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Spectral mixture of intertidal marine macroalgae around the island of Helgoland (Germany, North Sea)

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ABSTRACT

The monitoring of emersed and submersed aquatic macrophytes using airborne hyperspectral remote sensing is an innovative method to identify and quantify algal populations at a landscape scale. In general, a high spectral resolution means that one has to accept a lower spatial resolution. This is often considered problematic for the mapping of patchily distributed intertidal macroalgal vegetation. Analysis of sub-pixel information of visually dominant algal species and vegetation units and their respective coverage is therefore of great interest. In this context, it is necessary to analyze the spectral and spatial mixture of macroalgae. This paper presents an experimental laboratory approach to analyze the spectral reflectance characteristics as well as the spectral mixture behaviour of common biomass-dominant macroalgae growing at the intertidal rocky shores of Helgoland (North Sea, Germany). It became evident that unmixing of spectral signatures can hardly be performed between species of the same genus or family due to their strong spectral analogies. At a higher taxonomic level, however, red-, green- and brown algae can be distinguished as groups via derivative analysis as well as with spectral slope calculation between specific wavelengths in the 400–680 nm spectral region. Both methods described the spectral mixing behaviour with high accuracy (Pearson's $R^2 > 0.8$). The newly introduced linear slope unmixing achieved best unmixing results in comparison to two state-of-the-art unmixing approaches.

1. Introduction

The rocky shore at the island of Helgoland represents a unique habitat at the North Sea coast of Germany. A mixture of diverse marine red algae (Rhodophyta), green algae (Chlorophyta) and brown algae (Phaeophyceae), associated with many marine invertebrates and fish, are growing in the inter- and subtidal zone in an area of approximately 35 sq. km (Janke, 1990). Detailed information about the spatial distribution of macroalgae is important, as they are an integral component of coastal ecosystems and provide food, habitat and shelter for many marine live forms (Andrews, 1979; Cavanaugh et al., 2010). Traditional field sampling techniques along transects, within quadrants or subsampling of randomly-stratified points are normally applied to describe the quantitative cover or abundance of species; they are, however, unable to capture the patchy spatial distribution of marine macroalgae at a landscape scale (Nelson et al., 2006). An alternative mapping technique is aerial photography, which is used since the 1980s (Malthus and George, 1997). Nevertheless, difficulties in the visual interpretation of analogue aerial images and high costs related to long-term studies prevented their further establishment. Multi-band photography is useful for mapping emergent aquatic plants, but turned out to be inappropriate to discriminate submersed species (Malthus and George, 1997). During the 1990s, multispectral sensors like Landsat became common, but the broad spectral bands are inappropriate to detect the spectral features characteristic for aquatic vegetation such as the specific chlorophyll absorption features between 600 and 700 nm (Dekker and Seyhan, 1988). The advent of hyperspectral remote sensing technology marks a major step forward to the mapping of macroalgae including the differentiation between red, green and brown algae as well as the identification of floating seaweeds. Bajjouk et al. (1996) demonstrated that narrow spectral bands in the visible

Abbreviations: ASD, Analytical Spectral Devices; FOV, field of view; AP, actual proportion; ASC, average slope classifier; Ascnod, *Ascophyllum nodosum*; BS-Plot, [B]est [S]lopes for unmixing plot; Chocri, *Chondrus crispus*; CP, calculated proportion; Fucser, *Fucus serratus*; Fucves, *Fucus vesiculosus*; Lamdig, *Laminaria digitata*; Masste, *Mastocarpus stellatus*; MDa, rithmetic mean of the deviations; MTMF, Mixture Tuned Matched Filtering; QA, overall accuracy of quarter classifier; QC, quarter classifier; R^2, Pearson's coefficient of determination; ROSIS^2, Reflective Optics System Imaging Spectrometer; Sarmut, *Sargassum muticum*; SDA, spectral derivative analysis; SRC, slope range classifier; Ulvlac, *Ulva lactuca*; Ulvsp, *Ulva [Enteromorpha]* sp.

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wavelengths of the airborne *casi*-spectrometer are most suitable for discriminating algae. Furthermore they demonstrated that reflectance spectra of macroalgae reveal spectral characteristics similar to those of terrestrial vegetation, namely a low reflectance in the visible part of the spectrum (VIS) and a significant increase towards the near infrared (NIR). Malthus and George (1997) were the first to state the strong attenuation effect of water, which prevents the monitoring of submersed algae at wavelengths beyond 700 nm. They successfully used the Daedalus Airborne Thematic Mapper to distinguish between submersed, floating-leaved and emergent algae; they discovered the green/red (626 nm/673 nm) wavelengths to be suitable to separate these algal classes. $ROSIS^2$ data allowed the mapping of dominant intertidal macrophyte vegetation and general intertidal structures, but mixed vegetation types could not be identified (Thiemann and Bartsch, 2005; Henning et al., 2007).

A study based on the spectral analysis of three seagrasses also identified wavelengths in the VIS to be most promising for the discrimination of submersed, floating and emergent aquatic species: Fyfe (2003) delineated that these species were spectrally distinct, regardless of being fouled by epibionts or not. Pinnel et al. (2004) published a new algorithm applying a linear separation of freshwater macrophytes in the spectral range of 465–700 nm on water column corrected HyMAP data; the water column correction removed the influence of the water cover on vegetation spectra resulting in an enhanced ability to distinguish macrophytic vegetation at species level.

Hyperspectral remote sensing techniques possess a high potential to identify and monitor emerged and submersed aquatic species but there exists a fundamental trade-off between spatial resolution, spectral resolution, and radiometric sensitivity resulting in a lower spatial resolution when the spectral resolution is enhanced (Eismann and Hardie, 2005). These restrictions raise the importance of information at a sub-pixel scale. A commonly accepted procedure to separate the spectral response of different constituents in a pixel into a set of constituent spectra is spectral unmixing (Keshava and Mustard, 2002). Classic linear unmixing techniques have been successfully applied to derive estimates of coral reef substratum proportions (Hedley et al., 2003; Goodman and Ustin, 2007); this method, however, is not yet operational for coastal environments (Hedley et al., 2003). To perform a successful unmixing, it is essential both to understand the spectral mixture behaviour (mixture equation) of macroalgal reflectance spectra and to determine the taxonomic scale at which unmixing is promising. Empirical research to analyze the spectral mixing of macroalgae has not been done yet; therefore the focus of this study was to investigate the spectral mixing behaviour of characteristic intertidal macroalgal species which occur at Helgoland, but are also widely distributed along cold-temperate North East Atlantic coastlines (Lüning, 1985).

To analyze whether algal species can be spectrally distinguished, their spectral behaviour has to be investigated using standardized laboratory protocols. The spectral reflectance can be measured with field or laboratory spectrometers, which are characterized both by a very high spectral resolution and by a high amount of spectral bands. A standardized measurement protocol eliminates effects due to changing illumination, varying water levels and different water content of algal tissues which are present in the field. Thus, laboratory derived measuring results mark the outer limits for the applicability of field, airborne or spaceborne spectrometry.

The study presented here has four main objectives: (1) to specify the level of taxonomic resolution at which unmixing of pure reflectance spectra of macroalgae is promising, (2) to identify wavelengths suitable for their spectral unmixing, (3) to determine, whether linear regression equations can describe the spectral mixture behaviour of macroalgae, (4) to describe the spectral behaviour of macroalgae during desiccation (simulating differential water loss of species during low tides), and (5) to combine and compare the findings with state-of-the-art unmixing algorithms.

Table 1
Investigated macroalgal species pairs and their corresponding group: brown algae (BA), red algae (RA) and green algae (GA).

Alga 1	Alga 2
Fucus serratus (BA, Fucser)	*Fucus vesiculosus* (BA, Fucves)
Fucus serratus (BA, Fucser)	*Ascophyllum nodosum* (BA, Ascnod)
Fucus serratus (BA, Fucser)	*Laminaria digitata* (BA, Lamdig)
Fucus serratus (BA, Fucser)	*Sargassum muticum* (BA, Sarmut)
Sargassum muticum (BA, Sarmut)	*Laminaria digitata* (BA, Lamdig)
Fucus serratus (BA, Fucser)	*Mastocarpus stellatus* (RA, Masste)
Fucus serratus (BA, Fucser)	*Ulva lactuca* (GA, Ulvlac)
Mastocarpus stellatus (RA, Masste)	*Ulva lactuca* (GA, Ulvlac)
Mastocarpus stellatus (RA, Masste)	*Chondrus crispus* (RA, Chocri)
Ulva lactuca (GA, Ulvlac)	*Ulva [Enteromorpha]* sp. (GA, Ulvsp)

The paper is organized as follows. Section 2 describes the algae material, the experimental framework and the methods used to evaluate the spectral mixture behaviour of macroalgae. Section 3 presents and discusses the results of the spectral mixture analysis and effects of desiccation. Finally, Section 4 summarizes the main findings.

2. Materials and methods

2.1. Algal material

The intertidal macroalgae used for spectral analysis were collected during a field campaign at the island of Helgoland (Germany, North Sea) between 17th May and 6th June 2010. Algal thalli were randomly collected at the north-eastern wave-cut platform, in the north-eastern harbour or at the Kringel area (for localities see Bartsch and Tittley, 2004) during low tide and were instantly carried to the laboratory of the Biologische Anstalt Helgoland. Visually healthy, well-pigmented material without epiphytes has been collected. Before spectral analysis, the algae were kept darkened in running seawater at ambient seawater temperatures for a maximum of 12 h. The following species were used: Phaeophyceae: *Fucus serratus* (Fucser), *Fucus vesiculosus* (Fucves), *Ascophyllum nodosum* (Ascnod), *Laminaria digitata* (Lamdig), *Sargassum muticum* (Sarmut); Rhodophyta: *Mastocarpus stellatus* (Masste), *Chondrus crispus* (Chocri); Chlorophyta: *Ulva lactuca* (Ulvlac), *Ulva [Enteromorpha]* sp. (Ulvsp).

2.2. Experimental set-up

The spectral mixture analysis of macroalgae is based on spectra obtained under laboratory conditions using living individuals. The measurements were performed in a darkened laboratory under ambient air temperatures (Fig. 1); the algae were spread at the bottom of five black polyethylene tanks with a bottom diameter of 45 cm. Tanks with high walls (35 cm) were used to reduce adjacency effects (Richter et al., 2006). Measurements of the spectral response of the tank bottom showed that reflectances in the spectral range of 400–700 nm were constantly below 5%.

In each recording series, two species of macroalgae were measured in varying ratios from 0 to 100% in 25% steps (Table 1): the bottom of a tank was covered according to a pie-principle with algal mixture ratios of 100%, 75%: 25% and 50%: 50%. The algae covered the tank bottom within the field of view of the spectrometer; the sample structure was dense but not multilayered (see Fig. 1A, example photo). The species as well as the species combinations investigated represent the most dominant assemblages at the rocky intertidal flats of Helgoland (Bartsch and Tittley, 2004). The wet