Quantification of bio-physical intertidal sediment properties using hyperspectral measurements

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ABSTRACT:
In this work, the use of hyperspectral remote sensing for the quantification of bio-physical characteristics of the surface intertidal sediments is explored.
A two-step approach is followed. Firstly, algorithms based on absorption features for the quantification of bio-physical sediment properties are developed using laboratory measurements of known sediment mixture compositions. Secondly, the appropriateness of the method in natural conditions is explored by i) applying the algorithms on in situ spectra, and ii) applying the methods on these spectra resampled to a lower spectral resolution, namely the resolution of HyMAP, a typical airborne hyperspectral sensor.
In laboratory conditions, high correlation coefficients (R^2 > 90%) are found between absorption features and moisture (<20%) or clay content.
In natural conditions, the relative moisture content lower than 20% is predicted with an error of ±3.5%. Clay content cannot be estimated from our field dataset, which can be caused by the limited amounts of clay or by noise in the spectral region of the absorption. High correlations (>75%) are obtained between the absorption feature of chlorophyll a and chlorophyll a content using in situ spectral measurements.
Interestingly, resampling the very high spectral resolution measurements to the spectral resolution of a HyMAP sensor influences the results to a very limited extent, leading to the conclusion that absorption features obtained by hyperspectral remote sensing might be suitable for quantifying bio-physical intertidal sediment properties. However, the appropriate spectral resolution for a particular application should be investigated.

1 INTRODUCTION

Mudflats are important for coastal zone ecosystems by providing wildlife habitats and by acting as natural sea defences that serve to dissipate tidal and wave energy. The primary production on intertidal flats can be considerable and is in our regions mainly accomplished by microphytobenthos (MPB), which typically consists of unicellular eukaryotic algae and cyanobacteria that grow within the upper millimeters of illuminated sediment (MacIntyre et al. 1996). The erodibility of cohesive sediments on these mudflats is dependent on physical sediment properties such as grain size distribution, density and moisture content, and on the biota living on the sediment which can have a stabilizing or destabilizing influence (Paterson 1997).
Remote sensing offers a means to acquire the necessary data to study these large mudflats.
Since the bio-physical sediment properties investigated in this study, namely clay content, relative moisture content (RMC) and chlorophyll $a$ content, have specific absorption features within the 350-2500nm region of the spectrum, these features are investigated in this work.

Absorption features of water at around 970nm and 1200nm have been used for the quantification of relative water content in vegetation (Peñuelas et al. 1993; Pu et al. 2003). Clay absorption features are successfully used for the identification of clay minerals in geological applications (Hunt 1977; Van der Meer & Bakker 1988), and a recent study (Lagacherie et al. 2008) showed the capability of the absorption feature at 2206nm for clay content prediction both in laboratory and in the field for relatively dry soil samples. Microphytobenthos on mudflats have been studied using hyperspectral remote sensing and the absorption of chlorophyll $a$ at around 673nm (Carrère 2003; Méléder et al. 2003).

In this paper, absorption features are used to assess the clay, RMC and chlorophyll $a$ content in intertidal sediments using a dataset consisting of laboratory and field measurements.

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2 METHODOLOGY

2.1 Measurements

Hyperspectral laboratory and field measurements are acquired with the Analytical Spectral Device (ASD), which records the reflectance from 350nm till 2500nm, i.e. in the visible (VIS), near infrared (NIR) and short wave infra-red (SWIR) region of the spectrum. The spectral resolution is 3nm from 350 till 1000nm and 10nm from 1000 till 2500nm.

2.1.1 In the laboratory

The height of measuring of the ASD is 50cm, and the instrument is nadir looking. The field of view is set to 1 degree. The experimental setup is described by Biliouris et al. (2005). Calibration is performed every 30 minutes using a Spectralon panel (Biliouris et al. 2005).

Sediment is collected at the IJzermonding, a small intertidal flat located at the outlet of the IJzer river at the Belgian coast. Fine sand (125-250µm) is the most abundant and therefore the most often used in the experiments. Water and a clay fraction without organic matter bought in a shop are also used to make the sediment mixtures in small black pots with minimal reflectance (<0.05%).

Two sets of spectral measurements are carried out (Table 1).

- With varying grain size distribution of sand/clay mixtures (n=193).
- With varying moisture content of sand/clay mixtures (n=972). Fine sand and mixtures of fine sand and clay are saturated with water, and heated on a warm plate to ensure homogeneous drying. Relative moisture content (%) is calculated as

$$RMC(\%) = \frac{WS - DS}{WS} \times 100$$

with WS and DS are the weights of the wet and dry sample.

Table 1: Overview of the laboratory measurements. The third column giving the number of samples with RMC smaller than 20% is a subset of the second column.

<table>
<thead>
<tr>
<th>Clay content</th>
<th>Moisture content</th>
<th>Moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0 - 64% by weight)</td>
<td>(0 - 36% RMC)</td>
<td>RMC &lt; 20%</td>
</tr>
<tr>
<td>fine sand + clay</td>
<td>n=98</td>
<td>n=535</td>
</tr>
<tr>
<td>fine sand + water</td>
<td>n=535</td>
<td>n=278</td>
</tr>
<tr>
<td>medium sand + clay</td>
<td>n=95</td>
<td>n=437</td>
</tr>
<tr>
<td>fine sand + clay + water</td>
<td>n=305</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>n=193</td>
<td>n=972</td>
</tr>
<tr>
<td>Total</td>
<td>n=583</td>
<td></td>
</tr>
</tbody>
</table>
2.1.2 In the field

In situ spectral measurements from field campaigns at the IJzermonding in 2005 and at the Molenplaat and IJzermonding in 2007 are used. The field campaigns are performed in the framework of the STEREO program, supported by the Belgian Science Policy. The Molenplaat is an intertidal sandbank in the Westerschelde estuary, the Netherlands, described in e.g. Deronde et al. (2006). The height of the ASD sensor is 0.7m and the field of view 25degree, leading to a diameter of ±31cm. Calibration using the Spectralon panel is performed every 30 minutes under stable illumination conditions. If clouds are present, calibration is performed more frequently.

Surface sediment samples are collected for pigment, grain size and moisture content analysis with a 2.5cm diameter contact corer (Ford & Honeywill 2002), which freezes a layer of 2mm including all photosynthetically-active algal cells, as well as the bulk of sediment chlorophyll (Forster & Kromkamp 2004). Samples for pigment analysis are freeze-dried and extracted using 90% acetone. The extracts are then analysed using the HPLC-method by Wright et al. (1991) and quantified using a calibration with commercial standards. The sediment water content is determined by calculating the weight difference after 12h drying at 105°C. Grain size is determined in a Coulter Counter (Coulter LS Particle Size Analyser; Beckman Coulter).

2.2 Absorption

The degree of absorption by clay, water and chlorophyll a can be characterized by i) the ratio between minimal reflectance in the absorption feature and reflectance outside the absorption feature: $R_a/R_c$ ($R_a =$reflectance at maximum absorption, $R_c =$reflectance out of absorption feature), ii) the scaled band depth after continuum removal, and iii) the scaled band area of the absorption feature after continuum removal (figure 1). Continuum removal is a normalization technique in order to compare absorption features from a common baseline. This continuum consists of straight-line segments that connect local spectra maxima. It is then removed by taking the ratio between the spectrum and the continuum (Clark and Roush, 1984). Before the calculation of the continuum, the spectral region of interest is isolated and the continuum is calculated between the two local maxima. It is observed that the first maximum can shift to lower wavelengths for deeper absorption features. However, the position of the second maximum can be assumed constant.

![Figure 1: Measures that quantify absorption features. $R_a$ is the reflectance at maximum absorption, $R_c$ is the reflectance out of the absorption feature. Example for the chlorophyll a absorption feature.](image)

The relation of the bio-physical sediment parameters to the measures of the absorption feature is investigated using regression analysis. A regression model, which can be linear or non-linear, is chosen by minimizing the mean squared error of the residuals. The model parameters are estimated using the laboratory dataset. The goodness of fit and the usefulness of the absorption features to assess the clay, moisture and chlorophyll a content are expressed by the R-squared value. The developed models are then applied on the in situ datasets.
2.3 Spectral resampling

In order to assess the influence of lower spectral resolutions on the use of absorption features for quantification of sediment properties, the field spectra are resampled using a Gaussian model based on the full width at half maximum (FWHM) and band center properties of the HyMAP sensor.

3 RESULTS

3.1 Laboratory reflectance measurements

The spectrum of fine sand with clay shows absorption features at around 1420nm, 1950nm and 2204nm. The absorption feature at 2204nm is caused by Al-OH present in the clay mineral (Yang et al. 2000) and will be considered. The spectrum of moist fine sand shows clear water absorption features at 1450nm and 1950nm. If the sediment is saturated, light is absorbed at around 970nm and 1190nm. However, these water absorption features disappear when the sediment is drier. The water absorption around 1450nm will be used.

The relation of clay content to the measures of the clay absorption feature at 2204nm in dry sediment mixtures appears to be 4\textsuperscript{th} order polynomials (figure 2) and independent on grain size, with R\textsuperscript{2} values equal to 98%.

![Figure 2](image-url)

Figure 2: Clay content versus measures of the clay absorption feature for mixtures of fine sand with clay and medium sand with clay, n=193.

For moisture content, the dataset is split into two. A 2\textsuperscript{nd} order polynomial fit gives R\textsuperscript{2} values of 89% between measures of absorption feature and RMC lower than 20%. R\textsuperscript{2} values of 58% are found between the scaled band area and RMC higher than 20%, while for the ratio and the scaled band depth, the R\textsuperscript{2} values for RMC larger than 20% are smaller (figure 3). At RMC higher than 20%, a water film on the sediment is present. Once the RMC is lower than 20%, the water film disappears.

![Figure 3](image-url)

Figure 3: Relative moisture content versus measures of the water absorption feature at 1450nm for mixtures of fine sand with water and for mixtures of fine sand, clay and water, n=972.
The clay absorption feature becomes less apparent when the RMC increases. Therefore, a model using two independent variables, namely the scaled band area of the clay absorption feature at 2204nm and the scaled band area of the water absorption feature at 1450nm with a R-squared value of 87%, is developed.

3.2 Field reflectance measurements

3.2.1 Clay content

The clay absorption feature is not visible in the field spectra, so that it cannot be used for clay prediction.

3.2.2 Relative moisture content

During the field campaign at the IJzermonding in 2005, 69 sites are spectrally characterized and sampled for moisture content analysis. As shown in figure 4, the model developed in the laboratory is suited for predicting the RMC from spectral measurements as long as the RMC is lower than 20% (n=11). For this range, the root mean square error of prediction is equal to 4.5%, 3.6% and 3.3% using the ratio, scaled band depth and scaled band area respectively.

For the measurements with RMC higher than 20% (n=58), the model using the scaled band area from the laboratory measurements is used and the results shown in figure 4. The error of prediction is 14.4% RMC, while the mean value of the measured RMC is 40.2%. The model for the ratio and scaled band depth is not used, due to the low correlations obtained in the laboratory.

Figure 4: Measured and predicted RMC values for field measurements at the IJzermonding (2005). The predicted RMC values are obtained using the model developed in the laboratory. The filled symbols are for data with RMC lower than 20%.

3.2.3 Chlorophyll a content (chl a)

For chlorophyll a, the datasets of the field campaigns at the Molenplaat and IJzermonding in 2007 are used, with a total number of samples equal to 66.

Figure 5: Scaled band depth of the chl a absorption versus chl a content (n=66)
The correlation between the scaled band depth of the absorption feature of chlorophyll \( a \) at 673nm with chlorophyll \( a \) content is 77%. The model is

\[
\text{chlorophyll } a (\text{mg } / \text{m}^2) = a \times (\text{scaled band depth})^b
\]

with \( a = 357.4 \) and \( b = 0.7692 \).

For the scaled band area, the correlation coefficient is 77% and a similar model is obtained. The correlation coefficient using the ratio is lower (64%) using a second order polynomial.

3.3 Spectral resampling

The spectral resolution of the HyMAP sensor is 15-16nm in the visible region and in the short wave infrared 1 region, so at the absorption dip of chlorophyll \( a \) and water respectively.

The root mean square error of prediction for RMC lower than 20% using the resampled spectra and the model developed in laboratory conditions are 4.4%, 3.7% and 3.6% for the ratio, scaled band depth and scaled band area respectively. For RMC higher than 20%, the prediction error is 14.4% using the scaled band area.

For chlorophyll \( a \), the model obtained from the in situ original field spectra is applied on the measures of the absorption feature obtained from the resampled data. The root mean square error of prediction using the resampled spectra are 21.8, 20.3 and 27.3mg/m\(^2\) for the ratio, scaled band depth and scaled band area respectively, whereas the average of the measured chlorophyll \( a \) values is 74.7mg/m\(^2\).

As can be seen in figure 6, the difference in the values of the ratio between the spectra with ASD resolution and HyMAP resolution are negligible. For the scaled band area, there is a small offset for the higher chlorophyll \( a \) contents, which can be due to a deteriorated representation of the absorption dip after resampling.

4 CONCLUSION

4.1 Clay content prediction

In laboratory conditions, the hyperspectral signal in the short wave infrared (SWIR) and the absorption feature at 2204nm can be used to assess the clay in the surface layer of sand/clay mixtures. The R-squared values between absorption features and clay content are very high, as long as the sediment mixtures are relatively dry.
The clay absorption feature is not visible in our field measurements. Possible explanations are i) the low values of clay content, ii) the high moisture content of intertidal sediments, and iii) the high level of noise in the SWIR due to the lower energy amount and spectral resolution in the SWIR. Although Lagacherie et al. 2008 demonstrated the use of the clay absorption feature for clay content prediction in the field for relatively dry soils, the presented work brings about that the clay absorption feature cannot be used for clay prediction on intertidal mudflats.

4.2 Relative moisture content prediction

Relative moisture content is accurately predicted in laboratory conditions as long as the RMC is lower than 20%. This corresponds to the point of the appearance of a surface water film or the point of saturation. If the RMC is higher than 20%, the scaled band area performs better than the ratio and the scaled band depth, which can be explained by the fact that the scaled band area takes into account the widening of the absorption feature observed once the RMC is higher than 20%.

The relation obtained in the laboratory is successfully used on field measurements and on the resampled field measurements for RMC lower than 20%. This means that RMC lower than 20% can be estimated from HyMAP imagery.

4.3 Chlorophyll a content

Unfortunately, laboratory measurements of microphytobenthos are not available at the moment of writing this paper. However, high correlations are obtained between the measures of the absorption feature at 673nm from field spectra and chlorophyll a content, which is the main pigment of microphytobenthos.

After resampling these spectra to the HyMAP spectral resolution, the same model can be used to predict the chlorophyll a content from the resampled spectra with acceptable root mean square errors.

It is concluded that bio-physical sediment properties can be quantified using absorption features within certain limits. The three measures of absorption perform equally well, although the scaled band area should be used if the absorption feature becomes wider for higher quantities.

It is shown that it is feasible to extrapolate models developed in the laboratory to field measurements. However, this needs more investigation, especially for chlorophyll a, the most abundant pigment in microphytobenthos. For relative moisture contents lower than 20%, the model developed in the laboratory is suitable for field measurements. For higher moisture contents, several approaches can be investigated, e.g. using another water absorption feature or the overall spectrum.

However, we believe that a model calibrated using the field spectra or HyMAP images will yield better correlations and lower prediction errors.

Finally, the spectral resolution of the HyMAP sensor is appropriate for quantifying chlorophyll a content and relative moisture content lower than 20%.

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REFERENCES


