REMOTE SENSING OF SPHAGNUM STRESS: A PROXY FOR NEAR-SURFACE WETNESS CONDITIONS IN NORTHERN PEATLANDS?

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ABSTRACT
Remote sensing of near-surface hydrological conditions within northern peatlands has the potential to provide important large-scale hydrological information regarding ecological and carbon-balance processes occurring within such systems. The paper details how the spectral properties (400–2500 nm) of Sphagnum mosses may provide a suitable proxy for near-surface peatland hydrological conditions. We investigate the effects of changes in near-surface and surface moisture upon the spectral characteristics of Sphagnum moss canopies. Laboratory-based canopy reflectance data were collected from a number of Sphagnum species, subjected to drying and subsequent rewetting. Several spectral indices developed from the near infra-red (NIR) and shortwave infra-red (SWIR) liquid water absorption bands and a biophysical index were correlated with measures of near-surface moisture. Each species of Sphagnum exhibited a clear and well-defined spectral response to reductions in volumetric moisture content (VMC); reflecting the general water tolerance of each species, and its location in relation to the water table. Airborne imagery were also collected during 2002 for a raised bog located in W. Wales. Details regarding the integration of laboratory and airborne remote sensing data for mapping near surface hydrological conditions using the spectral reflectance characteristics of Sphagnum are discussed.

1. INTRODUCTION
Northern peatlands (those above 45°N) contain up to one third of the world’s soil carbon and have a fundamental role in the terrestrial carbon cycle [1]. Surface wetness, near-surface wetness and the position of the mean water-table in peatlands are thus both ecologically and climatically important.

Peatland environments continue to be subjected to extensive exploitation, modification and destruction, and many large peatland complexes have already been converted from carbon sinks to carbon sources due to drainage for agricultural purposes, for forestry and for peat production [2, 3]. Postulated future global climatic changes are expected to have a pronounced but as yet un-quantified effect on peatland systems, particularly upon the balance between photosynthesis and decomposition [1]. Understanding the hydrological and ecological mechanisms controlling peatland response to changes in the climatic conditions is crucial to predicting potential feedbacks in the global carbon cycle [4].

Current approaches for monitoring hydrological processes occurring in peatlands often involve collection of large numbers of small-scale hydrological measurements (i.e. using Time Domain Reflectometry (TDR) and water table dipwells [5]. Although highly detailed, these data are not necessarily representative of larger spatial peatland conditions and processes. Given the logistical and monetary difficulties associated with collecting such spatially-detailed measurements over large areas, there is evidently a need for an economic high-resolution synoptic tool capable of identifying and quantifying hydrological changes over entire peatland complexes. Observations from remote sensing platforms may allow such detailed temporal and spatial observations.

The use of optical image data (400–2500 nm) for monitoring near-surface and surface hydrological conditions in wetlands has been confined to identifying and monitoring patterns of vascular vegetation (e.g. [6,7]. Such methods are useful for identifying long-term changes in hydrological conditions, but vascular species are often insensitive to short-term (e.g. seasonal) changes in water-table position [6]. Thus intra-seasonal and inter-seasonal variation in near-surface hydrological conditions cannot be detected via vascular plants using such approaches.

Sphagnum mosses are a dominant component of the vegetation in many northern peatlands. Different species of the moss tend to occupy different microtopographical locations within a peatland due to interspecies

competition and their moisture demands. Unlike many vascular plants, *Sphagnum* spp. are very sensitive to short-term changes in moisture availability. The genus has a large water holding capacity because of the vast numbers of hyaline cells contained within the plant. However, *Sphagnum* lack internal water-conducting tissue and water can only be supplied to the plants’ capitula (i.e., plant head) by precipitation or capillary rise from the water-table below. Thus, when water availability is low, moisture is readily lost from the hyaline cells, accompanied by an apparent loss of pigmentation in the plant canopy, resulting in a whitish appearance; a process known as bleaching [8]. These unique physiological properties imply that variations in the moisture status of *Sphagnum* canopies may be a strong indicator of wetland hydrological conditions [9].

Research to date has included a combination of laboratory, field and airborne experiments to test the feasibility of using the spectral reflectance characteristics of *Sphagnum* as a proxy for detecting changes in peatland hydrological status. This paper reviews progress thus far. Findings from laboratory experiments are reviewed and the difficulty of scaling up such findings for use in airborne remote sensing is discussed.

### 2. MATERIALS AND METHODS

#### 2.1 Laboratory Experiment

A study by [10] investigated the changes in spectral response of *Sphagnum* mosses through deliberate manipulation of near surface water content. The experiment was undertaken on two different species of *Sphagnum* (*Sphagnum magellanicum* and *Sphagnum pulchrum*) collected from an ombrotrophic bog in west Wales, UK. Three samples of each species were collected, with one of each species kept as a control. Samples were approximately 12 x 9 cm in area and contained c. 10 cm of underlying litter. *S. magellanicum* occurs in drier microenvironments than *S. pulchrum* and is red in colour with tightly-packed capitula, forming a relatively homogenous canopy. *S. pulchrum* in contrast is green to orange in colour and has large loose capitula that form a complex and relatively open canopy. These species were chosen because they are representative of the range of Sphagna found in bog hollows (often of higher surface water content) and lawns.

Samples were initially hydrated to near-saturation and left to dry naturally for 15 days, after which they were gradually, re-hydrated using a rainfall simulator for a period of 6 days to near full saturation. The volumetric moisture content (VMC) of each sample was recorded daily for comparison with spectral response.

#### 2.2 Field Experiment

Further studies undertaken by [11] tested the laboratory-derived relationships between *Sphagnum* spectral reflectance and moisture at the field and airborne scale. In-situ field spectroradiometry studies were undertaken in the same raised bog in West Wales, UK in May and September of 2002. The predominant species of *Sphagnum* at this site is *S. Pulchrum*. Thirty six relatively homogenous patches of *S. pulchrum* (typically >6 x 6 m) were identified and used as sampling stations. In-situ spectral data and hydrological data (e.g., VMC and water-table depth) were collected from each sampling station on May 16th and September 24th 2002. Data collected from the sampling stations was also used to ground truth airborne imagery.

#### 2.3 Airborne Remote Sensing

Daedalus 1268 Airborne Thematic Mapper (ATM) imagery was acquired over Cors Fochno by NERC on May 16th and September 24th 2002, concurrently with on-site data collection. The ATM has 11 spectral bands covering the visible (VIS) and near infrared (NIR; bands 1-8), the shortwave infrared (SWIR; bands 9 and 10) and the thermal infrared (TIR; band 11).

A typical sensor scene consisted of 4 lines of imagery with a spatial resolution between 1.5 and 2 m. There were severe calibration problems with the ATM sensor during the late summer flying season of 2002 consequently the September 24th ATM data was replaced by an image dataset collected on September 11th (see [11] for further details). Because the problems with the data set from September 24th were not anticipated, no field data were collected on September 11th 2002.

### 3. DATA ANALYSIS

Laboratory, field and airborne spectral measurements were subjected to a range of pre-processing operations and analyses. Initial analysis focused on the differences in spectral characteristics between hydrated, dehydrated and re-hydrated samples for each species. A number of existing and modified water stress and biophysical indices were also applied to the data and compared with a range of hydrological measurements.

Due to the three stage nature of these investigations, i.e. laboratory - *in situ* - airborne, and the availability of equipment, not all the data analysis techniques were applied at every stage. Tab. 1 lists the data analysis techniques carried out at each stage.
Table 1 Spectral Indices used to detect changes in wetness conditions, and the precise wavebands used in this study and the stages at which they were calculated.

<table>
<thead>
<tr>
<th>Spectral Index</th>
<th>Formula</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>fWBI980</td>
<td>( \frac{R_{920}}{\text{min}(R_{950-1000})} )</td>
<td>Lab/Field</td>
</tr>
<tr>
<td>fWBI1200</td>
<td>( \frac{R_{920}}{\text{min}(R_{1150-1220})} )</td>
<td>Lab/Field</td>
</tr>
<tr>
<td>MSI</td>
<td>( \frac{R_{1550-1750}}{R_{760-800}} )</td>
<td>Lab/Field/Airborne</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>( \frac{(R_{750-800})}{(R_{695-740})} - 1 )</td>
<td>Lab/Field</td>
</tr>
</tbody>
</table>

Moisture stress index (MSI); * Floating water band index (fWBI)

4. RESULTS
4.1 Laboratory
Identifying relationships between spectra, species and moisture

Results from the laboratory experiment demonstrated marked changes in the spectral response of each species between 350 nm and 2500 nm with water content (Fig 1.). For both species, a reduction in the VMC led to increased reflectance in the VIS, NIR and SWIR regions of the electromagnetic spectrum. The depth of the NIR water absorption features, located at approximately 970 nm and 1200 nm, reduced as the plants became dehydrated.

The results indicate a strong relationship between the moisture content of Sphagnum canopies and reflectance characteristics. All regions were affected by moisture although changes in the SWIR were most pronounced.

Tab. 2 displays the results of all reflectance indices tested. For both species, reflectance spectra from the control samples remained constant throughout the experiment (results not shown). All of the water-based indices were more strongly correlated with VMC than those used to detect chlorophyll content. The strongest correlations between spectral reflectance and near-surface moisture (i.e., VMC) were found for those indices formulated from the NIR liquid water absorption bands (Tab. 2, Fig 2a.).

Reductions in VMC were accompanied by reductions in the fWBIs. Patterns of drying and rewetting were similar in the two species for both NIR indices, although the recovery pattern of the reflectance signal upon rewetting was hysteretic in S. magellanicum (results not shown). This hysteretic response is hypothesized to reflect water retention within the canopies. The canopy of S. magellanicum contains a large number of small capillary pores. As water is added to the canopies, the capillary pores hold the water against the pull of gravity, thus higher levels of moisture are likely to be present in the canopy after rewetting than at similar near-surface moisture conditions during drying. Hysteresis was not observed in the reflectance signal of S. pulchrum, reflecting the more open nature of its canopy. The observed differences in the spectral properties of Sphagnum during drying and rewetting have significant implications for the timing of image acquisition over peatland environments. For example, imagery collected just after a rainfall event may result in over-estimation of near surface/surface wetness.

Narrow band indices outperformed indices developed from broader bandwidths. However, the broad-band MSI also showed significant correlations with VMC for both Sphagnum species although responses across the entire range of VMC studied were nonlinear, and again, species specific (Tab. 2; Fig. 2b).

Table 2. Summary of results, illustrating, for each different spectral index, the property it was designed to detect and the coefficient of determination (r) that described the relation between the property and VMC

<table>
<thead>
<tr>
<th>Spectral Index</th>
<th>Property Detected</th>
<th>S. magellanicum</th>
<th>r (p&lt;0.0001)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sample</td>
<td>Sample Combined</td>
</tr>
<tr>
<td>fWBI980</td>
<td>Water</td>
<td>0.96</td>
<td>0.92</td>
</tr>
<tr>
<td>fWBI1200</td>
<td>Water</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>MSI</td>
<td>Water</td>
<td>-0.88</td>
<td>-0.81</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>Index</td>
<td>0.48</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Figure 1 Diagnostic mean spectral reflectance profiles for a) S. magellanicum and b) S. pulchrum at three key moisture levels during the laboratory experiment; (n =4).
Values of the MSI were significantly higher when samples were experiencing low levels of VMC. A comparison between species indicated that at high VMCs (i.e., >0.7), MSI values were similar for both *S. pulchrum* and *S. magellanicum*.

At these high moisture levels, reductions in VMC resulted in only slight increases in the index. As the VMC dropped, the MSI increased in both species. Increases in the index were more accentuated in *S. pulchrum*, although the MSI appeared to approach an asymptote at a VMC of approximately 0.3. Such a result is explained by the poor correlations often found between canopies with low water content and absorption at higher water absorption bands such as those located in the SWIR [12].

Figure 2 Mean MSI and fWBI as a function of VMC for *S. pulchrum* (a and b respectively), ± 1 standard error. Closed symbols indicate the results from samples i and open symbols indicate the results from samples ii (n = 4, p<0.0001). Results for *S. magellanicum* are not shown.

In contrast, the MSI for *S. magellanicum* did not approach an asymptotic value and appeared to be more sensitive over a greater range of wetness conditions (results not shown). The presence of species-specific relationships between the MSI and VMC may be explained by the different water holding capacities of the two species. Nevertheless, these results clearly indicate the ability of the index to detect variations in the near-surface wetness, which may often be limited by choice of target *Sphagnum* species.

A significant relationship was reported between the chlorophyll index and VMC (Tab. 2). The index suggested a general decrease in chlorophyll as the samples began to dry (results not shown). Highest index values for *S. pulchrum* and *S. magellanicum* were observed at VMC values of 0.6 and 0.7, respectively, suggesting optimal conditions for chlorophyll production at these moisture levels. The index decreased in both species as VMC dropped below this apparent optimum. Similar key levels of near-surface moisture were observed in the MSI, suggesting a close relationship between chlorophyll content and moisture. High levels of moisture (>0.7 VMC) also resulted in lower values of the index in *S. pulchrum*, suggesting that lower chlorophyll contents may also be characteristic of high levels of near-surface wetness. There was also a hysteretic response in the index as *S. magellanicum* was rewetted; higher index values were recorded when the samples were rewetted than at similar VMCs during drying. A probable cause of such a response is the tightly packed nature of the canopy. Water added from above during rewetting is likely to be retained in the canopy, thus at any given near-surface VMC during drying, the canopy water content would be lower than during rewetting.

4.2 Field

*In situ* relationships between spectra, species and moisture

Tab. 3 summarises the results of the spectral indices used to determine VMC and water-table position across a peatland using spectral data collected *in situ*. As observed in the laboratory experiment, the water-based indices outperformed those based on chlorophyll detection. The primary reason for the poor performance of the chlorophyll-based indices *in situ* is attributed to high water tables present in both May and September field sessions. Laboratory results suggested that chlorophyll indices are unresponsive until VMC/water table drop below 0.4 and 15 cm below the bog surface; respectively. All water-based indices tested were significantly correlated with both VMC and position of the water table and are comparable with those exhibited in the laboratory experiment.
Table 3 Summary of results, illustrating, for each field-derived spectral index, the property it was designed to detect and the coefficient of determination (r) that described the relation between the property and direct field hydrological measures. Figures are significant at the 0.05 level, NS = not significant at the 0.05 level. May and September data are combined.

<table>
<thead>
<tr>
<th>Spectral Index</th>
<th>Property Detected</th>
<th>r</th>
<th>Water Table</th>
<th>VMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>fWBI(_{380})</td>
<td>Water</td>
<td>-0.66</td>
<td>p&lt;0.0002</td>
<td>0.73 p&lt;0.0001</td>
</tr>
<tr>
<td>fWBI(_{1200})</td>
<td>Water</td>
<td>-0.63</td>
<td>p&lt;0.0003</td>
<td>0.75 p&lt;0.0001</td>
</tr>
<tr>
<td>MSI</td>
<td>Water</td>
<td>0.62</td>
<td>p&lt;0.001</td>
<td>-0.70 p&lt;0.0001</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>Chlorophyll</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Airborne Experiment
Mapping Sphagnum from airborne imagery

Identification of *S. pulchrum* within the imagery is an imperative stage in applying such indices at the peatland scale. The target species (*S. pulchrum*) was identified from the ATM imagery using mixed tuned match filtering (MTMF). The technique provides a rapid means of detecting specific cover types based on their spectral characteristics. The main advantage of using MTMF in a study such as this is that it does not require spectral identification of all cover types across the image scene. The technique provides a 'partial' un-mixing by only finding the abundance *Sphagnum*. Seventy percent of the sites used for *in situ* data collection were correctly identified from the imagery using MTMF.

Detecting changes in near-surface moisture using airborne imagery

The regions identified by MTMF in each image were subsequently used as the basis for locating *S. pulchrum* within the field study site. From these regions, maps of the MSI were produced for May and September. There was a small but significant increase in the index between May and September (df =28, p<0.0001), suggesting a slight drying of the bog surface (Fig. 3c). Mean MSI values for each site were significantly correlated with both VMC and position of the water table (results not shown, r =0.55 and 0.52, respectively; p<0.0001). Field and image-derived values of the MSI were significantly correlated with one another (r =0.44, p<0.03) and are akin to those reported in the laboratory, for similar levels of VMC (results not shown).

Indices maps of this nature not only allow easy visual comparisons of seasonal and inter-seasonal near-surface moisture conditions, and possibly productivity, but they also relay important spatial information, i.e. hydrological variability or species richness within a single image scene.

Figure 3 Remotely sensed Moisture Stress Index (MSI) calculated at Cors Fochno on (a) May 16th and (b) September 11th 2002 from Airborne Thematic Mapper (ATM). The change detection image (c) was created by subtracting the May MSI image from the September MSI image and indicates a slight drying of the bog surface between these two dates.

5. CONCLUSIONS AND FUTURE CHALLENGES

Detailed hydrological monitoring of near-surface moisture conditions and water-table position over large-scale peatland systems will undoubtedly provide the information required to improve current and future CH\(_4\) emission estimates. This paper has illustrated how airborne remote sensing can provide estimations of the hydrological status of northern peatlands. The technique utilizes the spectral reflectance of *Sphagnum* moss as an indicator of near-surface hydrological conditions. This
research has provided a clear understanding of the detailed spectral characteristics associated with *Sphagnum* vegetation and the responses of these signatures to near-surface moisture variations.

Changes in spectral reflectance can be identified not only by changes in spectral signature but also by ratios such as the MSI, fWBI and possibly biophysical indices. The findings also indicate species specific responses. To quantify these relationships further, more spectral measurements for a wider range of *Sphagnum* species and growth forms are in progress (Harris, unpublished data), although it is likely that species found in similar microtopographic locations will have similar spectral responses to moisture.

Preliminary results suggest that remote sensing may be used to provide high resolution, quantitative information that surpasses the capabilities of conventional hydrological measurement techniques. Such an approach may be further utilized for hydrological characterization of peatlands for carbon balance estimations and for ecological restoration projects and monitoring. Although airborne remote sensing can provide high spectral and spatial resolution imagery, this work highlights and reiterates well-established issues regarding the careful timing of image acquisition and consistency in the quality of data sets that must be achieved when planning continuous hydrological monitoring. It has been demonstrated here that airborne remote sensing has the potential for monitoring near-surface wetness across peatlands, and it is further suggested that satellite remote sensing may provide an even more viable and reliable alternative. Satellites will improve the quality and repeatability of the methods outlined in this study, and allow reliable monitoring of peatland hydrological conditions at a global scale. The challenge of modifying the approaches outlined here, in a way that will facilitate their use across a range of spatial and temporal scales, via high spatial and spectral resolution airborne and satellite remote sensing data, will form the basis of future research.

6. ACKNOWLEDGEMENTS
We wish to thank the UK Natural Environmental Research Council (NERC) Equipment Pool for Field Spectroscopy (EPFS) for the loan of field spectroradiometers, and the NERC Airborne Research Facility (ARSF) for the airborne image data collection. Mike Bailey from the Countryside Council for Wales (CCW) is also thanked for granting access to Cors Fochno study site.

7. REFERENCES