ISPRS Journal of Photogrammetry and Remote Sensing 90 (2014) 49–58

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Spectral monitoring of moorland plant phenology to identify a temporal window for hyperspectral remote sensing of peatland

Beth Cole [a,b,*], Julia McMorrow [a], Martin Evans [a]

[a] Upland Environments Research Unit, School of Environment and Development, University of Manchester, Oxford Road, Manchester M13 9PL, UK
[b] Centre for Landscape and Climate Research (CLCR), University of Leicester, University Road, Leicester LE1 7RH, UK

ARTICLE INFO

Article history:
Received 17 June 2013
Received in revised form 8 January 2014
Accepted 26 January 2014

Keywords:
Vegetation
Ecology
Hyper spectral
High resolution
Spectral
Monitoring

ABSTRACT

Recognising the importance of the timing of image acquisition on the spectral response in remote sensing of vegetated ecosystems is essential. This study used full wavelength, 350–2500 nm, field spectroscopy to establish a spectral library of phenological change for key moorland species, and to investigate suitable temporal windows for monitoring upland peatland systems. Spectral responses over two consecutive growing seasons were recorded at single species plots for key moorland species and species sown to restore eroding peat. This was related to phenological change using narrowband vegetation indices (Red Edge Position, Photochemical Reflectance Index, Plant Senescence Reflection Index and Cellulose Absorption Index); that capture green-up and senescence related changes in absorption features in the visible to near infrared and the shortwave infrared. The selection of indices was confirmed by identifying the regions of maximum variation in the captured reflectance across the full spectrum. The indices show change in the degree of variation between species occurring from April to September, measured for plant functional types. A discriminant function analysis between indices and plant functional types determines how well each index was able to differentiate between the plant functional groups for each month. It identifies April and July as the two months where the species are most separable. What is presented here is not one single recommendation for the optimal temporal window for operational monitoring, but a fuller understanding of how the spectral response changes with the phenological cycle, including recommendations for what indices are important throughout the year.

1. Introduction

To understand the optimal timing for image acquisition of hyperspectral images of vegetation, detailed information is required about the spectral characteristics of natural species over the growing season. Comparison of vegetation spectral behaviour needs an understanding of the seasonal as well as environmental characteristics for the ecosystem of interest. Interpretation of spectral data in relation to vegetation is dependent upon the temporal window in which it was collected. An understanding of the variations in spectral response throughout the phenological cycle is imperative to be able to interpret remotely sensed data successfully. The timing of image acquisition is important in vegetation studies. Knowledge of spectral responses to phenological change informs optimum acquisition windows for the purpose of the study whilst knowing the spectral response of the vegetation at the time of image acquisition helps define the best methods of analysis.

The use of multi-temporal data is established for global and large scale land cover classifications. However, to maximise the impact of multi and hyper-temporal analysis there is still a need to understand the seasonal spectral response of vegetation. Inter-seasonal spectral variation is limiting the accuracy of classification techniques, and to refine these a better understanding of seasonal spectral variation is needed (Hesketh and Sánchez-Azofeifa, 2012). Imaging spectroscopy analysis of seasonal changes in vegetation have been limited (Dennison and Roberts, 2003). Miller et al. (1991) identify the gap in knowledge of seasonal and short term variations of vegetation red-edge reflectance characteristics for forest areas. Recent investigations into the leaf-level spectro-temporal variability (Hesketh and Sánchez-Azofeifa, 2012), are addressing this gap in tropical forests, however there is still a limited amount of research at this fine scale. There has

* Corresponding author. Present address: Centre for Landscape and Climate Research (CLCR), Dept of Geography, Bennett Building, University of Leicester, University Road, Leicester LE1 7RH, UK. Tel.: +44 (0)116 2523796.

E-mail addresses: bc132@le.ac.uk (B. Cole), Julia.Mcmorrow@manchester.ac.uk (J. McMorrow), Martin.Evans@manchester.ac.uk (M. Evans).

http://dx.doi.org/10.1016/j.isprsjprs.2014.01.010
0924-2716/

been a number of recent studies using the phenological differences among plant species to map invasive species, in rainforests (Somers and Asner, 2012, 2013), temperate forests (Burkholder et al., 2011) and riparian areas (Fernandes et al., 2013). This application requires identification of vegetation at a species level and so optimizing the spectral separability of the species through intensive monitoring of species dynamics is essential to determine the time to discriminate between species.

Peatlands provide vital ecosystem services, including carbon storage, biodiversity, water supply and agricultural uses (Bonn et al., 2009; Holden et al., 2007; Van der Wal et al., 2011). The importance of peatlands is becoming widely recognised as a result in increased awareness of their potential to sequester and store carbon (Worrall et al., 2007), which is only possible when they are in a favourable condition with a vegetation cover to reduce erosion (Bellamy et al., 2005). Blanket bogs are a UK Biodiversity Action Plan (BAP) priority habitat, so peatland restoration is a tool that addresses UK government public service agreement targets for biodiversity, and soil and water protection in uplands. Remote sensing has the potential to provide tools for habitat monitoring and surveillance of many European Commission (EC) directive Annex 1 habitats and BAP priority habitats (Medcalf et al., 2011). Remote sensing of peatlands offers the potential to monitor restoration success by charting the succession of vegetation communities. However spectral differences between plant communities are subtle and change seasonally (Milton et al., 2005). Ecologically, they consist of a wide diversity and complexity in the composition and interaction of different vegetation types (Mehner et al., 2004).

Early work on moorland remote sensing (Morton, 1986) showed that a greater understanding of the phenological change in dominant moorland species was needed. Work on the spectral properties of a single species have improved this understanding (Harris, 2008; Mac Arthur and Malthus, 2008); however, there is still a need to develop a spectral library of key moorland species and their phenological change to enable the monitoring of ecosystem function, and vegetation succession, in the heterogeneous communities of peatlands (Schaepman-Strub et al., 2008).

This article addresses the knowledge gap of spectral-temporal response of upland vegetation over the seasonal cycle based on a field spectroscopy monitoring experiment of single species plots throughout spring autumn of 2009 and 2010. The analysis evaluates established narrow-waveband indices in identifying phenological change and the point in the season when plant functional groups are spectrally most distinguishable. Finally, recommendations for the optimal time for operational monitoring are discussed.

2. Changes in biophysical properties of vegetation over the phenological cycle

The spectral reflectance of vegetation is determined by the leaf surface properties, internal structure, and the concentrations and distributions of leaf biochemical components (Penuelas and Filella, 1998). Variations in the canopy structure are the dominant control on canopy reflectance data, however the relative contributions of tissue and structural attributes vary by wavelength, both between and within vegetation types (Asner, 1998). Changes in plant physiological properties are indicators of processes occurring within the leaf and canopy stand of vegetation. Leaf pigment concentrations are symptomatic of these changes and can be characterised by measuring the spectral reflectance of vegetation in a rapid, and importantly, non-destructive manner at a range of spatial scales.

Numerous spectral indices have been developed to estimate leaf pigment content. A subset of established narrow waveband indices that monitor the concentrations of chlorophyll and carotenoids have been selected in this study as indicators of senescence, which can be related to phenology. During senescence, chlorophylls degrade faster than carotenes so carotenoids pigments are unmasked and subsequently become the dominant chemical in the leaves (Elvidge, 1990; Kumar et al., 2001).

Chlorophyll-a and -b are the essential pigments in photosynthesis that convert light energy into stored chemical energy. Chlorophyll concentrations decrease during plant senescence (Fang et al., 1998), therefore changes in chlorophylls in the plant are indicative of phenological state as well as stress and stage of development (Blackburn, 2006; Gitelson and Merzlyak, 1997). Carotenoids are composed of carotenes and xanthophylls. Along with chlorophylls, carotenes absorb incident radiation and contribute to photosynthesis. The epoxidation state (EPS), expressing the relative concentrations of the different xanthophyll cycle pigments, is a useful indicator of changes in photosynthetic activity (Gamon et al., 1992).

Alongside this, changes in reflectance of the non-pigment biochemical leaf components at wavelengths above 700 nm also characterise vegetation senescence and phenological conditions. Biochemical attributes such as water, nitrogen, cellulose and lignin have measureable absorption and scattering features at these longer wavelengths (Kokaly et al., 2009). Strong water absorptions in particular characterise the SWIR region, above 1300 nm. Leaf water content therefore dominate the reflectance in this region (Kumar et al., 2001). During senescence, most compounds such as nitrogen, glucose and starch are withdrawn by the plant and the bulk of the remaining material is its cellular constituents such as cellulose-lignin (Elvidge, 1990). Cellulose and lignin are both structural components of leaf cell walls. Although they are different chemical components, they are complexly intertwined and their spectral absorbance features overlap (Kokaly et al., 2009). It is therefore common to combine the two together as cellulose-lignin or ligno-cellulose (Daughtry et al., 2004).

Traditional remote sensing of vegetation uses indices based on broad band sensors such as the Normalized Difference Vegetation Index (NDVI). Detailed physiological changes and processes that occur on smaller spectral scales are not captured with this approach (Blackburn, 2006; Gamon et al., 1992, 2001; Garbulsky et al., 2011; Penuelas et al., 1995; Stylinski et al., 2002; Vogelmann et al., 1993). Saturation of NDVI occurs at relatively low values of chlorophyll-a (Gitelson and Merzlyak, 1994), proving it unsuitable for distinguishing between very green leaves. We therefore look to narrow band indices to improve our ability to monitor vegetation function and differences between species, by enhancing the spectral features of the biophysical properties undergoing change during plant senescence.

There are few published papers relating foliar pigment indices to upland species. They have mainly been applied to a few and relatively simple species such as crops (Gamon et al., 2001; Inoue and Penuelas, 2006; Sims and Gamon, 2002) and forests (Filella et al., 2009; Sims and Gamon, 2002). Work by Nichol and Grace (2010) investigated the application of chlorophyll and carotenoid indices to *Calluna vulgaris*. Their work highlights the problems of applying universal indices to a structurally and biochemically complex species and showed the knowledge gap in applying these indices to ecologically important species. Correlations have been shown between the water content of Sphagnum mosses, a key indicator species in upland peatlands, and PRI (Harris, 2008; Van Gaalen et al., 2007), but there is still a gap in the application to these ecologically important environments.

3. Method

3.1. Study site and species

The spectral measurements were made on Blackhill, an upland blanket peatland undergoing restoration, in the Peak District National Park (PDNP) in the southern Pennines, in Northern England (Fig. 1). The peatlands of the PDNP, are a fragile environment