Available online at www.sciencedirect.com

SCIENCE DIRECT®

Remote Sensing of Environment 97 (2005) 371 – 381

Remote Sensing of Environment

www.elsevier.com/locate/rse

Detecting near-surface moisture stress in *Sphagnum* spp.

A. Harris [a], R. G. Bryant [a,*], A. J. Baird [b]

[a] Department of Geography, University of Sheffield, Winter St., Sheffield, S10 2TN, UK
[b] Department of Geography, Queen Mary, University of London, Mile End, London E1 4NS, UK

Received 5 April 2005; received in revised form 19 May 2005; accepted 20 May 2005

Abstract

Estimating near-surface moisture conditions from the reflectance spectra (400–2500 nm) of *Sphagnum* moss offers great opportunities for the use of remote sensing as a tool for large-scale detailed monitoring of near-surface peatland hydrological conditions. This article investigates the effects of changes in near-surface and surface moisture upon the spectral characteristics of *Sphagnum* moss. Laboratory-based canopy reflectance data were collected from two common species of *Sphagnum* 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 two biophysical indices (REIP and the chlorophyll index) were correlated with measures of near-surface moisture. All spectral indices tested were significantly correlated with near-surface moisture (with r between 0.27 and 0.94). The strongest correlations were observed using indices developed from the NIR liquid water absorption features ($fWBI_{980}$ and $fWBI_{1200}$). However, a hysteretic response was observed in both NIR indices when the canopies were re-hydrated, a finding which may have implications for the timing of remote sensing image acquisition. The Moisture Stress Index (MSI), developed from the SWIR liquid water absorption feature also showed strong correlations with near-surface wetness although the range of moisture conditions over which the index was able to detect change was highly dependent on *Sphagnum* species. Of the biophysical spectral indices tested (REIP and the chlorophyll index), the most significant relationships were observed between the chlorophyll index and near-surface wetness. All spectral indices tested were species specific, and this is attributed to differences in canopy morphology between *Sphagnum* species. The potential for developing estimations of surface and near-surface hydrological conditions across northern peatlands using remote sensing technology is discussed.

Keywords: *Sphagnum*; Moisture; Spectral reflectance; Carbon balance; Remote sensing

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 (Gorham, 1991). In their natural state, most peatlands act as net sinks for atmospheric carbon, although changes in climate, such as those predicted due to global warming, may result in many peatlands becoming net atmospheric carbon sources (Aurela et al., 2001; Gorham, 1991; Oechel et al., 1993). Surface wetness, near-surface wetness and the position of the mean water-table are climatically sensitive and are the primary factors controlling the rate at which atmospheric carbon gases (CO_2 and CH_4) are emitted from peatlands (Dise et al., 1993; Moore & Roulet, 1993; Roulet et al., 1992). Hydrological data such as these are often key forcing variables in physically-based models of carbon balance processes although such models rely heavily on small-scale point-based data extrapolated over large areas (Bubier et al., 1993; Walter et al., 1996). Small-scale point measurements (e.g., using Time Domain Reflectometry (TDR) or water-table dip-wells) are often highly detailed, but do not provide the spatial coverage necessary to characterise hydrological conditions across entire peatland complexes. As a consequence, important variations in peatland microtopography, and thus variability in the water-table position, are often unaccounted for (Walter et al., 2001). Given that it is both difficult and expensive to collect detailed sub-seasonal hydrological measurements within peatlands over large

* Corresponding author. Tel.: +44 114 222 7900; fax: +44 114 279 7912.
E-mail address: r.g.bryant@sheffield.ac.uk (R.G. Bryant).

0034-4257/$ - see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2005.05.001

spatial scales, there is a clear need to explore alternative economical, high-resolution synoptic tools. Such detailed hydrological data are required for reliable predictions of entire peatland hydrological behaviour.

Remote sensing may provide a means of identifying and quantifying spatially-detailed, seasonal and sub-seasonal hydrological changes across entire peatlands. A number of researchers have attempted to use emitted thermal infra red (TIR) (e.g., Cracknell & Xue, 1996; Sobrino & Raissouni, 2000) and microwave remote sensing (e.g., Biftu & Gan, 1999; Griffiths & Wooding, 1996; Oldak et al., 2003) to monitor near-surface soil moisture in wetlands. Although encouraging results have been observed using both methods, techniques relying on emitted TIR often require detailed prior knowledge of the area sensed, whereas the usefulness of microwave sensors is highly dependent upon a detailed understanding of the roughness of surface vegetation canopies (Altese et al., 1996; Benallegue et al., 1995; Oldak et al., 2003). Few studies have established whether optical image data (400–2500 nm) can be used to monitor near-surface hydrological conditions successfully. To date, the use of optical imagery for determining hydrological conditions has been confined to identifying and monitoring patterns of vascular vegetation (e.g., Bubier & Moore, 1994; Gilvear & Watson, 1995). A major drawback to this approach is that distributions of vascular species are often not influenced by short-term changes in water-table position (Bubier & Moore, 1994), thus inter-seasonal variation in near-surface hydrology cannot be accounted for.

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 position in relation to the water-table. Unlike many vascular plants, *Sphagnum* spp. are very sensitive to 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 which allows it to become whitish in appearance; a process commonly known as bleaching (van Breeman, 1995). Because of these unique physiological properties, it has been suggested that the moisture status of *Sphagnum* canopies may be a good indicator of peatland wetness (Bubier et al., 1995).

A number of previous investigations have looked at the spectral signatures of *Sphagnum* both at a laboratory and field scale (Bryant & Baird, 2003; Bubier et al., 1997; Hall et al., 1995; Solheim et al., 2000; Vogelmann & Moss, 1993). These studies have demonstrated that the spectral properties of a range of *Sphagnum* species appears to be separable from that of typical vascular vegetation (Fig. 1)

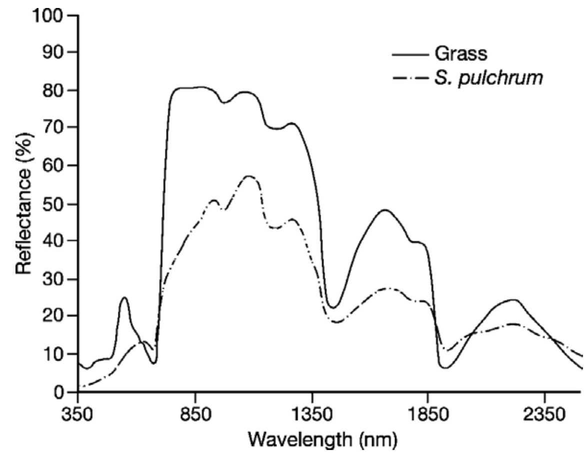

Fig. 1. The spectral reflectance properties of *Sphagnum* moss (*S. pulchrum*) and typical vascular vegetation (lawn grass). Spectra of lawn grass acquired from USGS digital spectral library, 2003 (http://pubs.usgs.gov/of/2003/ofr-03-395/datatable.html).

and that different species of the same genus are often distinguishable from one another (Bryant & Baird, 2003; Bubier et al., 1997; Vogelmann & Moss, 1993).

With the exception of Bryant and Baird (2003), previous studies have not looked in detail at the spectral response of entire *Sphagnum* canopies in relation to wetness, and none have attempted to optimise existing spectral indices for use with *Sphagnum*, even though the spectral signature is evidently different from that of vascular plants. A large gap in knowledge also exists regarding the response of *Sphagnum* canopies to rapid decreases and subsequent increases in near-surface and surface moisture. A hysteretic response from the canopy upon rewetting may have serious implications for the timing of image acquisition from remote sensing platforms.

This paper seeks to address these issues by using laboratory-based remote sensing to elucidate the spectral reflectance properties of two different species of *Sphagnum* as near-surface moisture content is reduced and subsequently increased under controlled laboratory conditions. A combination of high and low resolution (1–100 nm), moisture-based, physiological and biochemical spectral indices, were applied to the spectral reflectance data collected using a portable spectroradiometer. The results of the study are evaluated in terms of the ability to optimise spectral indices for determination of surface and near-surface moisture conditions using a range of remote sensing sensors. This serves as a basis for future field-scale and aircraft/satellite-based measurements.

2. Materials and methods

2.1. Study site, species and sample collection

Six *Sphagnum* samples were collected from Cors Fochno, an ombrotrophic peatland located on the Welsh coast approximately 10 km north of Aberystwyth, UK