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A comparison of spectral macroalgae taxa separability methods using an extensive spectral library

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ABSTRACT

Remote sensing is one the most promising approaches to coastal area cartography, including mapping algae forests. After discrimination of algal communities from other benthic habitats, next step is species discrimination (from other algae). Spectral signature provides the most complete remote description to characterize any algae. In this work spectral signatures are studied from the point of view of taxa separability to assess the potential use of remote sensors to map seaweed in coastal waters. Three approaches were tested: Red-Green-Brown colorimetry (sRGB), optimal spectral boundary separation based on True Skill Statistics (TSS-OB), and pigment absorbance band detection by Derivative Spectroscopy (DS). An extensive spectral library of 36 algal species present in the Atlantic Galician coast (NW of Spain) is used to test and validate these methods. The results show that the three broad taxa of red, green and brown algae can be separated by all three methods (Cohen's kappa of 0.697, 0.891 and 0.910, respectively). The TSS-OB and the DS approaches provide almost perfect classification (despite some anomalous specimens), with DS being slightly better. The sRGB approach, useful for in situ photographic classification, also provides good results.

1. Introduction

Submerged vegetation, seagrass and macroalgal communities, play an ecologically important functional role in coastal ecosystems as they serve as habitats [1–3], mating and nursery grounds [4,5], feeding areas [6,7], and refuge [8,9] for many species. Moreover, they have an important contribution to primary production [10], sediment stabilization and coastline protection [11]. Despite their ecological importance, in recent years a decrease in the extension of these communities has been observed, and although many studies have addressed this problem [12–16] the causes of this degradation are not yet known.

Since the 1980's these studies have taken advantage of remote sensing because of its large coverage, periodicity, multispectral information (including non-visible regions of the spectrum) and low relative cost (in €/km^2) compared with on field surveys. These capabilities allow researchers to monitor large areas [17] repeatedly, studying the distribution and dynamics of macroalgae forests with reduced costs and sampling time [18–26].

One of the most important challenges in these works has been to distinguish algae from other substrates (underwater or emerged; [27]); shallow water models show that up to 19 m of very clean sea water these differences can be appreciated in the visible range [28], although this limit can be much smaller depending on water conditions. One step further is to classify different algae groups apart (or even species), for example, to monitor retreat of an indigenous algal species often associated with the spreading of an alien one [29,30]. This goal can be addressed because of the capability to detect algal optical properties, that is the absorption (by pigments) and reflection (by tissular structures) of light, from remote sensing images. Pigments of each phylum (and species), together with tissular morphology and cellular architecture, shape the spectral signature of each algae (the value of the spectral reflectance for each wavelength in the optical range). These optical properties are directly related to the biophysical characteristics that are used to perform algae classification in three different phyla (Table 1), following Lee [31]:

i.) The phylum Rhodophyta, also called “red algae”, is composed by a large assemblage of between 2500 and 6000 species [32]. Their characteristic pigments are chlorophyll *a* (Chl-*a*) and *d*, carotenoids and phycobiliproteins (mainly phycocyanin and phycoerythrin); the latter being responsible for their red color.
ii.) The phylum Clorophyta, also called “green algae”, are primarily

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Table 1
Macroalgae biophysical features.

	Rhodophyta (red algae)	Clorophyta (green algae)	Heterokontophyta (brown algae)
Chl-*a*	X	X	X
Chl-*b*	–	X	–
Chl-*c*1	–	–	X
Chl-*c*2	–	–	X
Chl-*d*	X	–	–
Carotenoids	X	X (lutein)	X (fucoxanthin)
Phycocyanin	X	–	–
Phycoerythrin	X	–	–

freshwater algae; only about 10% of them are marine [33]. Their characteristic pigments are similar to those of higher plants: Chl-*a* and Chl-*b*, cause of their common green color, and carotenoids (mainly lutein).

iii.) The phylum Heterokontophyta, specifically the family Phaeophyceae or "brown algae", contains the species of largest algae, including kelp that form forests such as *Sargassum muticum*, *Macrocystis* spp., etc. They derive their characteristic color from the large amounts of the carotenoid fucoxanthin as well as from any phaeophycean tannins that might be present. They have also Chl-*a*, and chlorophylls *c*1, and *c*2.

All these pigments shape the spectral signature of each alga. The more similar two species are (due mostly to their pigment contents), the more similar are their signatures. In this sense, having a complete spectral library can drastically help remote sensing classification [34] or assessment of biophysical conditions [35]. Optical remote sensing is based on sampling of spectral signatures at small windows (bands). If we know in detail the reflectance spectrum of a species of interest, we can simulate how it would appear when observed through the water column, and compare this with the remote sensing reflectance spectrum; optimization algorithms can also derive water column properties from this comparison [36].

Other authors, not focused on cartography, have also pointed out that having an extensive spectral library would help overcome limitations associated to multispectral remote sensing such as the need for extensive collection of in situ data to calibrate sensor dependent spectral response, or depth-dependent water column correction [37]. Despite these applications, macroalgae libraries in the literature are scarce and incomplete because of the cost of measurement processes and the lack of interested industries (contrary to minerals, for example). Some examples of algae libraries can be found in Kutser et al. [39,49], Vahtmäe et al. [41], Thorhaug et al. [42], Pu et al. [43], García et al. [44].

Different remote sensing approaches of algae classification have been used both with multispectral [45] or hyperspectral [46,47] satellite sensors. Remote sensing classification methods highlight distinctive spectral features, either in pre-selected bands (e.g., from a multispectral sensor) or in ad hoc bands, best adapted to the purposes of a study. For classifications based on spectral libraries, characteristic features are often assessed from the in-air spectra, considering optimal viewing conditions without the water column attenuating some of them (that is, classification of submerged vegetation will be worse than the best in-air classification). Among the approaches already published we will focus on the following:

RGB-colorimetry: As can be inferred from phyla classification, a major taxonomic feature of macrophytes is their visual color, or otherwise RGB components determined from their reflectance spectra. This simple and cheap approach (as only a digital camera is needed) has already been proposed to quantitatively describe seawater color [48] and assess biochemical properties of living organisms: microalgae [49], and corals [50].

True Skill Statistics Optimal Band (TSS-OB): Kotta et al. [37] presented a method to separate taxa from their in-air spectra taking into account the statistical distribution of algae spectra in a library. From standardized spectra True Skill Statistics (TSS) [51] is computed to determine the optimal boundaries between spectral reflectances that best separate every pair of different phyla, thus obtaining binary rules to perform the final classification using a classification and regression tree (CART).

Derivative Spectroscopy (DS): DS techniques have been extensively used to assess information regarding light absorption by significant water constituents [38,52–55]. As far as most differences in the visible range between macroalgae phyla are caused by absorption bands of their different pigments, spectral derivative analysis can be used to highlight absorption features [56–58], thus allowing quantification of "absorption troughs" [59]. DS points out differences in pigmentation and/or structural properties between targets [60,61], allowing macrophyte discrimination [54,62].

The objective of the present study is to compare the spectral separability capabilities of the three above described classification methodologies (RGB-colorimetry, TSS-OB and DS) introducing and using an extensive library with spectral signatures of 36 macroalgal species found in the eastern coast of the Atlantic Ocean.

2. Methodology

2.1. Algae library and study area

The study area where algae specimens were collected is located into the Ría de A Coruña, a small oceanic embayment (around 16 km^2) Northwest of Galicia (NW Spain). The Ría has a length of 5 km with a NS orientation in its main axis and a maximum width of 3 km at its mouth [63] (Fig. 1). This area contains rocky coasts with cliffs combined with sandy beaches having semi-diurnal tidal regime with a range of 3 m.

An extensive field campaign was carried out on 22nd and 23rd August 2009, in Praia de Canabal, a sandy beach 40 m long, placed in a small and protected bay located close to A Coruña city (Fig. 1, inset). For the collection of the present spectral library of macroalgae, samples of both wet algae floating near the water line and dried on the sand beach were measured on the shore nearby. Therefore, during this campaign every specimen found at different points along the beach (intertidal or subtidal) was sampled, including specimens in different health states, humidity conditions or state of growth. With the aim of generating a comprehensive spectral library, each gathered specimen was documented, photographed and its spectra measured immediately after collection to minimize water evaporation or specimen degradation by ambient temperature or handling. A total of 134 specimens from 36 different species were acquired: 16 brown, 17 red, and 3 green algae (see Table 2).

Spectral reflectance measurements were performed on the beach using a spectroradiometer (ASD FieldSpec Pro FR, Analytical Spectral Devices, Boulder, CO, US) with a spectral range of 350–2500 nm and a spectral sampling interval of 1.4 nm for the VNIR detector and 2.0 nm for the SWIR detector. Each specimen was illuminated with a continuous spectrum halogen lamp through a contact probe (ASD High Intensity Contact Probe, Analytical Spectral Devices, Boulder, CO, US). The specimens covered completely the contact probe window, that was held in tight contact to avoid specular reflections of the tissue-air interfaces (improving optical contact simulated the optical behavior of submerged samples), but not exerting much pressure that could affect the specimens vegetal structure. A fiber-optic cable, having a field of view of 25°, thus, spanning an area of several square centimeters of the specimen, transmitted the reflected light to the spectroradiometer (Fig. 2). A Spectralon® white reference was used to calibrate the reflectance spectra that were computed by the spectroradiometer control software. Ten measurements were performed of each specimen in order to compute spectral averages, thus reducing noise and discarding accidental measurement errors.