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The influence of slope and peatland vegetation type on riverine dissolved organic carbon and water colour at different scales

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Highlights:

Topographic and vegetative controls on DOC and colour in 119 streams were investigated.

Mean slope was the strongest (negative) determinant of DOC and water colour.

A role for vegetation in determining DOC and water colour was detected but weak.

Abstract:

Peatlands are important sources of fluvial carbon. Previous research has shown that riverine dissolved organic carbon (DOC) concentrations are largely controlled by soil type. However, there has been little work to establish the controls of riverine DOC within blanket peatlands that have not undergone major disturbance from drainage or burning. A total of 119 peatland catchments were sampled for riverine DOC and water colour across three drainage basins during six repeated sampling campaigns. The topographic characteristics of each catchment were determined from digital elevation models. The dominant vegetation cover was mapped using 0.5 m resolution colour infrared aerial images, with ground-truthed validation revealing 82 % accuracy. Forward and backward stepwise regression modelling showed that mean slope was a strong (and negative) determinant of DOC and water colour in blanket peatland river waters. There was a weak role for plant functional type in determining DOC and water colour. At the basin scale, there were major differences between the models depending on the basin. The dominance of topographic predictors of DOC found in our study, combined with a weaker role of vegetation type, paves the way for developing improved planning tools for water companies operating in peatland catchments. Using topographic data and aerial imagery it will be possible to predict which tributaries will typically yield lower DOC concentrations and which are therefore more suitable and cost-effective as raw water intakes.

1. Introduction

The concentration of dissolved organic carbon (DOC) and water colour in stream water is predominantly controlled by the size of the catchment's soil carbon pool (Hope et al., 1997). Peatlands store more soil organic carbon (SOC) per unit area than any other soil type (Parry and Charman, 2013) and as a result stream water draining from catchments dominated by peatlands have been found to contribute considerably to DOC and colour export (Mitchell and McDonald 1995; Hope et al., 1997; Chapman et al., 2001). Peatlands play an important role in the global carbon cycle (Yu, 2012) and fluvial loss of DOC forms an important component of peatland carbon budgets (Dinsmore et al., 2010). Consequently, there is concern that the observed increase in DOC concentrations is leading to many peatlands becoming net sources of carbon (Billett et al., 2010). Peatlands are also globally important sources of fresh drinking water. However, elevated levels of DOC and colour in drinking water can result in the production of carcinogenic disinfection-by-products such as trihalomethanes, which have significant human health implications (Rook, 1977).

The process of removing DOC and water colour in water treatment works is expensive and rising levels of DOC and water colour substantially increases water treatment costs (Grayson et al., 2012). Consequently there is great interest in identifying the drivers of DOC production at the catchment scale in order to justify management decisions regarding vegetation composition. Temnerud and Bishop (2005), Bishop et al. (2008) and Oni et al. (2014) have each demonstrated that DOC and colour levels can be considerably variable between adjacent catchments with differing soil types, and recent research by Grayson et al. (2014) has shown a similar degree of variability in blanket peatland dominated catchments. Consequently, this indicates that variability in DOC production, at least to a certain extent, is driven by local processes. Many factors which influence the production of DOC and water colour at a local scale have been identified for catchments with a significant peat cover, including proximity of the peatland to the stream (e.g. Bishop et al. 2008), variability in hydrological flow pathways (Evans et al., 2005) and land management practices, such as burning (Yallop and Clutterbuck, 2009; Holden et al., 2012), artificial drainage (Wallage et al., 2006) and nutrient additions (Liu et al., 2014).

More recently, studies from a range of ecosystem and soil types have identified significant relationships between Plant Functional Type (PFT) and the production of DOC and water colour, in both the laboratory (Cleveland et al., 2004; Wickland et al., 2007) and the field (Pellerin et al., 2010). This relationship is thought to occur because the physical and chemical properties of litter, which vary between PFT, have a strong influence on the rate of decomposition and therefore DOC production (Hobbie et al., 2000). Blanket peatland vegetation communities are comprised of a range of PFT types and consequently vegetation composition is likely to influence the amount of DOC and colour in water draining from blanket peatlands. This hypothesis is supported by laboratory peat manipulation studies (Vestgarden and Austnes (2009), with bare peat producing more colour when saturated than over cover types while under dry conditions Calluna dominated cores doubled their colour production Millar (2008). A preliminary field study by Armstrong et al. (2012) found soil water in ditched areas of blanket peatland dominated by Calluna sp. had greater concentrations of DOC, than those ditched areas dominated by Sphagnum sp. and sedges. However, an understanding of the extent to which a catchment's vegetation composition influences the level of colour and concentration of DOC in stream water is lacking. Although plot and laboratory scale studies are of value in understanding drivers of DOC and water colour production, blanket peatland vegetation is typically highly heterogeneous, and multiple drivers may contribute towards the amount of DOC and water colour observed within stream waters at a catchment scale. Consequently, in order to establish the dominant drivers of DOC and colour in peatland stream waters and to establish an understanding of controls of value to land managers, vegetation must be investigated across multiple catchments.

In addition to vegetation, catchment topographic characteristics, including slope angle, aspect and catchment size, have been suggested as determinants of peatland stream water DOC concentration and colour (Mitchell, 1991; Grayson et al., 2012). However, the mechanisms by which each is thought to control DOC and colour production are thought to vary. For example, aspect may impact upon soil temperature and therefore also the rate at which decomposition and DOC production occurs (Mitchell, 1991). Slope angle will influence the hydrological characteristics of a peatland, such as the route and rate of runoff, the depth of the water table, and the water residence times, each of which may determine DOC and colour production and their characteristics (Evans et al., 2005; Holden, 2005; Kellerman et al., 2014; Kothawala et al., 2014). Catchments with shallower slope angles and which are less topographically variable may have a greater proportion of peat coverage (Parry et al., 2012), which in turn may also influence the amount of DOC production (Billett et al., 2006; Hope et al., 2007). In catchments with differing soil types, slope angle has been shown to be of particular importance (Mitchell and McDonald, 1995; Silva and Williams, 2001). However, despite the clear interactions between topographic parameters and DOC production, there has been little consideration given to the degree to which they are influential to the water quality of streams draining blanket peat covered catchments.

To establish relationships at the catchment scale, topographic and PFT characteristics must be mapped using a consistent and accurate methodology and linked to stream water DOC and water colour concentrations. Cole et al. (2014), Connolly and Holden (2011) and Malmer et al. (2005) have used hyper-spectral, multispectral and colour infrared (CIR) remote sensing datasets respectively to differentiate between different land-use and broad vegetation types in peatland environments. There is considerable potential for these technologies, particularly CIR, to detect surface characteristics in peatland environments (Harris and Bryant, 2009). In this study, we use CIR image analysis, combined with topographic analysis, together with water quality sampling to: i) determine if high spatial resolution CIR imagery can be successfully used to map broad peatland PFT; ii) establish whether vegetation and topography influence DOC and water quality; and, iii) determine the dominant controls on peatland stream water DOC and colour at a catchment scale.

2. Methodology

2.1 Site selection

Three regions, Angram-Scar, White Holme and Wessenden were selected as sampling sites within the Pennine uplands of Yorkshire, United Kingdom (Table 1). Each area contained over 80% coverage of National Soil Research Institute (NSRI) blanket peat soil series (mapped at 1:250 000 resolution see http://www.landis.org.uk), a broad range of moorland plant species, and had minimal artificial drainage, burning and restoration management (confirmed using land owner accounts and corroborated with aerial photography). Within each area, streams of lower than third order were selected for stream water grab sampling. The streams selected were not within nested catchments, in order to ensure water quality characteristics were independent.

2.2 Stream sample collection and chemical analysis

Six sampling campaigns were carried out during February, June and September in both 2012 and 2013. Rainfall was measured in each basin and is presented for each sampling month in Table 1. The monthly precipitation totals are very similar for the three basins during the sampling period. June and September 2012 were wet months with ~ 200 mm of rainfall while other months had rainfall between 48 and 83 mm. Thus our sampling spanned a range of conditions. Importantly, however, precipitation levels remained similar between each region before and during each sampling campaign and sampling within each region was completed within a day using teams of people in order to ensure discharge rates remained as stable as possible during the sampling. Stream water samples were collected in 50 mL plastic vials, and the same sampling point was returned to on each campaign, using a Garmin etrex 10 GPS (accuracy 5 m).

Each sample was analysed for pH, conductivity, DOC and water colour on samples through 0.45µm filters. DOC concentration was measured using a Thermalox Total Carbon (TC) analyser and water colour was determined from absorbance at 254, 265, 360, 400, 436 and 665 nm using a Jasco V-630 double beam spectrophotometer. Absorbance readings were converted to standardised water colour measurements of absorbance units per metre (Abs m^{-1}). The ratio of absorbance at 254 nm to the concentration of DOC was calculated and is normally termed the specific ultra violet absorbance (SUVA) and has been shown to vary over time in peatland systems (e.g. Wallage et al., 2006). The ratio of absorbance at 465 nm and 665 nm (E4/E6) was also calculated as it is a common variable reported in peatland water quality studies (e.g. Wallage et al 2006; Worrall et al., 2013; Grayson and Holden, 2012; Peacock et al., 2014) and has been suggested as a guide to the relative proportion of humic and fulvic acids in the DOC (Thurman, 1985).

2.3 GIS and Remote Sensing Analysis

Surface vegetation was mapped for each catchment using Landmap 0.5 m spatial resolution colour infra-red (CIR) aerial images (http://catalogue.ceda.ac.uk/) flown in 2009 when the plants were in full leaf. All images were mosaicked, in order to enable standardised interpretation between areas and then unsupervised classification with 50 classes was performed in ERDAS Imagine 2013. The 50 supervised classes were then further refined manually, using ground-based measurements for PFT coverage in each basin collected during site visits. The resulting output was summarised using manual interpretation into five PFT and surface classes (see Table 2). A small number of areas could not be classified due to shadow.

Catchments originating from each sampling point were determined using the NEXT MAP 5 m resolution digital elevation model (DEM) (http://www.intermap.com/) and the multiple flow direction water outlet function within OSGeo GRASS GIS. The DEM was then converted to slope angle (degrees) and aspect within ESRI ArcGIS 10, and cosine was then used to convert aspect values to between +1 (north) to -1 (south). Following this, for each catchment, the percentage cover of each vegetation class (PFT), mean slope (degrees) and median north/south values were extracted.

To examine reliability of the vegetation mapping, 236 sampling points were randomly assigned. The number of validation points assigned to each basin was proportional to its size. Care was taken to ensure that the areas validated were representative of PFT coverage across the basin as a whole. Each point was uploaded onto a Garmin eTrex10 GPS and validated in the field during summer 2013. The pixel resolution of the CIR imagery (0.5 m) was less than the GPS position accuracy (~5 m) and to account for this, the dominant vegetation within a 5 m radius of the given point was recorded. Subsequently, in ArcGIS 10, a 5 m buffer was placed around each validation point and the percent coverage of each vegetation class falling within it extracted. Using these data, a confusion matrix was generated, which cross correlates remote sensing classifications with points validated in the field, this enables the quantification of total error and misclassification rates for each PFT class (Campbell and Whynne, 2011). Validation points were deemed accurate if the majority class noted in the field matched the majority class extracted from the vegetation map.

2.2 Statistical analysis

Forwards and backwards stepwise regression was used to identify which catchment characteristics (PFT and topographic) form the strongest predicting variables of DOC and water colour at each absorbance wavelength. The median value from all sampling regimes at each sampling stream was used for each water quality variable (DOC and absorbance) and where data were not normal they were log10 transformed. Catchment characteristics were entered and removed for each model at the $p<0.15$ 'alpha to enter alpha to remove' level. Four stepwise regression models were developed to explore each water quality variable, including: 1) a model with data included from all sites (a dummy variable was also included within this model, as a predictor for each region to reflect the degree of inherent catchment impact on water quality); and, 2) three models using only data from single regions (Wessenden, White Holme and Angram-Scar) to identify if catchment characteristics exert an influence on a more local scale.

3. Results

3.1 Vegetation mapping output

The output and detail of selected catchments from White Holme and Angram-Scar are presented as examples in Figure 1. The distribution of PFT coverage between each area is similar for White Holme and Wessenden (Figure 2), where both sites are dominated by the mixed vegetation class. Mixed vegetation is much less prevalent at Angram-Scar which is instead dominated by Graminoids. Despite differences in distribution, all five vegetation classes can be found in each area. Areas unclassifiable due to shadow covered a small amount of each catchment (mean 1.3 %, standard deviation 1.7%) and therefore were excluded from analysis.

3.2 Vegetation mapping validation

A confusion matrix is presented in Table 3 which provides an overview of the vegetation classification accuracy. High accuracy was achieved for mapping PFT overall at 82%, however, the level of accuracy achieved was variable between PFT types. Graminoid vegetation had the highest level of accuracy, followed by the Ericaceous, mixed vegetation and sedge PFT, whilst bare peat received a much lower validation.

3.3 Stream chemical characteristics

Significant differences between areas were found for all chemical and water quality characteristics (Kruskal-Wallis, $p<0.01$). However, Figure 3 indicates these results are driven by Angram-Scar. Chemical and water quality characteristics were not significantly different between the White Holme and Wessenden datasets besides conductivity and the E4/E6 ratio. Median conductivity was lowest at Angram-Scar, at almost half that of White Holme and Wessenden, but was less than 100 $\mu S\ cm^{-1}$ in the majority of stream waters. Stream water at Angram-Scar contained approximately half the median concentration of DOC as at both Wessenden and White Holme. A similar difference was observed for water colour at all absorbance values tested. The composition of DOC was less aromatic at Angram-Scar, which had substantially lower SUVA values than at both Wessenden and White Holme.

3.4 Relationships between catchment characteristics and water quality

Highly variable relationships between individual catchment characteristics and median stream water quality (log_{10} transformed) can be seen in Figure 4. Catchment mean slope had a clear negative relationship with DOC and all other water quality variables, while catchment area and aspect demonstrate poor relationships. All relationships between PFT (including bare peat) and water quality variables are much weaker and contain a large amount of noise, both when all data are considered together and on a region by region basis. Significant multiple regression models ($p<0.05$) were returned for each water quality characteristic and the explanatory capability for all these models was reasonably strong with R^2(adj) between 0.28 – 0.54 (Table 4). Slope mean was consistently the most important predictor of water quality, displaying a negative relationship with all variables (Table 4). PFTs did not play a role in predicting DOC, Abs254 265, 360, 400, 436 or E4/E6 and often only had a minor role in developing models for Abs665 and SUVA254 (Table 4).

In order to investigate the influence of catchment characteristics without the overriding influence of regional differences, stepwise models were repeated individually for each region (Table 4). Results indicate that the importance of each catchment characteristic for determining DOC and colour varied between sites. Catchment characteristics were able to explain water quality to the highest degree at Angram-Scar, with a mean R^2(adj) value of 0.41 and up to four predictors in each model (Table 4). Models from Wessenden return a lower mean R^2(adj) of 0.23 and fewer predictors in each model (Table 4). White Holme returned only three significant models with relativly low R^2(adj) values of 0.23 to 0.34. As with the combined model, slope mean played an important role in predicting water quality variables in most regional models. The importance of each catchment characteristic as a predictor of each water quality varible varied between areas. For example, mixed vegetation featured in many of the Angram-Scar models, yet did not feature in the Wessenden or White Holme models.

4. Discussion

4.1 Vegetation mapping

The validation process returned a high total accuracy of 82%, suggesting classification of CIR imagery is broadly successful at delineating between PFT on blanket peatlands. However, on an individual PFT basis, the success of classification was variable. A good level of accuracy was achieved when classifying the Graminoid and mixed vegetation classes, and a lower, but still reasonable accuracy, was observed for Ericaceous shrubs and Sedge PFT. This level of accuracy for individual PFT classification is similar to that identified by Ihse (2007) and Tuxen et al. (2011) who used aerial CIR images to classify PFT in boreal and tidal wetland environments respectively. Using higher spectral resolution Compact Airborne Spectrographic Imager (CASI), Thomas et al. (2003) classified boreal peatland vegetation communities and reported lower accuracies of 40 – 60 % than we found in our study. However, Thomas et al. (2003) examined considerably different vegetation communities (shrub and birch covered fens) to our study and grouped vegetation in much finer detail and as a result it is difficult to directly compare the findings. Identifying the source of any inaccuracy is important for understanding the success of the approach. Inaccuracy in the Ericaceous class largely stems from the remotely sensed 'mixed vegetation' being validated as Ericaceous at a number of field points (Table 3). When performing validation in the field, Ericaceous shrubs are visually dominant, and due to the subjective nature of identifying 'mixed vegetation' there may have been a misclassification. The source of error is less consistent within the sedge PFT (Table 3) and thus the cause of inconsistency cannot be isolated. The bare peat classification returned a poor validation of 50%; however, due to the low spatial coverage of bare peat (Figure 2) few randomly allocated validation points fell on areas defined as bare peat by the remote sensing classification process (Table 2). Consequently, a few disagreements within the validation may disproportionately skew the outcome and therefore the result must be viewed with caution. Recognition must be given to the fact that the aerial photography was taken in 2009, three years prior to the stream water sampling. During this time it is reasonable to assume that some revegetation may have occurred, resulting in inconsistency in the bare peat classification. However the other PFT groupings are very broad and although some change in individual species may have occurred in this time period, it is very unlikely that switches in such broad PFT groupings would have taken place to an extent great enough to impact upon this study. Care was taken to ensure that sites were randomly validated across a broad area, however due to the large size of the basins some areas could not be covered and this factor must be taken into consideration when evaluating the validation results.

Notwithstanding the discussed areas of inaccuracy, CIR imagery analysis had a high total accuracy and performed reasonably for most PFTs. CIR imagery was also capable of providing a consistent approach to mapping over a far greater spatial scale and at a much higher spatial resolution than subjective manual surveys, therefore making the approach viable for investigating vegetative and bare peat coverage at a landscape scale.

4.2 Catchment characteristic influences on water quality

4.2.1 Topographic and catchment characteristic influences on water quality at a catchment scale

Mitchell (1991) highlighted that catchment aspect may be a topographic characteristic of particular importance in determining the production of DOC and water colour production, due to comparatively warmer temperatures on south facing slopes promoting greater decomposition than on cooler north facing slopes. Nonetheless, when Mitchell and McDonald (1995) investigated topographic influences on water colour (measured at absorbance at 400nm) in 45 upland catchments, aspect was not significantly correlated with water colour. However, the catchments included in Mitchell and McDonald (1995) were of mixed soil and land-use type and the variable influence of these factors on water quality may have disguised any influence aspect may have had on individual soil types. The 119 catchments considered within our present study were all situated on the same blanket peat soil series, classed as Winter Hill (Table 1). Catchments with a dominance of blanket peat were found to influence water colour to the greatest extent by Mitchell and McDonald (1995). Consequently, if aspect did exert a notable influence upon DOC and water colour production at a catchment scale on a single soil type, it may be detectable within our dataset as we have only included catchments that contain >80% blanket peat. However, when considered as a standalone relationship, no association between aspect and DOC or water colour variables is apparent (Figure 4). Despite this, aspect does appear in a small number of the water colour stepwise models (Table 4) at Wessenden (when measured at Abs254, 360, 400, 436 and E4/E6). However, all the catchments within all regions have a similar range of aspect orientations, and if aspect was exerting a strong influence it may be expected to also see the inclusion of aspect in the stepwise models of other regions. Instead, this indicates that an interaction may be occurring with another catchment characteristic included within the model for Wessenden. Nevertheless, the amount of explanatory power that aspect adds to each model is minimal and therefore aspect cannot be considered a major driver of DOC or water colour in stream waters.

Slope mean is an important topographic feature in many of the stepwise models and regularly features when data from all areas are considered together. Both Mitchell and McDonald (1995) and Yallop and Clutterbuck (2009) also included slope mean as a factor in models developed to predict stream water colour. Mitchell and McDonald (1995) found that the percentage of channel length with slopes less than five degrees was one of few parameters which significantly predicted stream water colour in catchments with multiple soil types. Conversely, Yallop and Clutterbuck (2009) do not report slope mean as a significant influence upon stream water colour. Instead they find managed burning, a potential control on DOC and colour production intentionally excluded from our study, was found to be the strongest influence on DOC. However, the strength of burn management on determining stream water colour in the dataset of Yallop and Clutterbuck (2009) may have masked any weaker influence of slope. Mitchell and McDonald (1995) suggested this relationship is associated with the slower rate of runoff and the extended period of time soil water has to dissolve organic matter and become coloured on shallow slopes, an explanation which could also apply in this study. An additional explanation may be that most peatlands form their deepest and most well developed deposits where terrain is flat and the peatland is able to spread unimpeded over extended areas (Charman, 2002). When the topography upon which peat accumulates and spreads begins to undulate, peatland development is restricted, as water is lost more rapidly on steeper slopes and a positive water balance, which is required for peat accumulation, is not maintained (Parry et al., 2012). Parry et al. (2012) found that peat depth was highly variable within NSRI mapped soil series, and areas of thin and organo-mineral soils could be found in areas of steeper slope. The NSRI soil mapping used within this study is of a low spatial resolution (1:250000) and therefore does not represent subtle changes in soil type. Consequently, it is likely that catchments with a high slope mean have a lower proportional coverage of peat and higher coverage of organo-mineral soils, which typically form on steeper slopes in the uplands. Unlike peat, organo-mineral soils are able to retain the DOC produced within their mineral horizons during low rainfall conditions (Cronan and Aiken, 1985; McDowell and Likens, 1988). Consequently, streams with catchments with high peat coverage have been found to have significantly higher concentrations of DOC and colour (Mitchell., 1991; Chapman et al., 2001) than those with greater proportions of organo-mineral soil. Thus this is potentially an explanation for why catchments which have higher slope means typically have lower concentrations of DOC and water colour in their stream water.

The final catchment characteristic considered within this study, catchment area, demonstrates no clear relationship with any water quality variables (Figure 4). Similarly poor relationships were observed by Mitchell and McDonald (1995), Temnerud and Bishop (2005) and Ågren et al. (2013) in catchments with multiple soil types. Nonetheless, a weak negative relationship did exist (Figure 4) and catchment area does feature in a number of the water colour stepwise models (Table 4).

4.2.2 Vegetative influences on water quality at a catchment scale

Although PFT variables appeared in many of the stepwise regression models, they were often not dominant predictors of water quality (Table 4). In most models, topographic parameters, particularly slope mean, took precedent over any PFT variables and in some models PFTs did not feature at all (Table 4). This pattern was particularly evident when data from all areas were analysed together. When all basins were considered together, no stepwise models had a 'PFT' variable (bare peat) which appeared before a topographic variable.

The trends and patterns in relationships observed when all three regions were evaluated together were often not reflected when data were analysed separately for individual regions (Figure 4 and Table 4). PFTs appear to play the most prominent role in determining water quality at Angram-Scar, while at both Wessenden and White Holme PFT variables feature less within models (Table 4). Moreover, there is poor uniformity between regions, or water quality variables, regarding which PFTs were selected by stepwise regression or the direction of the relationship. However, rather than a switch in processes influencing water quality, the inconsistency between regions may result from the varying distribution of PFT within each area (Figure 2). For example, the Angram-Scar catchments had a range in bare peat coverage between 0 - 3 %, compared to 0 - 21 and 0 - 27 % at Wessenden and

White Holme respectively (Figure 2). Consequently, the narrow spread of data at Angram-Scar would not be great enough to reflect a relationship with water quality if it existed and therefore bare peat would not be included within the model, even if it was a true determinant of any of the water quality variables. Consequently, by using datasets from individual regions it is very difficult to determine the strength or importance of trends, beyond that specific to the area itself. This outcome highlights the value of including multiple areas with well distributed data within analysis in order to ensure that bias is not introduced.

Although PFT coverage was included in a number of stepwise models (Table 4), its role in determining water quality was not strong when all basins were analysed together nor consistent between basins. This suggests that the significant differences which have been observed between blanket peatland PFT and DOC or colour production at the experimental (Millar, 2008) and plot scale (Armstrong et al., 2012) are often not reflected at the catchment scale. The differing outcomes observed may be explained by the varying spatial scales at which each study focuses. As spatial scales become larger it is increasingly difficult to control for other parameters which influence DOC and colour production. For example, in this catchment scale study, the topographic parameter slope mean, (see section 4.3.1) was consistently found to be the strongest predictor of DOC and colour in stream water when all basins were considered together. The strength of these variables in influencing DOC in stream waters may have masked any weaker PFT driven signal. Moreover, other environmental parameters which may influence DOC and water colour production, such as water table variability and surface micro-topography were not included within this study and may introduce additional noise. Nonetheless, both micro-topography and water table co-vary with PFT (particularly Ericaceous shrubs and sedge) and slope (Holden, 2005; Ulanowski and Branfireun, 2013) and given the high spatial resolution of the CIR images and DEM, these factors may have been accounted for, to a certain extent, within the dataset. In addition, no catchment contained coverage of only one PFT (for example see catchments in Figure 1). Consequently even if a specific vegetation type was influencing DOC and colour production, its signal may be diluted by less dominant PFTs by the time sampling occurred in stream waters. In studies carried out at smaller spatial scales it would be possible to control for these complexities within the experimental design and consequently there would be more potential to detect whether PFT did impact DOC and water colour production, explaining the differing outcomes between studies. Although this study considered most of the major PFTs associated with DOC and colour production outlined by Millar (2008), Vestgarden and Austnes (2009) and Armstrong et al. (2012), the PFT grouping may be too coarse to detect relationships. For example, it may not be a broad PFT that drives DOC production, but a few isolated species which determine water quality dynamics. As individual species could not be detected by the CIR analysis, these relationships will not have been identified. Further analysis using datasets with a higher spectral resolution, such as hyper-spectral satellite imagery, may facilitate this. Also, the structure of moorland vegetation often has multiple layers and CIR analysis would only be able to classify the vegetation present on the top layer. Armstrong et al. (2012) and Vestgarden et al. (2010) both found in their pilot studies that Sphagnum sp. produced less DOC in soil pore waters than other vegetation types. However, Sphagnum sp. often occurs as an understory to other moorland vegetation types, such as Calluna, and as a result could not be reliably detected by the CIR image analysis. Consequently, an important driving variable may unavoidably have been omitted. Thus further work is required at a plot scale (or smaller) to establish DOC and colour production processes associated with PFTs and individual species. Finally, the weak relationship between PFT and water quality variables may be explained by potentially rapid timescales of DOC degradation. Although Wickland et al. (2007) found differences between leachates in the laboratory associated with PFTs, this result was not repeated when they investigated DOC concentrations in soil pore water below the same PFTs. Wickland et al. (2007) suggested the reason for the loss of relationship maybe that the DOC released by the vegetation leachate may have been rapidly degraded and therefore the differences observed in the laboratory may have broken down rapidly under field sampling. Consequently, if DOC has degraded at a similarly rapid rate within our study, any differences between PFT may have been eradicated by the time the DOC entered the stream water. However, the work of Wickland et al. (2007) was not carried out on the same blanket peatland PFTs as our study and therefore further research is needed before this hypothesis can be validated.

5. Conclusion

CIR images and high resolution DEMs were successfully used to investigate relationships between water colour or DOC concentration and topographic and vegetation characteristics at the catchment scale. The topographic characteristic slope mean was found to be the strongest determinant of DOC and water colour in blanket peatland stream waters. This is thought to be related to the influence of slope on peat development and surface hydrology. PFTs were found to exert only a small influence at the catchment scale. Although this outcome does not reflect the relationships between PFT and DOC or colour production suggested by Armstrong et al. (2012) and Millar (2008) at much smaller spatial scales, it does not invalidate them. Instead, this study demonstrates that at the catchment scale vegetation may not be the dominant control on the level of DOC and colour in stream waters, and any local influence PFT may exert is diluted by noise from other drivers of DOC and colour production. These findings therefore indicate that management of the PFT compositions which we were able to study using CIR images on blanket peatlands, is unlikely to have a considerable impact on levels of DOC and colour in blanket peatland stream waters. Such management interventions may, however, have a local effect and could be important for some raw water intakes for water companies if the subcatchments of those water abstraction points are dominated by bare peat or Ericaceous shrubs as demonstrated by the research of Millar (2008) and Armstrong et al. (2012). Additionally, as Sphagnum was not an identified PFT using the CIR approach, further work should be undertaken to establish whether increased Sphagnum cover across blanket peatland sites could be associated with decreased colour and DOC in stream waters. This would be a particularly important step because practitioners are actively spreading Sphagnum diaspores in UK upland catchments.

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Table captions

Table 1. Physical characteristics of areas selected for sampling

Table 2. Vegetation classes identified using CIR imagery

Table 3. Confusion matrix quantifying the accuracy of each PFT classification and total accuracy of CIR imagery classification through cross-correlation with field validated data.

Table 4. Outputs of stepwise regression analysis investigating landscape controls on DOC and water colour in stream water. Columns labelled predictor 1 to 5 list the catchment characteristics which contribute towards multiple regression models with the greatest possible predictive power for each variable. Predictor 1 is considered the most important catchment characteristic and predictor 5 the least. Numbers list the value of R^2(adj) increase as each catchment characteristic is added to the model and symbols in parenthesis and italics state the coefficient.

Figure captions

Figure 1. Detail of vegetation mapping generated using CIR-Imagery within selected sub-catchments from White Holme (1a and b) and Angram-Scar (2 a and b).

Figure 2. Distribution of vegetation type within subcatchments of each region.

Figure 3. Selected box-plots of key stream water chemical characteristics in each area. Water colour distributions at each site for other wavelengths are not shown, but reflect similar trends as for Abs400.

Figure 4 Catchment characteristic influences on median water quality values at each grab sampling location. Data is grouped by area: blue circles represent Angram-Scar; green circles represent White Holme; red triangles represent Wessenden.

Table one Physical characteristics of areas selected for sampling

Area	**Wessenden**	**Angram - Scar**	**White Holme**
Site location (degrees lat, long)	53.563, -1.919	54.177, -1.951	53.684, -2.048
% coverage blanket peat	100	80	100
Elevation range (m)	232 - 518	290 - 703	370 - 420
Annual rainfall (mm)	1494	1449	1425
Rainfall during six sampling months Feb/Jun/Sep 2012 and 2013 consecutively (mm)	76.4, 213.6, 201.8, 48.0, 63.0, 74.2	71.0, 229.4, 201.6, 59.0, 40.8, 52.0	83.4, 210.4, 194.6, 70.0, 60.8, 73.8
Number of sampled catchments	34	62	23
Median area of sampled catchments (ha)	6.9	9.7	5.0
Catchment area range (ha)	0.3 – 46.5	0.1 – 97.5	0.5 – 25.5
Dominant geology	Kinderscout Grit stone	Millstone Grit	Kinderscout Grit stone

Table two Vegetation classes identified using CIR imagery

PFT Class	**Description**
Ericaceous shrubs	Dominated by Calluna sp.
Bare peat	Dominated by bare peat, low levels of revegetation may be present.
Mixed vegetation	No dominant vegetation type present resulting in unclear groupings for these pixels. Multiple vegetation types are present within each pixel.
Graminoids other than sedges	Dominated by moorland grasses including: Molinia caerulea; Deschampsia flexuosa; Nardus stricta; Juncus effusus and others.
Sedge	Dominated by Eripohorum sp.

Table three Confusion matrix quantifying the accuracy of each PFT classification and total accuracy of CIR imagery classification through cross-correlation with field validated data.

		Field validation classification					
		Ericaceous	Bare peat	Mixed vegetation	Graminoid	Sedge	User accuracy (%)
Remote sensing classification	Ericaceous	**34**	4	1	1	0	85
	Bare peat	1	**2**	1	0	0	50
	Mixed vegetation	14	2	**70**	3	1	78
	Graminoid	1	0	4	**67**	5	87
	Sedge	0	1	2	2	**20**	80
Total accuracy (%)							**82**

Table four Outputs of stepwise regression analysis investigating landscape controls on DOC and water colour in stream water. Columns labelled predictor 1 to 5 list the catchment characteristics which contribute towards multiple regression models with the greatest possible predictive power for each variable. Predictor 1 is considered the most important catchment characteristic and predictor 5 the least. Numbers list the value of R^2(adj) increase as each catchment characteristic is added to the model and symbols in parenthesis and italics state the coefficient.

	Variable	**One**	**Two**	**Three**	**Four**	**Five**	**Final Model R^2(adj)**
All areas	DOC	Slope mean (-0.06)	Area (-0.14)				0.44
	Abs254	Slope mean (-0.09)	Area (-0.13)				0.42
	Abs265	Slope mean (-0.09)	Area (-0.22)	Region (0.14)			0.28
	Abs360	Slope mean (-0.10)	Area (-0.16)				0.47
	Abs400	Slope mean (-0.10)	Area (-0.18)				0.48
	Abs436	Slope mean (-0.10)	Area (-0.21)				0.49
	Abs665	Slope mean (-0.05)	Area (-0.17)	Bare (0.01)			0.54
	SUVA254	Slope mean (-0.04)	Sedge (0.01)				0.39
	E4/E6	Slope mean (-0.05)	Area (-0.08)				0.37
Angram-Scar	DOC	Mixed (-0.03)	Graminoids (-0.06)	Slope mean (-0.03)	Area (-0.10)		0.38
	Abs254	Mixed (-0.07)	Sedge (0.02)	Slope mean (-0.06)			0.45
	Abs265	Mixed (-0.08)	Sedge (0.03)	Slope mean (-0.07)	Area (-0.23)		0.45
	Abs360	Mixed (-0.06)	Sedge (0.03)	Slope mean (-0.07)	Area (-0.12)		0.45
	Abs400	Mixed (-0.06)	Slope mean (-0.08)	Area (-0.14)	Sedge (0.02)		0.40
	Abs436	Slope mean (-0.07)	Area (-0.19)	Mixed (-0.05)	Graminoids (-0.01)		0.36

	Abs665	Area (-0.21)	Slope mean (-0.04)	Ericaceous (0.01)			0.42
	SUVA254	Slope mean (-0.03)	Sedge (0.01)	Mixed (-0.03)			0.49
	E4/E6	Slope mean (-0.04)	Mixed (-0.03)	Sedge (0.01)			0.27
Wessenden	DOC	Graminoids (-0.01)					0.10
	Abs254	Slope mean (-0.05)	Area (-0.20)	N/S facing (-0.12)			0.17
	Abs265	Area (-0.25)	Slope mean (-0.11)	Sedge (-0.02)			0.32
	Abs360	Slope mean (-0.09)	Area (-0.21)	N/S facing (-0.14)	Sedge (-0.02)		0.23
	Abs400	Slope mean (-0.10)	Area (-0.24)	N/S facing (-0.14)	Sedge (-0.02)		0.25
	Abs436	Slope mean (-0.10)	Area (-0.21)	N/S facing (-0.14)	Sedge (-0.02)		0.26
	Abs665	Slope mean (-0.09)	Sedge (-0.02)				0.29
	SUVA254						p>0.05
	E4/E6	N/S facing (-0.10)	Area (-0.12)				0.19
White Holme	DOC						p>0.05
	Abs254						p>0.05
	Abs265	Ericaceous (-0.03)					0.27
	Abs360						p>0.05
	Abs400						p>0.05
	Abs436						p>0.05
	Abs665						p>0.05
	SUVA254	Ericaceous (-0.04)	Slope mean (-0.04)				0.23
	E4/E6	Ericaceous (-0.01)					0.34