Remote Sensing of Environment 152 (2014) 536–546

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Spectral detection of near-surface moisture content and water-table position in northern peatland ecosystems

Karl M. Meingast [a], Michael J. Falkowski [b,*], Evan S. Kane [a,c], Lynette R. Potvin [c], Brian W. Benscoter [d], Alistair M.S. Smith [e], Laura L. Bourgeau-Chavez [f], Mary Ellen Miller [f]

[a] School of Forest Resources and Environmental Science, Michigan Technological University, 1400 Townsend Dr., Houghton, MI 49931, USA
[b] Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, USA
[c] USDA Forest Service Northern Research Station, Houghton, MI 49931, USA
[d] Department of Biological Sciences, Florida Atlantic University, Davie, FL 33314, USA
[e] Department of Forest Resources, University of Idaho, Moscow, ID 83844, USA
[f] Michigan Tech Research Institute, Michigan Technological University, Ann Arbor, MI, USA

ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form 18 July 2014
Accepted 19 July 2014
Available online xxxx

Keywords:
Peatland
Water table
Moisture content
Fire
Spectral
Hyperspectral

ABSTRACT

Wildland fire occurrence has been increasing in peatland ecosystems during recent decades. As such, there is a need for broadly applicable tools to detect and monitor controls on combustion such as surface peat moisture and water-table position. A field portable spectroradiometer was used to measure surface reflectance of two *Sphagnum* moss-dominated peatland experiments, one being an experimental study utilizing a factorial experiment of vegetation and water-table manipulations and the other being a field site located in the Upper Peninsula of Michigan that is broadly representative of northern peatland ecosystems. Relationships were developed correlating spectral indices to surface moisture as well as water-table position using the surface reflectance data. Spectral convolutions, or integrations of the hyperspectral data with the relative spectral response curves of multispectral sensors, were also applied to represent spectral sensitivity of commonly used Earth observing sensors. Band ratios previously used to monitor surface moisture with these sensors were assessed. Strong relationships with surface moisture and water-table position are evident for both the narrow-band indices as well as broad-band indices. This study also revealed a dependence of spectral relationships on changes in vegetation cover, particularly ericoid shrubs, within the vegetation manipulation experiment.

1. Introduction

Peatland ecosystems represent 3–5% of the land surface, yet harbor 12–30% (450–550 Pg) of soil organic carbon (C). Estimates suggest that global peat accumulation sequesters an average of 0.076 Pg of C per year (Gorham, 1991). Peat generally accumulates because decomposition is arrested when there is a consistently high water-table. As such, lower water-tables coincident with changing precipitation patterns or altered drainage often result in a decline in the C sink strength of northern peatlands. Lowered water-tables have also been shown to increase vulnerability of northern latitude peatlands to wildfire (Benscoter et al., 2011; Turetsky et al., 2011; Waddington et al., 2012) and hence further jeopardize peatland C stocks. Additionally, research has demonstrated that the extent of fires in boreal North America has steadily increased over the past decade (Kasischke & Turetsky, 2006), often with substantial peat combustion (Turetsky, Amiro, Bosch, & Bhatti, 2004) and significant CO_2 and CH_4 emissions (Randerson et al., 2006). The detection and monitoring of controls on fire activity (e.g., near-surface moisture content of vegetation and water-table position) are paramount to developing a stronger understanding of the global carbon cycle and the potential impacts of climate change.

Near-surface vegetation moisture content and water-table position strongly relate to changes in surface reflectance of *Sphagnum* mosses, which often dominate ground cover in these ecosystems (Bryant & Baird, 2003; Harris, Bryant, & Baird, 2005, 2006; Moore & Bellamy, 1974; Van Gaalen, Flanagan, & Peddle, 2007). *Sphagnum* mosses rely on capillarity within specially designed cells (hyaline cells) to transport water from the water-table to the photosynthesizing chlorophyllous cells in the *Sphagnum* leaf surface (Rydin & Jeglum, 2006). In addition to transporting and holding water, hyaline cells compose the majority of the surface area of the *Sphagnum* leaf (Rydin & Jeglum, 2006). This physical mechanism results in a strong relationship between water-table position and near-surface moisture of the *Sphagnum* (Rydin & McDonald, 1985; Titus, Wagner, & Stephens, 1983). Given the strong relationship between spectral reflectance, water held in near-surface

* Corresponding author.
E-mail addresses: kmmeinga@mtu.edu (K.M. Meingast), mfalkows@umn.edu (M.J. Falkowski), eskane@mtu.edu (E.S. Kane), lrpotvin@fs.fed.us (L.R. Potvin), bbenscot@fau.edu (B.W. Benscoter), alistair@uidaho.edu (A.M.S. Smith), lchavez@mtu.edu (L.L. Bourgeau-Chavez), marymill@mtu.edu (M.E. Miller).

http://dx.doi.org/10.1016/j.rse.2014.07.014
0034-4257/

Sphagnum tissues, and water-table position (Bryant & Baird, 2003; Harris et al., 2005, 2006; Letendre, Poulin, & Rochefort, 2008; Van Gaalen et al., 2007), remotely sensed surface reflectance measures of *Sphagnum* moss-dominated peatlands could provide a means to characterize the moisture status and water-table position in peatland ecosystems.

Remote sensing based assessments of *Sphagnum* moisture status (surface moisture content and water-table position) have largely employed spectral indices leveraging the near infra-red (NIR) and short wave infra-red (SWIR) regions of the electromagnetic spectrum. For example, Harris et al. (2005) employed the floating water band index (fWBI) in the NIR and moisture stress index (MSI) in the SWIR to assess *Sphagnum* moisture status and water-table position. They reported high Pearson correlation coefficients between *Sphagnum* surface moisture to fWBI and MSI. Highly significant relationships were also reported between these spectral indices and water-table position (Harris et al., 2006).

Although these studies (e.g., Bryant & Baird, 2003; Harris et al., 2005, 2006; Letendre et al., 2008; Van Gaalen et al., 2007) demonstrate the utility of employing remote sensing to characterize peatland moisture status and water-table positions, they are limited by two major factors. Laboratory measurements have been conducted over a large range of *Sphagnum* moisture content (Harris et al., 2005), field measurements of near-surface moisture and water-table position were confined to ranges typical of non-droughty conditions or seasonally high water-tables. A water-table position of 40 cm below the surface has been used as a threshold to indicate higher probability of combustion in deeper organics due to excessive upper peat drying (Waddington et al., 2012). When the depth to water-table is shallow, capillary action is able to keep the fuel moist enough to require more energy to combust than the flaming front could transfer (Benscoter et al., 2011). With an extension of growing season length and increasing precipitation variability, peatland fires are becoming more common (Benscoter et al., 2011; Turetsky et al., 2011), but it is logistically very difficult to capture the spectral character of peat during drought in a field setting without experimental manipulation. Secondly, the aforementioned studies only assess the moisture status of individual *Sphagnum* plants and relatively homogenous *Sphagnum* canopies. Peatland ecosystems typically contain vascular vegetation interspersed above the *Sphagnum* canopy at varying densities (Rydin & Jeglum, 2006; Schaepman-Strub, Limpens, Menken, Bartholomeus, & Schaepman, 2009). These vascular plants introduce large spectral variations (Sonnentag et al., 2007) and alter or degrade the spectral signal from the *Sphagnum*, which may ultimately reduce the efficacy of employing remote sensing approaches based solely on *Sphagnum* reflectance to assess the moisture status of peatland ecosystems. As such, the spectral character of whole communities of peatland sedges, shrubs, and *Sphagnum* is needed to assess limitations in using remote sensing for detecting changes in surface moisture.

The overarching objective of this study was to evaluate the utility of optical remote sensing methods to improve our understanding of moisture dynamics in peatland ecosystems through a series of experiments in peatland mesocosms as well as in the field. The ability to monitor near-surface moisture content and water-table positions typically associated with drought conditions could ultimately be employed to assess the vulnerability and susceptibility of peatland ecosystems to wildfires under future climate conditions (Smith et al., in press). Specifically, the compelling questions we sought to address were: (i) What relationships exist between the spectral response of the *Sphagnum* dominated peatland surface and both water-table position and near-surface moisture content under assemblages of vascular plants spanning a range of species compositions and densities?, (ii) How do these relationships respond under a range of moisture conditions that are commonly observed prior to wildfire and (iii) Are such relationships transferable to common Earth observing (EO) sensors?

2. Background: spectral indices definitions

2.1. Narrow-band indices

The infrared region of vegetation spectral reflectance is strongly influenced by overtones produced by the fundamental excitation frequency of hydrogen bonds of water (Palmer & Williams, 1974). These overtones, referred to as water absorption bands, are centered at approximately 970, 1200, 1450, 1950 and 2250 nm wavelengths in the electromagnetic spectrum (Sims & Gamon, 2003). The use of a field portable spectroradiometer allows precise measurement of these water absorption bands, which can be characterized in a variety of ways via high spectral resolution data (Sims & Gamon, 2003). The most straightforward way of quantifying vegetation water absorption features using high spectral resolution reflectance data is with ratio-based spectral indices that divide a reference wavelength where water is not strongly absorbing electromagnetic radiation by one where water is strongly absorbing (Eitel, Gessler, Smith, & Robberecht, 2006; Sims & Gamon, 2003). Other formulations such as normalized difference indices, which scale these relationships to a range of −1.0 to 1.0, can also be employed to characterize water absorption bands (Gao, 1996). In addition to ratio-based and normalized indices, dynamic, floating point indexes such as the floating water band index (fWBI) have been used for assessing vegetation moisture status (Peñuelas, Piñol, Ogaya, & Filella, 1997). The fWBI allows the strong water absorption denominator to be dynamic (i.e., it is set as the minimum of the water absorption feature, rather than centering in on a specific wavelength). This dynamism can strengthen the index's response to vegetation moisture since water absorption features can significantly shift under varying degrees of plant water stress (Peñuelas et al., 1997). Table 1 displays the equations used to calculate the spectral indices that have been investigated for use in assessing vegetation moisture content.

2.2. Broad-band indices

Employing the relationship between spectral signal and vegetation water status from EO satellite sensors may be warranted for monitoring peatland moisture status across large spatial extents. Indeed, several studies have employed EO sensors to assess vegetation moisture content for a variety of applications (Yebra et al., 2013). Landsat has been employed to derive spectral indices for assessing fuel moisture content in grasslands and shrublands (Chuvieco, Rian˜o, Aguado, & Cocero, 2002), and strong relationships have been reported with MODIS derived spectral indices and soil moisture content (Fensholt & Sandholt, 2003). MODIS has also been utilized in monitoring leaf water content (Zarco-Tejada, Rueda, & Usrin, 2003).

While EO sensors have been utilized in a range of ecosystems, few have attempted to employ these techniques to assess peatland moisture status. Understanding the sensitivity of indices derived from broad spectral bands, similar to those measured by these sensors is the first step in determining if EO sensors could potentially be employed to monitor peatland moisture status and fire susceptibility across large spatial extents. This is achieved by convolving the high spectral

Table 1
Spectral indices used for vegetation moisture content.

Index	Equation	Reference
$fWBI_{980}$	$R_{920}/\min(R_{960-1000})$	Peñuelas, Filella, Biel, Serrano, and Savè (1993)
$fWBI_{1200}$	$R_{920}/\min(R_{1150-1220})$	Harris et al. (2006)
MSI	$(R_{1550-1750})/(R_{760-800})$	Vogelmann and Rock (1986)
WI	R_{900}/R_{970}	Peñuelas et al. (1993)
NDWI	$(R_{860} - R_{1240})/(R_{860} + R_{1240})$	Gao (1996)
CI	$[(R_{750-800})/(R_{695-740})] - 1$	Harris et al. (2006)
NDVI	$(R_{850} - R_{680})/(R_{850} + R_{680})$	Harris (2008)

resolution spectroradiometer data to the relative spectral response curves for channels of common EO satellite sensors in order to generate band equivalent reflectance values (Smith, Eitel, & Hudak, 2010; Smith et al., 2005; Trigg & Flasse, 2001). Every band from each EO satellite has its own unique spectral response that varies with wavelength. The convolution of the spectroradiometer data with the spectral response functions allows us to estimate what each EO satellite sensor would measure if it was in the physical location of the spectroradiometer. It is important to remember that this is just an initial step in determining whether spectral changes related to water-table position and moisture content are detectable given the spectral sensitivity of optical EO satellite sensors. Other factors need to be considered as well; including atmospheric effects on these bands and the coarse spatial resolution of EO sensors in comparison to the spectroradiometer measurements.

3. Methods

3.1. Study sites

Two experimental sites were utilized in this study, one outdoor experimental facility and one field site. Both are described in detail in the subsequent sections. The outdoor experimental facility was utilized to assess these spectral-based methods under an extreme range of water-table positions. The field site was utilized to additionally assess these methods under conditions with greater heterogeneity in microtopography and vegetation structure.

3.1.1. Outdoor facility — PEATcosm

Spectral sampling of peatland vegetation across different species compositions and water-table positions was conducted at an outdoor experimental facility, called PEATcosm (Peatland Experiment At The Houghton mesocosm facility), located at the USDA Forest Service Northern Research Station in Houghton, Michigan USA. The PEATcosm experimental facility consists of 24 mesocosms containing intact monoliths of peat extracted from an extensive oligotrophic peatland in Meadowlands, MN (N47.07278°, W92.73167°) in May 2010. The peat monoliths were extracted using a 1 m^3 corer and transferred into Teflon-coated stainless steel bins (1 m^3) with minimal disturbance to aboveground vegetation. The peatland vegetation at the harvest site was dominated by the sedge *Carex oligosperma* Michx., ericaceous shrubs *Chamaedaphne calyculata* (L.) Moench., *Kalmia polifolia* Wangenh., *Vaccinium oxycoccus* L. and the mosses *Sphagnum rubellum* Wilson, *Sphagnum magellanicum* Brid., and *Sphagnum fuscum* (Schimp.) Klinggr. Also present were *Polytrichum strictum* Brid., *Polytrichum commune* Hedw., *Eriophorum vaginatum* L., *Andromeda polifolia* L. var. *glaucophylla* (Link) DC., *Rhododendron groenlandicum* Oeder, and *Drosera rotundifolia* L.

In the summer of 2011 a full factorial experiment with 2 water-table × 3 vegetation treatments with 4 replicates in a randomized block design was initiated. Long term water-table trends from the USDA Forest Service Marcell Experimental Forest (near the peat harvest sites) were used to inform the water-table treatments (Sebestyen et al., 2011) and vegetation manipulations were based on the 2 primary vascular plant functional groups in northern peatlands, Ericaceae and sedges. The target water-table treatments were based on 1) low variability, average water-table years and 2) high variability, low water-table years. The water-table treatments were maintained using a combination of artificial rainwater additions, rain-out shelters and regulated outflow. The depth of the water-table below the peat surface was calculated using mean peat elevation measurements and was monitored using submersible vented pressure transducers (Grainger 2HMC7) deployed in perforated PVC well pipe, with weekly manual checks to ensure sensor accuracy. The PEATcosm water-table draw down allowed for spectral sampling to occur when water-table reached up to 34 cm below the peat surface in 2012 and 46 cm below the peat surface in 2013 (Fig. 1). Near-surface moisture was measured in the

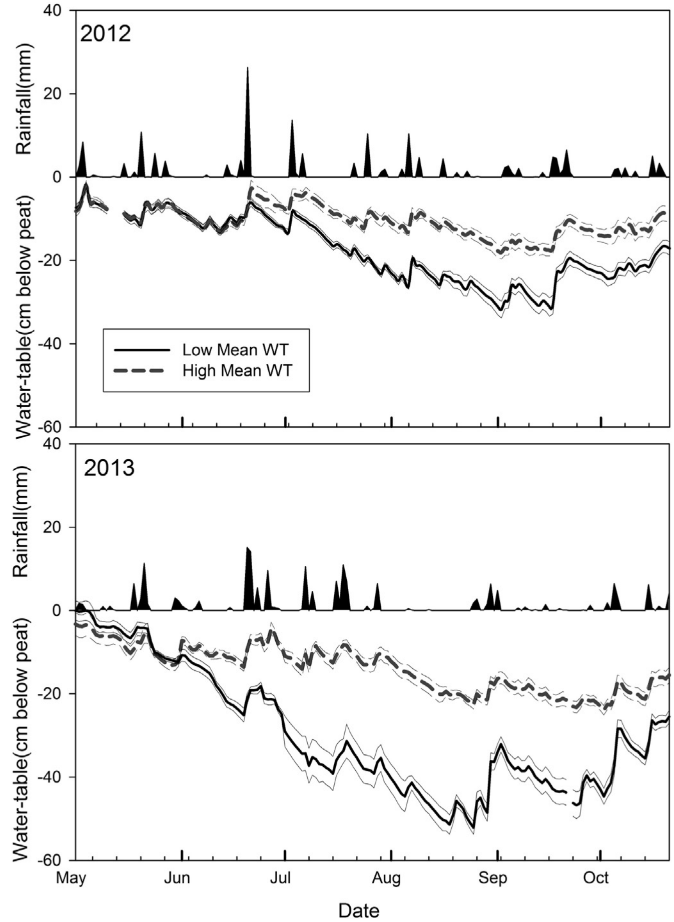

Fig. 1. Average water-table positions for the high and low water-table treatments in the PEATcosm experiment during the 2012 and 2013 growing seasons.

PEATcosm using a Thetaprobe (Delta-T Devices, Cambridge, UK), which measures integrated 7 cm volumetric moisture content (VMC). This device indirectly measures changes in the apparent dielectric constant of the peat (Delta-T Devices, 1999). Conversion of the output voltage signal to VMC was achieved using a calibration equation developed using peat from the Nestoria field site ($R^2 = 0.77$, RMSE $= 0.13$, $n = 20$).

Plant communities were manipulated to create three vegetation treatments. All plant removals were carried out by clipping at the base of the stem. The moss communities (*Sphagnum* and *Polytrichum*) were left intact in all treatments. In the sedge treatment all ericaceous shrubs were removed, in the Ericaceae treatment all sedges were removed and in the unmanipulated treatment the shrub and sedge communities were left intact. In the sedge treatments, the remaining vascular plants were *C. oligosperma* and *E. vaginatum*, with an average cover of 34%. In the Ericaceae treatment the remaining vascular plants were *C. calyculata*, *K. polifolia*, *V. oxycoccus*, *A. polifolia* var. *glaucophylla*, and *R. groenlandicum*, with a mean cover of 103% (due to canopy layering, the point-intercept sampling can result in multiple returns of the same species in one location, allowing for mean cover to exceed 100%). In the unmanipulated treatment, mean Ericaceous shrub cover was 71% and mean sedge cover was 16%. Vegetation treatments were maintained with weekly clipping of new growth of the excluded species.

3.1.2. Nestoria field site

The field site is an extensive poor fen located near Nestoria, MI (46°34′22.66″ N, 088°16′44.85″ W). The peatland is approximately 30 ha in size with a maximum peat depth exceeding 5 m (Fig. 2). This field site allowed for harvesting of the peat and over story vegetation

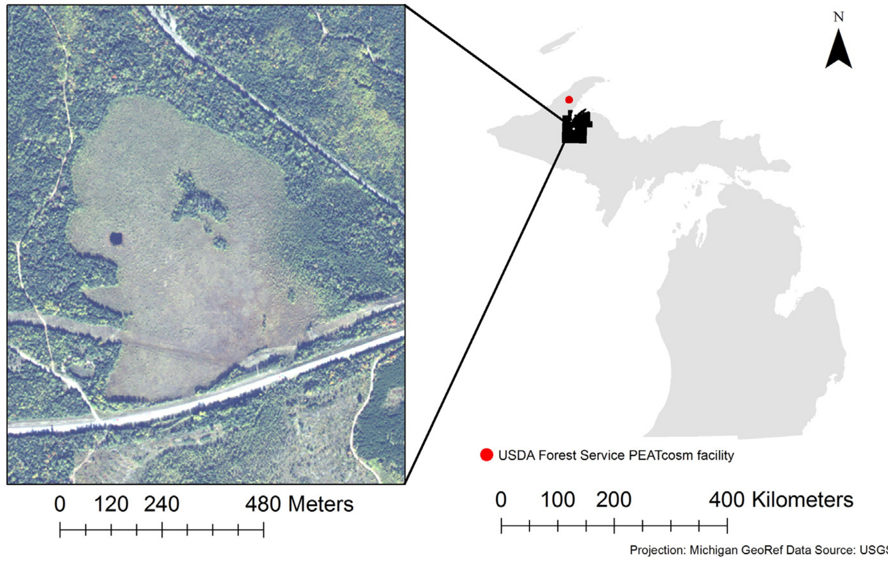

Fig. 2. The Nestoria field site in Baraga county MI and the PEATcosm facility location in Houghton, MI USA.

to provide a more precise measure of near-surface moisture than possible at the PEATcosm experiment. This particular site was chosen because vegetation community composition was similar to that of PEATcosm. The over story consists of *Larix laricina* and *Picea mariana* and the understory consists of mixed sedge (*Carex* spp.) and ericoid shrubs (*K. polifolia*, *C. calyculata*, *R. groenlandicum*, *A. polifolia* var. *glaucophylla*, *Vaccinium* spp.) with a *Sphagnum* moss ground cover. Three species of *Sphagnum* are present: Spp. *magellanicum*, Spp. *angustifolium*, and Spp. *fuscum*.

3.2. Reflectance measurements

An ASD Fieldspec 3 spectroradiometer (Analytical Spectral Devices, Boulder, CO) was used to collect spectral data at both the PEATcosm facility and Nestoria field site under clear and low haze conditions. This spectroradiometer has a nominal spectral range spanning 350–2500 nm. It is comprised of three sensors (VNIR, SWIR1 and SWIR2) and has a spectral resolution of 3 nm between 350 and 1000 nm and 10 nm for wavelengths from 1000 and 2500 nm. Each recorded reflectance measurement is an average of 10 samples. Prior to calculation of the spectral indices, a linear interpolation routine was applied to produce reflectance measurements every 1 nm.

At the PEATcosm facility, spectral measurements were taken immediately prior to moisture and water-table measurements. The spectroradiometer was attached to a steel sampling frame placed around the peat bin in order to allow repeated measurement of the same locations throughout the study season (Fig. 3). When fixed to the sampling frame, the fore optic was approximately 1 m above the vegetation surface at nadir. With an 8° viewing fore optic, this resulted in a field of view of approximately 14 cm. The fore optic was positioned at 5 different locations in each peat bin, which were averaged to calculate bin-level reflectance. The spectroradiometer was white referenced every 10 min to account for changes in sun angle and sky conditions using a Labsphere certified reflectance standards spectralon disk (Labsphere, North Sutton, NH). Spectral measurements were taken only under clear low haze conditions between 11:00 and 15:00 EDT.

In the field study, spectral measurements were taken systematically at 10 m intervals along 3 transects traversing a gradient of moisture, canopy, and micro-topographic conditions present at the site. Due to the high micro-topographic variability, precise locations were chosen to alternate between hummock, lawn and hollow across the study area. This was done to accurately characterize the heterogeneity in the system as well as increase moisture variability in the dataset. The spectroradiometer was held approximately 1 m above the peatland surface. The fore optic was held nadir at 60 cm in front of the operator (approximately arm's length), oriented perpendicular to the sun's azimuth. The spectroradiometer was again white referenced every 10 min to account for changes in sun angle and sky conditions using a Labsphere certified reflectance standards spectralon disk. The spectral signatures from both the PEATcosm experiment and field study were processed into spectral indices using the statistical software package R (v3.0.1). Specifically, spectral indices such as MSI, $fWBI_{980}$, and $fWBI_{1200}$ were calculated using equations provided in the literature (Tables 1 and 2). Spectral convolutions were applied to mimic the spectral measurements of the following EO satellite sensors: Landsat 8 OLI, MODIS Aqua/Terra, and Worldview 2 (Table 2). MODIS and Landsat were chosen due to their ability to detect physical changes relating to optical surface reflectance changes (Bryant & Baird, 2003; Gao, 1996; Sims & Gamon, 2003). Worldview 2 was selected due to its 8 spectral bands in the Visible and NIR regions as well as a much-improved spatial resolution over Landsat and MODIS (Table 2).

3.3. Moisture content

At the field site, moisture content of the moss was obtained by removing the *Sphagnum* peat immediately after spectral sampling. Constant volume cylinders of peat material were harvested by passing a sharpened circular tin ring of 7 cm diameter through the peat canopy to a depth of 3 cm. A serrated knife was used to separate the samples across the bottom of the ring. The samples were weighed fresh inside a pre-weighed plastic bag to determine fresh mass. They were then dried at 65 °C to constant mass in a pre-weighed paper bag. VMC was calculated by multiplying mass water content by bulk density. In addition to destructive sampling, Thetaprobe moisture measurements were taken immediately following spectral measurements and immediately prior to vegetation harvesting at the field site.

3.4. Vegetation frequency data

At the PEATcosm facility, shrub, sedge and moss cover were measured using the point-intercept method (Bonham, 1989). To estimate plant cover, a standard sampling frame was constructed to fit over the bins, with a movable bar to create an 8 × 8 grid over the 1 m^2 area. Using laser pointers mounted in the frame, all living and dead species which the laser intersected were recorded, carefully moving vegetation

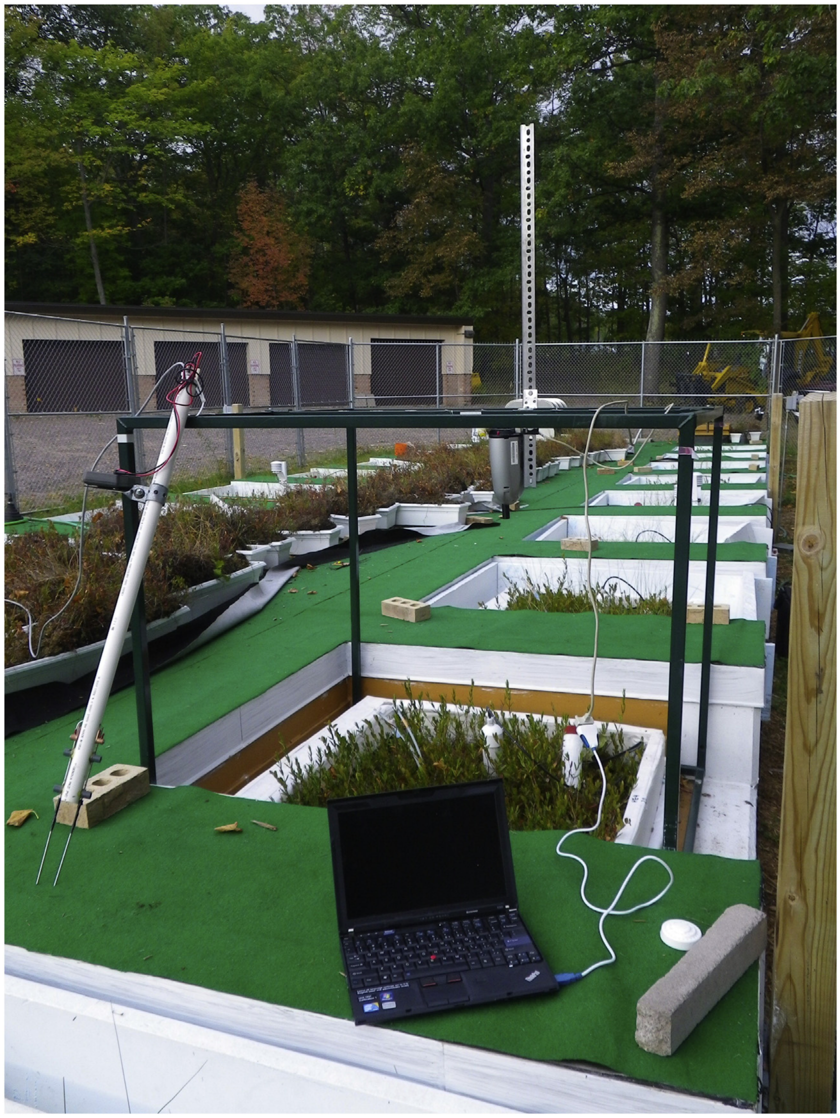

Fig. 3. Sampling frame used at the PEATcosm experiment to measure spectral reflectance and conduct vegetation frequency survey.

to capture all canopy layers including bryophytes (Bonham, 1989; Buttler, 1992).

3.5. Statistical analysis

Spectral indices were statistically related to VMC and water-table position using linear mixed effects models in the Linear and Nonlinear Mixed Effects Models (nlme) R package (Pinheiro, Bates, Sarkar, DebRoy, & R-core team, 2013). Linear mixed effects models were used to account for repeated measurements on the same experimental unit (e.g., an individual PEATcosm bin). This was achieved by setting a random intercept for each experimental unit within the model. The mixed linear model was compared to a linear least squares regression model using a likelihood ratio test to further support the need for using mixed effects models to account for artifacts of repeated sampling over the same experimental units. Model fits for mixed effects models were evaluated using the Akaike Information Criterion (AIC) as well as marginal R^2 (which describes the variance explained by fixed effects) and conditional R^2 (which describes variance explained by the full model) (Nakagawa & Schielzeth, 2013). This was accomplished using the rsquared.glmm function in R (V3.0.1) (Lefcheck, 2013). This provides useful summary statistics for analyzing the mixed effects models in conjunction with linear least squared regression models developed in the field study.

We also tested relationship stability across varying vegetation communities present in the PEATcosm. The top performing indices

Table 2
Sensor specific broad-band spectral indices employed in this study.

Index	Sensor	Spatial resolution	Temporal resolution	Equation	Reference
SRWI	MODIS	500 m	Daily	R_{860}/R_{1240}	Zarco-Tejada and Ustin (2001)
SIWSI (6,2)	MODIS	500 m	Daily	$(R_{1640} - R_{860})/(R_{1640} + R_{860})$	Fensholt and Sandholt (2003)
OLI5/OLI4	Landsat 8 OLI	30 m	16 days	(R_{SWIR1}/R_{NIR})	Rock, Vogelmann, Williams, Vogelmann, and Hoshizaki (1986)
WV2WI	Worldview 2	2 m	Tasked	(R_{NIR1}/R_{NIR2})	NA

Table 3
Model statistics for mixed effects models comparing narrow-band spectral indices in the PEATcosm experiment. Top performing spectral index is $fWBI_{980}$ to water-table position and 7 cm VMC.

Index	Water-table position n = 76					7 cm VMC n = 67				
	Marginal R^2	Conditional R^2	AIC	β_0	β_1	Marginal R^2	Conditional R^2	AIC	β_0	β_1
$fWBI_{980}$	0.70	0.80	493.64	−153.07	120.48	0.48	0.63	−106.04	−1.26	1.32
WI	0.68	0.78	498.66	−144.98	117.03	0.45	0.63	−101.75	−1.14	1.25
NDWI	0.59	0.73	519.94	−22.86	104.78	0.30	0.53	−86.17	0.18	0.96
$fWBI_{1200}$	0.58	0.68	533.99	−69.49	38.37	0.32	0.48	−88.84	−0.27	0.37
ln(MSI)	0.40	0.60	549.79	−37.17821	−20.26840	0.14	0.38	−74.69	0.0855097	−0.1502371
CI	0.002	0.24	554.29	NS	NS	0.01	0.05	−68.41	0.36	NS
NDVI	0.09	0.34	580.06	−50.60	44.89	0.00	0.11	−67.78	NS	NS

were tested by adding vegetation frequency data for individual species as a covariate to the linear mixed effects model. Sedge species used to inform the models included: *C. oligosperma* and *E. vaginatum*. Ericoid species included: *C. calyculata*, *K. polifolia*, *R. groenlandicum* and *Vaccinium oxycoccos*. Bryophytes included: *Polytrichum species*, *S. rubellum*, *S. magellanicum* and *S. fuscum*. To determine if the relationship between the spectral index and water-table position was affected by changes in vegetation frequency, an interaction term between the two covariates (spectral index and vegetation frequency by species) was added to the model. If this interaction was reported as a significant covariate in the model, a significant change in the relationship between spectral index and water-table position was assumed. For the field study, in which repeated measurements were not utilized, spectral measurements were related to VMC using least squares simple linear regression in R (V3.0.1). Models were evaluated and compared using R^2 and RMSE. p-Values are reported to show significance of the models. Competing models were ranked via R^2.

4. Results

4.1. PEATcosm indices

According to the linear mixed effects models, spectral indices in the NIR and SWIR were strongly related to water-table position (Table 3). The strongest relationship to water-table position for narrow-band indices was $fWBI_{980}$ followed closely by WI, with marginal R^2 values of 0.70 and 0.68, respectively. Spectral indices employing water absorption bands explained similar amounts of variance in VMC (Table 3). The dynamic index ($fWBI_{1200}$) was the only exception and was outperformed by NDWI for VMC, but not for water-table position. Indices employing the 980 nm region ($fWBI_{980}$ and WI) reported marginal R^2 values of 0.48 and 0.45 respectively when related to 7 cm VMC. Spectral indices leveraging visible wavelengths (CI and NDVI) had no correlative relationship with water-table position (marginal R^2 values of 0.002 and 0.09 respectively).

Broad-band indices tested at the PEATcosm experiment exhibited statistical relationships with strengths similar to those reported for narrow-band indices employing the same spectral regions (Table 4). There was a slight increase in marginal R^2 between SRWI to WI (0.58 to 0.68). Marginal R^2 values for SIWSI (6,2) and Landsat 8 OLI Ch5/Ch4 to MSI were 0.46 and 0.44, respectively.

By introducing an interaction term between spectral index and vegetation frequency, we were able to assess if vegetation frequency significantly changes the relationship between spectral index and water-table positions in the PEATcosm study. The results indicated certain species influence key spectral relationships (Table 5). Relationships between water-table position and spectral indices located in the 1450–1650 nm region appeared to be altered significantly by *K. polifolia*. The relationship between $fWBI_{980}$ and water-table position was influenced significantly by changes in two species; an Ericoid, *V. oxycoccos*, as well as a moss, *S. rubellum*. Worldview 2 WV2WI was not significantly altered by any of the vegetation frequency covariates. MODIS SIWSI (6,2), MODIS SRWI and Landsat 8 OLI Ch5/Ch4 relationships with water-table position were significantly altered by changes in Ericiod shrub, *K. polifolia*,

Table 4
Model statistics for mixed effects models comparing broad-band spectral indices for multiple EO sensors.

Sensor	Index	Water table position n = 76					7 cm VMC n = 67				
		Marginal R^2	Conditional R^2	AIC	β_0	β_1	Marginal R^2	Conditional R^2	AIC	β_0	β_1
MODIS	SRWI	0.58	0.70	521.96	−67.68	44.99	0.32	0.56	−88.48	−0.27	0.45
	SIWSI (6,2)	0.46	0.64	540.16	−43.57	−62.69	0.17	0.37	−77.23	0.03	−0.48
Landsat 8 OLI	OLI5/OLI4	0.44	0.63	544.20	6.73	−60.89	0.15	0.33	−75.66	0.40	−0.44
Worldview 2	WV2WI	0.41	0.68	551.28	−192.87	182.82	0.22	0.66	−74.40	−1.54	1.84

Table 5
Reported p-values of interaction terms for narrow and broad-band spectral indices. Bold values indicate significance at the $\alpha = 0.05$ level.

Covariate	Narrow-band		Broad-band			
	MSI p-value	$fWBI_{980}$ p-value	WV2 WBI p-value	SIWSI (6,2) p-value	SRWI p-value	OLI 5/4 p-value
Carex oligosperma	0.0987	0.1539	0.1446	0.1447	0.1234	0.1566
Eriophorum vaginatum	0.0702	0.2707	0.3199	0.6093	0.4941	0.7988
Chamaedaphne calyculata	0.1208	0.1415	0.8534	0.1133	**0.0397**	0.1062
Kalmia polifolia	**0.0101**	0.0922	0.5205	**0.0150**	**0.0199**	**0.0112**
Vaccinium oxycoccos	0.0804	**0.0021**	0.4014	0.0809	0.0629	0.0757
Polytrichum spp.	0.5330	0.349	0.7707	0.8844	0.5664	0.5977
Sphagnum fuscum	0.1249	0.1179	0.5933	0.1184	0.0635	0.1083
Sphagnum magellanicum	0.7194	0.2744	0.1276	0.5532	0.7399	0.5407
Sphagnum rubellum	0.0850	**0.0049**	0.8028	0.1705	**0.0224**	0.5495

Table 6
Summary statistics of regression models for surface VMC in the Nestoria field site.

Index	3 cm surface VMC					7 cm surface VMC				
	R^2	RMSE	p	β_0	β_1	R^2	RMSE	p	β_0	β_1
$fWBI_{980}$	0.83	0.02	<0.00001	−0.18	0.20	0.48	0.14	<0.00001	−0.52	0.71
WI	0.82	0.02	<0.00001	−0.17	0.20	0.48	0.14	<0.00001	−0.49	0.70
NDWI	0.84	0.02	<0.00001	0.04	0.22	0.47	0.14	<0.00001	0.27	0.74
$fWBI_{1200}$	0.82	0.02	<0.00001	−0.05	0.07	0.46	0.14	<0.00001	−0.05	0.26
ln(MSI)	0.79	0.02	<0.00001	0.012321	−0.046275	0.41	0.15	<0.00001	0.16516	−0.15369
CI	0.44	0.03	<0.00001	−0.08	0.16	0.26	0.16	<0.00001	−0.17	0.57
NDVI	0.31	0.03	<0.00001	−0.04	0.14	0.23	0.17	<0.00001	−0.06	0.56

frequency. The MODIS SRWI relationship was also altered by Ericoid shrub, *C. calyculata* as well as a *S. rubellum*.

4.2. Nestoria field site indices

Narrow-band indices located on water absorption features all show highly significant relationships to surface 3 cm VMC (Table 6). The indices located in the visible range, (CI and NDVI), display weaker, but still statistically significant relationships, which is consistent with the PEATcosm water-table study. Narrow-band indices located in the NIR region were the top performing indices with $fWBI_{980}$ and WI displaying R^2 values of 0.83 and 0.82, respectively. Correlations between peat moisture and narrow-band indices were stronger with measurements taken at 3 cm as compared to measurements taken at 7 cm (Table 6). Broad-band spectral indices perform similarly well to the narrow-band indices, which is also consistent with the PEATcosm water-table study. MODIS SISWI (2) and SRWI were the top ranked broad-band indices (Table 7). Tables 4 and 7 indicate similar relationships to 7 cm integrated VMC for both the field site and the PEATcosm experiment.

5. Discussion

5.1. VMC and water-table trends

Although previous studies have identified relationships between spectral indices in the NIR region and surface moisture dynamics (Bryant & Baird, 2003; Harris et al., 2006), this study is the first to our knowledge to demonstrate the strength and consistency of these relationships under an extreme range of water-table positions as well as with mixed species over story assemblages. Indeed, the moisture ranges tested are representative of fuel moisture conditions required for fire ignition in peatland systems (Benscoter et al., 2011), and the diversity of vegetation present in our experimental units and field site are broadly representative of the inherent complexity of natural peatland ecosystems. The ranking of the spectral regions presented herein consistently indicates that the water absorption features located around 980 and 1200 nm regions relate best to water-table position. The dynamic index, $fWBI_{980,}$ performs best for monitoring water-table position under this extended range (Table 7 and Fig. 4), which is consistent with previous results (Harris et al., 2005, 2006). The relative strength of the NIR region over the SWIR may be due to the relatively weaker absorption of NIR radiation by water (Harris et al., 2006; Sims & Gamon, 2003). This may lead to a greater sensitivity of NIR based indices to changes in near-surface VMC. It is also important to note that spectral indices employing the visible range show very little to no utility in assessing water-table position. Previous studies (Harris et al., 2005; Murray, Harley, Beyers, Walz, & Tenhunen, 1989), have shown reduced photosynthesis rates in *Sphagnum* for both high and low moisture contents. This indicates that indices such as CI, which measures chlorophyll concentrations of near surface cells, may not vary directly with water stress, but rather changes in photosynthetic activity.

Understanding the link between the spectral behavior of *Sphagnum* moss and the susceptibility to combustion is paramount towards understanding the utility of optical EO sensors for assessing ecosystem vulnerability to fire. Determining the vulnerability of these ecosystems to combustion involves linking changes in spectral character of the surface to changes in water-table position well below the peatland surface as well as determining how these relationships respond to variation in over story vegetation. The findings presented herein provide insight into the decay of this spectral relationship as a function of moisture measurement depth (i.e., the relationship between spectral response and moisture characteristics weakens with increasing measurement depth (from surface 3 cm VMC to water-table position)). It is also important to note that although this study found 7 cm integrated VMC to have a weaker relationship as compared to water-table position, the 7 cm integrated VMC measurement is estimated using an indirect measurement via the Thetaprobe. Such measurements (in addition to spectral measurements) contain additional inherent variability that is difficult to control. When determining 3 cm moisture content at the field site, destructive sampling allowed for more precise estimates of VMC. However, at the PEATcosm experiment, destructive sampling was not possible.

The weakening of signal from surface VMC to water-table position has been shown previously in Harris et al. (2006). The limited penetration of optical solar radiation into the canopy requires methods utilizing the optical region to estimate water-table position as a function of spectral changes which occur in the canopy of the peatland (i.e., discoloration of the canopy under lower water tables). Here, we confirm that the relationship between canopy spectral response and water-table position is maintained under an extreme range of VMC and water-table position.

Although water-table position strongly impacts vulnerability of peatlands to wildfire, VMC of the top 3 cm of peat has been shown to constrain burn susceptibility in lab experiments (Benscoter et al., 2011). Therefore assessment of relationships between spectral index and surface 3 cm VMC can be used to further assess susceptibility to burning in peatlands. The strength of these spectral relationships relative to those developed for water-table position is also encouraging. Benscoter et al. (2011) found successful ignition to occur in peat

Table 7
Summary statistics of regression models for surface VMC to broad-band spectral indices in the Nestoria field site.

Sensor	Index	3 cm surface VMC					7 cm surface VMC				
		R^2	RMSE	p	β_0	β_1	R^2	RMSE	p	β_0	β_1
MODIS	SRWI	0.80	0.02	<0.00001	−0.04	0.08	0.46	0.14	<0.00001	−0.03	0.28
	SIWSI (6,2)	0.81	0.02	<0.00001	0.01	−0.13	0.42	0.14	<0.00001	0.15	−0.44
Landsat 8 OLI	ln(Ch5/Ch4)	0.74	0.02	<0.00001	0.11	−0.11	0.35	0.15	<0.00001	0.49	−0.34
Worldview 2	WV2WI	0.62	0.03	<0.00001	−0.41	0.45	0.39	0.15	<0.00001	−1.38	1.65

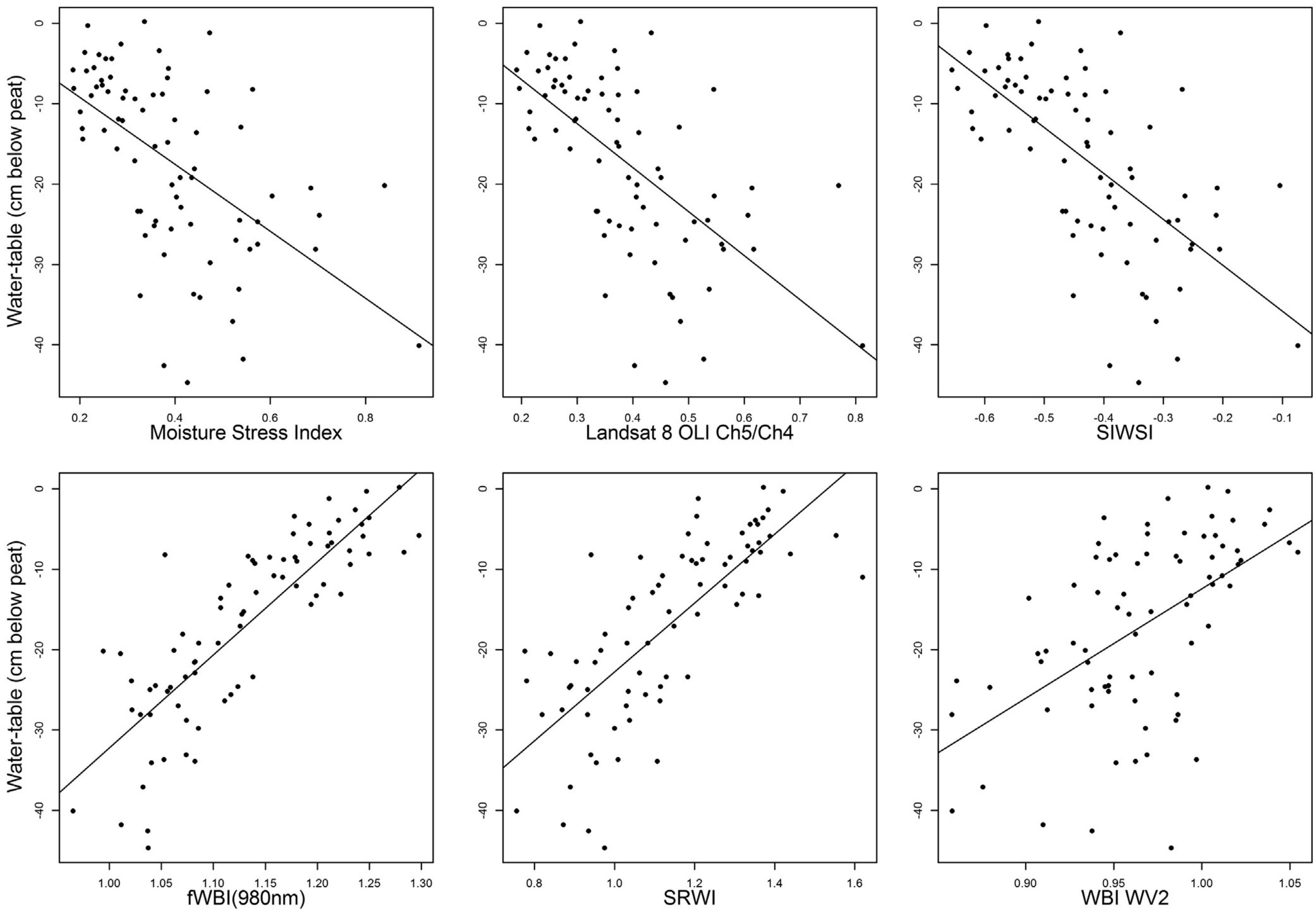

Fig. 4. Overview of high performing spectral indices in this study related to water-table position at the PEATcosm manipulation experiment. This figure graphically shows the similar relationships of broad-band and narrow-band spectral indices.

samples, which exhibited moisture contents within the driest range of values measured for surface 3 cm VMC in our study (0.003 cm^3/cm^3 to 0.013 cm^3/cm^3). The range of VMC values, which permits combustion is in the asymptotic region of the spectral relationships developed herein (Fig. 5). While the asymptotic behavior of these relationships at low VMC values indicates limited resolving power at very low VMC, the point of inflection occurring with the onset of drier conditions is apparent and could be used as an indicator of drier conditions in field applications. However, to accurately determine when the point of inflection associated with drier conditions is reached, continuous observation is necessary. EO sensors capable of monitoring the study site with fixed temporal frequency (e.g., Landsat, MODIS, VIIRS) would be most applicable in determining when this inflection point is reached.

Spectral indices display weaker relationships to water-table position than to surface VMC (Figs. 4 and 5). Physical factors inherent to the peat and its over story can influence this dependence. It is important to note that these indices rely on changes in water held in thin surface tissues and therefore are related to spectral changes and water content of the *Sphagnum* only at the surface (Sims & Gamon, 2003). Therefore we would expect stronger relationships to surface 3 cm VMC than water-table position. Physical factors such as changes in bulk density also impact how well the surface signature of the *Sphagnum* varies with water-table position (Benscoter et al., 2011). Although these relationships have been previously established (eg Harris et al., 2005, 2006), the increased range of water-table positions assessed in this study provides insight into the nature of these indices under drought conditions. Results indicate that, in line with previous research, indices employing the water absorption bands located in the NIR region perform best for monitoring under an extended range of water-table positions (Fig. 4).

It is also worth mentioning that, much work has been done using microwave data (specifically Synthetic Aperture Radar (SAR)) to retrieve soil moisture or fuel moisture estimates at 5 to 20 cm depths in boreal moss-covered soils dominated by *Sphagnum* or feather-mosses (Abbott, Leblon, Staples, Maclean, & Alexander, 2007; Bourgeau-Chavez, Leblon, Charbonneau, & Buckley, 2013a, 2013b, Bourgeau-Chavez et al., 2007, 2013a, 2013b). The Drought Code (DC) component of the Canadian Forest Fire Danger Rating System is indicative of moisture in the deeper (10–20 cm depth), more compact organic soil layers (e.g. partially decomposed moss layers, lower duff, or humic layer) which represents a measure of potential for wildfire to be sustained once ignition begins. C-band (~5.7 cm) SAR satellite imagery has been found to be strongly correlated to the DC and in situ moisture up to 12 cm depths (Bourgeau-Chavez et al., 2013b). Backscatter from a single SAR channel varies across a landscape due to heterogeneity in vegetative biomass and structure as well as surface roughness, making it difficult to develop a retrieval algorithm that can be universally applied. While addition SAR related research is underway, optical-IR sensors may be able to enhance SAR-based methodology in remote monitoring of soil moisture profiles in boreal *Sphagnum* dominated landscapes.

5.2. Spectral scaling

Broad-band spectral convolutions performed similar to original indices when assessing water-table position (Fig. 4). This is a positive finding demonstrating the possibility of using these relationships as monitoring tools via EO sensors. MODIS indices SRWI and SIWSI (6,2) were the top performing broad-band indices (Table 4). Given the high temporal resolution of MODIS, these findings offer strong promise

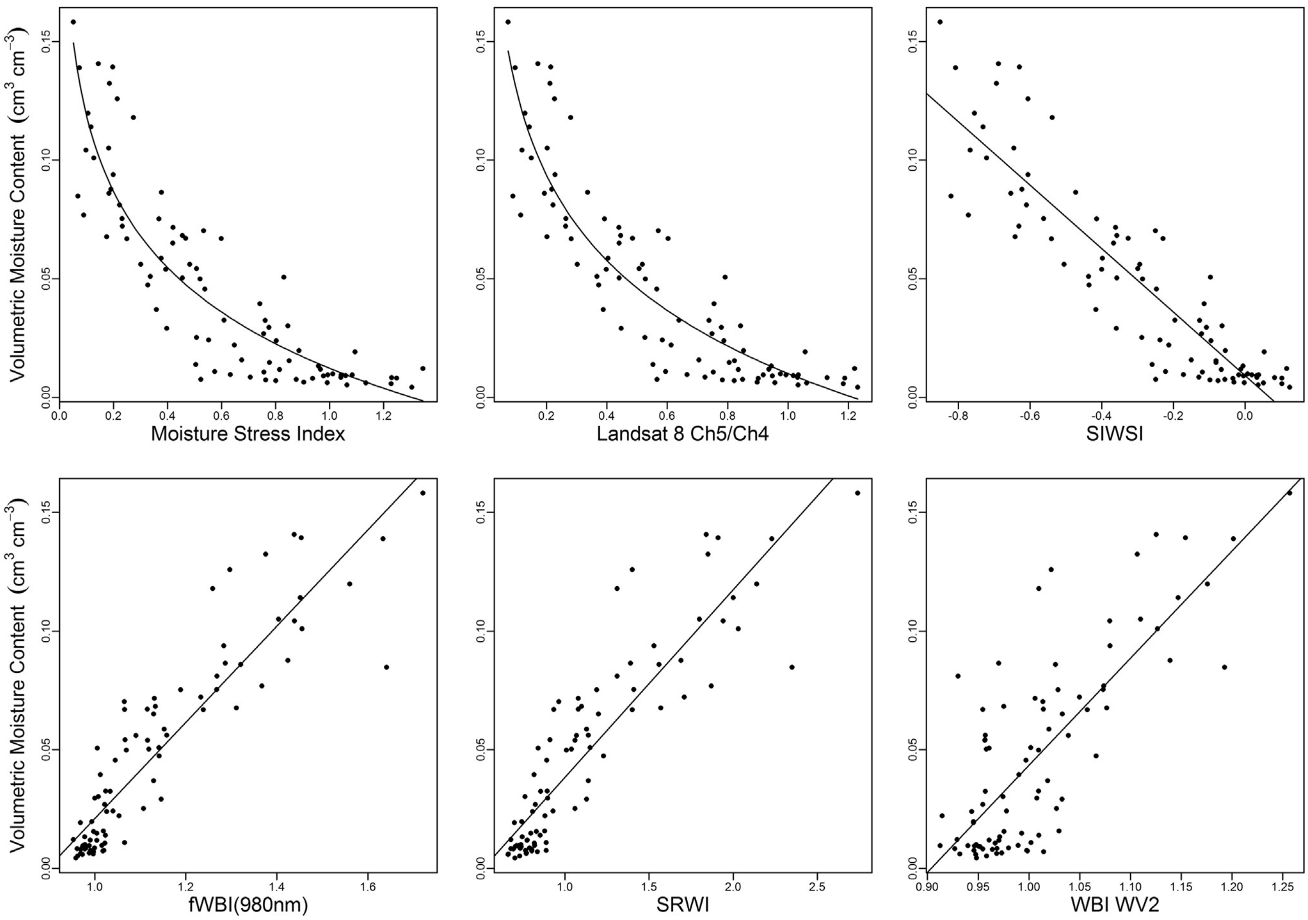

Fig. 5. High performing spectral indices related to surface 3 cm volumetric moisture content (cm^3/cm^3) at the Nestoria field site. Note similarity between broad-band and narrow-band spectral indices.

towards utilizing this sensor to monitor surface VMC and water-table position. However, the low spatial resolution of the MODIS data may introduce significant limitations given high species mixing within pixels. Future work on the spatial scaling of these indices is a crucial step in truly assessing the applicability of operationally using these EO sensors for assessing peatland moisture conditions. However, this study demonstrates that the spectral resolution of these EO sensors is sufficient for measuring moisture condition and water-table positions indicative of elevated wildfire susceptibility.

5.3. Vegetation frequency influence on spectral relationships

The unique design of the PEATcosm experiment subjected a gradient of vegetation assemblages, often present in northern peatland ecosystems, to extreme fluctuations in water-table position. A main objective of this study was to identify if key spectral indices such as $fWBI_{980}$ and SRWI are applicable under heterogeneous canopies. The aim was not to inform the model of vegetation components, but rather to assess if these components significantly alter the relationship (or slope of the regression models indicating these relationships) when present in a vegetation community, as would be observed on the ground. Leveraging the PEATcosm vegetation composition manipulations allowed us to assess the stability of the spectral indices under changes in vegetation fractional cover which may be present at both the landscape and EO sensor pixel scales. An assessment for multiple spectral indices provides evidence that the relationships involving the indices located in the NIR and SWIR regions are altered significantly by changes in ericoid shrub density, namely *K. polifolia* (Table 5). These ericoid shrubs occupy much of the sensor field of view (occluding the *Sphagnum*) when present, ultimately degrading the spectral signal from the *Sphagnum*. Previous work has demonstrated that the spectral reflectance of *Sphagnum* surfaces varies independently from ericoid canopies in the 760–900 nm and 1550–1750 nm regions (Schaepman-Strub et al., 2009; Vogelmann & Moss, 1993). For similar vegetation communities, Schaepman-Strub et al. (2009) report much higher biomass related to similar fractional cover for shrubs than graminoid sedges and Bubier, Moore, and Crosby (2006) also report a significant positive relationship between leaf area index and shrub cover. These results, along with the findings in this study, suggest that increases in ericoid shrub cover have the ability to occlude the spectral signal of *Sphagnum* moss related to water-table position. In turn, the importance of capillary water at the moss surface, which is highly dependent on proximity to water table, is attenuated in the spectral signal of surface moisture whereas effects of moisture stress on vascular vegetation (which is less dependent on water table in vascular plants than in mosses), and their spectral signature, become increasingly important. Therefore, caution must be used when utilizing these indices in areas with varying ericoid density. We also caution that variation in *Sphagnum* species, particularly *S. rubellum*, may significantly alter spectral relationships to water-table position (Table 5). This is concurrent with previous studies (Harris et al., 2005) indicating various spectral responses of *Sphagnum* species to water stress.

6. Conclusions

The key findings of this study suggest that: (i) as found in previous studies spectral indices leveraging changes in *Sphagnum* spectral reflectance located on the 980 and 1200 nm water absorption bands, such as SRWI, perform best for monitoring water-table position and surface moisture in peatlands with variable plant species composition and extreme water-table ranges; (ii) these indices appear to be most influenced by changes in ericoid cover, particularly *K. polifolia*; (iii) spectral convolutions applied to represent EO multispectral sensors have similar signal strength as compared to the narrow-band spectral indices, indicating the possibility of large area monitoring of surface VMC and water-table position from EO sensors.

These findings warrant future analysis into the response of ericoid shrubs to changes in water-table position and surface VMC, as well as the refinement of these relationships when a mixed over story is present. It may also be beneficial to determine the use of remote sensing products to accurately assess ericoid frequency. This may allow the use of multiple algorithms to estimate surface VMC and water-table position under various ericoid densities more accurately. This study found that the strength of water absorption features in the reflectance spectra strongly relate to surface 3 cm VMC, which has been directly linked to fire susceptibility. Further research is needed to assess the utility of these relationships in the context of assessing future fire risks and risks of fire severity via predicted water-table positions (French et al., 2008; Lentile et al., 2006). These relationships could prove fruitful in developing potential remote sensing indicators of peatland vulnerability; furthering the development of decision support and early warning systems of fire risk (Smith et al., in press) that have been proposed in European and other boreal forest regions (López et al., 2002; Taylor & Alexander, 2006). Previously developed fuel consumption models (Benscoter et al., 2011; Van Wagner, 1972) require bulk density profiles to accurately assess the relationship between water-table position and fuel consumption. Therefore, further work is needed to link these relationships directly to consumption and C losses due to wildfire in these ecosystems, especially with the perceived lack of fire weather indices' ability to predict general moisture status and fire susceptibility in peatland ecosystems (Waddington et al., 2012).

Acknowledgments

This project was primarily supported by the NASA Terrestrial Ecology Program (Grants: NNX14AF96G, NNX12AK31G, NNX09AM156) and the Joint Fire Sciences Program (Grant: L11AC20267-JFSP 11-1-5-16). The National Science Foundation (DEB-1146149), The USDA Forest Service and the MTU Ecosystem Science Center provided additional in kind support. We are grateful to Plum Creek Timber for allowing this research to be conducted on the Nestoria Field site. The authors would also like to thank Dr. Thomas Oommen and Dr. Nancy French as well as two anonymous reviewers for their helpful comments and suggestions on the manuscript.

References

Abbott, K. N., Leblon, B., Staples, G. C., Maclean, D. A., & Alexander, M. E. (2007). Fire danger monitoring using RADARSAT-1 in a northern boreal forest. *International Journal of Remote Sensing*, *28*(6), 1317–1338.

Benscoter, B. W., Thompson, D. K., Waddington, J. M., Flannigan, M.D., Wotton, B.M., DeGroot, W., et al. (2011). Interactive effects of vegetation, soil moisture, and bulk density on the depth of burning of thick organic soils. *International Journal of Wildland Fire*, *20*, 418–429.

Bonham, C. D. (1989). *Measurements for terrestrial vegetation.* New York: Wiley.

Bourgeau-Chavez, L. L., Kasischke, E. S., Riordan, K., Brunzell, S. M., Hyer, E., Nolan, M., et al. (2007). Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery. *International Journal of Remote Sensing*, *28*, 2133–2162.

Bourgeau-Chavez, L. L., Leblon, B., Charbonneau, F., & Buckley, J. R. (2013a). Assessment of polarimetric SAR data for fuel moisture estimation; analysis of wet versus dry conditions. *International Journal of Remote Sensing*, *34*(16), 5709–5730.

Bourgeau-Chavez, L. L., Leblon, B., Charbonneau, F., & Buckley, J. R. (2013b). Evaluation of polarimetric Radarsat-2 SAR data for development of soil moisture retrieval algorithms over a chronosequence of black spruce boreal forests. *Remote Sensing of Environment*, *132*, 71–85.

Bryant, R. G., & Baird, A. J. (2003). The spectral behaviour of *Sphagnum* canopies under varying hydrological conditions. *Geophysical Research Letters*, *30*, 1134–1137.

Bubier, J. L., Moore, T. R., & Crosby, G. (2006). Fine-scale vegetation distribution in a cool temperate peatland. *Canadian Journal of Botany*, *84*(6), 910–923.

Buttler, A. (1992). Permanent plot research in wet meadows and cutting experiment. *Vegetatio*, *103*(2), 113–124.

Chuvieco, E., Rian˜o, D., Aguado, I., & Cocero, D. (2002). Estimation of fuel moisture content from multitemporal analysis of Landsat Thematic Mapper reflectance data: Applications in fire danger assessment. *International Journal of Remote Sensing*, *23*(11), 2145–2162.

Delta-T Devices (1999). *ThetaProbe soil moisture sensor Type ML2, user manual—ML2-UM-1.* Cambridge: Delta-T Devices Ltd, 23.

Eitel, J. U. H., Gessler, P. E., Smith, A.M. S., & Robberecht, R. (2006). Suitability of existing and novel spectral indices to remotely detect water stress in *Populus* spp. *Forest Ecology and Management*, *229*, 170–182.

Fensholt, R., & Sandholt, I. (2003). Derivation of a shortwave infrared water stress index from MODIS near- and shortwave infrared data in a semiarid environment. *Remote Sensing of Environment*, *87*(1), 111–121.

French, N. H. F., Kasischke, E. S., Hall, R. J., Murphy, K. A., Verbyla, D. L., Hoy, E. E., et al. (2008). Using Landsat data to assess fire and burn severity in the North American boreal forest region: An overview and summary of results. *International Journal of Wildland Fire*, *17*(4), 443–462.

Gao, B. -C. (1996). NDWI—a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, *58*, 257–266.

Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, *1*, 182–195.

Harris, A. (2008). Spectral reflectance and photosynthetic properties of *Sphagnum* mosses exposed to progressive drought. *Ecohydrology*, *1*, 35–42.

Harris, A., Bryant, R. G., & Baird, A. J. (2005). Detecting water stress in *Sphagnum* spp. *Remote Sensing of Environment*, *97*, 371–381.

Harris, A., Bryant, R. G., & Baird, A. J. (2006). Mapping the effects of water stress on *Sphagnum*: Preliminary observations using airborne remote sensing. *Remote Sensing of Environment*, *100*, 363–378.

Kasischke, E. S., & Turetsky, M. R. (2006). Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters*, *33*, L09703.

Lefcheck, J. S. (2013). R^2 for linear mixed effects models. Retrieved from https://jslefche.wordpress.com/2013/03/13/r2-for-linear-mixed-effects-models/

Lentile, L. B., Holden, Z., Smith, A.M. S., Falkowski, M. J., Hudak, A. T., Morgan, P., et al. (2006). Remote sensing techniques to assess active fire and post-fire effects. *International Journal of Wildland Fire*, *15*, 319–345.

Letendre, J., Poulin, M., & Rochefort, L. (2008). Sensitivity of spectral indices to CO_2 fluxes for several platn communities in a *Sphagnum*-dominated peatland. *Canadian Journal of Remote Sensing*, *34*(2), S414–S425.

López, A. S., San-Miguel-Ayanz, J., & Burgan, R. E. (2002). Integration of satellite sensor data, fuel type maps and meteorological observations for evaluation of forest fire risk at the pan-European scale. *International Journal of Remote Sensing*, *23*(13), 2713–2719.

Moore, P. D., & Bellamy, D. J. (1974). *Peatlands.* New York: Spring-er-Verlag.

Murray, K. J., Harley, P. C., Beyers, J., Walz, H., & Tenhunen, J.D. (1989). Water-content effects on photosynthetic response of *Sphagnum* mosses from the foothills of the Philip Smith Mountains, Alaska. *Oecologia*, *79*, 244–250.

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142.

Palmer, K. F., & Williams, D. (1974). Optical properties of water in the near infrared. *Journal of the Optical Society of America*, *64*, 1107–1110.

Peñuelas, J., Filella, I., Biel, C., Serrano, L., & Savè, R. (1993). The reflectance at the 950–970 nm region as an indicator of plant water status. *International Journal of Remote Sensing*, *14*, 1887–1905.

Peñuelas, J., Piñol, J., Ogaya, R., & Filella, I. (1997). Estimation of plant water concentration by the reflectance water index WI (R900/R970). *International Journal of Remote Sensing*, *18*, 2869–2875.

Pinheiro, L., Bates, D., Sarkar, D., DebRoy, S., & R-core team (2013). Package 'nlme'. Retreived from http://cran.r-project.org/web/packages/nlme/nlme.pdf

Randerson, J. T., Liu, H. P., Flanner, M. G., Chambers, S. D., Jin, Y., Hess, P. G., et al. (2006). The impact of boreal forest fire on climate warming. *Science*, *341*(5802), 1130–1132.

Rock, B. N., Vogelmann, J. E., Williams, D. L., Vogelmann, A. F., & Hoshizaki, T. (1986). Remote detection of forest damage. *Bioscience*, *36*, 439–445.

Rydin, H., & Jeglum, J. (2006). *The biology of peatlands.* New York: Oxford University Press.

Rydin, H., & McDonald, A. J. S. (1985). Tolerance of *Sphagnum* to water level. *Journal of Bryology*, *13*, 571–578.

Schaepman-Strub, G., Limpens, J., Menken, M., Bartholomeus, H., & Schaepman, G. (2009). Towards spatial assessment of carbon sequestration in peatlands: Spectroscopy based estimation of fractional cover of three plant functional types. *Biogeosciences*, *6*, 275–284.

Sebestyen, S. D., Dorrance, C., Olson, D.M., Verry, E. S., Kolka, R. K., Elling, A. E., et al. (2011). Long-term monitoring sites and trends at the Marcell Experimental Forest. In R. K. Kolka, S. D. Sebestyen, E. S. Verry, & K. N. Brooks (Eds.), *Peatland biogeochemistry and watershed hydrology at the Marcell Experimental Forest* (pp. 15–72). Boca Raton, FL: CRC Press, Taylor and Francis Group.

Sims, D. A., & Gamon, J. A. (2003). Estimation of vegetation water content and photosynthetic tissue area from spectral reflectance: A comparison of indices based on liquid water and chlorophyll absorption features. *Remote Sensing of Environment*, *84*, 526–537.

Smith, A.M. S., Eitel, J. U. H., & Hudak, A. T. (2010). Spectral analysis of charcoal on soils: Implications for wildland fire severity mapping methods. *International Journal of Wildland Fire*, *19*, 976–983.

Smith, A.M. S., Kolden, C. A., Tinkham, W. T., Talhelm, A. F., Marshall, J.D., Hudak, A. T., et al. (2014). Remote sensing the vulnerability of vegetation in natural terrestrial ecosystems. *Remote Sensing of Environment*, http://dx.doi.org/10.1016/j.rse.2014.03.038 (in press).

Smith, A.M. S., Wooster, M. J., Drake, N. A., Dipotso, F. M., Falkowski, M. J., & Hudak, A. T. (2005). Testing the potential of multi-spectral remote sensing for retrospectively estimating fire severity in African Savanna environments. *Remote Sensing of Environment*, *97*(1), 92–115.

Sonnentag, O., Chen, J. M., Roberts, D. A., Talbot, J., Halligan, K. Q., & Govind, A. (2007). Mapping tree and shrub leaf area indices in an ombrotrophic peatland through multiple endmember spectral unmixing. *Remote Sensing of Environment*, *109*, 342–360.

Taylor, S. W., & Alexander, M. E. (2006). Science, technology, and human factors in fire danger rating: 1659 the Canadian experience. *International Journal of Wildland Fire*, *15*(1), 121–135.

Titus, J. E., Wagner, D. J., & Stephens, M.D. (1983). Contrasting water relations of photosynthesis for two *Sphagnum* mosses. *Ecology*, *64*, 1109–1115.

Trigg, S., & Flasse, S. (2001). An evaluation of different bi-spectral spaces for discriminating burned shrub-savannah. *International Journal of Remote Sensing*, *22*(13), 2641–2647.

Turetsky, M. R., Amiro, B.D., Bosch, E., & Bhatti, J. S. (2004). Historical burn area in western Canadian peatlands and its relationship to fire weather indices. *Global Biogeochemical Cycles*, *18*(4), GB4014.

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E., et al. (2011). Recent acceleration of biomass burning and carbon losses in Alaskan forsets and peatlands. *Nature Geoscience*, *4*, 27–31.

Van Gaalen, K. E., Flanagan, L. B., & Peddle, D. R. (2007). Photosynthesis, chlorophyll fluorescence and spectral reflectance in *Sphagnum* moss at varying water contents. *Oecologia*, *153*, 19–28.

Van Wagner, C. E. (1972). Duff consumption by fire in eastern pine stands. *Canadian Journal of Forest Research*, *2*, 34–39.

Vogelmann, J. E., & Moss, D.M. (1993). Spectral reflectance measurements in the genus *Sphagnum*. *Remote Sensing of Environment*, *45*, 273–279.

Vogelmann, J. E., & Rock, B. N. (1986). Assessing forest decline in coniferous forests of Vermont using NS-001 Thematic Mapper Simulator data. *International Journal of Remote Sensing*, *7*, 1303–1321.

Waddington, J. M., Thompson, D. K., Wotton, M., Quinton, W. L., Flannigan, M.D., Bensocter, B. W., et al. (2012). Examining the utility of the Canadian Forest Fire Weather Index System in boreal peatlands. *Canadian Journal of Forest Research*, *42*(1), 47–58.

Yebra, M., Dennison, P. E., Chuvieco, E., Riano, D., Zylstra, P., Hunt, E. R., et al. (2013). A global review of remote sensing of live fuel moisture content for fire danger assessment: moving towards operational products. *Remote Sensing of Environment*, *136*, 455–468.

Zarco-Tejada, P. J., Rueda, C. A., & Usrin, S. L. (2003). Water content estimation in vegetation with MODIS reflectance data and model inversion methods. *Remote Sensing of Environment*, *85*, 109–124.

Zarco-Tejada, P. J., & Ustin, S. L. (2001). Modeling canopy water content for carbon estimates from MODIS data at land EOS validation sites. *International Geoscience and Remote Sensing Symposium, 2001. IGARSS '01*, *1*. (pp. 342–344).