
Published article:

Holden, J, Chapman, PJ, Palmer, SM, Kay, P and Grayson, R (2012) *The impacts of prescribed moorland burning on water colour and dissolved organic carbon: a critical synthesis.* Journal of Environmental Management, 101. 92 - 103.

http://dx.doi.org/10.1016/j.jenvman.2012.02.002

The impacts of prescribed moorland burning on water colour and dissolved organic carbon: a critical synthesis

Holden, J., Chapman, P.J., Palmer, S.M., Kay, P. and Grayson, R.

water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK

j.holden@leeds.ac.uk; +44 113 343 3317

Date submitted to *Journal of Environmental Management*: 23 Dec 2011

Abstract

Discolouration of natural surface waters due to the humic component of dissolved organic carbon (DOC) is a costly problem for water supply companies. This paper reviews what is known about the impacts of prescribed moorland vegetation burning on water colour. Relevant research has taken place at three scales: laboratory experiments on peat cores, plot scale sampling of soil waters and catchment scale sampling of stream waters. While laboratory studies suggest burning increases colour production, the evidence from catchment and plot studies is contradictory. Plot studies suggest colour production may decrease or remain unchanged following burning although there is evidence for some transient changes. Catchment studies suggest prescribed moorland burning causes stream water colour to increase, although in most cases the evidence is not clear cut since most studies could not clearly disentangle the effects of burning from those of vegetation cover. The differences in findings between plot and catchment studies may be explained by: i) the short-term nature of some studies which do not measure long-term response and recovery times to burning; ii) the lack of colour measurements from shallow soil depths which contribute more to streamflow than soil water from deeper in the peat; and iii) the possibility of hydrological interactions occurring between different experimental plots at some sites. Additionally, the increase in recent patch burning in some catchments that has been statistically attributed by some authors to increases in stream water colour cannot be reconciled with theoretical calculations. When dilution with waters derived from other parts of the catchment are taken into account, large values of colour have to be theoretically derived from those recently burnt areas that occupy a small proportion of the catchment area in order to balance the change in stream water colour observed in recent years. Therefore, much further process-based work is required to properly investigate whether prescribed vegetation burning is a direct driver of enhanced colour and DOC in upland streams, rivers and lakes.

Keywords: moorland, peatland, fire, dissolved organic carbon, land management, water colour, burning

Highlights

- We critically review evidence for moorland burning impacts on water colour
- Laboratory leachate studies suggest burning increases water colour release
- Plot studies suggest a transient and varied response to burning
- Catchment correlations suggest burning increases stream water colour
- Shallow soil water data would help link catchment and plot scale studies

1. Introduction

Most fire impact work in peatlands has focussed on wildfire (e.g. Robinson and Moore, 2000; Turetsky et al., 2004; Maltby et al., 1990). However, prescribed burning in peatlands has been used as a management tool in many areas (e.g. Buytaert et al., 2006; Holden et al., 2007). These managed burns tend to operate at cooler temperatures than wildfires and are less intense (Tucker, 2003). In the UK, many upland moorland environments, dominated by blanket peat cover, have historically been burned to regenerate young heather shoots for winter fodder, and regenerate palatable sedges and grasses for sheep and deer. Burn management in small rotationally (5 to 20 years) burned patches has also been common over the past 150 years (Simmons, 2003) to produce heather age mosaics to support red grouse habitats as desired by the rural gun-sports industry. Burning may occur over a range of typically acid organic soils across the uplands, but, despite guidelines that recommend no burning on blanket peat (Defra, 2007), many burnt areas are in fact on blanket peatlands.

Where peat occurs within a catchment it typically dominates as a source of stream water discolouration and dissolved organic carbon (DOC) (Mitchell and McDonald, 1995; Aitkenhead et al., 1999). Water colour is a major problem for water companies because deterioration in water colour leads to breaches of European Union drinking water standards and an increase in water treatment costs. It also has health implications as the chlorination of highly coloured water can lead to the production of carcinogenic disinfection by-products (Pereira et al. 1992; Chow et al., 2003) which are tightly regulated. Additionally there are regulatory drivers associated with the EU Water Framework Directive, 2000/60/EC, which means that land management activities that could result in changes to the ecological status of water bodies must be examined and dealt with. Processes which enhance the potential for DOC release from peat, such as water table drawdown via drainage (Wallage et al., 2006), warmer temperatures (Tranvik and Jansson, 2002) or a reduction in sulphate deposition (Evans et al. 2006) may exacerbate the colour problem at water treatment works. There is some evidence to suggest there has been an increase in the area of land being burned in some parts of northern England in recent years. In the 10 years from 1995 air photo evidence for some parts of the Pennine hills suggested that burning significantly encroached on to blanket bog as the economic incentive grew for grouse production (Yallop et al., 2006). There is therefore an interest to understand whether burn management on peatland areas has an impact on stream water quality by increasing water colour. The carbon policy and climate change agenda also means that there is a strong interest in understanding management impacts on related DOC losses from soils, in particular peat (Holden et al. 2007).

There have been a number of reviews of the impacts of moor burning on environmental processes (Glaves and Haycock, 2005; Hobbs and Gimingham, 1987; Mowforth and Sydes, 1989; Shaw et al., 1996; Tucker, 2003; Stewart et al., 2004; Worrall et al., 2010). The Glaves and Haycock (2005) review of the Heather and Grass Burning Code for the UK government agency Defra, noted that because of a lack of scientific data it was difficult to provide evidence to support any major changes in the Code. They noted that virtually nothing was known about whether burning influences moorland hydrology, sediment release and water quality and that most research focussed on terrestrial ecology. However, there has been a surge in published reports since then. These have led to confusion among stakeholders since they appear to show conflicting results with some papers suggesting burning increases water colour (e.g. Yallop et al., 2010) while others suggest there is no impact or even a decline in water colour as a result of prescribed burning on peatlands (e.g. Clay et al., 2009b). There are also some older technical (unpublished) reports which may not have been available to the authors of previous reviews and which may contain useful information (e.g. McDonald et al., 1991; O'Brien et al., 2007).

The aim of this paper is to examine the available data on the impacts of prescribed moorland burning on water colour and DOC to establish whether there are consistent or conflicting results. In addition, we will comment on whether differences in experimental design, sampling methods and/or analytical measurements between studies may explain differences in findings. Where relevant to water colour or DOC we include studies that have examined prescribed moorland burning impacts on other water quality variables. We do not study the impacts of peatland wildfires in this paper which may have very different impacts since they usually burn at hotter temperatures, for longer and over much bigger areas than prescribed patch burning.

2. Terminology

Before embarking on our critical synthesis it is worth clarifying some of the terminology used. *Water colour* is measured in a number of different ways and yet some authors may still refer to colour as if it is a 'standard' variable. Water companies have traditionally measured water colour in degrees Hazen which is where the water colour is measured against a standard solution of platinum-cobalt in the presence of cobalt (II) chloride hexahydrate. One problem is that sometimes these colour measurements have been performed on unfiltered water (and the colour is therefore the 'apparent' colour) and other measurements have been performed on filtered samples to remove particulates (true colour) and so correction is needed to align datasets where they are to be used together to construct long-term records or form relationships with other variables. Many scientists measure water colour by determining absorbance per metre using a spectrophotometer on water samples at a particular wavelength. Commonly used wavelengths are 400, 450, 600 and 650 nm but many others have also been used (Grayson and Holden, in press). These values can be related to Hazen units via regression, although the slope of the regression line may vary from site to site and through time.

Dissolved organic carbon (DOC) concentration is typically determined on analytical instruments (e.g. total carbon analysers, or by oxidation on a combustion infra-red analyser) after filtering through a 0.45μm Whatman filter paper and is measured in units of mg L^{-1}. Some authors have used available colour data (e.g. Hazen) for river systems or water treatment works to estimate DOC concentrations and fluxes in these systems by linear regression (e.g. Tao, 1998, Worrall et al., 2003). However, the relationship between colour (in Hazen or absorbance at a particular wavelength) and DOC concentration is not stable and Wallage and Holden (2010) have shown that errors of > 50 % can be made in estimated DOC concentrations based on regressions from absorbance measurements. This is because DOC is made up of many compounds and contains uncoloured components. So this should be borne in mind when looking at results presented in the literature and may be one reason why Clutterbuck and Yallop (2010) chose to use the term 'humic coloured DOC' or hDOC (i.e. the parts of the DOC more closely related to discolouration) for their linear regressions using long-term water colour records with some DOC determinations. Indeed some common measures in the literature reflect the fact that the relationship between colour and DOC concentration is variable. One such example is *SUVA (specific ultra violet absorbance)* which is the ratio of absorbance at 254 nm to DOC concentration. Other similar ratio measures have also been derived which examine the ratio of colour (absorbance measured at a particular wavelength such as 400 nm) and DOC concentration (Wallage et al., 2006; Wallage and Holden, 2010).

3. Critical synthesis of research

The key research outputs focussing on the impacts of prescribed moorland burning on water colour, and/or DOC or related water quality variables are listed in Table 1. There are a number of other unpublished reports that examine the impact of burning on water colour and DOC that have been written for organisations such as water companies. However, where versions of these reports have been published then the published versions are cited only, so we do not duplicate our analysis. Where possible we have checked the original reports and if relevant additional information is available then we have made reference to it. Furthermore, where initial scoping data have been published but are provided in more detail and developed upon in other papers by the same authors (e.g. Yallop et al., 2008), we have only reported on the full paper.

The papers in Table 1 can be grouped into three 'types' of research; a) laboratory experiments using peat cores; b) plot scale studies sampling soil waters (almost entirely at the Moor House site in northern England) and c) catchment studies using stream water samples (almost entirely within the Yorkshire Pennine region of northern England). The findings of the research undertaken at theses different scales are described below.

a) Laboratory experiments

The three early papers that focus on laboratory experimentation (Allen, 1964; Allen et al., 1969; Forgeard and Frenot, 1996) generally concurred that burning does not result in a significant change in nutrients leached from the soil. However, all three papers agreed that pH increased in the upper soil layer as a result of burning. Although neither colour nor DOC was measured in these experiments, the change in pH has implications for DOC production since pH controls the solubility of DOC (Thurman, 1985); the higher the pH the greater the solubility of DOC.

Two projects used laboratory experiments on peat cores specifically to examine the impacts of burning on colour release (McDonald et al. 1991 and Miller, 2008). These studies extracted cores from areas that had been burnt and areas that had not been burnt and measured leachates from the cores. Miller (2008) ran experiments using cores from a burnt area with bare peat, a burnt area where vegetation was regrowing, an unburnt bare peat and an unburnt vegetated peat. Some of the cores from each treatment were inoculated with microbes and some were subject to different drying and wetting cycles. Overall, increased water colour release in leachate was detected from burnt peat compared with unburnt peat. Drying and re-wetting of burnt peat had little effect on colour or DOC release. There was a significant drying and inoculation interaction, with enhanced colour release for cores which had been dried and inoculated, immediately after the burn. One year after the burn, this drying/inoculation interaction had been lost in the bare peat but not in the burnt revegetated peat.

This difference between the years for the bare peat was suggested to be due to soil moisture content differences affecting the soil microbial community but Miller (2008) noted that further research was needed to clarify this. Miller (2008) also noted that it was very clear from the experiment that the effects of burning on water colour release lasted more than one year. However, this study investigated an accidental burn which occurred during the summer time, and the results, therefore, are unlikely to be applicable to burning conducted over winter as part of grouse moor management.

McDonald et al. (1991) provided leachate data from peat cores. They showed that one month after burning there was no difference in colour leaching from burnt and unburnt peat cores. However, over longer periods prescribed burning increased colour in leachate compared to unburnt peat cores vegetated with *Calluna* and *Eriophorum*. Some of the peat cores were burnt in the field by normal planned controlled fires and then extracted and returned to the laboratory whereas other peat cores has their vegetation burnt at controlled hot and cooler temperatures in the laboratory and were then leached with water. Hotter burns were associated with more colour release than cooler burns. This was the case for both the controlled laboratory burns and for field samples. However, in the field 'hot burns' were assumed from the state of the peat surface and vegetation rather than by temperature measurement or control. The lag between burning and colour increase was used as evidence by McDonald et al.(1991) to suggest that burning did not directly cause colour increases but lead to other changes which then in turn lead to colour increases. McDonald et al.(1991) suggested that these processes might include accelerated microbial decomposition in warmer temperatures below an unvegetated peat surface compared to under a cooler vegetated surface.

b) Plot scale

A field study on a dry *Calluna* heath in Wales has shown enhanced dissolved organic nitrogen (DON) leaching after burning (Pilkington et al., 2007) in plots (1m x 1m) that had been treated (monthly) with nitrogen (N) additions of between 0 and 120 kg $ha^{-1}yr^{-1}$ ammonium nitrate to simulate increases in atmospheric N deposition. The increased DON flux was observed in the six month period following the burn in both the organic horizon and in the underlying mineral soil horizon. However, by two years after the fire, DON fluxes from both horizons were lower than pre-burn rates, suggesting a transient source of DON such as the decomposing litter layer and *Calluna* roots (Pilkington et al., 2007). Pilkington et al. (2007) did not measure DOC directly. However, they suggested that because ratios of DOC:DON are approximately constant in upland surface waters (Harriman et al. 1998; Pellerin et al. 2006), significant increases in DON leaching after burning are likely to signal approximately proportional transient increases in DOC leaching.

In contrast, Helliwell et al. (2010) detected no effect of burning on N concentrations in soil solutions at approximately 10 cm depth in their plot-scale experiment on a *Calluna* alpine heath in Scotland. Helliwell et al. (2010) did detect a decrease in DOC nine months after burning, with no statistically significant trend during the six years following burning suggesting that decreased DOC concentrations persisted for at least six years. They did not measure soil solution chemistry during the period immediately post burn until nine months following burning. It should be noted that the soils at this site and at the Pilkington et al. (2007) site were coarse-grained podzols with a very thin (8-10cm) surface organic horizon, and therefore quite different to peat soils at other sites where burning experiments have taken place.

There are a set of papers investigating the impact of burning on soil water colour and DOC from the Hard Hill experimental plots at Moor House National Nature Reserve in the North Pennines, England. These include Ward et al. (2007), Worrall et al. (2007), Worrall and Adamson (2008), Clay et al. (2009a and 2009b), and Clay et al.(2010). The experimental set-up for the Hard Hill plots was designed in the 1950s and the experiment commenced in 1954 with the design as shown in Figure 1. In brief, there are four experimental blocks each consisting of six 10 m x 30 m plots. The long-term experimental management since 1954 (approximately 10 and 20 year cycles of burning and grazing exclusion) is unique and provides scientists with an insight under controlled conditions of ecological responses to different management practices. There have been several ecological publications based on the Hard Hill plots (Rawes and Williams, 1973; Rawes and Hobbs, 1979; Hobbs and Gimmingham, 1980; Hobbs, 1981; and Hobbs, 1984). These papers tend to note the difference in re-establishment of vegetation after burning at these plots, which are on blanket bog of 1 to 2 m depth, compared to vegetation cover on heaths elsewhere which are subject to burning. The Hard Hill plots (at 590 to 630 m above sea level) are close to the altitudinal/climate limit for *Calluna* and hence growth cycles can be slower here compared to lower altitudes. The *Calluna* at Moor House is thought to take 11 to 17 years after burning to reach its maximum abundance, during which time the sedge *Eriophorum* dominates. Without fire the *Calluna* reaches a steady-state in which it is constantly rejuvenated by smothering with *Sphagnum* which encourages new shoots. Hence, Adamson and Kahl (2003) suggested that burning is not necessary to regenerate heather at this altitude.

The Hard Hill plots on a 10 and 20 year cycle were burnt in winter 1995/6. Those on a 10 year cycle were last burnt in February 2007. After studying the Hard Hill plots, Clay et al. (2009b) concluded that there was no lasting effect of burning on DOC in soil water collected as a bulk sample from a depth of 0 to 90 cm. However, they did observe a peak in DOC and colour one month after the February 2007 burning which may suggest that the relationship between burning and DOC is transient, as also noted by Pilkington et al. (2007). Further research is required to ascertain whether this is the case or not. In contrast, Worrall et al. (2007), who studied the plots some 10 years after the last burn but using the same sampling points as Clay et al. (2009b) observed lower DOC concentrations in the burnt relative to unburned plots. This was explained by Clay et al. (2009b) as being because Worrall et al. (2007) only reported sampling over 7 summer months rather than the whole year and now they report findings for 52 samples collected over 34 months. In addition, Clay et al. (2009b) sampled both before and after a burn on the site. Nevertheless, the findings of Clay et al. (2009b) for the time period before the new burn took place (i.e. 11 years or 21 years after the previous burn) are in line with those reported by Ward et al. (2007) who collected soil solutions at 10 and 50 cm depth at the same site over the 12 months from June 2003 (i.e. seven to eight years after a burn for the '10 year' burn cycle plots). Overall, the Hard Hill results to date suggest that soil water DOC is not significantly affected by burning except in the immediate few weeks after a burn thereby highlighting that time since burn may be an important factor to take into account when interpreting results from field or laboratory experiments. This is similar to the findings of Pilkington et al., (2007) but at odds with the laboratory studies of McDonald et al. (1991) described above, who found no difference between burnt and unburnt leachate in the first month after the burn.

It should be noted, however, that the plots within a block on Hard Hill are all next to each other and on a slope (see Figure 1). Hydrologically this means that they may interact with one another. In other words the flow (and DOC or water colour) from the upper plots may flow into the lower ones and there could be mixing. This may distort the results and may be one explanation for why few significant differences are seen as a result of burn management compared to no burn. Lindsay (2010) has also criticised Worrall et al. (2007) and the Clay et al. papers for their measurement process stating that no protective boardwalk was used and regular trampling could have significantly impacted the results. The work of Robroek et al. (2010) at Moor House also shows that tracks made by researchers to small plots can impact the local hydrology and fluvial carbon release. Furthermore, the burns at Hard Hill are likely to have been very quick, cool burns under very controlled experimental conditions in order to prevent fire spreading to an adjacent plot. This may be somewhat unlike the burning that would be typically seen on moorlands elsewhere. Gray and Levy (2009, p20) have suggested that extrapolation of results from the Hard Hill plots more widely should be done with extreme caution.

There is a disconnection between the findings at the plot scale from Hard Hill (no effect of burning on DOC production) and the findings at the catchment scale as discussed below. This may reflect the fact that most of the studies carried out at the Hard Hill plots are sampling soil water from too deep in the soil profile where there may be no rapid response to burning at the soil surface (since water movement in deep peat layers is extremely slow; Holden and Burt, 2003b). Ward et al. (2007) used soil suction samplers at 10 and 50 cm depth, while Clay et al. (2009a and b, 2010) and Worrall et al. (2007) sampled water from each plot using three dipwells inserted to at least 90 cm depth with openings at all depths, hence the sample potentially integrated water from the whole 90 cm soil profile. Soil water from peat layers below 5 or 10 cm may not contribute significantly to stream flow in many blanket peatlands. High-resolution soil water monitoring carried out by Clark et al.. (2008) in the nearby Cottage Hill Sike catchment at Moor House showed that DOC dynamics varied with depth throughout the top 50 cm of the peat profile. Concentrations at 10 cm depth displayed a clear seasonal cycle and a wide range of concentrations (8 to 53 mg L^{-1}), whereas concentrations from 20 to 50 cm depth showed little seasonality and displayed a smaller range of concentrations (15 to 31 mg L^{-1}). In addition Clark et al. (2008) observed a strong positive correlation between stream water and soil water DOC concentrations at 1 and 5 cm depth (R^2 = 0.834 and 0.791, respectively), with weaker correlations between stream and soil water concentrations at 20 to 50 cm depth (R^2 = 0.269 to 0.656). The relationship between DOC in soil water at 1 cm depth and stream water was particularly strong during storm events. The importance of water from the top 5 cm of the peat profile in controlling stream water colour, is consistent with hydrological studies carried out at Moor House which have shown that most runoff that would transport DOC from soil to stream, originates from the top 5 cm and in particular the top 1 cm and above (Holden and Burt, 2003a). Clark et al. (2008) also pointed out that their observations were consistent with ^{14}C studies at other peatland sites that have found the age of carbon in stream water draining peatlands to be less than 40–50 years old, highlighting the importance of near surface flow paths (Schiff et al., 1997; Palmer et al., 2001) and the apparent disconnection between the older carbon in the lower peat layers and stream water (Billett et al., 2006). Hence in order to integrate plot and catchment studies and understand the impact of recently burned plots on stream water DOC and colour it is imperative that we have a greater understanding of how these burned patches are hydrologically connected to the stream and ensure that we are sampling soil water that contributes to stream water.

c) Catchment scale

Most of the catchment scale research on water colour and burning has involved collecting stream water samples and then statistically relating the colour or DOC data to the spatial coverage of burning. Two studies (Mitchell and McDonald, 1995; Chapman et al., 2010) did not set out to examine burning as a factor in water quality but they touch upon the issue as part of their research. Based on their field observations in northern England, particularly in the Nidd and Washburn catchments, McDonald et al. (1991) suggested that key factors contributing to increased colour risk in upland peatlands were: drought conditions, area of open-cut drainage, area of pre-afforestation ditching, areas of severely burnt moorland, south facing slopes, and areas of bare eroded peat. In their original report, McDonald et al. (1991) state that the links between burning and colour were not clear cut, mainly because the data on burnt area, types of burn and other confounding factors (e.g. drainage and burning occurring together etc) were rather limited. Later, Mitchell and McDonald (1995) suggested there was a link between colour and burning but they do acknowledge that there was insufficient data for a statistical validation of this link. Grayson et al. (2008) used GIS and air photo data for a regional analysis of land cover and water treatment works colour data around Yorkshire, northern England. They found that the areal extent of heather burning and vegetation type were the two most important variables for accurately predicting water colour, although other variables also had a significant impact including the extent of peat coverage, drainage and amount of precipitation (Grayson et al., 2008). Beharry-Borg et al. (2009) repeatedly surveyed 27 stream sites across the Upper Nidderdale region in northern England over a 12 month period. There was a significant positive relationship between the proportion of *Calluna* cover and

DOC. The proportion of catchment area burnt was associated with a change in the composition of DOC (reported as SUVA and also as a colour to DOC ratio). This suggests that burning is associated with an effect on DOC. Chapman et al. (2010) compared the spatial and temporal variability of water colour for fifteen streams in the How Stean catchment in Upper Nidderdale in 1986 and 2006/7. They observed that water colour increased in all sub-catchments between 1986 and 2006/7, but that there was considerable variability in the increase, which ranged from 22 to 155%. Six of the sub-catchments were intensively managed by burning in both 1986 and 2006, five were not burnt over the twenty year period and four were not managed for grouse in 1986 but had very small (<4%) areas of burning occurring post-2000. Despite this variation in burn management, no relationship between burning management and increase in water colour was apparent. For the catchments that were not managed by burning over the 20 year period water colour increased between 22 and 117%, whereas for the catchments that were consistently managed by burning water colour increased by 37 to 123%. Hence both types of catchments displayed a wide variation in the increase in water colour over the 20 years suggesting that factors other than burning, such as interactions of decreases in sulphate deposition with different soil types were more important in controlling the variability in water colour increase in these catchments (Chapman et al., 2010).

Yallop et al. (2008), Yallop and Clutterbuck (2009), Yallop et al. (2010) and Clutterbuck and Yallop (2010) use a regression technique to report a significant correlation between the proportional area of recently burnt land (based on interpretation of aerial photos and some ground truthing) and DOC, or the coloured component of DOC (termed hDOC derived by linear regression of DOC on colour in Hazen units) in stream waters. They demonstrate not only a spatial pattern in stream DOC, controlled by the proportion of the catchment with recent burns (Yallop and Clutterbuck, 2009), but also a temporal trend whereby hDOC concentrations in some catchments in recent years has coincided with an increase in the proportion of land with class 1 burn cover (Yallop et al., 2010). Class 1 burn cover was defined as being where recent burning has taken place and there is yet to be any visible regrowth of dwarf shrub cover. The time period since the burn will therefore be variable under class 1 cover but typically will have occurred within the previous four years. The laboratory findings of McDonald et al. (1991) described above correspond well to those of Yallop et al. (2008) in that they suggest that most colour is produced in the initial (but not immediate) period following a burn and then as vegetation recovers colour production may decrease.

In a variation on the above statistical procedures O'Brien et al. (2007) compared one catchment which was under moorland burning management with another catchment where burning ceased (with 14 months of data collection before burning stopped and 33 months after). Here there were no significant differences in stream water colour compared to the control. It could be argued that response times to recovery from burning cessation may be longer than 33 months and also that differences may be less than when comparing burnt versus non-burnt sites, recent burns versus old burns or sites which have not been burnt for a several decades.

The weight of the existing evidence at the catchment scale, (albeit still quite limited and requiring further work) suggests that moorland burning has an effect on stream water colour. Out of the five sets of catchment studies that aimed to directly find whether burn management impacted water colour (McDonald et al. 1991; O'Brien et al., 2007; Grayson et al., 2008; Beharry-Borg et al., 2009; and the papers by Yallop, Clutterbuck and colleagues), four of them found some effect. Only O'Brien et al. (2007) found no effect; however, their work tested cessation of burning versus continued burning and only measured cessation of burning for less than three years which may not have been enough to see a signal. The set of papers by Yallop and colleagues appear to provide a comprehensive argument to show that stream water colour is largely controlled by the proportion of recently burnt land on blanket peat. They do not claim that this is the only control, but where burning is part of moorland management they suggest that it is the dominant factor controlling spatial variations in water colour (>60%) and increases (>80%) in colour over time in the English

Pennines. However, if class 1 burns do indeed have a large influence on stream water hDOC then soil water and overland flow from these recently burnt patches distributed throughout the catchment must be considerably larger than from other parts of the catchment. Indeed, Yallop et al. (2010) note that 'It can be estimated from the results presented here that a given area of blanket peat exposed by new management burns produces 5 to 15 times the hDOC flux than fully canopied areas.' hDOC flux is the product of hDOC concentration and water flux, and an increase in either or both could contribute to an overall increase in hDOC export. Yallop et al. (2010) do not report an increase in water flux at the water treatment works which were the source of their colour data. If we assume no change in runoff and use the average DOC concentration of soil water from 10 cm depth beneath fully canopied heather on a blanket peat at Moor House, which is 23 ±7 mg L^{-1} for the period 1993 to 2002 (Chapman et al., 2008), then the DOC concentration from bare peat at 10 cm depth, as a result of recent class 1 heather burning, is expected to range between 115 and 345 mg L^{-1} if we assume a 5 to 15 times increase in hDOC concentration as suggested by Yallop et al. (2010). However, the plot experiments discussed above do not report such large soil water DOC concentrations beneath recently burnt areas. High DOC concentrations have been reported for burnt and mature heather patches in northern England (White et al. 2007), although these were at depths of 25, 50, 75 and 100cm. White et al. (2007) observed that DOC concentrations in all soil waters beneath the burnt patches were fairly constant throughout the year, at or below a value of 75 mg L^{-1}, whereas much larger DOC values (up to 250 mg L^{-1}) were observed in soil water under mature (i.e. not recently burnt) heather patches at these sites. Thus in order to integrate plot and catchment studies and understand the impact of recent burnt plots on stream water DOC and colour it is imperative that we have a greater understanding of: i) how DOC and colour in near-surface soil solutions respond to burnings; and ii) how these small burnt patches (<2 ha) are hydrologically connected to the stream.

If, as suggested by Clutterbuck and Yallop (2010), burning of heather moorland accounts for around 80% of the recent (1990-2005) increase in observed hDOC in stream water draining catchments where such management occurs it is possible to estimate the concentration of hDOC from the fully canopied areas of the catchment and the recently burnt (class 1) areas of the catchment using the data presented by Clutterbuck and Yallop (2010) in Table 2. For example, in the Lower Laithe catchment:

$$\text{in 1990,} \quad 0x + 100y = 5 \text{ mg hDOC L}^{-1} \qquad \text{eq. 1}$$

$$\text{in 2005,} \quad 0.1x + 99.9y = 5.8 \text{ mg hDOC L}^{-1} \qquad \text{eq. 2}$$

where x denotes the concentration of hDOC originating from each 1% of class 1 burn area in a catchment and y denotes the concentration of hDOC originating from each 1% of all other land cover types. Several assumptions are inherent in the application of this approach:

(i) It assumes that each 1 % of the catchment contributes runoff to the stream equally.

(ii) It assumes that the concentration of hDOC leaving each 1% of the catchment does not change along its pathway to the stream (i.e. no adsorption or precipitation of DOC occurs, or transformation of hDOC).

(iii) It assumes that hDOC from all other heather classes and other vegetation types (e.g. acid grassland) is the same.

(iv) It assumes that hDOC contribution from other vegetation cover has not changed between 1990 and 2005.

Accepting these assumptions, by solving equations 1 and 2 for each catchment presented in Table 2 (by using the % area of class 1 burn values specific to each catchment) it is possible to obtain the concentration of hDOC associated with each % of burnt (class 1) and non-burnt area of the catchment and give some indication of the increase in hDOC that is required under class 1 burn areas to account for the observed increase in hDOC in stream water at then catchment scale over time (Table 3). The results presented in Table 3 suggest that hDOC from class 1 burnt patches at Keighley Moor, Agden and Broomhead catchments have to be between 5 and 19 times greater than that coming from the rest of the catchment, which is similar to that reported by Yallop et al. (2010). However, at Lower Laithe where such a small area of the catchment (<0.1%) has been recently burnt the hDOC concentration from this area has to be over 160 times greater than the rest of the catchment. In addition, the small burnt patches would need to be well connected to the stream network for them to be the major factor contributing to the increase in hDOC at this catchment, suggesting that other factors are likely to be having a large control on hDOC in this catchment. The data for the Langsett catchment also suggest that the hDOC concentration from the class 1 burnt areas must be over 200 times greater than the rest of the catchment, which seems very unlikely. Thus again factors other than burning must be an important control on the increase in hDOC at this catchment.

Much of the catchment-scale work has involved correlating a percent area of burning or presence/absence of burning with water colour and/or DOC concentration. However, there is a difference between correlation and causation and hence independent evidence of mechanistic links between areas of burning and/or vegetation type and stream water colour is needed to support the interpretations of the catchment scale monitoring data. While there is currently some experimental evidence to support a link between burning and an increase in soil water colour or DOC from laboratory experiments (McDonald et al., 1991; Miller, 2008), the data from plot scale studies does not support a link between burning and an increase in soil water colour or DOC (Worrall et a., 2007; Ward et al. 2007, Clay et al., 2009b). Hence, there is an absence of empirical mechanistic evidence to verify the results obtained from statistical analysis of data at the catchment scale. Hence new research is urgently needed to investigate the effect of burning on: (i) the production of colour and DOC within the burnt areas compared to non-burnt areas, and (ii) transport of soil water to the stream network

A new set of evidence is now building which suggests that the moorland vegetation itself may have a strong impact on DOC or colour production (e.g. Miller, 2008). Vestgarden and Austnes (2009) investigated the impact of freeze-thaw cycles on carbon release from soils below plant species that are typical of moorland vegetation. They found that compared to *Calluna* and *Molina*, *Sphagnum* was associated with the lowest DOC concentrations. Luxton (2008) and Armstrong et al. (in review) also showed from a variety of scales; cores, patches, channels and small catchments that vegetation has a significant effect on DOC concentration. In UK blanket peat, *Calluna* was associated with the highest DOC concentrations, *Molinia* and *Sphagnum* with lower concentrations, and sedges with intermediate concentrations. Beharry-Borg et al. (2009) observed that the best predictor of stream water DOC in headwaters of the River Nidd was the proportion of acid and neutral grassland, with concentrations decreasing as the proportion of acid and neutral grassland increased. However, Beharry-Borg et al. (2009) also found that for some sites the percentage cover of dwarf shrub vegetation showed a strong positive relationship with DOC concentration. In addition, stepwise regression analysis indicated that variation in dwarf shrub vegetation accounted for the majority of the variation in DOC composition (indicated by SUVA and the ratio of absorbance at 400 nm to DOC concentration). Beharry-Borg et al. (2009) were unable to disentangle any possible effects of burning on DOC from that of dwarf shrub vegetation, as the percentage of dwarf shrub vegetation and burning were highly correlated. Grayson et al. (2008) also observed that dwarf vegetation and area of burn were important controls on water colour but they did not report the relationship between the two parameters. The strong positive correlation between dwarf shrub vegetation and burning is not really surprising, as it is heather that supports the grouse population and it is heather that has been managed by burning.

It is thought from catchment studies that higher colour originates from areas of bare, eroding peat (e.g. McDonald and Naden, 1988; Boon et al., 1988) but McDonald et al. (1991) studied Holme Moss, in the south Pennines area of northern England and found no difference in colour between eroding or vegetated peat, although this work was only conducted during a summer sampling period and colour flushing may be greatest during autumn (e.g. Chapman et al., 2010). More recently, laboratory experiments have suggested bare peat is associated with greater colour production (Miller, 2008). Indeed it may be the lack of vegetation cover in class 1 burn patches that is responsible for the correlations described above in the Yallop et al. papers. However, the processes by which bare peat or different types of vegetation cover control colour production require further investigation. The reasons for a vegetation cover influence are varied, but may include changes to: interception losses, infiltration rates, soil fauna activity, soil pH, geochemistry of soil water (Clymo, 1987; Kuhry et al., 1993), the physical properties of the peat, including temperature and the impacts on hydrology (McNamara et al., 2008), and the biological agents which live within the peat (Artz et al., 2007; Artz et al., 2008). DOC concentrations have been shown to vary between litter type and soils (Moore and Dalva, 2001; Wickland et al., 2007).

4. Conclusions

There are important regional drivers of stream water colour and DOC concentrations such as changes in atmospheric deposition chemistry, rainfall and temperature which may be over-riding factors controlling long-term DOC and water colour trends. However, on a local level, management of catchments (e.g. through drainage or drain blocking) influences water colour and DOC release (Wallage et al., 2006; Armstrong et al., 2010; Wilson et al., 2011). This paper has investigated literature on prescribed burning in moorland environments which are dominated by peat soils and the impact of this burning on water colour and DOC. Some authors consider that where prescribed burning occurs on peat-dominated catchments, it can be the dominant factor controlling stream water colour and increasing trends, having a much stronger influence than more regional factors such as changes in atmospheric deposition chemistry (e.g. Clutterbuck and Yallop, 2010). However, the research findings from different scales are somewhat inconsistent.

Research has taken place at three scales: laboratory experiments, plot scale sampling of soil waters and catchment scale sampling of stream waters. Laboratory studies suggest burning will increase colour production. Plot studies suggest colour production may either decrease or remain unchanged with burning although there is evidence for a transient increase in colour release in the short-term. A transient response was also suggested by the laboratory leachate measurements conducted by McDonald et al. (1991) and also by the catchment-scale work of Yallop and Clutterbuck (2009) who suggest that it is recent burn patches that are associated with increased colour production rather than patches that have fully revegetated some years after burning. Such evidence for transience suggests that a reduction in burning or an extended length of the burning cycle (i.e. longer durations between burns) would help reduced the impact of burning on water colour.

One problem with plot studies is that most have not involved measurement of colour or DOC at shallow soil depths that are important to streamflow water delivery in the peaty moorland systems. Most moorland burning and water colour plot studies have also focussed on the Hard Hill plots at the Moor House research site in Northern England which were designed for ecological experiments in the 1950s and not for hydrological or hydrochemical studies. As such the water from upslope plots flows downslope and probably mixes with water in plots under different treatments thereby causing difficulties in data interpretation. These plots are also close to the climate/altitudinal limit for *Calluna* and thus *Calluna* growth rates are rather different than at lower and warmer sites.

Catchment studies suggest prescribed burning in peatland systems results in water colour increases. While the balance of evidence suggests burning is related to increased colour/DOC in stream waters, most catchment studies are not absolutely clear cut since: i) vegetation cover may have been an important factor which the studies could not clearly disentangle from burning effects; or ii) the stream water data could not be immediately reconciled with data available from peatland soils. While several catchment studies do suggest a strong relationship between area of recent burn and water colour, the increase in colour or DOC that is required to account for this has not been observed in soil solutions sampled from burnt patches. Thus there is an urgent need to properly couple the catchment scale work with plot scale data, particularly as the burned areas typically are distributed throughout the catchment resulting in some burned areas being more hydrologically connected to the stream network than others. It will also be important to ensure that process understanding is embedded into future research and management programmes in order to demonstrate whether modifications to burning practice might be adopted to reduce negative impacts on water colour and DOC release. Further work on the role of vegetation and DOC production may also be fruitful within this context in order to place the role of burn management into that wider context.

Acknowledgements

We are grateful to Yorkshire Water Services Ltd for funding R&D project B4897 on which this paper is based.

References

Adamson, J.K., Kahl, J., 2003. Changes in vegetation at Moor House within sheep exclosure plots established between 1953 and 1972. Centre for Ecology and Hydrology, Merlewood.

Aitkenhead, J.A., Hope, D., Billett, M.F., 1999. The relationship between dissolved organic carbon in stream water and soil organic carbon pools at different spatial scales. Hydrological Processes, 13, 1289-1302.

Allen, S.E., 1964. Chemical aspects of heather burning. Journal of Applied Ecology, 1, 347-367.

Allen, S.E., Evans, C.C., Gromshaw, H.M., 1969. The distribution of mineral nutrients in soil after heather burning. Oikos, 20, 16-25.

Armstrong A, Holden J, Kay P, Francis B, Foulger M, Gledhill S, McDonald AT, Walker A., 2010. The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. Journal of Hydrology, 381, 112-120.

Artz, R.R.E., Anderson, I.C., Chapman, S.J., Hagn, A., Schloter, M., Potts, J.M., Campbell, C.D., 2007. Changes in fungal community composition in response to vegetational succession during the natural regeneration of cutover peatlands. Microbial Ecology, 54, 508-522.

Artz, R.R.E., Chapman, S.J., Siegenthaler, A., Mitchell, E.A.D., Buttler, A., Bortoluzzi, E., Gilbert, D., Yli-Petays, M., Vasander, H., Francez, A.J., 2008. Functional microbial diversity in regenerating cutover peatlands responds to vegetation succession. Journal of Applied Ecology, 45, 1799-1809.

Beharry-Borg, N., Hubacek, K., Termansen, M., Smart, J., Chapman, P.J. Robroek, B.J.M., Holden, J., Irvine, B.J., Kirkby, M.J., Ashley, D., Chapman, D.S., Quinn, C.H., Reed, M.S., Kay, P., 2009. Determining the socio-economic implications of different land management policies in Yorkshire Water's catchments. Report for Yorkshire Water, University of Leeds, Leeds.

Billett, M.F., Deacon, C., Palmer, S.M., Dawson, J.J.C., Hope, D., 2006. Connecting organic carbon in stream water and soils in a peatland catchment. Journal of Geophysical Research, 111, G02010.

Boon, R., Crowther, J. and Kay, D., 1988. Elan valley catchment protection. Land use investigations. Final report to Severn Trent and Welsh Water.

Buytaert, W., Celleri, R., De Bièvre, B., Hofstede, R., Cisneros, F., Wyseure, G. and Deckers, J., 2006. Human impact on the hydrology of the Andean paramos. Earth-Science Reviews, 79, 53-72.

Chapman, P.J., McDonald, A.T., Tyson, R., Palmer, S.M., Mitchell, G., Irvine, B., 2010. Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK. Biogeochemistry, 101, 281-294.

Chapman, P.J., Clark, J.M., Reynolds, B. and Adamson, J.K., 2008. The influence of organic acids in relation to atmospheric deposition in controlling soil and surface water acidity on a seasonal basis. Environmental Pollution, 151, 110-120.

Chow, A.T., Tanji, K.K. and Gao, S., 2003. Production of dissolved organic carbon (DOC) and trihalomethane (THM) precursor from peat soils. Water Research, 37, 4475-4485.

Clark, J.M., Lane, S.N., Chapman, P.J., Adamson, J.K., 2008. Linking DOC in soil and stream water in an upland peat catchment. Science of the Total Environment, 404, 308-315.

Clay, G.D., Worrall, F., Clark, E., Fraser, E.D.G., 2009a. Hydrological responses to managed burning and grazing in an upland blanket bog. Journal of Hydrology, 376, 486-495.

Clay, G.D., Worrall, F., Fraser, E.D.G., 2009b. Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. Journal of Hydrology, 367, 41-51.

Clay, G.D., Worrall, F., Fraser, E.D.G., 2010. Compositional changes in soil water and runoff water following managed burning on a UK upland blanket bog. Journal of Hydrology, 380, 135-145.

Clutterbuck, B., Yallop, A.R., 2010. Land management as a factor controlling dissolved organic carbon release from upland peat soils 2: Changes in DOC productivity over four decades. Science of the Total Environment. 408, 6179-6191.

Clymo RS. 1987. Interactions of Sphagnum with water and air. In Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems, Hutchinson T.C., Meema, K.M. (eds). Springer-Verlag. Berlin, 513-529.

Defra, 2007. The Heather and Grass Burning Code (2007 Version), Defra, London.

Evans, C.D., Chapman, P.J., Clark, J.M., Monteith, D.T., Cresser, M.S., 2006a. Alternative explanations for rising dissolved organic carbon export from organic soils. Global Change Biology, 12, 2044-2053.

Forgeard, F., Frenot, Y., 1996. Effects of burning on heathland soil chemical properties: an experimental study on the effect of heating and ash deposits. Journal of Applied Ecology, 33, 803-811.

Glaves, D.J., Haycock, N.E., 2005. Defra review of the Heather and Grass Burning Regulations and Code: Science panel assessment of the effects of burning on biodiversity, soils and hydrology, Defra, London.

Grayson, R., Holden, J., in press. Continuous sampling of spectrophotometric absorbance in peatland streamwater in northern England: implications for understanding fluvial carbon fluxes. Hydrological Processes.

Grayson, R., Kay, P., Holden, A., Whelan, M., Hannam, J., Hallett, S., Foulger, M. and Gledhill, S., 2008. GIS-based analysis of the impacts of land management on colour, nitrate and pesticides in raw water. Final report for Yorkshire Water, University of Leeds, Leeds.

Gray, A. and Levy, P. (2009) A review of carbon flux research in UK peatlands in relation to fire and the Cairngorms National Park. CEH Project Number C03530. 34pp.

Harriman, R., Curtis, C., Edwards, A.C., 1998. An empirical approach for assessing the relationship between nitrogen deposition and nitrate leaching from upland catchments in the United Kingdom using runoff chemistry. Water, Air and Soil Pollution, 105, 193–203.

Helliwell, R.C., Britton, A.J., Gibbs, S., Fisher, J.M., Potts, J.M., 2010. Interactive effects of N deposition, land management and weather patterns on soil solution chemistry in a Scottish alpine heath. Ecosystems, 13, 696-711.

Hobbs, R.J., 1981. Post-fire succession in heathland communities. PhD Thesis, University of Aberdeen.

Hobbs, R.J., 1984. Length of burning rotation and community composition in high-level Calluna-Eriophorum bog in N England. Vegetatio, 57, 129-136.

Hobbs, R.J., Gimingham, C.H., 1980. Some effects of fire and razing on heath vegetatoion. Bulletin d'Ecologie, 11, 709-715.

Hobbs, R.J., Gimingham, C.H., 1987. Vegetation, fire and herbivore interactions in heathland. Advances in Ecological Research, 16, 87-193.

Holden, J., Burt, T.P., 2003a. Runoff production in blanket peat covered catchments. Water Resources Research, 39, Art.No.1191.

Holden, J., Burt, T.P., 2003. Hydraulic conductivity in upland blanket peat; measurement and variability. Hydrological Processes, 17, 1227-1237.

Holden, J., Shotbolt, L., Bonn, A., Burt, T.P., Chapman, P.J., Dougill, A.J., Fraser, E.D.G., Hubacek, K., Irvine, B., Kirkby, M.J., Reed, M.S., Prell, C., Stagl, S., Stringer, L.C., Turner, A., Worrall, F., 2007. Environmental change in moorland landscapes. Earth-Science Reviews, 82, 75-100.

Kuhry, P., Nicholson, B.J., Gignac, L.D., Vitt, D.H., Bayley, S.E., 1993. Development of Sphagnum dominated peatlands in boreal continental Canada. Canadian Journal of Botany, 71, 10–22.

Lindsay, R., 2010. Peat bogs and carbon, a critical synthesis. Report for RSPB. RSPB Scotland.

Luxton, K.E., 2008. Investigating the impacts of vegetation on DOC and water colour, throughout a small catchment: a study in conjunction with Yorkshire Water. Unpublished MSc thesis, University of Lancaster. Yorkshire Water project B2612.

Maltby, E., Legg, C. J., Proctor, M. C. F., 1990. The ecology of severe moorland fire on the North York Moors - Effects of the 1976 fires, and subsequent surface and vegetation development. *Journal of Ecology,* **78,** 490-518.

Martin, D.S.J., 1992. The influence of land management on water quality, notably the production of soluble colour in supply. PhD Thesis, University of Leeds.

McDonald, A.T., Naden, P.S., Mitchell, G., Martin, D., 1991. Discoloured water investigations. Final report to Yorkshire Water plc, University of Leeds, Leeds, 432pp.

McNamara NP, Plant T, Oakley S, Ward S, Wood C, Ostle N., 2008. Gully hotspot contribution to landscape methane (CH4) and carbon dioxide (CO2) fluxes in a northern peatland. Science of the Total Environment, 404, 354-360.

Miller, C.J., 2008. Mechanisms of water colour release from organic soils and consequences for catchment management. Unpublished PhD thesis, University of Aberdeen.

Mitchell, G., McDonald, A.T., 1995. Catchment characterisation as a tool for upland water quality management. Journal of Environmental Management, 44, 83-95.

Moore, T.R., Dalva, M., 2001. Some controls on the release of dissolved organic carbon by plant tissues and soils. Soil Science, 166, 38-47.

Mowforth, M.H., Sydes, C., 1989. Moorland management: a literature review. Nature Conservancy Council, Peterborough.

McDonald, A.T., Naden, P., 1988. Investigations associated with water discolouration in Derbyshire. Report for contract 2561 for the Water Research Centre.

O'Brien, H., Labadz, J. and Butcher, D., 2007. The role of blanket peat moorland management in the generation and amelioration of drought-induced discolouration of surface water supplies. Report for Severn Trent Water, Nottingham Trent University, Nottingham, 11pp.

Palmer, S.M., Hope, D., Billett, M.F., Dawson, J.J.C., Bryant, C.L., 2001. Sources of organic and inorganic carbon in a headwater stream: evidence from carbon isotope studies. Biogeochemistry, 52, 321–338.

Pellerin, B.A., Kaushal, S.S., McDowell, W.H., 2006. Does anthropogenic nitrogen enrichment increase organic nitrogen concentrations in runoff from forested and human dominated watersheds? Ecosystems, 9, 852–864.

Pereira, M.A., Lin, L.H., Lippitt, J.M., Herren, S.L., 1982. Trihalomethanes as initiators and promotors of carcinogenesis. Environmental Health Perspectives 46, 151-156.

Pilkington, M.G., Caporn, S.J.M., Carroll, J.A. Cresswell, N., Phoenix, G.K., Lee, J.A., Emmett, B.A., Sparks, T., 2007. Impacts of burning and increased nitrogen deposition on nitrogen pools and leaching in an upland moor. Journal of Ecology, 95, 1195-1207.

Ramchunder, S., 2010. The effects of artificial drainage, drain-blocking and burning on peatland stream ecosystems. PhD Thesis, University of Leeds.

Rawes, M., Hobbs, R., 1979. Management of semi-natural blanket bog in the northern Pennines. Journal of Ecology, 67, 789-807.

Rawes, M., Williams, R., 1973. Production and utilisation of Calluna and Eriophorum. Colloquim Proceedings of the Potassium Institute, 3, 115-119.

Reynolds, S.E., Kneale, P.E., McDobald, A.T., 1996. Quantifying the store of water soluble colour in upland peaty soils: the effect of forestry. Scottish Forestry, 50, 22-30.

Robinson, S.D., Moore, T.R., 2000. The influence of permafrost and fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada. Arctic Antarctic and Alpine Research, 32, 155-166.

Robroek, B.M.J., Smart, R.P., Holden, J., 2010. Sensitivity of blanket peat vegetation and hydrochemistry to local disturbances. Science of the Total Environment, 408, 5028-5034.

Schiff, S.L., Aravena, R., Trumbore, S.E., Hinton, M.J., Elgood R., Dillon P.J., 1997. Export of DOC from forested catchments on the Precambrian Shield of Central Ontario: clues from C-13 and C-14. Biogeochemistry, 36, 43–65.

Shaw, S.C., Wheeler, B.D., Kirby, P., Phillipson, P., Edmunds, R., 1996. Literature review of the historical effects of burning and grazing of blanket bog and upland wet heath. English Nature, Peterborough,172pp.

Simmons, I.G., 2003. The Moorlands of England and Wales:An Environmental History 8000 BC–AD 2000. Edinburgh University Press, Edinburgh, UK.

Stewart, G.B., Coles, C.F., Pullin, A.S., 2004. Does burning degrade blanket bog? Systematic Review No 1. Centre for evidence based conservation.

Tao S., 1998. Spatial and temporal variation in DOC in the Yichun River, China. Water Research, 32, 2205–2210.

Thurman EM., 1985. Orangic Geochemistry of Natural Waters. Kluwer Academic Publishers Group, Amsterdam.

Tranvik L.J., Jansson. M., 2002. Climate change (Communication arising): Terrestrial export of organic carbon. Nature, 415, 861-862.

Tucker, G., 2003. Review of the impacts of heather and grassland burning in the uplands on soils, hydrology and biodiversity, English Nature, Peterborough.

Turetsky, M.R., Amiro, B., Bhatti. J., 2004. Peatland burning and its relationship to fire weather in western Canada. Global Biogeochemical Cycles 18, GB4014, doi:10.1029/2004GB002222.

Vestgarden, L.S., Austnes, K., 2009. Effects of freeze–thaw on C and N release from soils below different vegetation in a montane system: a laboratory experiment. Global Change Biology, 15, 876–887.

Wallage, Z.E., Holden, J., 2010. Spatial and temporal variability in the relationship between water colour and dissolved organic carbon concentrations in blanket peat pore waters. Science of the Total Environment, 408, 6235-6242.

Wallage, Z.E., Holden, J., McDonald, A.T., 2006. Drain blocking is an effective treatment for reducing dissolved organic carbon loss and water colour in peatlands. Science of the Total Environment, 367, 811-821.

Ward, S.E., Bardgett, R.D., McNamara, N.P., Adamson, J.K., Ostle, N.J., 2007. Long-term consequences of grazing and burning on northern peatland carbon dynamics. Ecosystems, doi: 10.1007/s10021-007-9080-5.

White, S., Yallop, A.R., Thacker, J. and Clutterbuck, B., 2007. Control of water quality from upland catchments. Report to Yorkshire Water, Cranfield University, Cranfield.

Wickland, K.P., Neff, J.C., Aiken, G.R., 2007. Dissolved organic carbon in Alaskan boreal forest: sources, chemical characteristics, and biodegradability. Ecosystems, 10, 1323-1340.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., Morris, M., 2011. Ditch blocking, water chemistry and organic carbon flux: evidence that blanket bog restoration reduces erosion and fluvial carbon loss. Science of the Total Environment, 409, 2010-2018.

Worrall F, Burt T, Shedden R., 2003. Long term records of riverine carbon flux. Biogeochemistry 64, 165–178.

Worrall, F., Armstrong, A., Adamson, J.K., 2007. The effects of burning and sheep-grazing on water table depth and soil water quality in an upland peat. Journal of Hydrology, 339, 1-14.

Worrall, F., Adamson, J.K., 2008. The effect of burning and sheep grazing on soil water composition in a blanket bog: evidence for soil structural changes? Hydrological Processes, 22, 2531-2541.

Worrall, F., Clay, G., Marrs, R., Reed, M., 2010. Impacts of moorland burning management on peatlands. Review for the IUCN UK Peatland Programme Commission of Inquiry.

Yallop, A.R., Thacker, J.I., Thomas, G., Stephens, M., Clutterbuck, B., Brewer, T., Sannier, C.A.D., 2006. The extent and intensity of management burning in the English uplands. Journal of Applied Ecology, doi: 10.1111/j.1365-2664.2006.01222.x.

Yallop, A.R., White, S.M., Clutterbuck, B., 2008. Evidence for a mechanism driving recent observed trends in dissolved organic carbon release from upland peat soils. Aspects of Applied Biology, 85, 127-132.

Yallop, A.R., Clutterbuck, B., 2009. Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. Science of the Total Environment, 407, 3803-3813.

Yallop, A.R., Clutterbuck, B., Thacker, J., 2010. Increases in humic dissolved organic carbon export from upland peat catchments: the role of temperature, declining sulphur deposition and changes in land management. Climate Research, 45, 43-56. doi 10.3354/cr00884.

Table 1. Summary of scale of work, sites used and methods adopted in moorland burning water quality studies.

Authors	Burning impact colour in runoff?	Burning impact colour in soil water?	Burning impact other water quality?	Scale	Study site(s)	Methods used	Key findings/issues
Allen (1964)			No (soil water)	Lab experiments	Kirkby Moor, Ulverston (peat, clay) & Moor House (blanket peat)	Measured K, Ca, Mg, P & N. Burned heather; top of the soil not subject to heating; ash added to soil & water sprinkled on top, collected leachate. Compared different temperatures & fresh/partially decomposed (unburnt heather).	Leaching from heather ash of K, Mg, Ca, P > than from decomposing or fresh heather (most N lost in the fire to the atmosphere). No impact of burning on nutrient release through soil (except for Ca). Higher pH in upper soil after application & leaching of heather ash. No colour or DOC measured. No measurement over long time scales after burning.
Allen et al (1969)			No (soil water)	Lab & field block experiments	7 sites across UK, shallow peat (<15cm) heaths	Heather ash applied to soil blocks. Exposed soil burnt too. Soil samples taken for up to a year afterwards.	Blanket peat not studied. Most nutrients leached from burnt material were held within upper peat layer. Only downward movement of nutrients in sandy soils. No surface runoff/erosion measured.
McDonald et al (1991) including the related PhD thesis by Martin (1992)	Yes	Yes	Yes	Lab experiments & catchments	N. England with a focus on Upper Nidd, Burn & Washburn	Cores compared between burnt/unburnt peat using lab leaching. Burn temperature expts, field cores taken from hot & cool burn sites. Impacts of drying & wetting periods on burn / unburnt cores tested. Stream data used.	Higher colour leached from burnt peat cores. Apparently hotter burns = more colour. Implied that as burn patches revegetate the colour production is likely to decline. Catchment sampling statistical analysis suggested burning was very likely a factor for colour.
Mitchell & McDonald (1995)	Yes (not directly shown)			45 streams in one catchment	River Burn, North Yorks	14 grab samples over one year from each of 45 points. Absorbance at 400nm.	Highest colour in catchments with drainage & burning but no direct statistical evidence presented of colour & burning link
Forgeard & Frenot (1996)			No (soil water)	Lab experiments	Britanny heathlands. Not peat.	Successive exposure to hot temperatures. Ash & water applied to soil blocks – soil & leachate measured.	Heating = less SOM in uppermost layer at hottest temperature (300°C). No 'organic matter movement' during water percolation. Increased pH of upper soil with burn. No change in leached Na, K with fire, significant decrease in Ca & Mg concentrations in soils.
Pilkington et al (2007)			Yes (N in soil water leached out)	Small plots	Ruabon Moor, N. Wales Iron-pan stagnopodzol, 8cm peaty layer	N additions at 4 different levels to plots before a burn & measure N leaching before & after the burn. Lysimeters to measure leachate	Burning encouraged leaching of N. More leaching where more N added in rainwater in the year before burning. N leaching continued at enhanced rate for at least two years after a burn.
O'Brien et al (2007)	No			Catchment	River Ashop (Derbyshire) – blanket peat	Samples from treatment & control sites. 14 months pre treatment data. 4 yrs data. Discharge, pH & conductivity logged. Water tables sampled. Burn areas	No statistical difference between control & treatment (stopping burning). Stopping burning appeared to cause a statistical rise in water table when compared to control. Suggestion of colour flush during the 'recovery' phase, not

						relatively new.	enough data to confirm
Worrall et al (2007)		Yes (decrease)		Plot	Hard Hill (Moor House)	Soil water sampled down entire length (0-90cm) of dipwells. Samples biweekly during summer 2005 from each dipwell (3 per plot, 12 plots).	Water table depth shallower where burning occurred. Burning decreased pH & conductivity of soil water. DOC concentration & colour of soil water was less where burning occurred. Work carried out 9 years since the last burn.
Ward et al. (2007)		No		Plot	Hard Hill (Moor House)	Pore water sampling from 10 cm & 50 cm depth monthly for 1 yr; suction samplers.	No impact of burning on soil water DOC. Site was 8 years into a 10 year burn cycle.
Grayson et al (2008)	Yes (burnt area & colour strongly related)			Catchment	YW catchments	Land cover, air photos & water treatment works colour data with other variables. Regression & modelling approach	Heather burning & vegetation type were two most important variables; other variables had significant impact including extent of peat, drainage & rainfall. Study catchments had limited drainage which may be more important at other sites.
Worrall & Adamson (2008)			Yes (soil water)	Plot	Hard Hill (Moor House)	Integrated soil water samples from 0-90 cm. Collected 18 times over 1 yr from each dipwell (3 per plot, 12 plots).	Ca, Na, Mg & P concentrations lower, Al higher in burnt soil water.
Miller (2008)		Yes		Lab experiments	Peat samples used	Lab leaching experiments & different temperature/drying cycles applied	Burning associated with increase in colour compared with vegetated soil, but little effect on DOC composition. Investigated accidental summer burn; may not be applicable to prescribed burning.
Beharry-Borg et al (2009)	Yes (composition)			Catchment	Nidderdale AONB	Bi-weekly stream sampling over 1 yr from 27 points. Colour & DOC measured.	Heather cover strongly associated with higher DOC/colour, % heather cover positively correlated with DOC concentration in main river channels. Burning affected DOC composition.
Clay et al (2009a)				Plot	Hard Hill (Moor House)	Overland flow traps, water table. Monitored before/after 10 yr burn.	Shallower water table & more overland flow on burnt plots. In the year after a burn, water tables shallower than before.
Clay et al (2009b)	Yes (decrease, but in overland flow at plot scale)	Yes (decrease in colour but not DOC)		Plot	Hard Hill (Moor House)	Integrated soil water samples from 0-90 cm, monthly. DOC, colour & water table depth. Monitored before burn, plot burnt 10 yrs earlier) & one year after. Compared to non burn controls.	Immediately after burn there were short-lived peaks in colour & DOC in soil water compared to unburnt. Overall concentration & composition of DOC not affected.
Yallop & Clutterbuck (2009)	Yes (increase with recent burn)			Regional	South Pennines & North York Moors –from peat to heath,.	50 catchments – sampled four times in a year (but all in the winter half year Nov-March) for DOC. 8 long term colour treatment works records. Burn age/class split into four groups. Class 1 is exposed peat.	Proportion of 'class 1' burn area (mean duration is 3.8 years) significantly positively correlated with colour. Significant in Pennines, not in North York Moors (but little blanket peat in tested NYM catchments). New burn area explains >60% of spatial difference in DOC concentrations in Pennines.
Chapman et al (2010)	No			Catchment	Nidd	15 subcatchments sampled over a year in 1986 & 2006/7 for colour	No relationship between % of area burnt & colour or increase in colour. Focus of work not on burning.

Clay et al (2010)			Yes (soil water)	Plot	Hard Hill (Moor House)	Before & after burn & burn vs no burn. Integrated soil water samples from 0-90 cm, monthly. Measured Al, Fe, Ca, Mg, K, Na, Si, F, Cl, Br, NO_3, PO_4, SO_4, pH, conductivity, overland flow.	Burning lowers concentration of Ca, Mg, PO_4 & Na in soil water & increases Al & Fe in overland flow. Immediately after burn Al, Fe & Na increase in soil water & Ca, Cl & Br decrease.
Yallop et al (2010)	Yes (increase with recent burn)			Catchment	Agden, Broomhead & Langsett	Long term colour records to determine hDOC. Estimated discharge in 3 study catchments. Burn class from photos.	Rising colour concentrations = rising export. Increase in recent burn area correlated with estimated increase in hDOC export. New burn area increased since 1970s. Recent burn estimated to produce 5-15 times hDOC export than revegetated areas.
Ramchunder (2010)	Yes (pattern of DOC production during storms)		Yes (river sediment and invertebrates)	Catchment	3 burnt & 3 unburnt catchments, Pennines, all blanket peat	Water quality (cations, anions, sediment, DOC, temperature) & invertebrate sampling every quarter, five times, 6 catchments with more intensive sampling in two catchments.	Prescribed burning impacts peatland stream ecology. Sediment from burning linked to changes in species composition.
Helliwell et al (2010)		Yes (decrease)	Yes (decrease in soil water)	Plots	Coarse pozdols with thin (10cm) organic horizon	Nitrate additions & burning. Soil solution chemistry collected in zero-tension lysimeters installed below shallow surface horizon.	Lower DOC in mineral soil solutions 9 months after burning (not measured immediately post-burn). Decreases in Na, K, Al & Cl in burned plots. No effect of added N on DOC & no interaction between burning & N addition. No significant trend in DOC during 6 years post burning.
Clutterbuck & Yallop (2010)	Yes (increase with recent burn)			Catchment	Trout Beck, Agden, Broomhead, Langsett, Lower Laith, Keighley	Weekly DOC record for Trout Beck, colour record for other sites from treatment works. Burn class from air photos.	hDOC rose with increased area of new burn for four catchments over time. Where burns were not significant catchment features (Trout Beck & Sladen Valley) no significant colour increase. ~80% of recent rise in stream water hDOC related to burn management.

Table 2. The change in percentage of catchment covered in class 1 burn between 1990 and 2005 and associated change in hDOC concentration in five reservoir catchments (data from Clutterbuck and Yallop, 2010).

Reservoir catchment	1990 Class 1 burn (% of catchment)	2005 Class 1 burn (% of catchment)	hDOC (mg L^{-1} in 1990)	hDOC * (mg L^{-1} in 2005)
Lower Laithe	0	0.1	5.0	6.0 (5.8)
Keighley Moor	2	8	4.0	9.0 (8.0)
Agden	3.5	7.5	5.5	8.5 (7.9)
Broomhead	2	13	6.5	11 (10.1)
Langsett	4	7	6	11 (10)

*Value in brackets represents hDOC value assuming 80% of increase in hDOC is accounted for by increase in area of class 1 burn.

Table 3. The hDOC concentration originating from each 1% class 1 burn area (x) in a catchment and each 1% class 2-4 heather and other vegetation types (y).

Reservoir catchment	hDOC from 1% of class 1 burn (mg L^{-1})	hDOC from 1% of non class 1 burn (mg L^{-1})	% hDOC from class 1 burn relative to DOC generated by remainder of catchment
Lower Laithe	8.05	0.05	161
Keighley Moor	0.605	0.034	17.6
Agden	0.636	0.034	18.8
Broomhead	0.362	0.062	5.8
Langsett	1.34	0.0067	201

Figure captions

Figure 1. Hard Hill plot design installed in 1954 on which a number of the papers on burning and water colour have been based. Each square plot is 30 m x 30 m within a rectangular block of six plots. It should be noted that all of the water quality papers mentioned in the text or Table 1 that have worked on the site only use block 1 and 2 in the design except for Ward et al (2007).