Mapping the effects of water stress on *Sphagnum*: Preliminary observations using airborne remote sensing

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Received 10 August 2005; received in revised form 24 October 2005; accepted 29 October 2005

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. This article details how field knowledge of the spectral properties of *Sphagnum* spp., airborne remote sensing data and a range of image analysis approaches, may be combined to provide a suitable proxy for near-surface wetness. Co-incident field and airborne remote sensing data were acquired in May and September 2002 over an important UK raised bog (Cors Fochno). A combination of laboratory-tested NIR and SWIR water-based and biophysical spectral reflectance indices were applied to field and airborne reflectance spectra of *Sphagnum pulchrum* to elucidate changes in near-surface moisture conditions. Field results showed significant correlations between water-based indices (moisture stress index (MSI) and floating water band indices (fWBI\(_{980}\) and fWBI\(_{1200}\))) and measures of both near-surface volumetric moisture content (VMC) and water-table position. Spectral indices formulated from the NIR (fWBI\(_{980}\) and fWBI\(_{1200}\)) proved to be the most useful for indicating near-surface wetness across the widest range of moisture conditions because of their ability to penetrate deeper into the *Sphagnum* canopy. Correlations between a biophysical index based upon chlorophyll content and both hydrological measures were not significant, possibly due to relatively high levels of surface wetness at the field site in both May and September. *S. pulchrum* lawns were successfully located and mapped from airborne imagery using the mixed tuned match filtering (MTMF) algorithm. Importantly, MSI derived from airborne data was significantly correlated with both field moisture and the water-table position. Relationships between measures of near-surface wetness and the MSI for naturally heterogeneous canopies were, however, found to be weaker for airborne imagery than for associated field data. This is likely to be a result of the formulation of the MSI itself and the possible preferential detection of “wetter” pixels within the imagery. This effectively reduced the ability of MSI to detect subtle changes in near-surface wetness under high moisture conditions, but would not impede the use of the index under drier conditions. Results from the field data suggest that indices formulated from the NIR may be more suitable for detailed estimations of near-surface and surface wetness at the landscape-scale although reliable hyperspectral data are required to test fully the performance of such indices. The relative merits of using such an approach to determine near-surface hydrological conditions across entire peatland complexes are also discussed.

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Keywords: *Sphagnum*, Water stress; Peatlands; Airborne remote sensing

1. Introduction

Peatlands form one of the world’s largest carbon stores and are an important component of the global carbon cycle through their sequestration of atmospheric carbon into peat and the release of carbon gases (CH\(_4\) and CO\(_2\)) through peat decay. Northern peatlands alone contain between 270 Gt (Turunen et al., 2002) and 450 Gt (Gorham, 1991) of carbon, representing approximately one-third of the total global soil carbon pool (Post et al., 1982).

Surface wetness, near-surface wetness and the position of the mean water table in peatlands are ecologically and climatically important. Near-surface wetness exerts an important control on the carbon balance of peatland soils in several ways. In bogs, one of the most widespread types of northern peatland (see Section 1.1), the productivity of *Sphagnum* mosses depends on water being supplied to their growing...
apices or capitula. Because *Sphagnum* spp. are non-vascular, water is supplied to their capitula either directly by rainfall or via capillary rise from the water-table through the pore space between *Sphagnum* stems, branches and leaves. During dry conditions, the water-table falls and capillary supply may be outstripped by water loss through evaporation at the peatland surface. The near-surface water content of the peat soil will fall, as will the water content of the capitula. This can lead to dramatic reductions in rates of *Sphagnum* growth (i.e. photosynthetic activity), and therefore, carbon fixation (see, e.g., Gerdol et al., 1996; McNeil & Waddington, 2003; Schipperges & Rydin, 1998).

Near-surface water content is also an indicator of the thickness of the unsaturated zone in peat soils. It is in this zone that decay of *Sphagnum* litter is most rapid. Aerobic decay occurs at a rate approximately a thousand times greater than anaerobic decay (Belyea & Clymo, 2001; Ingram, 1978). If the unsaturated zone is thin (i.e. near-surface water contents high), less decay takes place and more litter is passed to the saturated zone. CH$_4$ is produced below the water table but when it moves into the unsaturated zone via diffusion or bubble transport (ebullition). When the unsaturated zone is thin (near-surface water contents are high), there will be less opportunity for CH$_4$ oxidation so that the CH$_4$ flux from the peatland surface will be greater than when the water table is low (near-surface water contents are low).

Despite the sensitivity of peatland systems to small hydrological changes, these environments continue to be subjected to extensive exploitation, modification and destruction. 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 (McNeil & Waddington, 2003; Moore & Knowles, 1989). Future changes in climate, such as those predicted due to global warming, are likely to result in many more peatlands becoming net atmospheric carbon sources (Aurela et al., 2001; Gorham, 1991; Oechel et al., 1993).

Near-surface water content can be used to indicate a suite of carbon balance processes in northern wetlands and it is no surprise that current wetland carbon models require as inputs measurements of water-table position (e.g. Frolking et al., 2002; Walter et al., 1996) or attempt to model near-surface moisture dynamics (e.g. Walter et al., 2001). The ability to monitor near-surface hydrological conditions across entire peatlands would provide invaluable knowledge regarding the ecological status of, and carbon balance processes occurring within, such systems.

Conventional hydrological monitoring of peatlands often involves collection of large numbers of small-scale hydrological measurements (e.g. using time domain reflectometry (TDR) and water-table dipwells) (e.g. Belyea, 1999). These data are often highly detailed, but are not necessarily representative of larger spatial scales. Given the logistical and monetary difficulties associated with collecting detailed hydrological measurements over large spatial scales, 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 for such detailed spatial and temporal detection of changes in near-surface hydrological conditions.

Attempts have been made to monitor near-surface moisture using the thermal infrared (TIR) (e.g. Cracknell & Xue, 1996; Sobrino & Raissouni, 2000) and microwave (e.g. Biftu & Gan, 1999; Griffiths & Wooding, 1996; Oldak et al., 2003) regions of the electromagnetic spectrum. However, techniques relying on emitted TIR often require detailed prior knowledge of the area sensed (e.g. knowledge of surface materials and their emissivity), whereas the usefulness of microwave sensors often necessitates a detailed understanding of the roughness of surface vegetation canopies (e.g. Altese et al., 1996; Benallegue et al., 1995; Oldak et al., 2003). 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. Bubier & Moore, 1994; Gilvear & Watson, 1995). Such methods are useful for identifying long-term changes in near-surface hydrological conditions, but vascular species are often not influenced by short-term (e.g. seasonal) changes in water-table position (Bubier & Moore, 1994). Thus intra-seasonal and inter-seasonal variation in near-surface hydrological conditions cannot be accounted for using such approaches. This paper will explore how the moisture status of *Sphagnum* moss and its underlying litter may be used as indicators of near-surface wetness in northern peatlands using a remote sensing approach.

### 1.1. *Sphagnum* moss

Relatively few species of plant are found in those northern peatlands in which the dominant water supply mechanism is precipitation (i.e. bogs). The combination of high water tables, low nutrient availability and low pH present conditions to which few plants are adapted. Of the plants that do occur, the *Sphagnum* mosses are usually dominant and are the principal species involved in peat accumulation (Clymo, 1970; Gerdol et al., 1996; Rydin & McDonald, 1985). *Sphagnum* mosses are important indicators of peatland surface and near-surface moisture variation. The distribution of *Sphagnum* species within northern peatlands is often related to the depth of the water table below the surface (cf. Grosvernier et al., 1997). Many northern peatlands have a complex array of autogenic microtopographical locations with peatland systems depending on their water availability requirements and inter-specific competition (Clymo, 1970, 1973; Green, 1968). Unlike...
vascular vegetation, *Sphagnum* lacks internal water-conducting tissue, meaning that water can only be supplied to the capitula by precipitation or via capillary rise from the water table below (Clymo & Hayward, 1982). Thus, the amount of water held within the canopy of *Sphagnum* is often a function of water availability (Titus et al., 1983). The implication of this for remote sensing is that any alterations in vegetation moisture content are likely to influence spectral reflectance properties. *Sphagnum* has a distinctive spectral reflectance signature in relation to both vascular plant species and other mosses (Bubier et al., 1997; Vogelmann & Moss, 1993). It is this ease of identification, coupled with the unique physiological properties of the genus, which provides a basis for the remote detection and utilisation of *Sphagnum* as an indicator of near-surface hydrological conditions in northern peatlands (Bryant & Baird, 2003; Bubier et al., 1995; Harris et al., 2005).

1.2. Airborne remote sensing and field detection of vegetation moisture status

An understanding of vegetation moisture status has widespread importance in agriculture, forestry and hydrology (e.g. Jackson et al., 2004; Paltridge & Barber, 1988; Penuelas et al., 1993; Ustin et al., 1998). Consequently, a plethora of literature exists concerning a number of different techniques that have been used to detect vegetation moisture status using earth observation data. Penuelas et al. (1993, 1997) measured plant water concentration by combing reflectance at 900 nm (a reference wavelength) and 970 nm (the NIR liquid water absorption feature). The resulting water band index (WBI) demonstrated significant correlations with vegetation water content. Similarly, correlations with moisture content were reported by Hunt et al. (1987) and Hunt and Rock (1989) using the moisture stress index (MSI), which utilises broad reflectance wavebands in the SWIR (1550–1750 nm) and NIR (760–900 nm). Other investigations have attempted to utilise the relationship between vegetation moisture and chlorophyll content to determine vegetation moisture status from biophysical indices. As a result, existing indices such as the red edge inflection point (REIP) and the normalized vegetation index (NDVI) have been used to detect changes in vegetation moisture content and moisture stress (e.g. Bryant & Baird, 2003; Fiella & Penuelas, 1994; Illera et al., 1996; Paltridge & Barber, 1988; Penuelas et al., 1993).

Whilst considerable efforts have been made to identify moisture stress in many species of vascular plants, only a limited amount of research has focused on *Sphagnum* mosses. Using laboratory experiments, Vogelmann and Moss (1993) reported significant relationships between the reflectance properties of individual *Sphagnum* plants and the MSI. Similar experiments conducted by Bryant and Baird (2003) and Harris et al. (2005) identified clear relationships between the MSI and measures of near-surface moisture content from undisturbed *Sphagnum* canopies (i.e. groups of capitula, rather than a single capitulum) and the rest of the acrotelm (i.e. the surface layer of bog soil, often consisting of poorly decomposed *Sphagnum* litter (Ingram, 1978)). Harris et al. (2005) also identify significant correlations between near-surface moisture content and variants of the WBI (Penuelas et al., 1993, 1997) and a chlorophyll index (Gitelson et al., 2003). Despite promising results, it remains unclear how applicable such findings are to the field environment, where water deficits may be more subtle than in the laboratory, and where background interference, atmospheric absorption, solar angle and sensor view, may all have a confounding influence upon surface reflectance properties. Consequently, to expand our understanding of the relationships between surface and near-surface moisture content and the spectral properties of *Sphagnum*, there is a need for quantitative tests of such indices, both at the field-scale and from a wider remote sensing perspective.

In this paper, we build on previous research by utilising the unique spectral reflectance properties of *Sphagnum* to develop a means of detecting changes in surface and near-surface wetness across peatlands from a remote sensing platform. In particular, we tested the utility of laboratory-derived moisture and biophysical vegetation indices (i.e. fWBI880, fWBI1200, MSI and a chlorophyll index), identified by Harris et al. (2005), for detecting changes in the surface and near-surface wetness of northern peatlands, at the field-scale and from airborne remote sensing platforms.

2. Methods

2.1. Field site

The work was conducted at Cors Fochno, a peat bog located on the Welsh coast approximately 10 km north of Aberystwyth (52°32′N, 04°00′W) and lying just to the south of the Dyfi estuary (Fig. 1a). The mean annual rainfall at this site is 1220 mm, with 60–70% of the rainfall falling between October and February (Fig. 1b). The bog is the third largest ‘active’ raised bog in Britain (covering approximately 10 km2) and has a clear and well-defined microtopographical structure. Although Cors Fochno is smaller than many peatlands in more northern latitudes, the bog is one of only a handful of UK bogs which may be considered as representative of northern peatland complexes more generally. The central dome of the bog has a high cover of *Sphagnum* mosses, with lower elements of the microtopography often waterlogged. *Sphagnum paluchrum* (Lindb.) Warnst. is prevalent on bog lawns and hollow edges, whereas *Sphagnum magellanicum* Brid., *Sphagnum fuscum* (Schimp.) Klinggr. and, more rarely, *Sphagnum imbricatum* Hornsch. ex Russ. are all found on lawn edges and/or on bog hummocks. A number of common vascular plants are also present at Cors Fochno. These include greater sundew (*Drosera anglica*), white-beak sedge (*Rhynchospora alba*), common cotton grass (*Eriophorum angustifolium*), bog-rosemary (*Andromeda polifolia*) and varieties of heath (e.g. *Calluna vulgaris* and *Erica tetralix*). The outer periphery of the bog supports elongated zones of reeds and rushes (*Phragmites* spp. and *Juncus* spp.) (Taylor, 1983).

Fieldwork was undertaken at Cors Fochno throughout 2002. Rainfall in the winter of 2001/2 at the site was generally above average, and below average rainfall was observed in the June–
Fig. 1. (a) Location of the study area at Cors Fochno. (b) Comparison of monthly rainfall totals for 2002 and mean total rainfall throughout 1981–2003. Rainfall data are from a weather station located at an altitude of 80 m asl on a hillside 1 km SE of Cors Fochno. As a consequence of the altitude, the values of rainfall reported here may be slightly higher than on the bog itself. (c–d) A map of the locations of field sampling sites, and a photograph of typical primary and sub-sampling stations.
September period (Fig. 1b). In April 2002, a ground survey was undertaken to identify key site characteristics including; (1) land cover type, (2) bog microtopography, and (3) the cover of Sphagnum species. The baseline survey was used to identify 36 sampling locations across the field site (Fig. 1c and d). Each sampling location consisted of a large (typically >6 x 6 m²) relatively homogenous lawn of S. pulchrum that was hoped to be unambiguously identified from airborne imagery with a spatial resolution of 1–2 m. The 36 sampling locations were sub-divided into two parts: (1) station a was known as the primary sampling station and (2) station b was the sub-station. Each location was divided into two in an attempt to characterise any small-scale variability in near-surface moisture content in the lawns (see below). High-visibility wooden stakes were used to mark each of the sampling stations and their geographical locations were accurately surveyed. At each of the 36 primary stations (i.e. stations a), a dipwell was inserted into the peat for recording water-table depth (see below). Measurements of volumetric moisture content (VMC) were also made, together with field measurements of spectral reflectance (i.e. obtained using a hand-held spectroradiometer) (see below). Field measurements were made in conjunction with airborne imagery collection on May 16th and September 24th 2002. A limited window of flying opportunity was available in 2002 such that these dates were chosen to coincide with wet surface conditions in May and relatively dry conditions in September, thus giving a good range of moisture conditions for which to test the moisture and biophysical vegetation indices (Fig. 1b). On both dates, clear-sky conditions prevailed for most of the time, thus allowing collection of reliable field spectra and airborne data.

2.2. Field measurement design and data acquisition

2.2.1. Hydrological data

Measurements of the near-surface (i.e. the top 6 cm of the surface including Sphagnum canopies and underlying litter) moisture content were made across the field site in conjunction with measurements of water-table position. It is important to look at the spectral response of Sphagnum in relation to both variables because, although they are generally strongly positively correlated (e.g. Gilvear & Watson, 1995; Watson et al., 1992), the relationship between the two can become weak, particularly during periods of excessive drought when water tables are typically more than 20 to 30 cm below the bog surface (Hayward & Clymo, 1982).

As noted above, water-table position below the bog surface was recorded using dipwells. Manual recordings of water-table level were obtained by blowing through a hollow tube which was lowered inside each dipwell. Near-surface VMC was measured in the upper 6 cm of the bog, using a ThetaProbe (Delta T-Devices) which measures, indirectly, the dielectric constant of the peat and outputs a signal in the approximate range of 0–1 V DC depending on the VMC (Delta-T Devices, 1998; Miller & Gaskin, 1996). In an attempt to characterise the spatial variability of near-surface moisture, VMC was recorded at each primary and each sub-station across the site (i.e. 72 locations). A 1 x 1 m² quadrat was laid over each primary and sub-station and VMC measurements were taken from five randomly selected 10 x 10 cm² squares in each quadrat. Conversion of the voltage output from the ThetaProbe was undertaken using calibration equations developed in the laboratory using surface peat from Cors Fochno.

2.2.2. Field reflectance data

Field reflectance data were collected near-simultaneously with measurements of near-surface wetness. An Analytical Spectral Device (ASD) FieldSpec Pro Spectroradiometer was used to collect field reflectance spectra in the 350 to 2500 nm range, in wavebands approximately 1 nm in width. All spectra were collected in white reference mode with dark current and white reference (spectronal panel) measurements taken every 2–3 min. Each spectrum consisted of 30 individual measurements taken consecutively and averaged by the spectroradiometer. The number of repeat measurements made using the spectrometer was directly determined by the integration time; with the 30 measurements often collected in less than 10 s. Measurements were acquired using an 8° optic head attached to a fiberoptic cable. All measurements were made with the nadir-pointing optic head approximately 1 m above the target material resulting in a ground field of view (GFOV) diameter of approximately 14 cm. The fiberoptic head was held at arm’s length with the operator’s body positioned perpendicular to the suns azimuth.

Time constraints, imposed largely by the difficult nature of carrying the bulky instrument across boggy terrain, meant that spectral measurements were not collected at all of 36 sampling stations. Additional problems with the battery-life of the accompanying laptop computer during the May field session meant that at the time of image over-flight 74 spectra were collected from 10 monitoring stations on that occasion, although during the September over-flight, a total of 116 spectra were collected from 23 of the stations.

2.3. Spectral analyses

Post-processing of the field spectra consisted of removing those wavebands affected by atmospheric absorption and careful examination of spectra to remove any that were clearly not Sphagnum. All field spectra were then re-sampled to match the wavelengths and band-pass of the airborne sensors (i.e. CASI-SWIR and ATM, see below), based on wavelength calibration files supplied by the UK Natural Environment Research Council Equipment Pool for Spectroscopy (NERC EPFS). A range of vegetation indices (fWBI1080, fWBI1200, the chlorophyll index and MSI) were calculated using the formulas shown in Table 1 and correlated with in situ values of VMC and water-table position at each sample site.

2.4. Airborne reflectance data

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 VIS and NIR (bands 1–8), the SWIR (bands 9 and 10) and the TIR (band 11).

A typical sensor scene consisted of 4 lines of imagery with a spatial resolution between 1.5 and 2 m. On both collection dates, the composite of all flight lines covered the entire length and breadth of Cors Fochno (Fig. 1a). Colour aerial photographs were also collected concurrently with the September 24th imagery. Unfortunately, after the ATM imagery had been received and pre-processed, it came to light that there had been severe calibration problems with the ATM sensor during the late summer flying season of 2002. This effectively meant that the September 24th ATM image was deemed unusable. Fortunately, near-hyperspectral data were also collected on September 11th 2002 at the Cors Fochno site, and these data were used as a replacement data set. The near-hyperspectral data set was collected using a combination of two sensors: (1) the Compact Airborne Spectrographic Imager (CASI), and (2) the Shortwave Infrared Spectrographic Sensor (SWIR). CASI collected spectra in the VIS and NIR with a sampling interval of between 10 and 20 nm. For this study, CASI was used in spatial mode with the default vegetation band set (NERC, 2002). The SWIR sensor was an experimental hyperspectral sensor which collected spectra in 160 bands from 850 to 2450 nm with a sampling interval of 10 nm. The spectral ranges of the CASI and SWIR sensors overlapped to provide a repeatable spectral ‘seam’ between the two instruments. Thus, as well as providing a near-hyperspectral data set for the September sampling period, these data were also merged to create a replacement pseudo ATM image (know herein as pATM) for comparison with May ATM data. The resultant available image data sets from the two collection periods are listed in Table 2. Because the problems with the data set from September 24th were not anticipated, no field data were collected on September 11th 2002. It should be noted that some rainfall was recorded between September 6th and 10th, and that no precipitation was recorded between September 11th and collection of the field data on September 24th. Both September 11th and September 24th fell within a longer period of generally dry weather; thus, despite the rain events prior to data collection, it is suggested that surface moisture conditions across the bog remained broadly comparable.

### 2.5. Image processing methods to map Sphagnum

#### 2.5.1. Atmospheric and geometric correction

All images were radiometrically corrected (using gains/offsets), geometrically corrected (first-order) to the UK national grid with a pixel size of 1 × 1 m² using a nearest-neighbour interpolation algorithm (to best preserve the spectral values), and converted to apparent at-surface reflectance using dark object subtraction (Chavez, 1975, 1988; Vincent, 1973). The dark object subtraction approach was used in this instance to provide ‘first-order’ atmospheric correction and therefore did not include the correction of atmospheric transmittance; hence the DN values (haze values) selected for the correction may not accurately represent realistic relative atmospheric scattering models. Dark object subtraction was undertaken on the May 16th ATM image (taken as the reference image) with the remaining data being corrected through detailed image normalisation. For the purposes of quality control, reflectance values from the first-order atmospherically corrected images were compared directly with the original raw images before pre-processing continued. During the corrections of the CASI-SWIR data, there appeared to be some problems with a number of bands in the SWIR data set primarily located at or around the NIR water absorption features (located at approximately 970 and 1200 nm). These bands were removed from any further analysis. Similar problems with the experimental SWIR sensor during 2002 have been reported by other users (e.g. Verbeiren et al., 2004; NERC, 2004). Because of the problems with certain bands in the SWIR sensor, the usefulness of the CASI-SWIR data as a near-hyperspectral data set was compromised. Importantly, however, the use of CASI-SWIR data to derive a pATM product was not compromised.

The September pATM scene was co-registered with the May ATM scene with an overall spatial accuracy of ~40 cm. The success of the co-registration process was further checked using orthorectified aerial photographs collected concurrently with the September airborne data. To aid further analysis, the flight lines were then sub-set to encompass the centre of the bog where the field stations were located (Fig. 1c). All image processing was then carried out using programs within the Environment for Visualisation of Images (ENVI) version 3.5 software package (Research Systems Incorporated, 2000).

#### 2.5.2. Minimum noise fraction transformation (MNF)

Accurate identification of *S. pulchrum* from remotely sensed data was imperative for elucidating near-surface

### Table 1
Spectral indices used to detect changes in wetness conditions, and the precise wavebands used in this study

<table>
<thead>
<tr>
<th>Spectral index</th>
<th>Formula</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>fWBI1460</td>
<td>$R_{920\text{min}}/(R_{760\text{min}}-1000)$</td>
<td>Penuelas et al. (1997)</td>
</tr>
<tr>
<td>fWBI1220</td>
<td>$R_{920\text{min}}/(R_{1150\text{min}}-1220)$</td>
<td>Penuelas et al. (1997)</td>
</tr>
<tr>
<td>MSI</td>
<td>$(R_{1550\text{min}}-150)/(R_{760\text{min}}-800)$</td>
<td>Vogelmann and Rock (1986)</td>
</tr>
<tr>
<td>Chlorophyll index</td>
<td>$[(R_{750\text{min}}-800)/(R_{695\text{min}}-740)]-1$</td>
<td>Gitelson et al. (2003)</td>
</tr>
</tbody>
</table>

Table 2
Image data sets for Cors Fochno in 2002

<table>
<thead>
<tr>
<th>Data set</th>
<th>Coincident field</th>
<th>Flight Line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Campaign</td>
<td>ATM</td>
</tr>
<tr>
<td>May 16th 2002</td>
<td>Yes</td>
<td>A136011b.hdf</td>
</tr>
<tr>
<td>September 24th 2002</td>
<td>Yes</td>
<td>A26701b.hdf</td>
</tr>
<tr>
<td>September 11th 2002</td>
<td>No</td>
<td>Cors_line1_g.pix</td>
</tr>
</tbody>
</table>

*Files deemed unusable.*
moisture conditions via spectral response at an airborne scale. Mapping of *Sphagnum* was primarily undertaken on the May 16th ATM reference data, which were collected at a time of optimum growth of *S. pulchrum*. Due to the heterogeneous nature of vegetation canopies within and around the sample stations, and despite the 1-m resolution of the airborne data, a sub-pixel approach to mapping the proportion of *S. pulchrum* in each pixel was deemed appropriate for the accurate estimation of cover statistics. Before sub-pixel analysis was attempted from these data, a minimum noise fraction transformation (MNF) was first applied. MNF is a data reduction transformation specifically designed to de-correlate and segregate any noise apparent in the data, thereby reducing the number of bands necessary for classification procedures (Green et al., 1988). Examination of the spatial information contained in the MNF-transformed ATM image data, together with the associated eigenvalues, indicated that 81% of the total statistical variance in the 10-band ATM image data set was contained in the first 4 MNF bands of the image. Consequently only these bands were carried forward in the sub-pixel analyses.

### 2.5.3. Mixed tuned match filtering (MTMF)

A mixed tuned match filtering (MTMF) approach to sub-pixel data extraction (Boardman, 1998) was used to derive *S. pulchrum* fractional cover $F_{sp}$ from the image data. MTMF has been documented to be one of the most appropriate methods for vegetation mapping, particularly when all the end members within a scene are unknown or are not required (e.g. Glenn et al., 2005; Williams & Hunt, 2002). The technique performs a ‘partial’ un-mixing by only finding the abundance of user-defined end members. MTMF therefore maximises the response of such end members and, by suppressing the response of other composite background materials, attempts to ‘match’ the known signature (Boardman, 1993; Boardman, 1998; Harsanyi & Chang, 1994). *Sphagnum* is a good candidate for MTMF because it has a very distinctive spectral signature when compared to many of the associated vascular plant species found on Cors Fochno (Bubier et al., 1997; Vogelmann & Moss, 1993), thus increasing the chance of successful extraction of a pure *Sphagnum* end member from non-hyperspectral data.

The *S. pulchrum* end member was derived by plotting various combinations of the first four MNF bands in both 2 and n-dimensional planes. The ‘pure’ end member pixels (which were assumed to represent up to 100% *S. pulchrum* cover) were located and identified at the extremities of feature-space (Bryant, 1996). Pixels were interactively clustered, based on their spatial relationship to each other and upon examination of their spectral signatures. The spectral features of each pixel group were compared with field and laboratory spectra (Harris et al., 2005) until a tightly clustered group of pixels matched the spectral signature of *S. pulchrum*. The end member was entered into the MTMF algorithm and applied to the first four bands of the MNF transformed reflectance data. The results of MTMF were presented as two grey-scale images: (1) an infeasibility image and (2) a matched filter (MF) score. Each pixel was assigned a MF score between approximately 0 and 1, where 1 equated a perfect spectral match and 0 indicated that no match had occurred. The infeasibility image indicated the plausibility of the MF score. Pixels with a high MF and low infeasibility were likely to contain the purest end member pixels. To ensure the most accurate classification of *S. pulchrum* possible, a 2-D scatter plot of MF values versus infeasibility was produced. When large thresholds were used (i.e. low MF score and high infeasibility), many of the *Sphagnum* pixels were misclassified. When very small thresholds (high MF score and low infeasibility) were used, many of the pixels were not classified at all. The optimum threshold value was determined by comparing the spectral profile of matched pixels against the end member spectral profile.

Processing remotely sensed imagery in this instance was largely an iterative process with the ultimate aim of increasing the quality of the final product; although at the same time this process can inevitably increase user bias and may reduce accurate repeatability of the classification (Glenn et al., 2005). Consequently, MTMF was only undertaken on the May ATM reference image. Because the September image was co-registered (and the registration error between scenes was low i.e. <40 cm), the results from the MTMF May image were used as a mask to extract candidate *S. pulchrum* pixels from the image data collected in September. Field observations in May and September suggested that the location and size of the patches of *S. pulchrum* remained relatively constant throughout this period.

### 2.6. Thematic information extraction

The MSI was calculated from those pixels identified as *S. pulchrum* using MTMF on the ATM and pATM data. Index values were extracted from each pixel and combined to produce a representative value for each patch of *S. pulchrum*. Due to the problems with a number of the SWIR sensor bands, the hyperspectral fWBIs could not be reliably extracted from the data set. Details of the spectral reflectance indices used in each image scene, the sensor and the sensor bands used in this study are given in Table 3.

### 3. Results and discussion

#### 3.1. Near-surface moisture and water-table dynamics

Near-surface VMC and water-table position relative to the bog surface measured at each sampling site in May and September are shown in Fig. 2. The results indicate that clear differences existed in both water-table position and VMC between the wetter May and drier September field sessions at
The highest water-table position and maximum values of near-surface VMC were both recorded in May (0.3 cm below the surface and 0.91, respectively), whereas the lowest water-table position and minimum levels of near-surface VMC were recorded in September (18 cm below the surface and 0.32, respectively). However, the water-table position at the study site was not as low in September as anticipated (water tables >20 cm deep were observed at Cors Fochno in 2001 and 2003). Nevertheless, a significant relationship was identified between near-surface moisture and water-table position during 2002 ($r = -0.78$, $p < 0.0001$) (Fig. 3) suggesting that near-surface moisture is often indicative of underlying water-table position in peatland environments.

3.2. The influence of surface and near-surface moisture upon field spectral reflectance

Fig. 4 compares characteristic reflectance signatures for *S. pulchrum* collected from the same sampling location on May 16th and again on September 24th 2002. The spectral profiles reveal a series of marked changes in the spectral response between 350 and 2500 nm. A reduction in near-surface moisture between May and September 2002 resulted in increased reflectance in the VIS/NIR boundary, NIR and SWIR regions of the electromagnetic spectrum. The most obvious difference in the spectral data from the two field sessions can be seen along the Red Edge (~680–880 nm) and at the NIR liquid water absorption features, centred at approximately 980 nm and 1200 nm; although a marked increase in reflectance can also be seen in the SWIR (approx. 1550–1750 nm). Previous work on the spectral reflectance of *Sphagnum* has demonstrated the usefulness of these regions in discriminating between different levels of surface and near-surface wetness (Bryant & Baird, 2003; Harris et al., 2005; Vogelmann & Moss, 1993).

Table 4 and Fig. 5 display the results from each spectral index that was extracted from field spectral data. In line with the findings of Harris et al. (2005), the moisture-based indices were significantly correlated with both VMC (Fig. 5a, c, and e) and water-table position (Fig. 5b, d and f), although relationships with water-table position were slightly weaker than those for VMC (Table 4). Slightly higher correlations were found between spectral reflectance and the hydrological measures for those indices formulated from the NIR liquid water absorption bands (fWBI980 and fWBI1200) compared to those that did not incorporate these features (chlorophyll index and MSI) (Table 4). The highest values of the fWBIs were observed in May when VMC was high and water tables were close to the surface.
whereas the lowest ratio values were observed in September when both VMC and the position of the water table were lowest (Fig. 5a–d). Significant correlations were observed between the broader band SWIR MSI and field wetness, although the correlations between MSI and both hydrological measures were weaker than for the fWBIs (Table 4). The difference in response of these two indices to changes in near-surface moisture content may be explained by the inherently different sensitivities of the indices, and the varying impacts which increases in heterogeneity of the canopy of S. pulchrum have on each of them as near-surface moisture begins to decrease (Hayward & Clymo, 1982).

The MSI is composed of wavelengths located in the NIR (760–900 nm) and the SWIR (1550–1750 nm). Radiation is strongly absorbed by water in the SWIR. Thus, although the MSI is sensitive to changes in moisture, the index tends to have a narrow effective range; saturating at high moisture contents (Cohen, 1991; Hunt & Rock 1989; Riggs & Running, 1991). In addition, because of the strength of absorption in the SWIR, radiation is unable to penetrate beneath the surface of the canopy; thus, the MSI is likely to be more indicative of surface moisture (i.e. moisture held within the top of the canopy) than near-surface VMC (i.e. top 6 cm of the bog surface). Rapid increases in the MSI for S. pulchrum have been observed in laboratory experiments as VMC was reduced below ~0.7, approaching an asymptotic value at a VMC of approx. 0.3 (Harris et al., 2005). This is because S. pulchrum has an open canopy with relatively few capillary pores, and as VMC is reduced below 0.7, the species is unable to supply water continually to its capitula. Thus, moisture is rapidly lost from the canopy causing a sharp increase in the MSI below this moisture threshold (Harris et al., 2005). In contrast to the MSI, the fWBIs are composed of wavelengths located in the NIR, where radiation is only weakly absorbed by water and thus penetrates more deeply into the canopy. Greater penetration of the NIR radiation decreases the sensitivity of the index to rapid moisture changes in the surface of the canopy (Bull, 1991). Consequently, the NIR indices are more representative of the near-surface VMC as opposed to just the very surface, which often becomes more heterogeneous as the canopy begins to dry.

The fWBIs are also more linearly correlated with measures of near-surface wetness than the MSI (Fig. 5a–f). Such a finding is thought to be associated with the position of the reference wavelength in relation to the water absorption feature of interest. As discussed earlier, decreases in near-surface moisture result in increased reflectance not only in the regions of the electromagnetic spectrum specifically affected by moisture (i.e. water absorption features) but also across many parts of the NIR, owing to the influence of water stress on internal cellular structure (Harris et al., 2005). However, such changes in wetness do not affect all regions of the electromagnetic spectrum in equal proportions. For example, as moisture content decreases, reflectance increases in the SWIR are far smaller than those in the neighbouring NIR (Fig. 4). To compensate for this effect, the reference wavelength should be located near the absorption feature of interest (Bull, 1991; Penuelas et al., 1993). The reference wavelengths for the NIR fWBI indices are situated in close proximity to the corresponding water absorption features (i.e. 920 in relation to 980 and 1200 nm) but the MSI is formulated such that the reference wavelengths (760–900 nm) are located in the NIR whereas the wavelengths used to determine moisture are positioned in the SWIR (1550–1750 nm). Because the NIR reference wavelength is also influenced by moisture variation, the range over which the relationship

<table>
<thead>
<tr>
<th>Spectral index</th>
<th>Property detected</th>
<th>$r$</th>
<th>Water-table</th>
<th>VMC</th>
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<tr>
<td>fWBI&lt;sub&gt;980&lt;/sub&gt;</td>
<td>Water</td>
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<tr>
<td>MSI</td>
<td>Water</td>
<td>$S, 0.62, p&lt;0.001$</td>
<td>$S, -0.70, p&lt;0.0001$</td>
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<tr>
<td>Chlorophyll index</td>
<td>Chlorophyll</td>
<td>NS</td>
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S=significant at the 0.05 level, NS=not significant at the 0.05 level. May and September data are combined.
Fig. 5. Field-derived spectral indices as a function of volumetric moisture content (VMC) (a, c, e and g) and water-table position (b, d, f and h) at Cors Fochno in 2002. (●) Data from May 16th; (○) data from September 24th 2002 ($n \geq 4$, mean ± 1 standard error).
between moisture and the MSI is linear is small in comparison to that of the indices formulated from the NIR (Bull, 1991). The results from the field moisture-based indices suggest that the dynamic range of the MSI is small, and may not be suitable for detailed estimations of near-surface and surface wetness at high moisture contents, using S. pulchrum as a key indicator species. However, the MSI may be useful as an indicator of surface and near-surface wetness conditions when applied to Sphagnum species that have better water transport ability (e.g. S. magellanicum, S. balticum and S. fuscum). This is because their canopy structure is often more compact and only minor visual structural changes appear to occur as moisture is lost. Thus the dynamic range of the MSI is likely to be wider for these species than it is for S. pulchrum (Harris et al., 2005).

In contrast to the moisture-based indices, the chlorophyll index was not significantly correlated with any measures of near-surface moisture, and changed very little between May and September (Table 4 and Fig. 5g–h), suggesting little change in the chlorophyll content between the two field sessions. One of the primary reasons is the relatively high level of precipitation that fell on Cors Fochno during the summer of 2002 (Fig. 1b). Laboratory experiments have suggested that the chlorophyll index is unresponsive above VMC values of $\geq 0.4$ because any decrease in moisture in the range above this level is unlikely to cause cell damage and subsequent chlorophyll leaching or degradation (Harris et al., 2005). The lack of variability in VMC, which was a result of high levels of near-surface moisture throughout May and September, is another likely reason for the correlation coefficients between the moisture-based spectral indices being weaker than those reported in laboratory experiments that provided a greater range in VMC values or wetness conditions (Harris et al., 2005). The reduced strength of correlation between each airborne-derived spectral index and the associated hydrological variables, as compared to the laboratory relationships, are also a result of variations in background reflectance, solar and sensor view angles, atmospheric conditions and problems associated with comparing point measurements of heterogeneous patterns of near-surface moisture conditions with spectral characteristics of S. pulchrum, by its very nature a species whose canopy becomes more open and structurally variable as moisture availability decreases. Nevertheless, the amount of variability in spectral data should theoretically decrease with an increase in scale from field to airborne data sets because of the pixel averaging effect of the sensor. As a consequence, airborne data may provide more meaningful information than smaller-scale field measurements.

3.3. Sphagnum abundance images

The output from MTMF analysis was a fraction image with values for each pixel representing the relative sub-pixel abundance of S. pulchrum. A false colour composite of one of the ATM scenes and the MTMF fraction image covering the field study area is shown in Fig. 6. Small patches of yellow dotted throughout the fraction image represent patches of S. pulchrum. A MF threshold value of 0.7 resulted in the majority of Sphagnum pixels being correctly classified. Using this threshold value, 86% of the field monitoring stations were identified from the image. The remaining sites were not detected because (i) they were too small (so that S. pulchrum was not a dominant component of the pixels) or (ii) the stations were situated too close to one another relative to the sensor’s spatial resolution, and were thus identified as a single location. The results of the MTMF were in good agreement with the Sphagnum distribution in the area as identified from aerial photographs, ground truthing and ATM false colour composite images, thus confirming the applicability of MTMF for this purpose.

3.4. Detecting changes in surface and near-surface moisture from airborne imagery

Assessment of the field spectral data suggests that the MSI and both fWBIs, derived from image data, may enable us to...
map near-surface wetness from airborne imagery. MSI values from the study sites located in Fig. 1 were extracted from the May and September images (Fig. 7a and b). 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. 7c). Mean MSI values for each site were significantly correlated with both VMC and position of the water table ($r=-0.55$ and $0.52$, respectively; $p<0.0001$ in both cases).

Lower values correspond to higher moisture contents and higher values correspond to lower moisture contents (Fig. 8), although the correlation between both hydrological measures and MSI is weaker than exhibited by the field spectral data (Table 4).

Field and image-derived values of the spectral moisture indices were significantly correlated with one another ($r=0.44$, $p<0.03$) (Fig. 9a) and are akin to those reported by Harris et al. (2005) in the laboratory, for similar levels of VMC. However, both the May and September MSI values consistently fall

Fig. 7. Remotely sensed Moisture Stress Index (MSI) calculated at Cors Fochno on (a) May 16th and (b) September 11th 2002 from Airborne Thematic Mapper (ATM) and Pseudo Airborne Thematic Mapper (pATM) data, respectively. 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.

Fig. 8. Remotely sensed moisture stress index (MSI) as function of (a) volumetric moisture content (VMC) and (b) water-table position at Cors Fochno in 2002. (●) Data from May 16th; (○) data from September 11th 2002 (mean±1 standard error, $r=-0.55$ and 0.52, respectively, $p<0.0001$ in both cases).
near-surface moisture may be weakened. Small reductions in surface moisture, at high moisture contents, actually overestimating near-surface wetness. Because of the tendency for the MSI to saturate at high levels of moisture, the airborne imagery tends to overestimate near-surface moisture resulting in pixels with lower MSI values (i.e. wetter pixels) dominating the image. Fig. 9b plots image values against the wettest field regions only, for each station at Cors Fochno in May (●) and September (○) 2002 (r=0.42, p<0.05, n ≥ 5). Dotted lines indicate 1 to 1 relationships.

4. Conclusions

The remote sensing based hydrological monitoring approach developed in this study enables relatively simple determination of hydrological conditions across vast areas of Sphagnum-dominated peatlands, and as a result, a number of conclusions can be made:

1. When applied to field spectra of S. pulchrum, all of the moisture-based vegetation indices tested here (fWBI980, fWBI1200 and MSI) were significantly correlated with both near-surface hydrological measures (i.e. near-surface VMC and water-table position), both in the field and when extracted from remotely sensed imagery. The biophysical chlorophyll index was not significantly correlated with either of the hydrological measures for S. pulchrum. Relationships between spectral indices and near-surface moisture at both the field and airborne-scale were similar to those reported by Harris et al. (2005) under laboratory conditions, thus demonstrating the potential of such an approach for deriving proxy measures for large-scale monitoring of near-surface moisture. The strength of the correlations between all spectral indices and measures of surface wetness were lower than those reported for laboratory experiments. This was not a surprising result and it has been attributed to the unusually low variability in moisture conditions experienced in the field. Nevertheless, encouragement should be drawn from the positive results presented here because, generally, water tables in most northern peatlands are likely to fluctuate more widely on a seasonal basis, and often can be >40 cm below the bog surface (Lapen & Wang, 1999).

2. Indices formulated from the weaker NIR liquid water absorption bands (fWBI980 and fWBI1200) were almost linear in their response to moisture fluctuations, and also more strongly correlated with hydrological measures than the SWIR-based index (MSI). Weaker correlations between the MSI and hydrological measures, together with the non-linearity of the index, may be explained by the inherent wavelength-dependent sensitivity of the MSI and its inability to cope with observed increases in the S. pulchrum canopy heterogeneity during drying.

3. Mixed tuned match filtering (MTMF) was successfully used to detect S. pulchrum from Daedalus ATM imagery. A match filter (MF) threshold of 0.7 combined with infeasibility values of less than 15 was deemed the most appropriate threshold for repeated delineation of S. pulchrum across Cors Fochno. This method has a distinct advantage in that it only requires knowledge of the spectral characteristics of the target Sphagnum species, and thus represents a major advantage over other sub-pixel techniques when applied to spatially and spectrally complex vegetation assemblages. Further work is required to: (a) derive a comprehensive accuracy assessment of the approach, (b) define the minimum size of Sphagnum patches which can be identified using both multispectral and hyperspectral imagery, and (c) address issues of the robust
nature of the approach for long-term monitoring for a range of spatial scales and spectral bandwidths. This forms the basis of ongoing research.

4. Correlations between measures of near-surface wetness and the MSI for naturally heterogeneous canopies were found to be weaker for airborne imagery than for associated field data collected at the same sites. Such a decrease in the strength of correlation between data sets was attributed to the wavelength sensitivity of the MSI and the resulting preferential detection of “wetter” pixels within the imagery.

5. Despite the identified short-comings of the MSI, the index may be used for the detection of meaningful changes in near-surface moisture at the landscape level if hyperspectral data were unavailable.

6. Results from the field data suggest that indices formulated from the NIR (fWBI_{980} and fWBI_{1200}) may be more suitable for detailed estimations of near-surface and surface wetness at the landscape-scale than the MSI. However, further data are required over a wider range of near-surface moisture conditions to test fully the performance of such indices.

Fundamentally, this preliminary investigation has demonstrated 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 utilised for hydrological characterisation of peatlands for carbon balance estimations or for ecological restoration projects and monitoring. Although airborne remote sensing can provide high spectral and spatial resolution imagery, this investigation highlights and reiterates well-established issues regarding the careful timing of image acquisition and consistency in quality of data sets that must be considered when planning for continuous hydrological monitoring. Whilst it has been shown here that airborne remote sensing has the potential for monitoring near-surface wetness across peatland complexes, it is suggested that satellite remote sensing may provide a more viable and reliable alternative. The increasing availability of high spectral and spatial resolution 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.

Acknowledgements

We wish to thank the University of Sheffield for a scholarship awarded to Angela Harris; the UK Natural Environmental Research Council (NERC) Equipment Pool for Field Spectroscopy (EPFS) for the loan of field spectro-radiometers, 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 and Paul Coles for drafting the figures.

References


