HYPERSPECTRAL REMOTE SENSING OF PEAT HUMIFICATION

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ABSTRACT

The ability to estimate the spatial variability in the degree of humification in exposed and eroding peats is important for carbon budget studies as well as having implications for water quality and drinking water supplies. This paper examines the potential of using hyperspectral remotely sensed data to estimate peat humification in exposed peats in the southern Pennines, UK. Hyperspectral HyMap images were acquired as art of the BNSC/NERC SAR and Hyperspectral Airborne Campaign (SHAC). Spectra were extracted for selected sample sites where ground-based spectra had been acquired with a spectro-radiometer and peat samples had been collected. The peat samples were analysed in the laboratory to determine their physico-chemical properties, including moisture content, organic content and the degree of humification. A number of candidate indices were investigated by testing the strength of correlation between the remotely sensed data and humification. The effect of water content was also investigated by comparing the results from *in situ* wet peat and samples that had been dried and measured using a spectro-radiometer with a contact probe. The index most strongly correlated with humification across a range of moisture content was the normalised gradient of the NIR plateau, especially the normalised slope of the shoulders of the absorption feature at 1200 nm. The results suggest that such indices could be used to estimate the spatial variability of peat humification, although further work is required to test the spatial and temporal stationarity of the results and further understand the relationships between peat properties and reflectance, especially for burned peat.

INTRODUCTION

The erosion of upland blanket peat in the UK is a significant environmental problem (i) (ii). Along with the potential loss of habitat, the erosion of peat from bogs and mires represents an important source of carbon (iii), while undisturbed accumulating peatlands in the UK sequester some 0.4 – 0.7 t C ha^{-1} and represent and important carbon store (iv). Knowing the spatial extent of exposed and eroding peat is, thus, an important component in the carbon budget of peatlands.

In addition to simply mapping those areas where eroding peat is found, the physico-chemical properties of the peat itself is also of importance. In particular, the type of peat exposed is an indicator of geomorphological process, recent fire history and the spatial severity of erosion and risk of further erosion. In addition, the degree of peat humification is also important for water quality as peats that are well-humified are more likely to be associated with the release of heavy metals into the local surroundings and potentially drinking water supplies, due in part to the breakdown of lignin to fulvic and humic acids (v).

This paper focuses on whether the spatial variability in the degree of peat humification, and hence erosion potential and severity, can be estimated using ground-based and airborne hyperspectral remotely sensed data. In particular, candidate indices for the estimation of the degree of peat humification are investigated, while the compounding effects of water, other biochemical constituents and burning is explored.

METHODS

A mixture of ground-based and airborne hyperspectral data were used to investigate the relationships between remotely sensed data and a range of peat types in the Bleaklow Head area of the south Pennines, UK.

Study Area

The erosion of blanket peat in the southern Pennines has left an environment that is often dominated by large expanses of bare, eroding peat. The study area is a 7 km transect in an area close to the town of Glossop, UK. It follows a section of the Pennine Way (a long distance footpath) from the Longdendale Valley to Snake Pass, with most of the peat sampling conducted in a part of the transect known as the Bleaklow plateau (Figure 1). This area includes a variety of peat erosion types, from Bower's (vi) anastomising, type 1 gullies to linear, type 2 gullies and extensive peat flats. The exposed peat exhibits varying degrees of humification, from poorly- to well-humified *in situ* peat (exposed by erosion), washed (re-deposited) peat and burned peat. The semi-natural upland vegetation includes acid dry heath (heather and bilberry), acid bog communities (bilberry, crowberry, heather and cotton grass), acid grassland (*Nardus* and *Molinia* spp.), bracken and wet flush (vii).

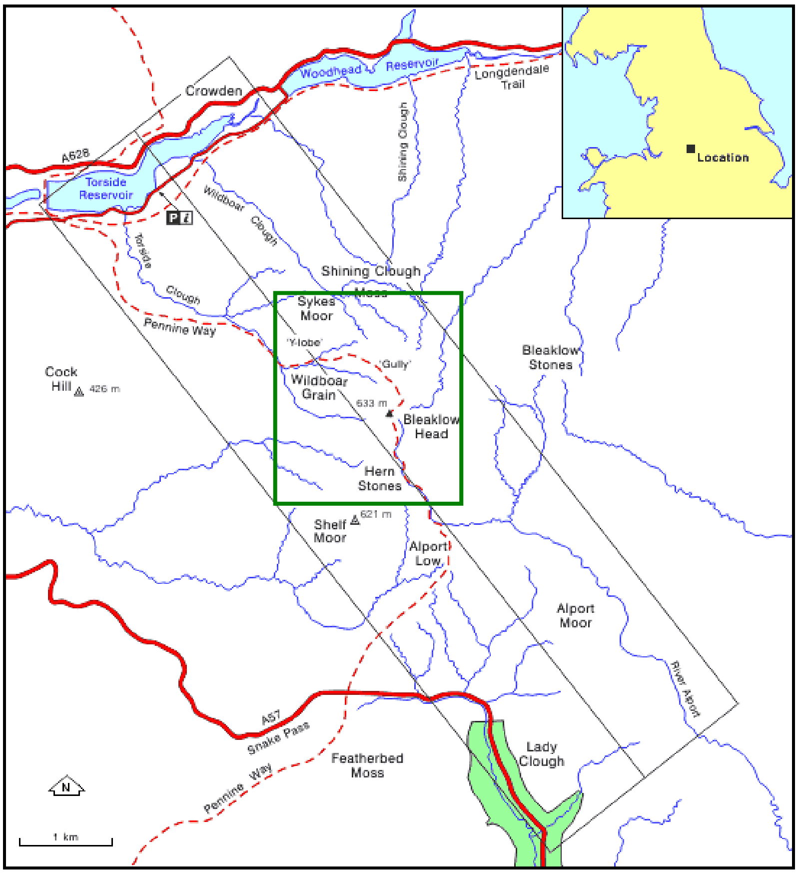

Figure 1: Location of the Longdendale HyMap SHAC transect (black diagonal rectangle), with study area indicated by the green box

Field Sampling

Peat samples from a total of eighteen sites were collected concurrent with the time of airborne remotely sensed data acquisition. Samples from a further 17 sites were collected subsequently. All samples were collected by pushing a 14 cm sampling ring into the peat surface to a depth of 2 cm in an attempt to maintain a constant volume. The samples were then removed to the laboratory for analysis of their physico-chemical properties. Prior to sampling, the spectral properties of each site were recorded using an ASD FieldSpec Pro spectroradiometer and the geographical coordinates of the sample site found using a differential GPS. In addition, a digital photograph was taken to record the surface texture. While it would have been preferable to have collected all samples on the same day as the remotely sensed data were collected, this was unrealistic given the four hours required to walk the transect.

Peat sample sites were chosen for their within-site homogeneity and observed between-site variability in peat type. They included five types: (a) well humified peat where erosion has exposed stratigraphically older peat, such as Bleaklow Head, where remnant summits are visible or in the sides of incised gullies; (b) poorly humified, usually younger peat, which is often found in less dissected col locations, such as the Hern Stones site; (c) washed peat, redeposited by water from haggs into intervening low areas, which generally forms into shallow, ephemeral pools, which, when dry, may exhibit a slightly specular crust; (d) peat flats, seen as large, gently sloping expanses of peat, often having been created by an old fire event but not re-vegetated and typified by the Y-lobe sample site, and; (e) recently burned peat with a blackened crust, sometimes partially re-vegetated by lichens and higher plants.

Laboratory analysis of peat properties

All 35 peat samples were analysed in an identical manner to determine four properties, chosen in accordance with available methodology and a literature survey to identify spectrally sensitive components.

Transmission was assessed colorimetically by washing the peat sample in 5% NaOH solution and measuring the transmission of light at 540 nm through filtered liquid (viii). Values of transmission are relative and are inversely related to the degree of humification, with high transmission values (%) relating to low humification.

Organic content was determined by loss on ignition at 550 degrees C for one hour. Particle size distribution was measured by wet sieving the material at one Phi intervals from 2 mm to 63 μm. Samples were dispersed in sodium hexametaphosphate and then wet sieved with a large quantity of water. Sieved fractions were recovered by settling and decantation, with the size distribution of the organic content determined separately. The particle size distribution was determined as a possible proxy for woodiness of the peat and because particle size is known to affect soil reflectance (ix).

Moisture content was measured to try to account for the known negative relationship with reflectance (x). It was assessed gravimetrically on the 2 cm depth disc of sample removed from the peat surface. Note that only those samples collected during the time of aircraft overflight were used to investigate the relationship between the remotely sensed data and moisture content.

Pre-processing HyMap data

Hyperspectral airborne remotely sensed data were acquired as part of the British National Space Centre (BNSC) and Natural Environment Research Council (NERC) SAR and Hyperspectral Airborne campaign (SHAC) in June 2000. The HyMap sensor was used to collect data along the study transect at a spatial resolution of 3 m. The images were supplied with ephemeris geometric correction and ATREM atmospheric correction (xi), with "Effort" correction for residual atmospheric and instrument effects.

Twelve HyMap bands were removed because of poor signal to noise ratio to leave 114 spectral bands in total for the analysis. At each sample site, pixel values were extracted. An area containing four pixels was normally extracted to ensure that the sample area was covered. However, the geometric correction and 3 m spatial resolution remain a source of error, particularly for small peat patches.

Simulated spectra

Because the small sample size concurrent with HyMap did not allow the effects of moisture content on reflectance to be investigated, a controlled laboratory drying experiment was conducted on peats of different humification in an attempt to decouple moisture and humification effects. A FieldSpec Pro FR Analytical Spectral Device (ASD) spectro-radiometer (xii), loaned from the Natural Environment Research Council (NERC), was used in contact probe mode to obtain laboratory spectra for a further 58 peat samples collected in two subsequent field seasons. The range of humification matched that for the HyMap samples, although not all sites were the same as those used for HyMap. The advantage of the contact probe (2 cm field of view) is that it has its own integral light source, so that spectra can be collected regardless of illumination conditions in the laboratory or field. However, the field of view, illumination geometry and signal to noise ratio clearly do not match those of HyMap, thus, comparisons between the two sets of spectra remain tentative.

The peat samples were not subjected to grinding, so that the surface texture better matched that of the surfaces recorded by HyMap. An optically thick sub-sample of 0.5cm deep was saturated with measured amounts of water to approximately 90% water by mass. The wet samples were then oven dried at 20°C in progressive stages. Every hour, ASD contact probe reflectance spectra were recorded at 10 points over each sample. Mean spectra were calculated for each sample. HyMap spectra were simulated from the ASD spectra using a filter based on the spectral band passes for HyMap during the SHAC Europe flights. For brevity, only the spectra from the driest stage are used here.

Calculation of spectral indices

Forty-nine candidate spectral indices expressing humification had been identified from previous published work and empirically by inspection of spectra and by stepwise multiple regression and modified partial least squares regression (vii). They included those developed for plant litter decomposition, which characterise the depth of absorption features due to cellulose, lignin, nitrogen and water below their continuum, for instance, the cellulose absorption index at 2100 nm (xiii). Indices derived by inspection included those expressing the gradient between absorption feature shoulders, expressed as difference indices, normalised difference indices and simple ratios. For instance, n47_58 represented the NIR slope above the red edge, that is, the normalised gradient between bands 47 and 58 (1123 and 1181 nm) (xiv).

The indices were calculated for HyMap and simulated HyMap reflectance spectra and correlated against transmission. Other physico-chemical properties were not strongly correlated with reflectance, so only transmission results are reported in detail here. The equations used and correlation coefficients for ten of the indices are shown in Table 1. Note that the HyMap spectra were divided into two groups; all spectra and those which did not show signs of recent of burning. This was because some of the HyMap burned sites had roots and lichen present, so were not directly comparable to other bare peat sites. Further, burning was likely to have combusted any remaining cellulose and lignin, as seen by the flattening effect on the spectra in Figure 3, even though transmission values appear to remain little affected.

RESULTS

Comparison of HyMap and simulated spectra

All the peat reflectance spectra (Figures 2 and 3) show elements of both vegetation and soil. A shallower red edge is still present, but instead of a NIR plateau, there is a NIR slope between HyMap bands 21 -47 (738 – 1123 nm), more reminiscent of soil spectra.

The *in situ* HyMap spectra (Figure 2) show an interesting switch at band 63 (1406 nm); beyond this in the shortwave infrared (SWIR), the well humified peat is brighter than poorly humified samples. The switch is not seen in the dry samples (Figure 2), so the result could have more to do with the presence of water than humification. Indeed, both well and poorly humified dry spectra are brighter than the two wet samples by about 10% in the SWIR. In the visible and NIR, for bands 1-62, humification appears to be more important than moisture. Poorly humified peat, whether wet or dry, is brighter than well humified peat. However, all these observations make no allowance for the differing modes of data acquisition between HyMap and the ASD contact probe.

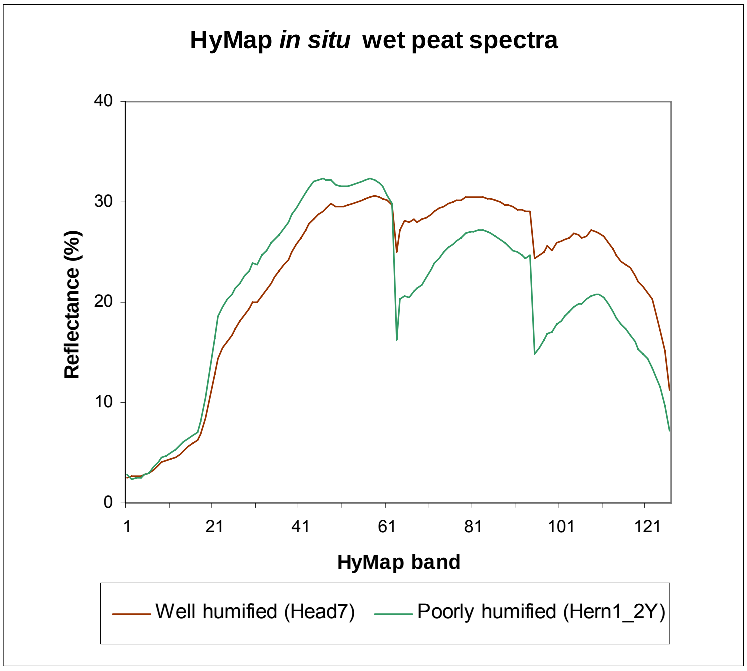

Figure 2 HyMap spectra for in situ wet, well and poorly humified peat

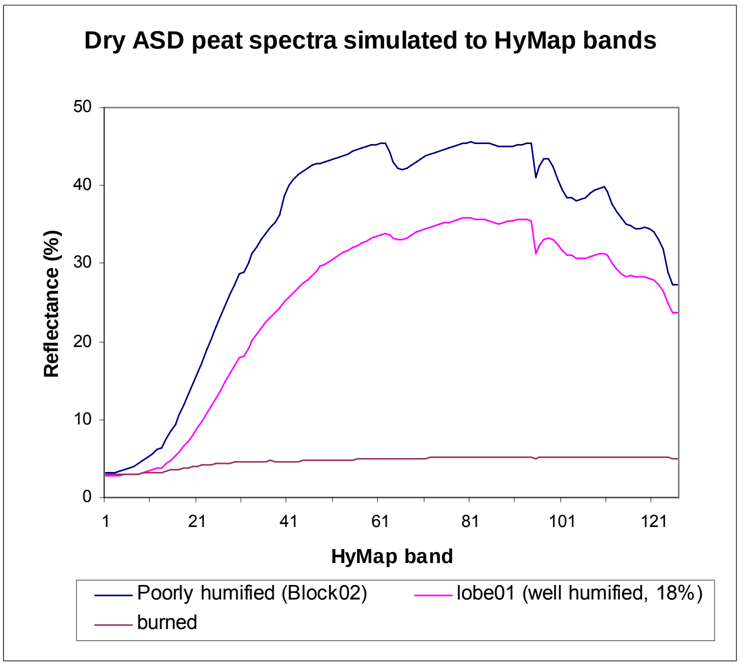

Figure 3 Laboratory spectra for selected dry peat samples simulated from the ASD contact probe

Spectra for peat with a burned crust are very distinctive. They are flat, with a low albedo, especially in the NIR and SWIR. These parts of the spectrum would, therefore, be useful for detecting burn scars and monitoring re-vegetation of bare peat surfaces created by fire, even with a broad-band sensor. No obvious absorption features remain in the dry simulated spectrum for burned peat in Figure 3. It appears that burning may have removed remaining cellulose material at the surface seen by the sensor, but this cannot be confirmed until lignin and cellulose data are available. It might be expected that transmission values were similarly lower, but this was not the case, and, as will be shown below, is problematic for the estimation of humification as measured by transmission.

Assessment of spectral indices

This section assesses the strength of the relationship between candidate spectral indices of humification and transmission, which is inversely related to humification. Formulae for the indices and their correlation coefficients and significance are given in Table 1. Results for three sets of spectra are compared: 35 HyMap *in situ* wet spectra; 32 of the same *in situ* spectra, with burned sites excluded; and the 58 HyMap spectra simulated from laboratory ASD contact probe spectra.

Table 1: Correlation of transmission with spectral indices for in situ HyMap (all samples), in situ HyMap unburned samples and dry HyMap spectra simulated from the ASD spectro-radiometer. Indices with consistent, strong relationships across the three sets of spectra are underlined. Significance level in parenthesis.

Spectral feature (wavelength, nm)	HyMap band	Index and formula	Correlation with transmission measured at 540 nm		
			In situ HyMap (all samples)	In situ HyMap unburned samples)	Dry HyMap simulated from ASD
Absorption feature at 2137 nm	105	Ab_105, 0.5(Hy98+Hy110)-Hy105	-0.879** (0.000)	-0.908** (0.000)	0.629** (0.000)
Cellulose absorption at 2100 nm	103	Cai_nagl Cellulose Absorption Index, CAI. Depth of absorption at Hy103 0.5 (Hy99 + Hy110) – Hy103	0.489** (0.003)	0.562** (0.001)	0.765** (0.000)
Absorption feature at 2083 nm		Ab_102, 0.5(Hy98+Hy110)-Hy102	0.423* (0.011)	0.522** (0.002)	0.750** (0.000)
Gradient between shoulders of 2100 nm cellulose absorption	110 to 99	N110_99 Normalised difference index: (Hy110 – Hy99)/(Hy110 + Hy99)	0.885** (0.000)	0.907** (0.000)	-0.132 (0.471)
Lignin and water absorption at 1450 nm; Lignin at 1420 nm; Water at 1400 nm	66, 63, 63	**Gradient of right limb of water absorption:** N82_68 Normalised difference index, (Hy82 – Hy68)/(Hy82 + Hy68).	0.883** (0.000)	0.899** (0.000)	0.180 (0.323)
Water, cellulose and lignin absorption at 1200 nm	52	Ab2_52 0.5 (Hy46 + Hy58) – Hy52	0.621** (0.000)	0.638** (0.000)	0.746** (0.000)
Gradient between shoulders of absorption at 1200 nm (NIR shelf)	47 to 58	R58_47 Ratio: Hy58/Hy47 N58_47 Normalised difference index (Hy58-hy47)/(Hy58+Hy47)	-0.755** (0.000) -0.759** (0.000)	-0.759** (0.000) -0.763** (0.000)	-0.809** (0.000) -0.813** (0.000)
Gradient of NIR slope	31 to 62	N62_31 Normalised difference index, (Hy62 – Hy31)/(Hy62 + Hy31).	-0.710** (0.000)	-0.818** (0.000)	-0.640** (0.000)
Red edge gradient, 677 to 799 nm	17 to 25	R25_17 Ratio, Hy25/Hy17	0.466** (0.005)	0.494* (0.003)	-0.392* (0.026)

When HyMap wet *in situ* spectra are considered, the indices most significantly correlated with transmission are those that express the gradient of the right shoulders of the two major water absorptions in the SWIR. The strongest relationship is for the normalised gradient between bands 110 and 99 (2225 – 2027 nm), known here as n110_99. This index is significantly correlated to transmission for all wet *in situ* HyMap samples (r 0.885, and 0.907 when burned samples are excluded). The gradient is steeper for samples with high transmission (low humification). However, the correlation is not significant and is reversed for dry spectra simulated from the ASD (r -0.132, p 0.471). This suggests that moisture content was responsible for steepening the gradient and masks any effect of cellulose absorption at band 103 (2100 nm). To test the contribution of water, moisture content was correlated against the n110_99 index, but the relationship was not significant (r 0.334, p 0.244 for all HyMap samples; r 0.248, p0.437 for unburned HyMap samples). Firm conclusions about the contribution of moisture cannot be made due to the small number of moisture samples concurrent with the flight.

Similar results were found for the gradient of the right shoulder of the feature at band 63 (1400 nm). The index expressing the normalised gradient between bands 82 and 68, n82_68, appeared to offer potential. It was steeper for HyMap samples with high transmission (low humification) (r 0.883, p 0.000 for all HyMap samples; r 0.899, p 0.000 for unburned samples). However, there was no significant correlation between the index and transmission for dry spectra simulated from the ASD (r 0.180, p 0.323). There was a slight positive correlation with moisture content, but it was not highly significant (r 0.509 for all HyMap samples, p 0.063; r 0.442, p 0.151 for unburned HyMap samples).

It has already been suggested that water has a masking effect on the overall gradient between bands 110 and 99 (2225 – 2027 nm). For this reason, the cellulose index (CAI) (xiii), which was devised to measure absorption at band 103 (2100 nm) in dry plant litter, would not be expected to show a significant correlation with transmission for the wet *in situ* HyMap samples. In fact, significant positive correlations are found (r 0.489, p 0.003; r 0.562, p 0.001), with and without burned samples included, respectively (Figure 4). The relationship suggests that the depth of the feature is greater for less well humified samples, that is, those with higher transmission. However, in fact, the index is negative for all but the two least humified samples; a relative reflectance peak exists here instead of an absorption feature. Either, not enough cellulose remains in the peat to cause absorption, or other constituents, such as water, are masking the feature completely. The latter is suggested by the fact that the CAI is positive for all the dry samples, with values between 0.7 and 2.7, and is more strongly correlated with transmission (r 0.765, p 0.000). A cellulose absorption feature is only detectable in dry peat. However, the index expressing it may still be useful to characterise the reflectance feature that develops for more humified wet peats, if the effect of water can be discounted. The partial correlation of CAI with transmission, controlling for moisture, is 0.526, but is only significant at the 90% level (p 0.010).

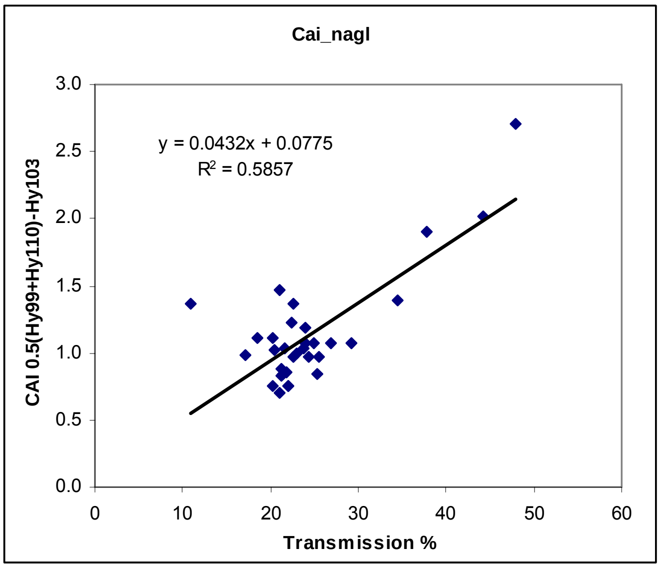

Figure 4 Relationship between transmission (inversely related to humification) and the cellulose absorption index for dry peat samples, calculated for simulated HyMap bands using laboratory spectra obtained with the ASD contact probe

The opposite situation exists for the complex water-cellulose-lignin absorption feature at band 52 (1200 nm). The feature exists in the wet samples but becomes a reflectance peak (negative index) in the dry samples. The index used to express the feature, denoted here as ab2_52, measures the depth of the feature at band 52 (1200 nm) below the continuum between bands 48 and 58 (1138 – 1281 nm). The correlation with transmission is positive and significant (p 0.00) for all three sets of samples (r 0.621 for all HyMap, 0.638 for HyMap excluding burned samples, and 0736 for the dry simulated samples). Again, this hides the fact that all but one of the dry samples yielded a negative index, and suggests that the band 52 feature in wet peat is primarily governed by moisture content. Again, the index does appear to relate to the degree of humification, but by expressing the reflectance peak that develops here as a negative value, this time for dry peats.

The position of the continuum is important, as shown by results presented in McMorrow *et al*. (xiv). The correlation of transmission with the depth of the band 52 absorption feature falls to 0.33 when the left shoulder is set at band 46 (1108 nm), and reverses to – 0.47 when it is set at band 48 (1138 nm). It seems to be due to the presence of a further small feature at band 47 (1123 nm) in some of the *in situ* HyMap spectra.

A good potential index of humification is one which is relatively insensitive to moisture content, that is, one which shows significant correlation to transmission for both wet and dry samples. The strongest relationship obtained for both wet *in situ* HyMap spectra and HyMap spectra simulated from dry ASD lab samples is a normalised difference index expressing the gradient of the shoulders either side of the band 52 feature (1200 nm), between bands 47 and 58 (1123 and 1281 nm, known here as n58_47. This index is significantly correlated to transmission for wet HyMap spectra (r -0.759 for all HyMap sites and -0.763 excluding burned sites). The relationship remains significant for dry spectra simulated from the ASD (r -0.813). The shoulders of the band 52 feature pivot as humification increases. This is expressed as a change in the n58_47 index from negative at high transmission (low humification) to positive as transmission falls below 40% for increasingly well humified samples. Effectively, reflectance is increasing at band 58 (1281 nm) relative to that at band 47 (1123 nm).

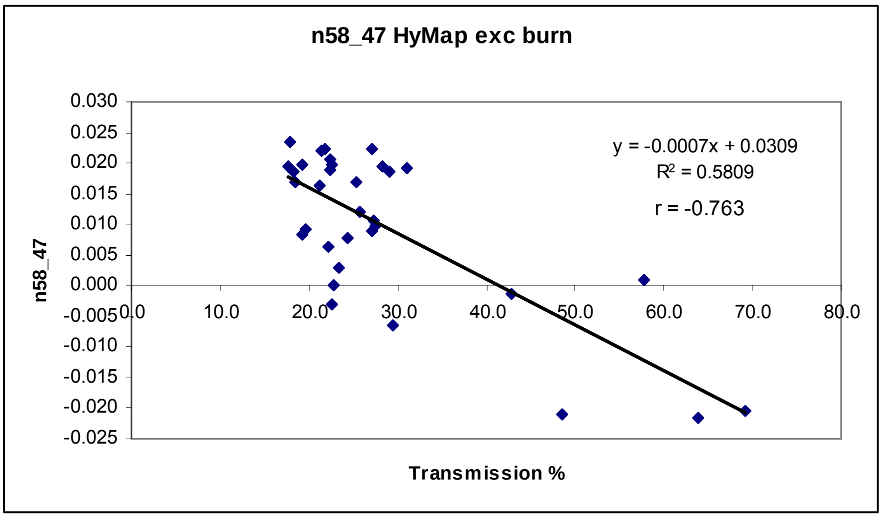

Figure 5 Relationship between transmission (inversely related to humification) and n58_47, the normalised difference index expressing the gradient of the shoulders of the band 52 (1200 nm) absorption feature between bands 58 and 47 (1123 and 1281 nm) for unburned in situ HyMap samples.

Effect of burning

Transmission values were very variable for the samples with a burnt crust, which explains why correlation coefficients were higher when burned samples were excluded (Table 1). This may suggest that humic acid content was not affected, even if lignin and cellulose had been combusted. It is suggested, therefore, that transmission may not be an effective surrogate for humification for recently burned peats, and ligno-cellulose content should be investigated as an alternative.

CONCLUSIONS

Spectral indices of humification have been identified which offer potential for mapping humification of exposed peat using airborne imaging spectrometry. The index most strongly correlated with humification across a range of moisture content is the normalised gradient of the NIR plateau, especially the normalised slope of the shoulders of the absorption feature at 1200 nm (band 52). Indices expressing the depth of absorptions at band 103 (2100 nm, CAI) and at band 52 (1200 nm) become negative for dry peat, indicating a change to an, as yet, unexplained reflectance peak, yet still retain information on humification. Peats with a burned crust have distinct flat spectra, which reduces correlation between humification indices and transmission

While these results are promising, there exist a number of limitations and uncertainties in the understanding of the relationship between the remotely sensed data and peat humification. In particular, the use of transmission as a surrogate to estimate humification relies on a strong relationship between the two, which may not always be present, especially in recently burned peat. A more direct estimate would be to use the lignin-cellulose ratio, a method that is currently being tested by the authors. A whole spectrum approach, such as spectral angle mapping, should also be investigated. Other limitations include the lack of samples available for estimating the moisture content concurrent with airborne spectral data, the effects of surface texture and micro-shadowing and the comparability of *in situ* and simulated spectra.

Further work is concentrating on extending the number of samples and peat types to address both the limitations and uncertainties in understanding. In particular, the transferability of the results and relationships observed will be tested by comparison to other sites with different peat properties and using sensors with different spectral sampling properties.

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