Reviews and Syntheses: Understanding the impacts of peatland catchment management on DOM concentration and treatability

Jennifer Williamson[1*], Chris Evans[1], Bryan Spears[2], Amy Pickard[2], Pippa J. Chapman[3], Heidrun Feuchtmayr[4], Fraser Leith[5], Susan Waldron[6], Don Monteith[4]

[1]UK Centre for Ecology & Hydrology, Environment Centre Wales, Deiniol Road, Bangor, Gwynedd, LL57 2UW

[2]UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB

[3] School of Geography, Faculty of Environment, University of Leeds, Leeds, LS2 9JT

[4]UK Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP

[5]Scottish Water, 6 Castle Drive, Dunfermline, KY11 8GG

[6]School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ

[*]*Corresponding Author* (jwl@ceh.ac.uk)

Abstract

In the UK, most large reservoirs constructed for public water supply are in upland areas and situated in catchments characterised by organic-rich soils, including peatlands, that are often in poor condition. Such catchments leach large amounts of dissolved organic matter (DOM) to water, with water draining peatlands tending to release the most. High and rising DOM concentrations in these regions raise treatment challenges for the water industry.

In the UK, water companies are increasingly considering whether upland catchment peat restoration measures can slow down or even reverse rising source water DOM concentrations and thus reduce the need for more costly and complex engineering solutions. There remains considerable uncertainty around the efficacy of such measures, and a comprehensive overview of the research in this area remains lacking. Here we review the peer-reviewed evidence for the effectiveness of four catchment management options in controlling DOM release from peat soils: ditch blocking, revegetation, reducing forest cover, and cessation of managed burning.

Results of plot scale investigations into effects of ditch blocking on DOM leaching are currently largely equivocal, while there is a paucity of information regarding impacts at spatial scales of more direct relevance to water managers. There is some, although limited evidence that terrestrial vegetation type may influence DOM concentrations and treatability. The presence of plantation forestry on peat soils is generally associated with elevated DOM concentrations, although reducing forest cover has little short-term benefit and can even exacerbate concentrations further.

Catchment management measures have rarely been monitored with downstream water quality as the focus. To mitigate the uncertainty surrounding restoration effects on DOM, measures should be undertaken on a site-specific basis, where the scale, effect size and duration of the intervention are considered in relation to subsequent biogeochemical processing that occurs in the reservoir, the treatment capacity of the water treatment works and future projected DOM trends.

Introduction

Peatland restoration has become an integral part of the UK environment strategy, particularly in the drive toward Net Zero (Hm Government, 2021). It is founded on the potential to achieve multiple benefits that include improving biodiversity, enhancing carbon sequestration, and controlling water runoff and quality, in catchments that are deemed to have been degraded by anthropogenic stressors. Nearly three quarters of the storage capacity of drinking water reservoirs in the UK is sourced from peatland areas (Xu et al., 2018). Peatlands release particularly high amounts of organic matter as dissolved organic matter (DOM) into drainage waters, and DOM concentrations have been rising since the 1980s (e.g. Naden and Mcdonald, 1989; Robson and Neal, 1996; Harriman et al., 2001; Freeman et al., 2001; Worrall et al., 2004). Mean DOM concentrations in UK Upland Waters Monitoring Network (UWMN) surface waters, most of which are dominated by organic-rich soils, have approximately doubled over the last three decades (Figure 1). At the sub-catchment scale, Chapman et al. (2010) found that water colour increased by between 22 and 155 percent over a 20 year period between 1986 and 2006. This phenomenon has now been observed across much of industrialised North America and north-west Europe, and appears to result largely from an long-term increase in the solubility of terrestrial organic matter as soils recover from the effects of acid rain (Monteith et al., 2007; De Wit et al., 2021; Monteith et al., 2023). One consequence of these changes is that water treatment works in some regions are having to adjust to much higher source water DOM concentrations than they were originally designed to cope with, since most were built at a time of much higher atmospheric deposition. Atmospheric deposition of pollutants across the UK uplands has now declined to a very low level, and it is expected that in future, changes in DOM export will be increasingly affected by other factors including temperature, changes in precipitation seasonality and intensity and marine ion deposition (Monteith et al., 2023). Rising levels of DOM in waters draining many of these peatland catchments pose considerable water treatment challenges, with respect to increasing treatment costs and risks of regulatory failure (see Figure 1). It has been proposed that peatland restoration measures might help slow or even reverse these DOM trends, along with other important benefits including increased terrestrial carbon storage, water retention and improvements in upland biodiversity (e.g. Glenk and Martin-Ortega, 2018).

Although consumption of DOM in drinking water is not directly harmful to people, coloured water reduces customer satisfaction (Ritson et al., 2014) and can be indicative of further problems. Indirectly, elevated DOM concentrations have implications for human health due to their potential influence on treatment processes and the production of carcinogenic disinfectant by-products (DBPs) such as trihalomethanes (THMs) during chemical disinfection, which are regulated by the Drinking Water Inspectorate due to their potential carcinogenic properties (Ding and Chu 2017). DOM also may hamper the efficacy of chlorine as a disinfectant while simultaneously acting as a substrate for bacterial regrowth (Prest et al., 2016), thus increasing the risk of regulatory failure from bacterial contamination and the subsequent loss of customer trust.

The composition of DOM can have a large influence on the performance of the water treatment processes and the formation of DBPs upon chlorination (Matilainen et al., 2010). DOM in water draining peatland areas tends to be predominantly hydrophobic, and relatively photoreactive and biologically recalcitrant. It is relatively easily removed by conventional coagulation and filtration during drinking water treatment due to the presence of charged functional groups (Matilainen et al., 2010). Hydrophilic DOM, on the other hand, is mostly produced within the waterbodies by phytoplankton (Imai et al., 2002), and is biologically labile but less easily degraded by sunlight

(Berggren and Del Giorgio, 2015; Berggren et al., 2018). The relative balance of hydrophobic to hydrophilic DOM in water is referred to as hydrophobicity, and is conventionally assessed in the water treatment system using Specific UV Absorbance measurements at 254 nm ($SUVA_{254}$), i.e. absorbance at 254 nm per unit dissolved organic carbon concentration (Weishaar et al., 2003). Values greater than 4 L mg^{-1} m^{-1} indicate hydrophobic dominance, while values less than 2 L mg^{-1} m^{-1} show the DOM is primarily hydrophilic and will not be effectively removed using conventional coagulation and filtration alone (Matilainen et al., 2010).

Higher concentrations of DOM in raw water necessitate a greater amount of treatment to provide potable water to customers (Monteith et al., 2021). This may include larger coagulant dosages, shorter filter run times, and longer and more frequent cleaning of filtration units, and result in higher energy costs, higher sludge removal costs and an increase in direct and indirect (energy-related) greenhouse gas (GHG) emissions from the treatment process (Jones et al., 2016). Major additional costs are incurred where capital investment is needed to upgrade treatment infrastructure designed for lower concentration ranges experienced in the past (Monteith et al., 2021).

Peatland restoration (physical interventions to return them to a more natural state i.e. high water table and active peat-forming vegetation) has been suggested as a catchment scale method for reducing DOM concentrations in water draining peatlands (IUCN Peatland Programme). The primary restoration methods undertaken to date in the UK uplands are: blocking of peatland drainage to raise the water table, revegetation of bare peat with peatland species, removal of plantation forestry to allow peatland species to recolonise and water tables to rise, and cessation of managed burning to encourage growth of peatland plant species (Figure 2) (IUCN Peatland Programme). It is important, therefore, for water industry decision makers to understand the extent to which peatland restoration could make a positive contribution to reducing DOM concentrations of raw water and thus relieve stresses on the treatment system and potentially remove the need for major additional capital investment in treatment plant. This work reviews the available peer-reviewed literature and provides an assessment of the impacts of peatland restoration on DOM concentrations and treatability of raw drinking water.

2. Evidence for the efficacy of catchment management approaches in the reduction of DOM

To answer the question "will peatland catchment management reduce DOM concentrations in raw water" we explored the evidence within the peer-reviewed scientific literature for catchment management approaches within peatland dominated drinking water catchments to influence DOM concentrations in the soils and waters of peatland catchments. This was achieved by applying a standard set of Boolean search terms within Web of Science and Google Scholar. The terms were: ("dissolved organic matter" OR "dissolved organic carbon" OR "DOM" OR "DOC" OR "colour") AND ("peatland" OR "bog" OR "fen" OR "moor") AND ("ditch blocking" OR "forest" OR "plantation" OR "managed burning"). Initial results, including titles and abstracts, were rapidly reviewed to determine whether the information within the papers was relevant, both in terms of subject matter and in region (limited to temperate peatlands), then relevant papers were read in full and included in the review.

2.1. Ditch blocking

Extensive areas of upland peatlands across the UK uplands were drained in the mid-20th century in an attempt to increase agricultural productivity. Peatland drainage reduces water tables, resulting in a loss of peat forming plant species. The consequent drying and cracking of peat surfaces exposes previously permanently saturated organic matter to oxidative processes, making them more vulnerable to erosion and dissolution into DOM (e.g. Clark et al., 2009). Extensive efforts have been made by the water industry and organisations concerned with peatland conservation to block ditches in an attempt to restore the hydrological, biogeochemical and ecological functions of these landscapes (IUCN Peatland Programme 2023) (Figures 2 & 3).

Search results of the scientific literature showed that the impact of ditch blocking on DOM concentrations had been assessed in pore waters and in ditches at streams at the sites being restored. Of the five plot-scale studies of peat soil water identified during this review, four (Table 1) reported significant changes in DOM concentrations . The studies investigated effects between five and twenty years following ditch blocking, and reported a cross-study average 34% reduction in DOC concentration (range 0 to 69%) (Wallage et al., 2006; Holl et al., 2009; Haapalehto et al., 2014; Strack et al., 2015; Menberu et al., 2017). While therefore suggesting a general tendency for ditch blocking to reduce pore water DOM concentrations, these studies do not necessarily imply that effects will be translated through to surface waters and ultimately to the point of abstraction.

Changes observed in DOM concentrations at a drainage ditch scale, are more variable than those for pore waters (Table 1, Figure 3). The eleven studies reviewed showed a mean 8% increase in DOM concentrations following ditch blocking, although this figure is skewed by the large increases reported by Worrall et al. (2007b) and Haapalehto et al. (2014) (100% increase immediately following ditch blocking and 50-75% increases after ten and five years respectively); the median change is zero. Importantly, no significant change in DOM concentration was reported in over half of these studies (O'brien et al., 2008; Gibson et al., 2009; Armstrong et al., 2010; Wilson et al., 2011; Evans et al., 2018; Pickard et al., 2022). Likewise, a recent study found no reduction in DOM concentrations in the restored site compared to the ditched site six years after ditch blocking, while both drained and restored site DOM concentrations remained elevated compared to the non-drained control (Pickard et al., 2022). Differences between studies in apparent effect size may in part be related to experimental design, including whether the work included a simultaneous control and the time period over which post-restoration monitoring was carried out.

Studies of DOM flux changes following ditch blocking report an average 24% reduction (range 0 – 88% reduction) in DOM flux, primarily attributed to decreased water fluxes from the restoration site. However, the measurement and reporting of water fluxes (and hence DOM fluxes) at a site- or catchment-scale requires careful consideration of the potential for dominant water flow pathways to be altered following ditch blocking. For example, Holden et al. (2017) showed that damming of drainage ditches in North Wales reduced discharge along the original ditch lines, but that most, or all, of the displaced flow instead left the peatland via overland flow or near-surface through-flow. Subsequent reporting from the same experiment demonstrated that DOM concentrations in water displaced along these surficial pathways were approximately the same as those in water travelling along the ditches, with the result that ditch-blocking was not found to have any clear effect on either DOM concentrations or fluxes at the catchment scale (Evans et al., 2018).

We identified nine studies that have assessed the potential impact of ditch blocking on DOM treatability and hence the ease of treatability within a conventional water treatment works. The majority of studies at UK and continental European ditch blocking locations, along with results from their experimental work, showed little effect of ditch blocking on DOM treatability as measured by commonly reported metrics such as SUVA, E2:E3 ratios (ratio of light absorbance at 250 and 365 nm) and E4:E6 ratios (ratio of light absorbance at 465 and 665 nm) (Glatzel et al., 2003; Strack et al., 2015; Gough et al., 2016; Lundin et al., 2017; Peacock et al., 2018). While none of the studies included direct measures of DOM hydrophobic and hydrophilic fractions, one measured THM formation potential and found no change between water samples taken from drained and rewetted blanket bog mesocosms (Gough et al., 2016), suggesting that in the short term ditch blocking may not reduce THM formation following water treatment.

More broadly, therefore, while the evidence suggests that ditch blocking may reduce DOM concentrations within pore waters (Table 3, Figure 3), there is no published evidence for such activities to have successfully influenced DOM concentrations in runoff at a catchment scale, and thus at a level of potential relevance to raw water supply to treatment works. It is important to note, however, that catchment-scale studies are hugely challenging logistically and financially to design and maintain.

2.2. Revegetation of bare peat

Exposure of bare peat following anthropogenic disturbance has been an extensive problem in a number of UK peatland regions, most notably in the Peak District (Pilkington et al., 2015). The subsequent erosion of the peat has caused significant problems for the water industry because of the high particulate loads from the catchment to the downstream reservoirs. There have been significant efforts in recent years to revegetate some of the most degraded upland peatland areas in order to stabilise these systems (Pilkington et al., 2015).

Published research on the impacts of revegetation of peatland areas on DOM is limited, but Qassim et al. (2014) found that pore water DOM concentrations were higher in revegetated sites compared to bare peat areas and vegetated controls over a five-year period. The initial revegetation mix in this work was a nurse crop of *Agrostis* sp., *Deschampsia flexuosa* and *Festuca* sp. applied in combination with additions of lime and fertiliser to ensure grass growth. Heather brash was also applied to stabilise the peat surface and provide a seed source of peatland species. The use of lime is likely to have increased DOM solubility through a reduction in acidity of the peat (Evans et al., 2012), and the re-establishment of vegetation may have increased the production of 'new' DOM via root leachate and fresh litter decomposition. Particulate losses from peatland systems decreased following stabilisation of the peat surface through revegetation irrespective of gully blocking activities (Pilkington et al., 2015), as overland flow velocities are lower on vegetated peat than bare peat (Holden et al., 2008). However, the same study (Pilkington et al., 2015), and more recent assessments of the effects of revegetation on DOM concentrations (Stimson et al., 2017; Alderson et al., 2019), found no long-term changes in DOM concentrations following revegetation at the headwater catchment scale.

Radiocarbon (^{14}C) measurements of DOM in UK upland waters indicate that the principal source of DOM in waters draining relatively undisturbed soils is recent primary production, probably formed within the last few years (Evans et al., 2014). It follows, therefore, that plant productivity, and plant tissue composition and degradability, which depend both on ambient environmental conditions and species composition, may be important factors, both for DOM concentrations and the treatability of the DOM produced. In a laboratory-based extraction experiment, DOM leached from *Sphagnum* was more easily removed by a conventional coagulation process and decomposed more rapidly than DOM leached from *Molinia caerulea* or *Calluna vulgaris* litter. In addition, *M. caerulea* and *C. vulgaris* litter released more DOM per unit dry weight compared to Sphagnum litter (Ritson et al., 2016). At the field scale, published results are less clear cut: one study found that DOM concentrations in pore waters were higher in areas of blanket bog dominated by *C. vulgaris* compared to areas dominated by sedges or Sphagnum species (Armstrong et al., 2012). In contrast, Parry et al. (2015) found no correlation between dominant vegetation type (differentiated into ericoids, grasses, sedges and bare peat) and stream water DOM concentrations in headwater catchments. This may reflect the greater biotic heterogeneity of peatland environments at the catchment scale in comparison to single species experiments.

The evidence available to date suggests that while revegetation of peatland sites has stabilised bare peat surfaces (e.g. Pilkington et al., 2015), and is likely to have reduced particulate organic matter loss, it has not changed DOM export from peat headwater catchments. Laboratory based work has shown that the species present could impact DOM treatability, with *Sphagnum* derived DOM being more easily treatable that *M. caerulea* or *C. vulgaris* litter (Ritson et al., 2016). This suggests that catchment management via revegetation should aim to achieve high cover of *Sphagnum* species compared to vascular plants to maximise DOM treatability (Table 3).

2.3. Plantation forestry / deforestation

It has long been recognised that forestry activities can have detrimental impacts on reservoir water quality and treatability. For example, in 1984 it was shown that drainage and deforestation resulted in large sedimentation issues at Crai Reservoir in south Wales (Stretton, 1984 cited in: Hudson et al. 1997), while large pulses of nutrients (N and P) to upland streams were observed after forest-felling (Neal, 2002). This review covers the impact of ground preparation and forest planting, in-situ forest growth, and forest removal (including forest to bog restoration) on peat on DOM concentration and quality.

To reduce the impacts of forest operations on sediment and nutrient loss and consequent raw water quality in the UK, the Forest and Water Guidelines now state that no more than 20% of a drinking water catchment should be felled in any 3 year period (Forestry Commission, 2017). In addition to this, although primarily to conserve soil carbon stocks rather than for improved water quality, the 2000 Forestry Commission guidance note on forest and peatland habitats (Patterson and Anderson, 2000) states that approval will no longer be given for forestry planting or regeneration on active raised bog or inactive raised bogs that could be restored to active bog, and areas of active blanket bog greater than 25 ha area and > 45 – 50 cm depth.

A recent review for Yorkshire Water (Chapman et al., 2017) noted that conventional conifer site preparation on peat, peaty gley and peaty podzol soils would be expected to increase DOM concentrations. This would be largely due to the implemented drainage reducing the height of the water table and consequently increasing the production of DOM via increased aeration of the peat surface (Clark et al., 2009). Jandl et al. (2007), in their review of studies of the effect of forest management on soil carbon sequestration, highlighted two Finnish studies where DOM concentrations increased following drainage ditch installation but returned to pre-drainage levels later in the forest cycle, while Schelker et al. (2012) observed increased colour in sites being prepared for forestry in northern Sweden. Furthermore, Rask et al. (1998) reported an increase in colour in streams draining peat dominated catchments following afforestation in Finland, while in Sweden afforestation has also been linked to long-term increases in water colour (Skerlep et al., 2019). At a regional to national scale in the UK, recent work suggests that the presence of plantation forestry on peat soils is associated with higher DOM concentrations in streams and rivers compared to peat soils supporting semi-natural vegetation (Williamson et al., 2021).

The presence of conifers on peat soils in a UK and Irish context is associated with higher pore water DOM concentrations across the four studies covered in this review (Table 2), with a mean difference of approximately 130%. The exception to this pattern was found in spruce plantations in north Wales where DOM concentrations in pore waters were 19% lower than in adjacent blanket bog (Gough et al., 2012). We found only one study (Gaffney et al., 2018) that compared DOM concentrations in drainage ditches between forested and intact blanket bog areas, with DOM concentrations approximately 100% higher in the former. The presence of forestry on peat had less clear cut impacts on streamwater DOM concentrations, with two out of three studies reporting no significant difference between streams draining catchments with forestry and intact blanket bogs (Shah et al., 2021; Flynn et al., 2022), and the third showing an DOM concentrations approximately 25% higher in a stream draining a forested catchment compared to a blanket bog catchment (Cummins and Farrell, 2003).

Tree felling tends to cause an increase in DOM, though the effects are not universal across studies and locations. Three of five studies of streamwater DOM concentrations reported increases following felling (Cummins and Farrell, 2003; Zheng et al., 2018; Shah and Nisbet, 2019), with a mean increase of approximately 43%, although the two studies in the Flow Country showed no change (Muller et al., 2015) and a 6% decrease in concentrations (Muller and Tankere-Muller, 2012), which was attributed to the success of buffer strips between the plantation and the monitored stream. The mean increase in DOM concentrations in ditches was nearly 200% (ranging from a 50% increase to a 500% increase, see Table 2) (Cummins and Farrell, 2003; Muller and Tankere-Muller, 2012; Muller et al., 2015; Gaffney et al., 2018). Most studies measuring DOM concentrations from forestry on peat were relatively short-term in timeframe, lasting two years or shorter. Only two studies monitored DOM concentrations for five years or longer.

There has been comparatively little research on the effects of forest presence on the treatability of DOM, although Gough et al. (2012) evaluated DOM concentrations and $SUVA_{254}$ values in waters draining catchments forested with different tree species. They found that pore water leachates from pine and larch plantation yielded particularly high DOM concentrations relative to a blanket bog control (19 and 13 mg L^{-1}, respectively, compared to 9 mg L^{-1}). Leachates also had lower $SUVA_{254}$ values (1.2 and 2.4 respectively, compared to 3.3 L mg^{-1} m^{-1}). This would suggest that DOM leaching from plantations dominated by these tree types may be less easily treatable than DOM from blanket bogs. Similarly, samples taken from Scottish blanket and raised bog sites (Howson et al., 2021) found that $SUVA_{254}$ values were lower from forested sites, again suggesting that forestry on peat results in less aromatic, hydrophobic DOM that may be less easily removed via conventional coagulation.

Recently there have been attempts to restore previously afforested fen and bog peatlands in parts of Europe and North America under what is often referred to as ‘forest-to-bog’ restoration (Chimner et al., 2017; Andersen et al., 2017). Although still a relatively new practice within the UK, this type of restoration has been carried out for 18 years in the Flow Country in northern Scotland, and national policies on peat restoration may lead to its expansion in the future. Some of the studies listed in Table 2 (Muller and Tankere-Muller, 2012; Muller et al., 2015; Gaffney et al., 2018; Shah and Nisbet, 2019; Gaffney et al., 2020; Howson et al., 2021; Shah et al., 2021) monitored the impacts of felling as part of ongoing forest-to-bog restoration monitoring, with the main differences in management being that the trees were felled to waste (the practice of leaving felled trees *in-situ* to rot) and there was less ground disturbance at the site compared with the use of machinery to extract felled timber (Gaffney, 2017). However, the practice of felling trees to waste has been suggested to provide a potential additional DOM source as the trees slowly decompose (Muller et al., 2015), with mulched fallen trees providing a major source of water soluble DOM (Howson et al., 2021).

As bog vegetation regenerated after such restoration in the Flow Country, DOM concentrations reduced from elevated levels towards those seen in forest control areas. The time frame for complete recovery to pre-intervention levels is to date inconsistent, with some areas still showing elevated DOM in the restoration sites relative to the control sites after 17 years (Gaffney et al., 2018). In others, DOM concentrations had returned to those seen in intact blanket bog within the same time frame (Howson et al., 2021), or were showing inconsistent effects across sub-catchments, with the most upstream catchments showing increased DOM concentrations compared to bog controls, an effect not seen further downstream (Pickard et al., 2022). Other studies have reported shorter-term perturbations in DOM (~4-5 years) following forest-to-bog restoration, including within a Scottish lowland raised bog area, Flanders Moss, where stream water baseline DOM levels were reached within two years at one site (Shah, 2018). In a Finnish study of the impacts of forest to mire restoration, a short-term peak in pore water DOM concentration following initial restoration activity was followed by a return to reference concentrations within six years (Menberu et al., 2017).

In summary, coniferous afforestation of peatlands increases DOM concentrations in pore waters and streams, both during site establishment, potentially during the forest growth, and again as the trees are felled (by up to 500%) (summarised in Table 3). Forest-to-bog restoration as a method of land management produces short-term increases in DOM concentrations while trees are felled and brash remaining on site decomposes. However, given a long enough timeframe, DOM concentrations appear to reduce back towards levels seen from comparable control locations. From a water company perspective it is important to note that this time frame can be up to 20 years in blanket bogs, i.e. considerably longer than the standard funding cycle.

2.4. Managed burning

Managed burning of peatland vegetation (Figures 2 & 5) (primarily the burning of *Calluna* sp. as part of grouse moor management) is a contentious issue within peatland conservation and management (e.g. Davies et al., 2016) and has been extensively reviewed over the past decade, particularly in relation to the impacts on DOM (Worrall et al., 2010; Holden et al., 2012; e.g. Brown et al., 2015), and most recently by Harper et al. (2018). There is little evidence within these reviews to suggest that DOM concentrations or colour increase within peat pore waters following managed burns. A recent study showed no change in DOM concentrations following low and high intensity burning (Grau-Andres et al., 2019), and in previous studies pore water DOM concentrations were unchanged (Clay et al., 2009; Clay et al., 2012; Worrall et al., 2013) or decreased (Worrall et al., 2007a). At the catchment scale, positive correlations between the extent of burning and DOM concentrations and water colour have been interpreted as causal (Clutterbuck and Yallop, 2010; Yallop et al., 2010; Ramchunder et al., 2013) although this has been questioned in the literature (Holden et al., 2012). Burning as a management practice is designed to ensure that there is a mosaic of variously aged heather habitat so it seems plausible that these effects are linked to changes in vegetation cover. As previously discussed *C. vulgaris* produced higher amounts of DOM than *Sphagnum* in the laboratory (Ritson et al., 2016) and at plot scale (Armstrong et al., 2012). It is also worth noting that Evans et al. (2017b) found that a wildfire in Northern Ireland resulted in a temporary reduction of DOM concentrations in a downstream monitoring lake, which was attributed to re-acidification of catchment soils following the fire.

3: Discussion and conclusion

Table 3 summarises the range and extent of the current peer-reviewed evidence for the impacts of peatland restoration on DOM concentrations in raw water and the treatability of the DOM present. However, considerable knowledge gaps remain regarding the effects of peatland restoration on raw water DOM concentrations and treatability. Our thorough screening of the literature revealed remarkably few published studies in this area, to the extent that generalisations of the effects of most of the interventions examined must be taken with considerable caution.

The available literature does indicate that both revegetation of bare peat (particularly to *Sphagnum* dominated bog) and ditch blocking is associated with decreased DOM concentrations within pore waters and ditches at the location restoration occurs. However, and in contrast to much more widely reported positive impacts of these restoration actions with respect to carbon sequestration, soil particulate losses, flood management and upland biodiversity, evidence that such impacts may translate to comparable changes within the wider catchments of more relevance to drinking water resources is generally lacking.

There is arguably much stronger evidence pointing to the risks posed by the afforestation of peatlands, and the subsequent management of such plantations, with plantations felling tending to lead to increasing DOM concentrations and potentially reduced treatability of exported DOM. In the published literature we have been unable to find experimental evidence incorporating local changes in water chemistry in the vicinity of interventions with downstream DOM processing to show whether water quality effects are detectable at the point of abstraction for water treatment works. This extension beyond the plot and hillslope scale represents a significant gap in current understanding, as DOM processing continues within the aquatic environment downstream of peatland restoration sites.

Robust quantification of the impacts of catchment management on DOM concentration and treatability at the point of abstraction clearly represents a major current evidence gap. The size of the research challenge with respect to the necessary spatial and temporal scale and need for robust Before-After-Control Impact (BACI) of any field experiment cannot be underestimated, and perhaps explains in part the current dearth of reliable information. This is particularly pertinent when changes in water chemistry may take a number of years to be seen, depending on catchment dynamics and within reservoir processes. Our review has highlighted that catchment land management approaches have not been followed downstream to monitor their impacts to the wider catchment.

The general paucity of evidence to support widespread terrestrial-catchment focussed interventions specifically to manage source water DOM concentrations and treatability leads then to the question as to whether there are other water quality management options that could be applied within reservoirs. DOM in rivers and lakes is subject to both biotic and abiotic processing, which change both concentrations and chemical structure (e.g. Tranvik et al., 2009) and hence affect treatability. For example DOM is lost to respiration (Koehler et al., 2012; Stets et al., 2010), sedimentation (Einola et al., 2011; Von Wachenfeldt and Tranvik, 2008), photo-oxidisation (via UV radiation) (Moody et al., 2013; Koehler et al., 2014) and flocculation with naturally-occurring aluminium and iron (Mcknight et al., 1992; Koehler et al., 2014).

More importantly for treatability, however, DOM is generated within lakes and reservoirs via photosynthesis (production of algal exudates and release via cell lysis) and through processing of particulate matter (Tranvik et al., 2009) so that DOM concentrations at the point of abstraction from reservoirs represent the sum of these removal and generation processes. Consequently, the resulting DOM tends to be relatively transparent and hydrophilic in comparison with DOM generated by organic rich soils, and thus presents different challenges for treatment, particularly as the hydrophilic DOM is not easily removed through coagulation (Matilainen et al., 2010) and may lead to the need for additional capital investment in order to effectively reduce residual DOM in drinking water.

Algal production, and hence within-reservoir generation of DOM, is often limited by the availability of phosphorus, nitrogen, or both. Hence, waterbodies with high concentrations of inorganic nutrients, either delivered externally from their catchments or re-released internally from sediments, are likely to generate additional DOM within the water column (Feuchtmayr et al., 2019; Evans et al., 2017a). Further, evidence is growing on the importance of lake and reservoir bed sediments as a direct source of DOM to the water column, with reducing conditions occurring during stratification of lakes and reservoirs causing redissolution of previously sedimented organic matter (Peter et al., 2017).

In their assessment of DOM in lake inflows and outflows, including those of several reservoirs, Evans et al. (2017a) concluded that any measures that can reduce N and P export from the catchment or release from sediments, or which can strip nutrients from the water column, could provide effective mitigation for high DOM concentrations by reducing algal DOM production. For example, measures for reducing nutrient loading to lakes from the catchment (Spears and May, 2015) and bed sediments (Spears et al., 2016) can be effective in reducing algal biomass in UK lakes - although the effects on algal DOM production in relation to drinking water treatment require further assessment. To date, this option has rarely been considered in relation to DOM-related treatment issues, although nutrient management is often considered in relation to other (taste and odour) related treatment issues. The available evidence therefore suggests that measures to reduce taste and odour problems could deliver co-benefits in relation to DOM levels.

It is pertinent, therefore, to consider whether measures which reduce in-reservoir DOM production, and/or favour in-reservoir DOM removal, may be as – or perhaps more – effective than measures aimed at reducing DOM export from the terrestrial catchment. For lakes acting as DOM sources, management regimes that reduce nutrient (primarily N and P) inputs from catchments and/or internal loading of nutrients and DOM from sediment to the water column may be more effective than those focussed on reducing inflowing DOM concentrations directly. Restricting nutrient inputs is also likely to reduce organic nitrogen concentrations relative to organic carbon concentrations, which has the added benefit of reducing the formation potential of nitrogenous DBPs. In addition, Birk et al. (2020) suggest that rising DOM loading from the catchment may act to dampen algal responses to nutrients through light limitation of primary production within some European lakes. If, by extension, this also limits in–reservoir DOM production then catchment interventions that relieve DOM load, but not nutrient load, may result in an increase in in-reservoir DOM production. Even in the case of less nutrient-rich water bodies, it appears that reducing N and P loadings would be beneficial for water treatment as this is likely to restrict additional DOM formation.

In summary, our review demonstrates that catchment management initiatives, while providing clear overall restoration benefits for peatlands, have yet to deliver a generalised solution to the challenge of stabilising or reversing DOM increases in drinking water sources, although there is some evidence that catchment interventions may provide benefits for DOM export in specific cases. Catchment management measures that reduce in-reservoir DOM production, or favour in-reservoir DOM removal, may be as or more effective, particularly with respect to more nutrient rich systems. More generally, it seems clear that catchment management should be considered part of the response strategy to rising DOM levels, and as part of a process to improve the resilience of source waters, not a panacea. It is therefore important that the water industry also develops effective tools to predict likely future DOM levels resulting from a combination of large-scale and catchment-scale drivers, to ensure that investments in both catchment management measures and DOM treatment infrastructure are correctly targeted, integrated, timely and cost-effective.

The authors declare that they have no conflict of interests.

The work was conceptualised by DM and CE, funding acquisition was by DM, CE and BS, JW carried out the initial review and wrote the manuscript with contribution from all authors.

Acknowledgements:

We thank staff from Scottish Water, United Utilities, Yorkshire Water, Irish Water and Dŵr Cymru Welsh Water for their informative discussions and comments on early drafts of this manuscript. Discussions with Nadeem Shah and Tom Nisbet regarding work being undertaken by Forest Research are also gratefully acknowledged, as are the comments from 2 reviewers of an earlier draft of this manuscript. The artwork in Figure 2 is by Andy Sier (UKCEH). This work was funded by a NERC Environmental Risks to Infrastructure Innovation Programme grant NE/R009198/1, UKRI SPF UK Climate Resilience programme – Project no. NE/S016937/2, NERC LTSM LOCATE (Land Ocean Carbon Transfer, NE/N018087/1) and Scottish Water.

References

Alderson, D. M., Evans, M. G., Shuttleworth, E. L., Pilkington, M., Spencer, T., Walker, J., and Allott, T. E. H.: Trajectories of ecosystem change in restored blanket peatlands, Sci. Total Environ., 665, 785-796, 10.1016/j.scitotenv.2019.02.095, 2019.

Andersen, R., Farrell, C., Graf, M., Muller, F., Calvar, E., Frankard, P., Caporn, S., and Anderson, P.: An overview of the progress and challenges of peatland restoration in Western Europe, Restoration Ecology, 25, 271-282, https://doi.org/10.1111/rec.12415, 2017.

Armstrong, A., Holden, J., Luxton, K., and Quinton, J. N.: Multi-scale relationship between peatland vegetation type and dissolved organic carbon concentration, Ecological Engineering, 47, 182-188, 10.1016/j.ecoleng.2012.06.027, 2012.

Armstrong, A., Holden, J., Kay, P., Francis, B., Foulger, M., Gledhill, S., McDonald, A. T., and Walker, A.: The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey, J. Hydrol., 381, 112-120, 10.1016/j.jhydrol.2009.11.031, 2010.

Berggren, M. and del Giorgio, P. A.: Distinct patterns of microbial metabolism associated to riverine dissolved organic carbon of different source and quality, J. Geophys. Res.-Biogeosci., 120, 989-999, 10.1002/2015jg002963, 2015.

Berggren, M., Klaus, M., Selvam, B. P., Strom, L., Laudon, H., Jansson, M., and Karlsson, J.: Quality transformation of dissolved organic carbon during water transit through lakes: contrasting controls by photochemical and biological processes, Biogeosciences, 15, 457-470, 10.5194/bg-15-457-2018, 2018.

Birk, S., Chapman, D., Carvalho, L., Spears, B. M., Andersen, H. E., Argillier, C., Auer, S., Baattrup-Pedersen, A., Banin, L., Beklioğlu, M., Bondar-Kunze, E., Borja, A., Branco, P., Bucak, T., Buijse, A. D., Cardoso, A. C., Couture, R.-M., Cremona, F., de Zwart, D., Feld, C. K., Ferreira, M. T., Feuchtmayr, H., Gessner, M. O., Gieswein, A., Globevnik, L., Graeber, D., Graf, W., Gutiérrez-Cánovas, C., Hanganu, J., Işkın, U., Järvinen, M., Jeppesen, E., Kotamäki, N., Kuijper, M., Lemm, J. U., Lu, S., Solheim, A. L., Mischke, U., Moe, S. J., Nõges, P., Nõges, T., Ormerod, S. J., Panagopoulos, Y., Phillips, G., Posthuma, L., Pouso, S., Prudhomme, C., Rankinen, K., Rasmussen, J. J., Richardson, J., Sagouis, A., Santos, J. M., Schäfer, R. B., Schinegger, R., Schmutz, S., Schneider, S. C., Schülting, L., Segurado, P., Stefanidis, K., Sures, B., Thackeray, S. J., Turunen, J., Uyarra, M. C., Venohr, M., von der Ohe, P. C., Willby, N., and Hering, D.: Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems, Nature Ecology & Evolution, 4, 1060-1068, 10.1038/s41559-020-1216-4, 2020.

Brown, L. E., Holden, J., Palmer, S. M., Johnston, K., Ramchunder, S. J., and Grayson, R.: Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems, Freshw. Sci., 34, 1406-1425, 10.1086/683426, 2015.

Chapman, P. J., Moody, C. S., Grayson, R., and Palmer, S. M.: Factors controlling water colour on the North York Moors (Part 1), University of Leeds, 2017.

Chapman, P. J., McDonald, A. T., Tyson, R., Palmer, S. M., Mitchell, G., and Irvine, B.: Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK, Biogeochemistry, 101, 281-294, 10.1007/s10533-010-9474-x, 2010.

Chimner, R. A., Cooper, D. J., Wurster, F. C., and Rochefort, L.: An overview of peatland restoration in North America: where are we after 25 years?, Restoration Ecology, 25, 283-292, https://doi.org/10.1111/rec.12434, 2017.

Clark, J. M., Ashley, D., Wagner, M., Chapman, P. J., Lane, S. N., Evans, C. D., and Heathwaite, A. L.: Increased temperature sensitivity of net DOC production from ombrotrophic peat due to water table draw-down, Global Change Biology, 15, 794-807, 10.1111/j.1365-2486.2008.01683.x, 2009.

Clay, G. D., Worrall, F., and Aebischer, N. J.: Does prescribed burning on peat soils influence DOC concentrations in soil and runoff waters? Results from a 10 year chronosequence, J. Hydrol., 448, 139-148, 10.1016/j.jhydrol.2012.04.048, 2012.

Clay, G. D., Worrall, F., and Fraser, E. D. G.: Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog, J. Hydrol., 367, 41-51, 10.1016/j.jhydrol.2008.12.022, 2009.

Clutterbuck, B. and Yallop, A. R.: Land management as a factor controlling dissolved organic carbon release from upland peat soils 2 Changes in DOC productivity over four decades, Sci. Total Environ., 408, 6179-6191, 10.1016/j.scitotenv.2010.08.038, 2010.

Cummins, T. and Farrell, E. P.: Biogeochemical impacts of clearfelling and reforestation on blanket-peatland streams - II. major ions and dissolved organic carbon, For. Ecol. Manage., 180, 557-570, 10.1016/s0378-1127(02)00649-7, 2003.

Davies, G. M., Kettridge, N., Stoof, C. R., Gray, A., Ascoli, D., Fernandes, P. M., Marrs, R., Allen, K. A., Doerr, S. H., Clay, G. D., McMorrow, J., and Vandvik, V.: The role of fire in UK peatland and moorland management: the need for informed, unbiased debate, Philos. Trans. R. Soc. B-Biol. Sci., 371, 10.1098/rstb.2015.0342, 2016.

de Wit, H. A., Stoddard, J. L., Monteith, D. T., Sample, J. E., Austnes, K., Couture, S., Fölster, J., Higgins, S. N., Houle, D., Hruška, J., Krám, P., Kopáček, J., Paterson, A. M., Valinia, S., Van Dam, H., Vuorenmaa, J., and Evans, C. D.: Cleaner air reveals growing influence of climate on dissolved organic carbon trends in northern headwaters, Environmental Research Letters, 16, 104009, 10.1088/1748-9326/ac2526, 2021.

Einola, E., Rantakari, M., Kankaala, P., Kortelainen, P., Ojala, A., Pajunen, H., Makela, S., and Arvola, L.: Carbon pools and fluxes in a chain of five boreal lakes: A dry and wet year comparison, J. Geophys. Res.-Biogeosci., 116, 10.1029/2010jg001636, 2011.

Evans, C. D., Futter, M. N., Moldan, F., Valinia, S., Frogbrook, Z., and Kothawala, D. N.: Variability in organic carbon reactivity across lake residence time and trophic gradients, Nature Geoscience, 10, 832-+, 10.1038/ngeo3051, 2017a.

Evans, C. D., Malcolm, I. A., Shilland, E. M., Rose, N. L., Turner, S. D., Crilly, A., Norris, D., Granath, G., and Monteith, D. T.: Sustained Biogeochemical Impacts of Wildfire in a Mountain Lake Catchment, Ecosystems, 20, 813-829, 10.1007/s10021-016-0064-1, 2017b.

Evans, C. D., Peacock, M., Green, S. M., Holden, J., Chapman, P. J., Lebron, I., Callaghan, N., Grayson, R., and Baird, A.: The impact of ditch blocking on fluvial carbon export from a UK blanket bog, Hydrological Processes, 32, 2141-2154, 2018.

Evans, C. D., Jones, T. G., Burden, A., Ostle, N., Zielinski, P., Cooper, M. D. A., Peacock, M., Clark, J. M., Oulehle, F., Cooper, D., and Freeman, C.: Acidity controls on dissolved organic carbon mobility in organic soils, Global Change Biology, 18, 3317-3331, 10.1111/j.1365-2486.2012.02794.x, 2012.

Evans, C. D., Page, S. E., Jones, T., Moore, S., Gauci, V., Laiho, R., Hruska, J., Allott, T. E. H., Billett, M. F., Tipping, E., Freeman, C., and Garnett, M. H.: Contrasting vulnerability of drained tropical and high-latitude peatlands to fluvial loss of stored carbon, Global Biogeochemical Cycles, 28, 1215-1234, 10.1002/2013gb004782, 2014.

Feuchtmayr, H., Pottinger, T. G., Moore, A., De Ville, M. M., Caillouet, L., Carter, H. T., Pereira, M. G., and Maberly, S. C.: Effects of brownification and warming on algal blooms, metabolism and higher trophic levels in productive shallow lake mesocosms, Sci. Total Environ., 678, 227-238, https://doi.org/10.1016/j.scitotenv.2019.04.105, 2019.

Flynn, R., Mackin, F., McVeigh, C., and Renou-Wilson, F.: Impacts of a mature forestry plantation on blanket peatland runoff regime and water quality, Hydrological Processes, 36, e14494, https://doi.org/10.1002/hyp.14494, 2022.

Forestry Commission: The UK Forestry Standard, Edinburgh2017.

Freeman, C., Evans, C. D., Monteith, D. T., Reynolds, B., and Fenner, N.: Export of organic carbon from peat soils, Nature, 412, 785-785, 10.1038/35090628, 2001.

Gaffney, P.: The effects of bog restoration in formerly afforested peatlands on water quality and aquatic carbon fluxes, Environmental Research Institute, University of the Highlands and Islands, 2017.

Gaffney, P. P. J., Hancock, M. H., Taggart, M. A., and Andersen, R.: Measuring restoration progress using pore- and surface-water chemistry across a chronosequence of formerly afforested blanket bogs, J. Environ. Manage., 219, 239-251, https://doi.org/10.1016/j.jenvman.2018.04.106, 2018.

Gaffney, P. P. J., Hancock, M. H., Taggart, M. A., and Andersen, R.: Restoration of afforested peatland: Immediate effects on aquatic carbon loss, Sci. Total Environ., 742, 140594, https://doi.org/10.1016/j.scitotenv.2020.140594, 2020.

Gibson, H. S., Worrall, F., Burt, T. P., and Adamson, J. K.: DOC budgets of drained peat catchments: implications for DOC production in peat soils, Hydrological Processes, 23, 1901-1911, 10.1002/hyp.7296, 2009.

Glatzel, S., Kalbitz, K., Dalva, M., and Moore, T.: Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs, Geoderma, 113, 397-411, https://doi.org/10.1016/S0016-7061(02)00372-5, 2003.

Glenk, K. and Martin-Ortega, J.: The economics of peatland restoration, Journal of Environmental Economics and Policy, 7, 345-362, 10.1080/21606544.2018.1434562, 2018.

Gough, R., Holliman, P. J., Fenner, N., Peacock, M., and Freeman, C.: Influence of Water Table Depth on Pore Water Chemistry and Trihalomethane Formation Potential in Peatlands, Water Environ. Res., 88, 107-117, 10.2175/106143015x14362865227878, 2016.

Gough, R., Holliman, P. J., Willis, N., Jones, T. G., and Freeman, C.: Influence of habitat on the quantity and composition of leachable carbon in the O2 horizon: Potential implications for potable water treatment, Lake Reserv. Manag., 28, 282-292, 10.1080/07438141.2012.741187, 2012.

Grau-Andres, R., Davies, G. M., Waldron, S., Scott, E. M., and Gray, A.: Increased fire severity alters initial vegetation regeneration across Calluna-dominated ecosystems, J. Environ. Manage., 231, 1004-1011, 10.1016/j.jenvman.2018.10.113, 2019.

Haapalehto, T., Kotiaho, J. S., Matilainen, R., and Tahvanainen, T.: The effects of long-term drainage and subsequent restoration on water table level and pore water chemistry in boreal peatlands, J. Hydrol., 519, 1493-1505, 10.1016/j.jhydrol.2014.09.013, 2014.

Harper, A. R., Doerr, S. H., Santin, C., Froyd, C. A., and Sinnadurai, P.: Prescribed fire and its impacts on ecosystem services in the UK, Sci. Total Environ., 624, 691-703, 10.1016/j.scitotenv.2017.12.161, 2018.

Harriman, R., Watt, A. W., Christie, A. E. G., Collen, P., Moore, D. W., McCartney, A. G., Taylor, E. M., and Watson, J.: Interpretation of trends in acidic deposition and surface water chemistry in Scotland during the past three decades, Hydrol. Earth Syst. Sci., 5, 407-420, 10.5194/hess-5-407-2001, 2001.

HM Government: Net Zero Strategy: Build Back Greener, 2021.

Holden, J., Chapman, P. J., Palmer, S. M., Kay, P., and Grayson, R.: The impacts of prescribed moorland burning on water colour and dissolved organic carbon: A critical synthesis, J. Environ. Manage., 101, 92-103, 10.1016/j.jenvman.2012.02.002, 2012.

Holden, J., Kirkby, M. J., Lane, S. N., Milledge, D. G., Brookes, C. J., Holden, V., and McDonald, A. T.: Overland flow velocity and roughness properties in peatlands, Water Resour. Res., 44, 10.1029/2007wr006052, 2008.

Holden, J., Green, S. M., Baird, A. J., Grayson, R. P., Dooling, G. P., Chapman, P. J., Evans, C. D., Peacock, M., and Swindles, G.: The impact of ditch blocking on the hydrological functioning of blanket peatlands, Hydrological Processes, 31, 525-539, 10.1002/hyp.11031, 2017.

Holl, B. S., Fiedler, S., Jungkunst, H. F., Kalbitz, K., Freibauer, A., Drosler, M., and Stahr, K.: Characteristics of dissolved organic matter following 20 years of peatland restoration, Sci. Total Environ., 408, 78-83, 10.1016/j.scitotenv.2009.08.046, 2009.

Howson, T., Chapman, P. J., Shah, N., Anderson, R., and Holden, J.: A comparison of porewater chemistry between intact, afforested and restored raised and blanket bogs, Sci. Total Environ., 766, 144496, https://doi.org/10.1016/j.scitotenv.2020.144496, 2021.

Hudson, J. A., Gilman, K., and Calder, I. R.: Land use and water issues in the uplands with reference to the Plynlimon study, Hydrol. Earth Syst. Sci., 1, 389-397, 10.5194/hess-1-389-1997, 1997.

Imai, A., Fukushima, T., Matsushige, K., Kim, Y.-H., and Choi, K.: Characterization of dissolved organic matter in effluents from wastewater treatment plants, Water Res., 36, 859-870, https://doi.org/10.1016/S0043-1354(01)00283-4, 2002.
Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinen, K., and Byrne, K. A.: How strongly can forest management influence soil carbon sequestration?, Geoderma, 137, 253-268, https://doi.org/10.1016/j.geoderma.2006.09.003, 2007.
Jones, T. G., Evans, C. D., and Freeman, C.: The greenhouse gas (GHG) emissions associated with aquatic carbon removal during drinking water treatment, Aquat. Sci., 78, 561-572, 10.1007/s00027-015-0458-8, 2016.
Koehler, B., von Wachenfeldt, E., Kothawala, D., and Tranvik, L. J.: Reactivity continuum of dissolved organic carbon decomposition in lake water, J. Geophys. Res.-Biogeosci., 117, 10.1029/2011jg001793, 2012.
Koehler, B., Landelius, T., Weyhenmeyer, G. A., Machida, N., and Tranvik, L. J.: Sunlight-induced carbon dioxide emissions from inland waters, Global Biogeochemical Cycles, 28, 696-711, 10.1002/2014gb004850, 2014.
Lundin, L., Nilsson, T., Jordan, S., Lode, E., and Strömgren, M.: Impacts of rewetting on peat, hydrology and water chemical composition over 15 years in two finished peat extraction areas in Sweden, Wetlands Ecology and Management, 25, 405-419, 10.1007/s11273-016-9524-9, 2017.
Matilainen, A., Vepsäläinen, M., and Sillanpää, M.: Natural organic matter removal by coagulation during drinking water treatment: A review, Advances in Colloid and Interface Science, 159, 189-197, https://doi.org/10.1016/j.cis.2010.06.007, 2010.
McKnight, D. M., Bencala, K. E., Zellweger, G. W., Aiken, G. R., Feder, G. L., and Thorn, K. A.: Sorption of dissolved organic carbon by hydrous aluminum and iron oxides occurring at the confluence of Deer Creek with the Snake River, Summit County, Colorado, Environmental Science & Technology, 26, 1388-1396, 10.1021/es00031a017, 1992.
Menberu, M., Mattila, H., Tahvanainen, T., Kotiaho, J. S., Hokkanen, R., Klove, B., and Ronkanen, A.: Changes in pore water quality after peatland restoration: assessment of a large scale replicated before-after-control-impact study in Finland, Water Resour. Res., 53, 8327-8343, 2017.
Monteith, D., Pickard, A. E., Spears, B. M., and Feuchtmayr, H.: An introduction to the FREEDOM-BCCR project: FREEDOM-BCCR briefing note 1 to the water industry, 2021.
Monteith, D. T., Henrys, P. A., Hruška, J., de Wit, H. A., Krám, P., Moldan, F., Posch, M., Räike, A., Stoddard, J. L., Shilland, E. M., Pereira, M. G., and Evans, C. D.: Long-term rise in riverine dissolved organic carbon concentration is predicted by electrolyte solubility theory, Science Advances, 9, eade3491, doi:10.1126/sciadv.ade3491, 2023.
Monteith, D. T., Stoddard, J. L., Evans, C. D., de Wit, H. A., Forsius, M., Hogasen, T., Wilander, A., Skjelkvale, B. L., Jeffries, D. S., Vuorenmaa, J., Keller, B., Kopacek, J., and Vesely, J.: Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry, Nature, 450, 537-U539, 10.1038/nature06316, 2007.
Moody, C. S., Worrall, F., Evans, C. D., and Jones, T. G.: The rate of loss of dissolved organic carbon (DOC) through a catchment, J. Hydrol., 492, 139-150, 10.1016/j.jhydrol.2013.03.016, 2013.
Muller, F. L. L. and Tankere-Muller, S. P. C.: Seasonal variations in surface water chemistry at disturbed and pristine peatland sites in the Flow Country of northern Scotland, Sci. Total Environ., 435, 351-362, 10.1016/j.scitotenv.2012.06.048, 2012.
Muller, F. L. L., Chang, K.-C., Lee, C.-L., and Chapman, S. J.: Effects of temperature, rainfall and conifer felling practices on the surface water chemistry of northern peatlands, Biogeochemistry, 126, 343-362, 10.1007/s10533-015-0162-8, 2015.
Naden, P. S. and McDonald, A. T.: Statistical modeling of water color in the uplands - the Upper Nidd catchment 1979-1987, Environmental Pollution, 60, 141-163, 10.1016/0269-7491(89)90224-8, 1989.
Neal, C.: Nutrient concentrations and fluxes for podzolic and gley soils at Plynlimon, mid-Wales: implications for modelling inorganic nitrogen and phosphorus in upland UK environments, Hydrol. Earth Syst. Sci., 6, 403-420, 10.5194/hess-6-403-2002, 2002.

O'Brien, H. E., Labadz, J. C., Butcher, D. P., Billett, M. F., and Midgley, N. G.: Impact of catchment management upon dissolved organic carbon and stream flows in the Peak District, Derbyshire, UK., 10th BHS National Hydrology Symposium, Exeter,

Parry, L. E., Chapman, P. J., Palmer, S. M., Wallage, Z. E., Wynne, H., and Holden, J.: The influence of slope and peatland vegetation type on riverine dissolved organic carbon and water colour at different scales, Sci. Total Environ., 527, 530-539, 10.1016/j.scitotenv.2015.03.036, 2015.

Patterson, G. and Anderson, R.: Forests and Peatland Habitats, Forestry Commission, Edinburgh, 2000.

Peacock, M., Jones, T. G., Futter, M. N., Freeman, C., Gough, R., Baird, A. J., Green, S. M., Chapman, P. J., Holden, J., and Evans, C. D.: Peatland ditch blocking has no effect on dissolved organic matter (DOM) quality, Hydrological Processes, 32, 3891-3906, https://doi.org/10.1002/hyp.13297, 2018.

Peter, S., Agstam, O., and Sobek, S.: Widespread release of dissolved organic carbon from anoxic boreal lake sediments, Inland Waters, 7, 151-163, 10.1080/20442041.2017.1300226, 2017.

Pickard, A. E., Branagan, M., Billett, M. F., Andersen, R., and Dinsmore, K. J.: Effects of peatland management on aquatic carbon concentrations and fluxes, Biogeosciences, 19, 1321-1334, 10.5194/bg-19-1321-2022, 2022.

Pilkington, M., Walker, J., Maskill, R., Allott, T. E. H., and Evans, M.: Restoration of blanket bogs; flood risk reduction and other ecosystem benefits, Edale, 2015.

Prest, E. I., Hammes, F., van Loosdrecht, M. C. M., and Vrouwenvelder, J. S.: Biological Stability of Drinking Water: Controlling Factors, Methods, and Challenges, Frontiers in Microbiology, 7, 10.3389/fmicb.2016.00045, 2016.

Qassim, S. M., Dixon, S. D., Rowson, J. G., Worrall, F., Evans, M. G., and Bonn, A.: A 5-year study of the impact of peatland revegetation upon DOC concentrations, J. Hydrol., 519, 3578-3590, 10.1016/j.jhydrol.2014.11.014, 2014.

Ramchunder, S. J., Brown, L. E., and Holden, J.: Rotational vegetation burning effects on peatland stream ecosystems, J. Appl. Ecol., 50, 636-648, 10.1111/1365-2664.12082, 2013.

Rask, M., Nyberg, K., Markkanen, S.-L., and Ojala, A.: Forestry in catchments: effects on water quality, plankton, zoobenthos and fish in small lakes, Boreal Environment Research, 3, 75-86, 1998.

Ritson, J. P., Graham, N. J. D., Templeton, M. R., Clark, J. M., Gough, R., and Freeman, C.: The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: A UK perspective, Sci. Total Environ., 473-474, 714-730, https://doi.org/10.1016/j.scitotenv.2013.12.095, 2014.

Ritson, J. P., Bell, M., Brazier, R. E., Grand-Clement, E., Graham, N. J. D., Freeman, C., Smith, D., Templeton, M. R., and Clark, J. M.: Managing peatland vegetation for drinking water treatment, Sci Rep, 6, 10.1038/srep36751, 2016.

Robson, A. J. and Neal, C.: Water quality trends at an upland site in Wales, UK, 1983-1993, Hydrological Processes, 10, 183-203, 10.1002/(sici)1099-1085(199602)10:2<183::Aid-hyp356>3.0.Co;2-8, 1996.

Schelker, J., Eklof, K., Bishop, K., and Laudon, H.: Effects of forestry operations on dissolved organic carbon concentrations and export in boreal first-order streams, J. Geophys. Res.-Biogeosci., 117, 10.1029/2011jg001827, 2012.

Flanders Moss Peatland Restoration: https://www.forestry.gov.uk/fr/beeh-atugla, last access: 12/04/2018.

Shah, N. and Nisbet, T.: The effects of forest clearance for peatland restoration on water quality, Sci. Total Environ., 693, 133617, 10.1016/j.scitotenv.2019.133617, 2019.

Shah, N. W., Nisbet, T. R., and Broadmeadow, S. B.: The impacts of conifer afforestation and climate on water quality and freshwater ecology in a sensitive peaty catchment: A 25 year study in the upper River Halladale in North Scotland, For. Ecol. Manage., 502, 119616, https://doi.org/10.1016/j.foreco.2021.119616, 2021.

Skerlep, M., Steiner, E., Axelsson, A. L., and Kritzberg, E. S.: Afforestation driving long-term surface water browning, Global Change Biology, 26, 1390-1399, 10.1111/gcb.14891, 2019.

Spears, B. M. and May, L.: Long-term homeostasis of filterable un-reactive phosphorus in a shallow eutrophic lake following a significant reduction in catchment load, Geoderma, 257-258, 78-85, https://doi.org/10.1016/j.geoderma.2015.01.005, 2015.

Spears, B. M., Mackay, E. B., Yasseri, S., Gunn, I. D. M., Waters, K. E., Andrews, C., Cole, S., De Ville, M., Kelly, A., Meis, S., Moore, A. L., Nürnberg, G. K., van Oosterhout, F., Pitt, J.-A., Madgwick, G., Woods, H. J., and Lürling, M.: A meta-analysis of water quality and aquatic macrophyte responses in 18 lakes treated with lanthanum modified bentonite (Phoslock®), Water Res., 97, 111-121, https://doi.org/10.1016/j.watres.2015.08.020, 2016.

Stets, E. G., Striegl, R. G., and Aiken, G. R.: Dissolved organic carbon export and internal cycling in small, headwater lakes, Global Biogeochemical Cycles, 24, 10.1029/2010gb003815, 2010.

Stimson, A. G., Allott, T. E. H., Boult, S., and Evans, M. G.: Fluvial organic carbon composition and concentration variability within a peatland catchment-Implications for carbon cycling and water treatment, Hydrological Processes, 31, 4183-4194, 10.1002/hyp.11352, 2017.

Strack, M., Zuback, Y., McCarter, C., and Price, J.: Changes in dissolved organic carbon quality in soils and discharge 10 years after peatland restoration, J. Hydrol., 527, 345-354, 10.1016/j.jhydrol.2015.04.061, 2015.

Stretton, C.: Water supply and forestry - a conflict of interests: Cray reservoir, a case study, J Inst Water Eng Scient, 38, 323 - 330, 1984.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., Dillon, P., Finlay, K., Fortino, K., Knoll, L. B., Kortelainen, P. L., Kutser, T., Larsen, S., Laurion, I., Leech, D. M., McCallister, S. L., McKnight, D. M., Melack, J. M., Overholt, E., Porter, J. A., Prairie, Y., Renwick, W. H., Roland, F., Sherman, B. S., Schindler, D. W., Sobek, S., Tremblay, A., Vanni, M. J., Verschoor, A. M., von Wachenfeldt, E., and Weyhenmeyer, G. A.: Lakes and reservoirs as regulators of carbon cycling and climate, Limnology and Oceanography, 54, 2298-2314, 10.4319/lo.2009.54.6_part_2.2298, 2009.

Turner, E. K., Worrall, F., and Burt, T. P.: The effect of drain blocking on the dissolved organic carbon (DOC) budget of an upland peat catchment in the UK, J. Hydrol., 479, 169-179, 10.1016/j.jhydrol.2012.11.059, 2013.

Urbanova, Z., Picek, T., and Barta, J.: Effect of peat re-wetting on carbon and nutrient fluxes, greenhouse gas production and diversity of methanogenic archaeal community, Ecological Engineering, 37, 1017-1026, 10.1016/j.ecoleng.2010.07.012, 2011.

von Wachenfeldt, E. and Tranvik, L. J.: Sedimentation in boreal lakes - The role of flocculation of allochthonous dissolved organic matter in the water column, Ecosystems, 11, 803-814, 10.1007/s10021-008-9162-z, 2008.

Wallage, Z. E., Holden, J., and McDonald, A. T.: Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland, Sci. Total Environ., 367, 811-821, 10.1016/j.scitotenv.2006.02.010, 2006.

Weishaar, J. L., Aiken, G. R., Bergamaschi, B. A., Fram, M. S., Fujii, R., and Mopper, K.: Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon, Environmental Science & Technology, 37, 4702-4708, 10.1021/es030360x, 2003.

Williamson, J. L., Tye, A., Lapworth, D. J., Monteith, D., Sanders, R., Mayor, D. J., Barry, C., Bowes, M., Bowes, M., Burden, A., Callaghan, N., Farr, G., Felgate, S., Fitch, A., Gibb, S., Gilbert, P., Hargreaves, G., Keenan, P., Kitidis, V., Juergens, M., Martin, A., Mounteney, I., Nightingale, P. D., Pereira, M. G., Olszewska, J., Pickard, A., Rees, A. P., Spears, B., Stinchcombe, M., White, D., Williams, P., Worrall, F., and Evans, C.: Landscape controls on riverine export of dissolved organic carbon from Great Britain, Biogeochemistry, 10.1007/s10533-021-00762-2, 2021.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., and Morris, M.: Ditch blocking, water chemistry and organic carbon flux: Evidence that blanket bog restoration reduces erosion and fluvial carbon loss, Sci. Total Environ., 409, 2010-2018, 10.1016/j.scitotenv.2011.02.036, 2011.

Worrall, F., Armstrong, A., and Adamson, J. K.: The effects of burning and sheep-grazing on water table depth and soil water quality in a upland peat, J. Hydrol., 339, 1-14, 10.1016/j.jhydrol.2006.12.025, 2007a.
Worrall, F., Armstrong, A., and Holden, J.: Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth, J. Hydrol., 337, 315-325, 10.1016/j.jhydrol.2007.01.046, 2007b.
Worrall, F., Rowson, J., and Dixon, S.: Effects of managed burning in comparison with vegetation cutting on dissolved organic carbon concentrations in peat soils, Hydrological Processes, 27, 3994-4003, 10.1002/hyp.9474, 2013.
Worrall, F., Clay, G. D., Marrs, R., and Reed, M.: Impacts of burning management on peatlands, 2010.
Worrall, F., Harriman, R., Evans, C. D., Watts, C. D., Adamson, J., Neal, C., Tipping, E., Burt, T., Grieve, I., Monteith, D., Naden, P. S., Nisbet, T., Reynolds, B., and Stevens, P.: Trends in dissolved organic carbon in UK rivers and lakes, Biogeochemistry, 70, 369-402, 10.1007/s10533-004-8131-7, 2004.
Xu, J., Morris, P. J., Liu, J., and Holden, J.: Hotspots of peatland-derived potable water use identified by global analysis, Nature Sustainability, 1, 246-253, 10.1038/s41893-018-0064-6, 2018.
Yallop, A. R., Clutterbuck, B., and Thacker, J.: Increases in humic dissolved organic carbon export from upland peat catchments: the role of temperature, declining sulphur deposition and changes in land management, Clim. Res., 45, 43-56, 10.3354/cr00884, 2010.
Zheng, Y., Waldron, S., and Flowers, H.: Fluvial dissolved organic carbon composition varies spatially and seasonally in a small catchment draining a wind farm and felled forestry, Sci. Total Environ., 626, 785-794, 10.1016/j.scitotenv.2018.01.001, 2018.

Tables:

Table 1: Summary of the impacts of drainage ditch blocking on DOM concentrations and fluxes from peatlands, reported in increasing time since ditch blocking. BA = Before/After, CI = Control/Intervention

Reference	Location	Sampling scale	Concentration or flux measured	Time since ditch blocking	Experimental Design	Change since ditch blocking
Worrall et al. (2007b)	UK, blanket bog	Ditches	DOM concentration	7 months	BACI	100% increase in DOM concentration.
Turner et al. (2013)	UK, blanket bog	0 and 1st order ditches	DOM concentration and flux	1 year	BACI	DOM concentration decreased by 2.5% compared to control, DOM flux decreased by 2.2 – 9.2% as a result of decreased water export.
Gibson et al. (2009)	UK, blanket bog	Ditches	DOM concentration and flux	1 year	CI	DOM concentrations unchanged, water flux decreased by 39% meaning DOM flux also declined by the same amount.
Wilson et al. (2011)	UK, blanket bog	Ditches and headwater streams	DOM concentration and flux	2 years	BACI	DOM concentrations unchanged, fluxes were 88% lower in streams draining ditch-blocked catchments due to much lower estimated water export.
O'brien et al. (2008)	UK, blanket bog	Headwater streams	DOM flux and water colour	2 years	BACI	Water colour was unchanged. Fluxes decreased by 24% in streams as a result of decreasing water export.
Menberu et al. (2017)	Finland fen, pine mire and spruce mire	Pore water	DOM concentration	3 years	BACI	41% reduction in DOM concentration.
Evans et al. (2018)	UK, blanket bog	Ditches	DOM concentration	4 years	BACI	No change in DOM concentration
Wallage et al. (2006)	UK, blanket bog	Pore water	DOM concentration	5 years	CI	DOM concentration lower in porewaters adjacent to blocked ditches (69% lower compared to open ditches)
Haapalehto et al. (2014)	Finland, raised bog	Pore water	DOM concentration	5 years and 10 years	Chronosequence	DOM concentration approx. 10% lower in sites 5 years post restoration and 25% lower in sites 10 years post restoration
Haapalehto et al. (2014)	Finland, raised bog	Ditches	DOM concentration	5 years and 10 years	Chronosequence	Concentrations approx. 75% higher in sites 5 years post restoration and 50% higher in sites 10 years post restoration
Armstrong et al. (2010)	UK, blanket bog	Ditches	DOM flux	7 years	CI	No change in DOM flux
Strack et al. (2015)	Canada, bog	Pore water and ditch water	DOM concentration	10 years	CI	No change in pore water DOM concentration. Ditch water DOM concentrations

						were similar in spring and summer and up to 30% lower in the restored site in autumn.
Armstrong et al. (2010)	UK, blanket bog	Ditches from a survey in Northern England and Northern Scotland	DOM concentration	6 months to 18 years	Survey	DOM concentrations 28% lower on average in blocked drains compared to unblocked drains.
Holl et al. (2009)	Germany, ex-fenland extraction site	Pore water	DOM concentration	20 years	CI	DOM concentrations 37% lower at restored site compared to drained site.
Urbanova et al. (2011)	Czech Republic, bog	Pore water	DOM concentration	NA comparison between drained and intact sites	CI	No difference in DOM concentration between intact and moderately degraded site, 50% higher DOM concentrations at highly degraded site.
Pickard et al. (2022)	UK, blanket bog	Headwater streams	DOM concentration	6-8 years	CI	No difference in DOM concentration between drained and restored sites. DOM concentrations significantly higher (50% increase) in drained and restored sites compared to non-drained controls.

Table 2: UK studies reporting DOM concentration monitoring of forestry activities on peat. Note that where percentage differences are preceded by ~ concentrations were not explicitly listed in text, figures and tables or supplementary information so are estimated from graphs.

Paper	Location	Forestry activity monitored	Scale	Timescale of monitoring	% difference
Muller and Tankere-Muller (2012)	Flow Country	Felling compared to blanket bog	Stream (upstream and downstream)	1 year post felling	-6%
Zheng et al. (2018)	Central Scotland	Felling compared to windfarm on blanket bog	Stream	1 year ~ 8 years after felling	~ 100%
Muller et al. (2015)	Flow Country	Felling compared to blanket bog	Stream	3 months before ~ 1 year after	No difference
Shah and Nisbet (2019)	Central Scotland (raised bog)	Before / after felling	Stream	1 year before and up to 8 years after	0%, 29% & 51% (mean 27%)
Cummins and Farrell (2003)	Ireland	Before / after felling	Stream	5 years	~0 – 100%
Gaffney et al. (2020)	Flow Country	Before / after felling and	Stream	2 years	No significant difference

		felling compared to blanket bog			
Muller et al. (2015)	Flow Country	Before / after felling	Ditch	3 months before ~ 1 year after	~ 75%
Gaffney et al. (2018)	Flow Country	Before / after felling	Ditch	1 year post felling	~ 150%
Cummins and Farrell (2003)	Ireland	Before / after felling	Ditch	5 years	~50%
Gaffney et al. (2018)	Flow Country	Felling compared to blanket bog	Ditch	0 – 17 years post felling. 1 year of measurement	~500%
Muller and Tankere-Muller (2012)	Flow Country	Felling compared to blanket bog	Ditch	1 year post felling	30-325% (overall average 159%)
Gough et al. (2012)	North Wales	Presence / absence of forestry	Pore waters	1 off sampling	-19% - 111% (average 45%)
Howson et al. (2021)	Flow Country	Presence / absence of forestry	Pore waters	~ 20 months	~ 66%
Howson et al. (2021)	Central Scotland (raised bog)	Presence / absence of forestry	Pore waters	~ 20 months	~14%
Flynn et al. (2022)	Ireland	Presence / absence of forestry	Pore waters	~ 2 years	~400%
Gaffney et al. (2018)	Flow Country	Presence / absence of forestry	Ditch	0 – 17 years post felling 1 year of measurement	~ 100%
Flynn et al. (2022)	Ireland	Presence / absence of forestry	Stream	~ 2 years	No significant difference
Shah et al. (2021)	Flow Country	Presence / absence of forestry – time series	Stream	25 years	No significant difference
Cummins and Farrell (2003)	Ireland	Presence / absence of forestry	Stream	5 years	~25%

Table 3: summary of the published impacts of catchment management activities on DOM concentrations and treatability, focussing on those studies relevant in a UK and Irish context. Numbers in brackets refer to the number of studies showing that effect in each case, while the overall impacts on DOM concentration and treatability for water treatment are shown as +/=/- (positive/neutral/negative) for concentrations and treatability respectively.

Catchment	Impact on DOM concentration	Impact on DOM treatability

intervention		
Ditch blocking (=/=)	**Increase (2)** (Worrall et al., 2007b; Haapalehto et al., 2014) **No change (8)** (O'brien et al., 2008; Gibson et al., 2009; Armstrong et al., 2010; Wilson et al., 2011; Urbanova et al., 2011; Turner et al., 2013; Strack et al., 2015; Evans et al., 2018) **Decrease (5)** (Wallage et al., 2006; Holl et al., 2009; Armstrong et al., 2010; Haapalehto et al., 2014; Menberu et al., 2017)	**No change (5)** (Glatzel et al., 2003; Strack et al., 2015; Gough et al., 2016; Lundin et al., 2017; Peacock et al., 2018)
Revegetation (to grass species) (=/-)	**Increase (2)** (Qassim et al., 2014; Ritson et al., 2016) **No change (4)** (Parry et al., 2015; Pilkington et al., 2015; Stimson et al., 2017; Alderson et al., 2019)	**Decrease (1)** (Ritson et al., 2016)
Revegetation (to heather) (-/-)	**Increase (2)** (Armstrong et al., 2012; Ritson et al., 2016) **No change (1)** (Parry et al., 2015)	**Decrease (1)** (Ritson et al., 2016)
Revegetation (to *Sphagnum*) (+/+)	**Decrease (1)** (Armstrong et al., 2012)	**Improve (1)** (Ritson et al., 2016)
Forest presence (-/-)	**Increase (5)** (Cummins and Farrell, 2003; Gough et al., 2012; Gaffney et al., 2018; Howson et al., 2021; Flynn et al., 2022) **No change (2)** (Shah et al., 2021; Flynn et al., 2022)	**Decrease (2)** (Gough et al., 2012; Howson et al., 2021)
Clearfell and forest-to-bog conversion (-/-)	**Increase (6)** (Cummins and Farrell, 2003; Muller and Tankere-Muller, 2012; Muller et al., 2015; Gaffney et al., 2018; Zheng et al., 2018; Shah and Nisbet, 2019) **No change (3)** (Muller and Tankere-Muller, 2012; Muller et al., 2015; Gaffney et al., 2020)	**Decrease (1)** (Zheng et al., 2018)
Managed burning (-/no evidence)	**Increase (3)** (Clutterbuck and Yallop, 2010, Yallop et al., 2010, Ramchunder et al., 2013) **No change (4)** (Clay et al., 2009; Clay et al., 2012; Worrall et al., 2013; Grau-Andres et al., 2019) **Decrease (1)** (Worrall et al., 2007a)	

Figure legends:

Figure 1: Mean (+/- Standard error) annual dissolved organic carbon (DOC) concentrations from the 23 UK Upland Water Monitoring Network sites. These sites are predominately situated in the north and west of the UK – see www.uwmn.uk for more details.

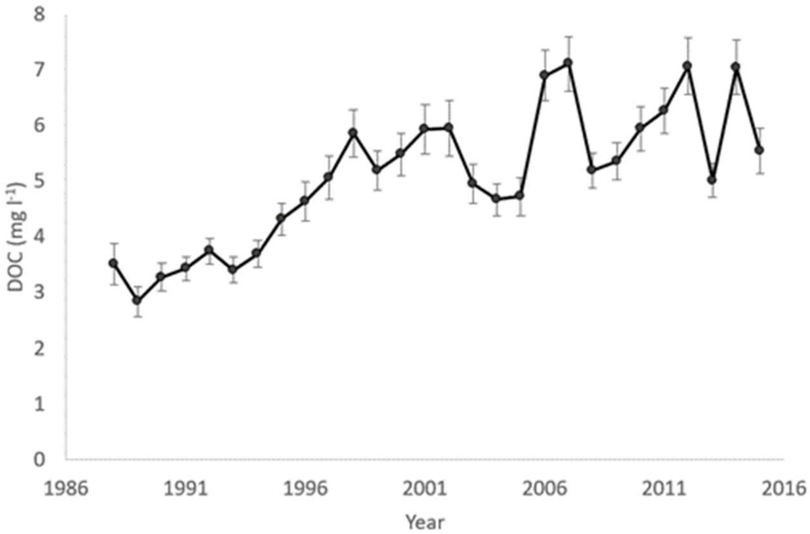

Figure 2: Schematic showing anthropogenic pressures on peatland catchments, and the potential peatland management processes covered in this review.

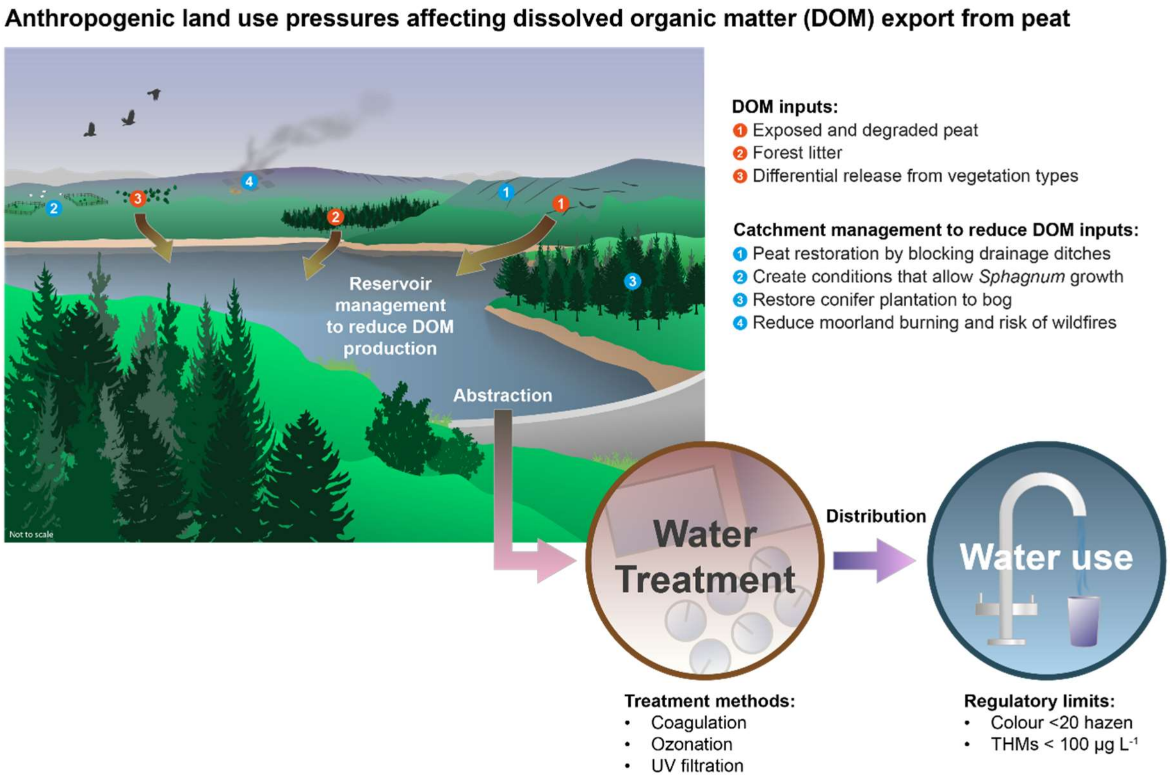

Figure 3: Percentage change in DOM concentration following ditch blocking. Grey circles show DOM percentage change in peatland pore waters, and black circles show DOM percentage change in ditches and streams.

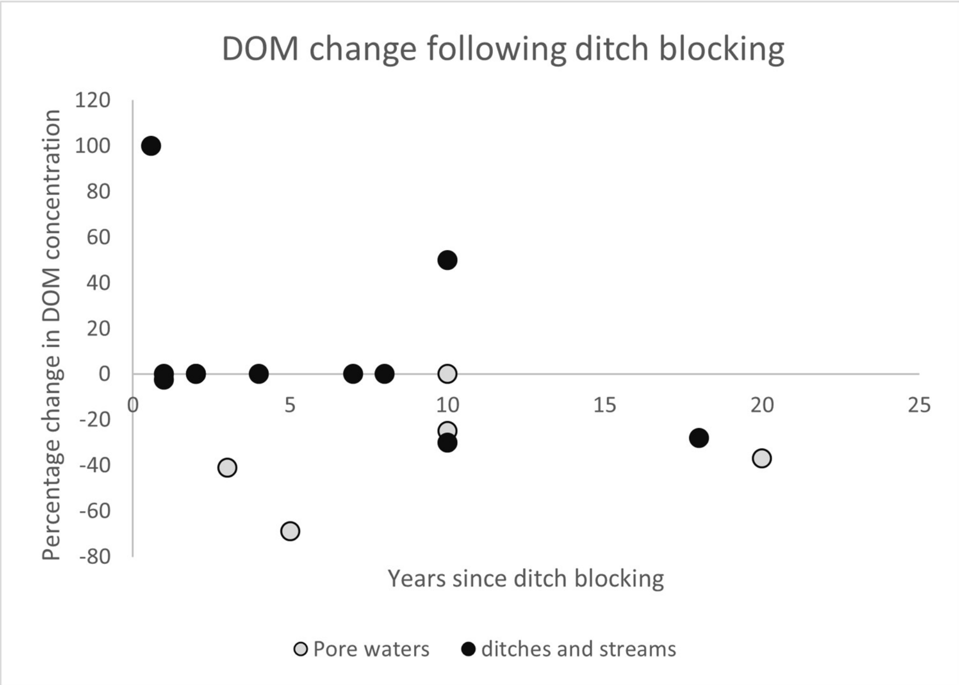

Figure 4: Drainage ditches before (left) and after (right) blocking on a blanket bog in North Wales, the ditches run down the slope and individual dams can be seen crossing the ditches (Photos: Chris Evans).

Figure 5: Burning of vegetation on peat in North Wales (Photo: Chris Evans).