface and z is a generic depth. Eq. (4) describes the vertical irradiance attenuation assuming the coefficient K_d for zenith sun. Neglecting skylight, whose distribution depends on solar elevation, Eq. (5) takes into account the directional behaviour of the light field in the upper layer of the sea (35):

$$E(z, \lambda) = E_{0^-}(\lambda) \cdot e^{-K_d(\lambda) \cdot z \big/ \cos j} \tag{5}$$

with:

$$\frac{\sin i}{\sin j} = \frac{\sin\left(90° - h_s\right)}{\sin j} = \frac{4}{3} \tag{6}$$

where h_s is the solar elevation and i, j are the absolute refraction angles for air and water.

The seagrass colonization depth (or depth limit) strongly depends on the underwater light penetration. Duarte (1991) related the seagrass depth limit z_c with the light extinction coefficient K_d at 555 nm (36). Recently, Duarte *et al.* (2007) (37) reported depth limit prediction equations for specific seagrass species, including the deep-growing *P. oceanica*:

$$\log z_c = 0.09 - 1.07 K_d(490) \tag{7}$$

However, the predicted colonization depth is a *potential* value since it may not be reached due to other factors including colonization time lags and/or an unsuitable substrate.

While the upper limit of seagrasses can be directly mapped using optical remote sensing, the lower depth limits cannot often be mapped, since it may be deeper than the value reachable in visible wavelengths due to the spectral visibility characterising the water. However, K_d can be used to infer the potential depth reachable by the submerged vegetation.

Data processing - leaf optical properties

Two methods were used to calculate the single leaf spectral reflectance and transmittance: the single leaf model of Lillesaeter (38) and the multiple scattering model of Miller (39). It was necessary to measure the radiance of a single leaf layer over an almost white and black background for both methods. The single leaf layer model states:

$$R_{leaf}(\lambda) = R(\lambda) + R_{bg}(\theta) \cdot \tau(\lambda)^2 \tag{8}$$

where $R(\lambda)$ is the required inherent leaf reflectance, $R_{leaf}(\lambda)$ is the measured leaf over a background reflectance, $R_{bg}(\lambda)$ is the reflectance of the background (reported below with the "white" or "black" suffixes) and $\tau(\lambda)$ is the leaf transmittance.

The leaf transmittance and inherent reflectance were obtained as:

$$\tau(\lambda)^2 = \frac{R_{leaf-white}(\lambda) - R_{leaf-black}(\lambda)}{R_{bg-white}(\lambda) - R_{bg-black}(\lambda)} \tag{9}$$

$$R(\lambda) = R_{leaf-white}(\lambda) - R_{bg-white}(\lambda,\theta) \cdot \tau(\lambda)^2 \tag{10}$$

The multiple scattering model gives more accurate results in comparison to the single leaf layer model, which tends to slightly overestimate derived values of transmittance and reflectance. It derives the leaf properties as:

$$R(\lambda) = \frac{R_{leaf-white}(\lambda) \cdot R_{bg-black}(\lambda,\theta) - R_{leaf-black}(\lambda) \cdot R_{bg-white}(\lambda,\theta)}{R_{bg-black}(\lambda,\theta) - R_{bg-white}(\lambda,\theta) - R_{bg-black}(\lambda,\theta) \cdot R_{bg-white}(\lambda,\theta) \cdot \left(R_{leaf-black}(\lambda) - R_{leaf-white}(\lambda)\right)} \tag{11}$$

$$\tau(\lambda)^2 = \frac{\left(R_{leaf-white}(\lambda) - R(\lambda)\right) \cdot \left(1 - R(\lambda) \cdot R_{bg-black}(\lambda)\right)}{R_{bg-white}(\lambda)} \tag{12}$$

Data processing - underwater spectral signatures

The reflectance signatures described in the previous section have been compared to those retrieved from directly measured radiances of seagrasses *in situ*. As reported in the data acquisition section, the spectral radiances were acquired in shallow water. Radiance measurements were made orthogonal to the solar azimuth to avoid both sun-glint and boat shadow. Following Mueller and Austin (40) the emergent spectral radiance $L_W(\lambda)$ was calculated by means of:

$$L_W(\lambda) = L_T(\lambda,\theta,\phi) - \rho(\theta) \cdot L_S(\lambda, 180° - \theta, \phi) \tag{13}$$

where:

θ is the aiming angle of the pistol grip from the zenith (45°);

ϕ is solar azimuth;

$L_T(\lambda, \theta, \phi)$ is spectral radiance measured pointing at the target;

$\rho(\theta)$ is a reflectivity factor of the water surface, assumed equal to 0.028 according to Mobley (41);

$L_S(\lambda, 180°-\theta, \phi)$ is the downwelling sky spectral radiance, measured aiming the spectroradiometer field-of-view in the opposite direction with regard to the L_T direction measurement.

The transmitted radiance from just beneath to just above the water surface is reduced by almost half (~0.55). This reduction is due to the radiance propagated through a narrow solid angle (Snell's law) and because the unpolarised interface transmittance $T(\theta) \approx 0.98$ for incidence angles less than about 40°. For larger θ, Kirk (34) shows that $T(\theta)$ is a function of θ and wind velocity. The spectral irradiance is reduced by $T(\theta)$ being independent of the solid view angle.

The ratio of the calculated emerging radiance $L_w(\lambda)$ to the calibrated radiance of the white panel $L_R(\lambda)$ allows the determination of the spectral signatures in terms of spectral reflectance $R_z(\lambda)$. $L_R(\lambda)$ is given by the product of the measured spectral radiance of the white panel multiplied by its calibration curve. Following Eq. (1) and neglecting R_∞ we can write:

$$R_{0^+}(\lambda_i) = 0.545 R_b(\lambda_i) \cdot e^{(-2K_d z)} \tag{14}$$

RESULTS

Water column correction

The underwater spectral irradiance peak in Stagnone Lagoon was approximately located at 550-580 nm, increasing slightly towards longer wavelengths with increasing depth (while the analogous measurements in Mondello Bay gave a spectral maximum in the blue region of the spectrum (~ 470-450 nm). This difference is due to the relatively high concentrations of optically active constituents of the water column in Stagnone Lagoon. The concentrations of optically active water quality constituents were acquired for the same period (unpublished data): total dissolved solids varied from 30.57 to 36.64 g/L and chlorophyll concentrations ranged from 1 to $2 \cdot 10^{-6}$ g/L, while in Mondello Bay total dissolved solids is ~ 37.12 g/L and chlorophyll concentrations is ~ $0.7 \cdot 10^{-6}$ g/L, Even though bottom vegetation could affect the optical properties of the water, no significant differences were found in calculated attenuation using the measurements obtained above either non-vegetated or vegetated bottoms. The $K_d(\lambda)$ values were calculated for both sites for the central wavelengths corresponding to MODIS, SeaWiFS and CZCS optical sensors (Table 1).

Table 1: Average parameters of water column attenuation (Eq. 4) above vegetated bottoms in the lagoon and open bay.

Centre wavelength /nm	Wavelength ranges /nm			$K_d(\lambda)$ /m^{-1} Stagnone di Marsala lagoon	$K_d(\lambda)$ /m^{-1} Mondello bay
	MODIS	SeaWiFs	CZCS		
412	405-420	402-422	-	0.57	0.07
443	438-448	433-453	433-453	0.48	0.08
490	483-493	480-500	-	0.23	0.04
510	-	500-520	510-530	0.20	0.01
531	526-536	-	-	0.17	0.01
555	546-556	545-565	540-560	0.16	0.11
670	662-672	660-680	660-680	0.30	0.31
678	673-683	-	-	0.31	0.33
756	743-753	745-785	-	1.49	0.86
865	862-877	845-885	700-800	2.29	0.66

The retrieved values of $K_d(\lambda)$ were compared with the values reported by Jerlov (35) for different water types and this comparison placed Stagnone Lagoon as a “type 3” water (coastal waters: moderate transparency). The same analysis carried out for Mondello Bay gave a class between types IA and II (oceanic types: intermediate transparency). Figure 2 shows attenuation values for the central band wavelengths described in Table 1.

An exponential law describing the spectral quantity $K_d(\lambda)$ allows us to estimate the virtual depths for which only a small part of the downwelling incoming irradiance (e.g. 1%) re-emerges after travelling through the water column firstly as downwelling irradiance, and then as upwelling irradiance. These values give us an idea of the depth of spectral visibility of an optical remote sensor in this type of water. For the lagoon water type, we found the depth of maximum visibility to be approximately 8 m at 562 nm, while for the bay water type it was nearly 100 m at 512 nm (Figure 3). In both cases we implicitly hypothesised that the bottom reflects 100% of the downwelling irradiance, while the actual reflection depends on the bottom type and is typically much lower (Figure 5). As a consequence, the actual visibility depth would be expected to be lower. Furthermore, depth of visibility should not be confused with the maximum depth of classification using remotely sensed data because it refers to a single wavelength and because the separability of two bottom types is more dependent on spectral value differences than on absolute values.

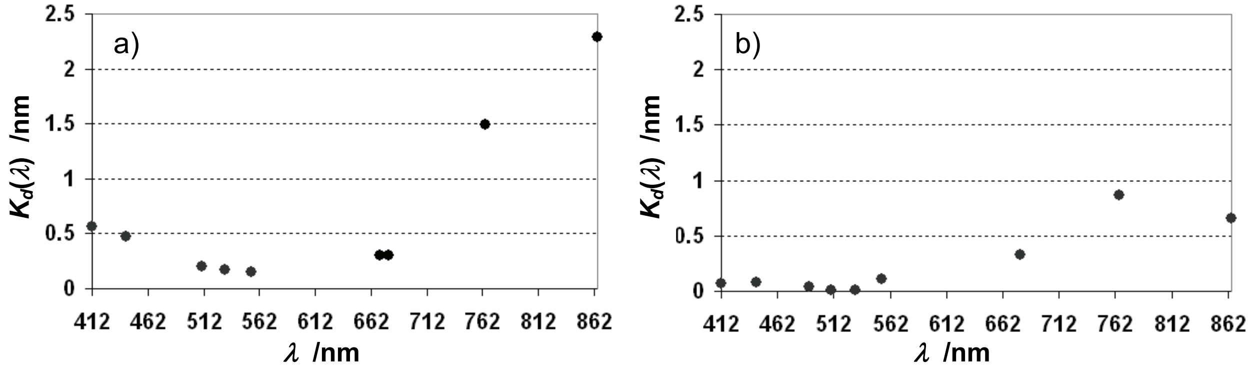

Figure 2: Water column diffuse attenuation coefficient values for each centre wavelength reported in Table 1. a) Stagnone di Marsala lagoon; b) Mondello Bay.

The analysis of the irradiance decay in the water shows that Stagnone Lagoon is characterised by strong attenuation compared to Mondello Bay where the spectral visibility depth could be up to 10 times greater (Figure 3).

Figure 4 shows the depth of maximum spectral visibility for the central band wavelengths described in Table 1. The depth of visibility is low in the blue region in both water bodies, probably due to strong backscattering phenomena, and it increases with increasing wavelength reaching a maximum at 562 nm in the lagoon water type, while the Mondello water type shows a visibility depth maximum at lower wavelengths (512 nm). At higher wavelengths the visibility depth decreases again in the red and near infrared because of strong absorption by the water itself. The comparison with the predicted depth limit of seagrass colonization shows that the 531 and 555 nm wavebands are suitable to map the lower limit of the submerged vegetation in the lagoon water type, while the 510 and 531 nm wavebands have enough visibility to map the submerged lower limit in the bay water type.

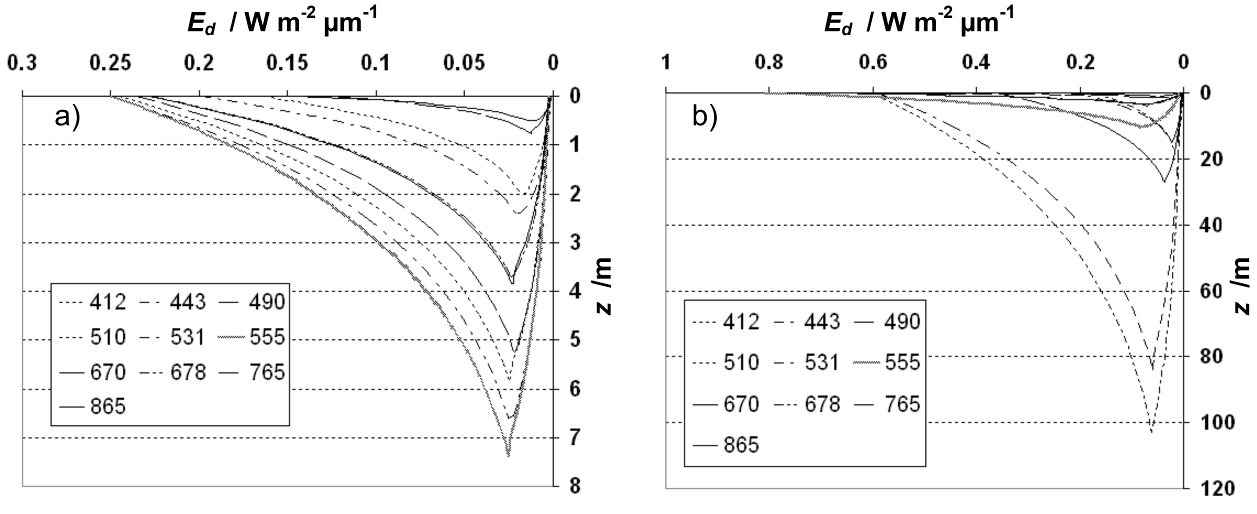

Figure 3: Calculated irradiance decay in the waters for the centre wavelengths presented in Table 1. a) Stagnone di Marsala lagoon; b) Mondello Bay.

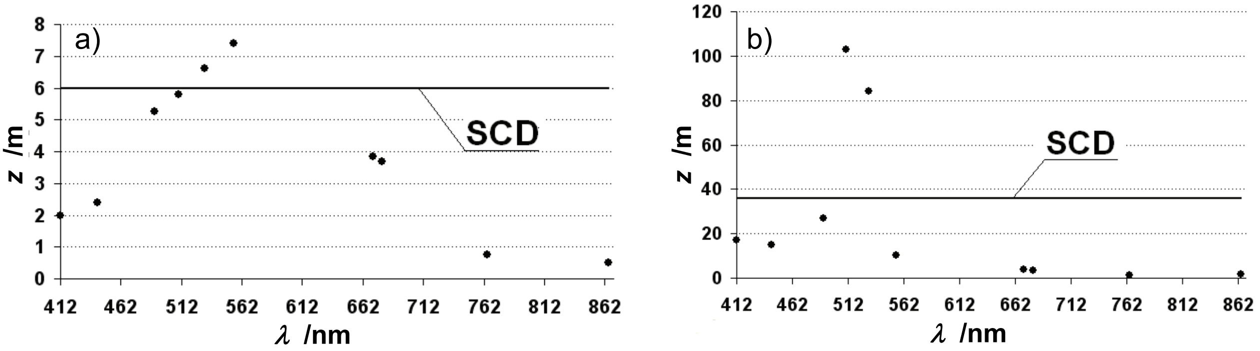

Figure 4: Spectral visibility depth and predicted limit of seagrass colonization depth (SCD) according to Duarte (34), for the centre wavelengths presented in Table 1. a) Stagnone di Marsala lagoon; b) Mondello Bay.

In Eq. (1), the value of $R_{\infty}(\lambda_i)$ characterises an optically infinite water column. Figure 3a (Stagnone Lagoon) shows that above 8 m, this optical type of water could be considered infinitely deep over the visible part of the spectrum. As the maximum depth is only ~ 4 m, it was not possible to measure $R_{\infty}(\lambda_i)$. Thus, for the retrieval of bottom reflectance in the lagoon the term $R_{\infty}(\lambda_i)$ in Eq. (1) was neglected, implying that the contribution of the water column is negligible in comparison to that of the bottom. To test this hypothesis, we calculated spectral reflectance using $R_{\infty}(\lambda_i)$ values acquired near the southern mouth of the lagoon (≈ 4 m in depth) and we compared these values with those calculated neglecting $R_{\infty}(\lambda_i)$ for a number of common bottom types. The error neglecting the water column component is less than 10% in the visible part of the spectrum and is higher at longer wavelengths (Table 2).

Table 2: Errors in the calculation of bottom reflectance neglecting the water column contribution.

	up to 650 nm	650 - 900 nm
P. oceanica	± 10%	± 5%
P. oceanica with epiphytes	± 3%	± 6%
C. nodosum	± 5%	± 25%

Leaf optical properties

Leaves of both species displayed strong absorbance in the 450-700 nm range with a decrease near 550 nm where reflectance and transmittance are greater (Figure 5). In the near-infrared portion of the spectrum (700-950 nm), both reflectance and transmittance are high whereas absorbance is very low. Reflectance and transmittance showed an opposite pattern, with a small peak in both properties at 550 nm. Both models give similar patterns although the multiple scattering model differs from the single layer in transmittance values especially for *C. nodosum*.

P. oceanica had slightly lower reflectance and transmittance compared to *C. nodosum* in both the visible and the near infrared parts of the spectrum. This spectral similarity causes difficulties in the use of remote sensing images for their differentiation. Also the different phenological cycles of these species could represent a further confusion factor in the classification process, especially using the current sensors characterised by a low spectral resolution.

Epiphytes significantly increase apparent transmittance and reflectance in visible wavelengths, with a corresponding decrease in absorbance, while both reflectance and transmittance are reduced in the near infrared. Furthermore, the red edge is considerably flattened and the prominent green reflectance peak is reduced when epiphytes are present. For mapping purposes the presence of epiphytes represents a good tracer of *P. oceanica* presence: in any case the best phenological period to map the meadows is July - August for Mediterranean areas.

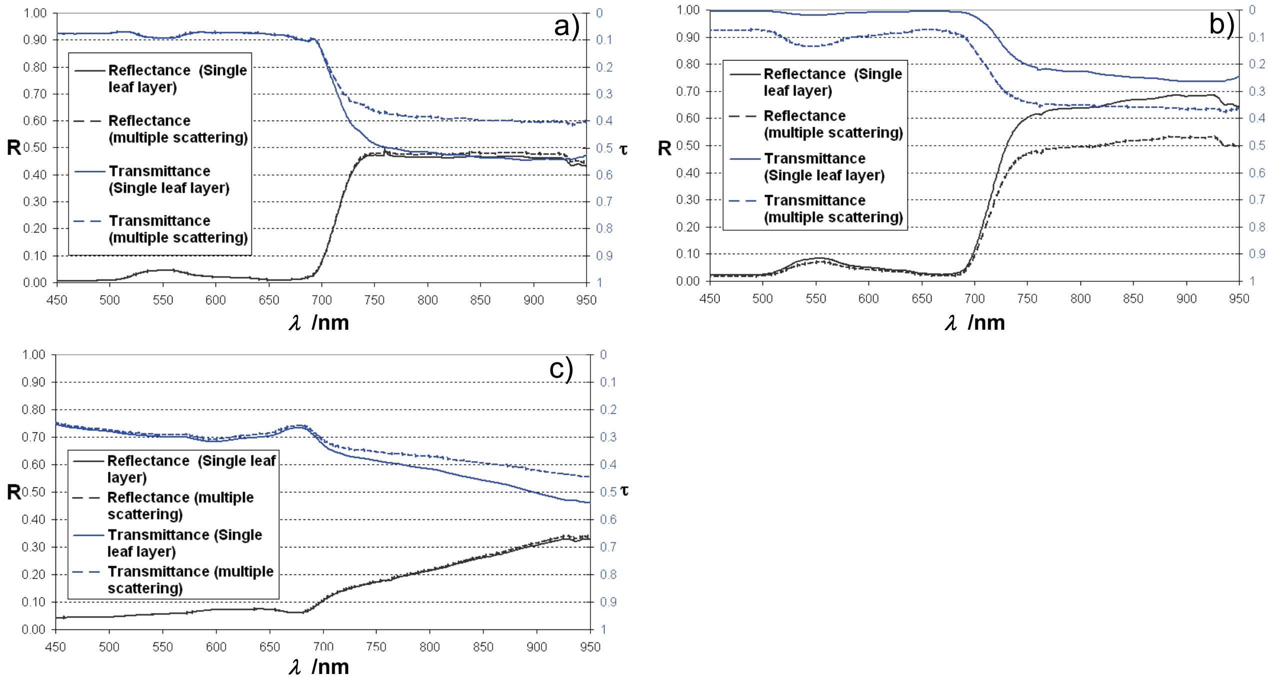

Figure 5: Calculated leaf reflectance (R) and transmittance (τ) of extracted seagrass leaves. a) P. oceanica; b) C. nodosum; c) P. oceanica with epiphytes. Continuous lines represent the leaf optical property calculated using the single leaf layer model (29) while dotted lines are calculated using the multiple scattering model of Miller (30).

Underwater spectral signatures

Eq. (15) allows us to extrapolate the spectral signatures of the different vegetation types from *in situ* measurements to remove the influence of the overlying water column. They are compared to the calculated in-air reflectances in Figure 6. These results show that for *P. oceanica* with and without epiphytes calculated *in situ* reflectances are greater than those for the either of the single leaf layer in air reflectances. The red-edge feature for all *in situ* spectra is lost due to strong water attenuation and the very low signal recorded at these wavelengths at the water surface. Calculated *in situ* reflectance for *C. nodosum* closely approximates the shape and magnitude of the multiple scattering method of Miller; for this species the single scattering method appears to significantly overestimate reflectance. The shapes of the *in situ* spectra in *P. oceanica* peak at longer wavelengths in the visible spectral region than do the curves for the in-air measured reflectances.

Below 450 nm and above 700 nm the mismatch could be due to the application of the Muller and Austin method used for the derivation of emergent spectral radiances; for these wavelengths, the contribution of the reflected radiance (ρL_S) is approximately the same of the water leaving radiance (L_W).

CONCLUSIONS

In this paper we have investigated the problem of the accurate derivation of spectral signatures of submerged vegetation when it is difficult to obtain direct measurements of such canopies *in situ* and where most measurements of spectral signatures are made above surface on extracted samples (e.g. 20,42). Such spectral spectral signatures are often required for the use of some classification algorithms.

For the first time, we have compared reflectances measured on extracted single layer leaf samples to those retrieved from subsurface reflectance measurements. The research has shown that in shallow and/or clear waters accurate reflectances of plant canopies measured *in situ* can be retrieved, providing that additional measurements of water column optical properties are also made to characterise K_d and other useful information. The method based on the Moussa equation (14) to extrapolate the bottom reflectance has been shown to work well for the shallow lagoonal waters considered here. Optical *in situ* measurements involving the calculation of K_d are preferable to in-air measurements made on extracted leaf or tissue samples because such measurements do not take into account the effects of the canopy structure on the reflectance. Reflectances of a canopy can be expected to vary significantly from those of stacked layers of leaves.

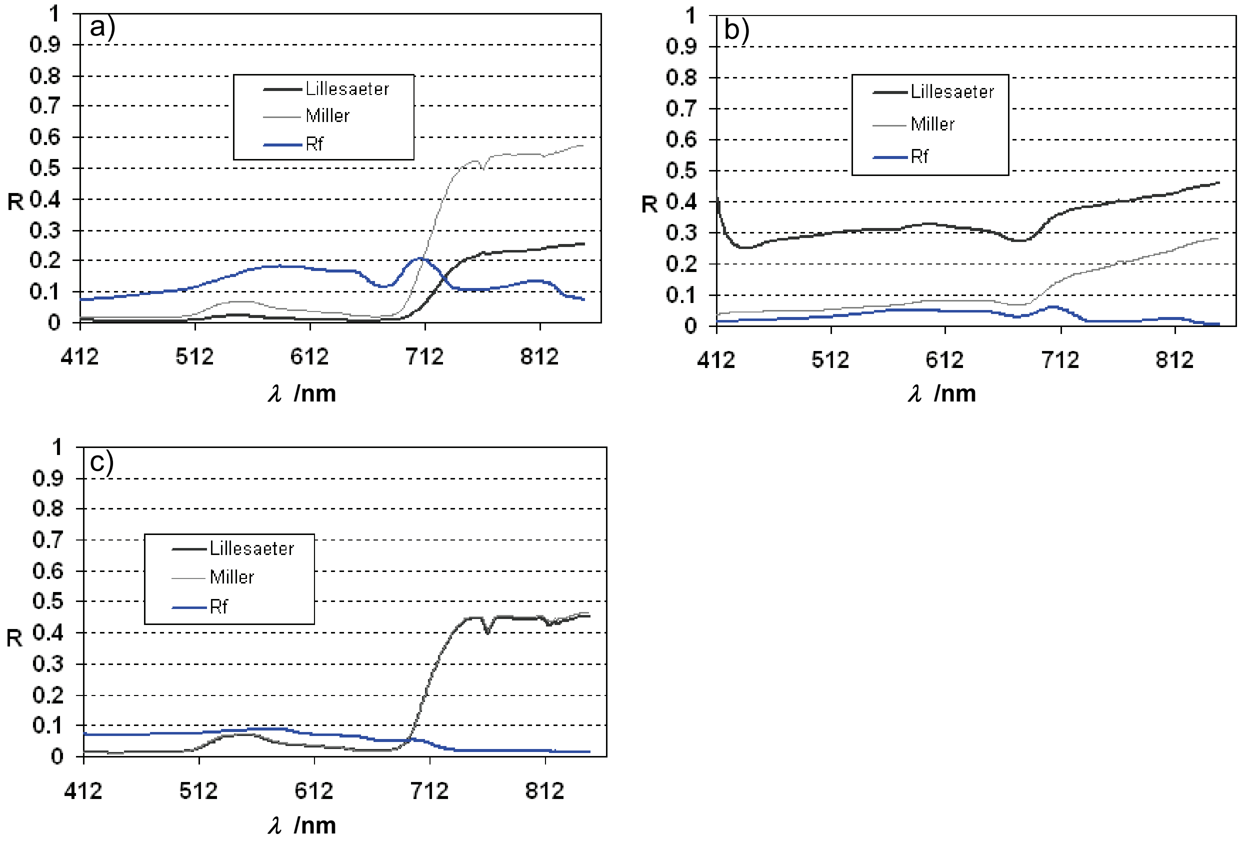

Figure 6: Extrapolated spectral reflectance signatures (Rf) in the case of an absent overlying water column (blue lines) from signatures measured at several depths and spectral signatures of the leaf calculated following the Lillesaeter single leaf model (black lines) and the Miller multiple scattering model (grey lines). a) P. oceanica; b) P. oceanica with epiphytes; c) C. nodosum.

Comparison between the extrapolated spectral signatures and leaf reflectances measured over the different backgrounds shows good agreement with the Miller multiple scattering model in the visible part of the spectrum. In the near infrared there is a sharp disagreement between the two methods, largely attributable to the absence of *in situ* water leaving signal at these wavelengths.

Whilst most investigations of the properties of submersed aquatic vegetation have been performed on extracted plant samples, the further investigation of the optical properties of vegetation canopies *in situ* is warranted. As stated, extracted leaf samples laid out as a single layer do little to mimic actual reflectances of leaves in a canopy. Indeed, in some cases the stacks of leaves measured can be up to 7 layers deep (20). As such, they give only a relative measure of differences in spectral reflectance between species. In this study, we have for the first time presented the optical properties for both seagrass species under study in terms of their reflectance, transmittance and absorbtance characteristics, parameters useful as input in to radiative transfer models of shallow-water systems. These show that the optical properties of the two species are similar, which has implications for their classification and characterisation using remote sensing methods.

The optical properties of many submersed macrophytic species are significantly altered when epiphytes are present which most frequently increase during the growing season (20). Epiphytes are likely to have a significant effect on above surface reflectances if present on leaf surfaces. In this study, the influence of epiphytes was found dramatically to influence the signal from *P. oceanica*, where, mimicking the results found by Fyfe (20), their effect was to flatten visible reflectance and to significantly reduce near infrared reflectance. But the influence of epiphytes in this species is much more significant than it is on *C. nodosum* suggesting a potentially useful means for separating the species spectrally. The same differential effect of epiphytes on seagrass species has also been noted by others (e.g. 20).

Similarly, the phenological cycle of the species themselves can also significantly affect measured reflectance (20). Although the spectral signature of the submerged vegetation is expected to vary with phenological period, one aim of this research is the determination of spectral signatures of some of the most important Mediterranean submerged vegetation species, during the periods suitable for optical remote sensing acquisitions.

This work has also highlighted the possibility, from *in situ* optical measurements, to predict and hence to map the lower limits of submerged vegetation and to discriminate different submerged vegetation types using different wavebands in the visible spectrum. Predictions using the Duarte equation (37) are sensible, showing a predicted lower limit for seagrass colonisation in the lagoon of 6 m and ~35 m in the bay, the latter being close to actual depth limits found for seagrasses in Mondello Bay. Our method, based on the calculation of the diffuse attenuation coefficient allows, through an empirical relationship, to determine which wavebands are suitable to map the deep limit of the submerged vegetation or at least to infer its potential value. Indeed, measurements confirmed the strong attenuation of light in the lagoon but showed that the depth of maximum penetration (~ 8 m at 562 nm) exceeded physical depth limits in the lagoon (up to 4 m). Thus, there was a broad range of wavelengths in the 530 to 555 nm region capable of reaching the bottom of the lagoon. As such, given sufficient spectral resolution, remote sensing should provide a useful tool to map the enterie lagoon. In contrast, light penetration in Mondello Bay exceeded 80 m. To detect seagrass extent and density, it is clear that a remote sensor will need to collect information within the spectral range where attenuation by the water column is low. From our results, the range between 450 to 570 nm is the most appropriate range in terms of light penetration and suggests that a remote sensor needs to have as many spectral bands as possible within this range. However, species discrimination may be limited, where the main differences between seagrass and macroalgal species tend to be found in the green to red parts of the spectrum (20,42). Clearly this has implications for monitoring and discrimination of species in deeper open waters. Furthermore, the absence of sun-glint phenomena during acquisition, and low winds are also required to reduce extraneous signals. In our field sites wind usually builds up around midday due to thermal phenomena.

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