Drain blocking: an effective treatment for reducing dissolved organic carbon loss and water discoloration in a drained peatland

Zoe E. Wallage, Joseph Holden and Adrian T. McDonald

Introduction

Peatlands are particularly unbalanced ecosystems in which the rate of production and accumulation of organic material far exceeds the rate at which it is degraded and exported (Gorham, 1991). Consequently, peatlands form an important terrestrial carbon reserve. These carbon-rich soils are a principal source of dissolved organic carbon (DOC) to the fluvial environment. The transportation of DOC in rivers from terrestrial to marine environments constitutes a significant link in the global carbon cycle, with the average global riverine flux estimated to be between 1 and 10×10^{11} kg C yr^{-1} (Hope *et al.*, 1994). However, while peatlands are often regarded as a net carbon sink, the increasing levels of degradation associated with environmental change could shift the balance of the carbon budget, such that they become a net carbon source (Gorham, 1991). For example, although the release of DOC from peatland areas is a widespread natural process, in recent years elevated DOC concentrations have been observed across the UK (e.g. Freeman *et al.,* 2001) and in many other locations throughout the boreal zone including: Nova Scotia (Gorham *et al.*, 1986), Labrador (Engstrom, 1987), Sweden (Forsberg, 1992) and Ontario (Schindler *et al.*, 1997).

A significant threat to the sustainability of peatlands has been the degradation associated with the installation of open-cut drainage ditches (Holden *et al.*, 2004). This has been prevalent in many peatlands across the world, but is particularly common in blanket peats. Artificial drainage was introduced in UK blanket peats to lower the water table in an attempt to improve the productivity of the land for grazing and reduce downstream flood risk by establishing a soil moisture deficit. However, in addition to a limited improvement in productivity, several negative environmental impacts have been observed, including heightened flood risk and an increased release of DOC (Conway and Miller, 1960; Mitchell and McDonald, 1992; Holden *et al.*, 2004), although some of the flood claims are contested by contradictory results (Holden *et al.*, 2004). A significant increase in the flux of fluvial DOC would mean not only the loss of a valuable terrestrial carbon store, but would also lead to increasing levels of secondary environmental degradation because DOC mobilises metals and pollutants, reduces in-stream light penetration, and has the potential to produce carcinogenic trihalomethane compounds during chlorinated water treatment (Kneale and McDonald*,* 1999). Furthermore, because DOC contains a large proportion of coloured humic substances, increasing concentrations seriously affect water quality in terms of colour, taste, safety and aesthetic value, as well as significantly altering the acid-base and metal complexion characteristics of the water (Mitchell, 1990).

Consequently, many drained peatlands have been targeted for restoration aimed towards re-establishing a naturally functioning, self-sustaining ecosystem and reinitiating the peat-forming processes to improve carbon storage potential and ameliorate water quality (Wheeler and Shaw, 1995; Waddington and Price, 2000; Holden *et al.*, 2004).

Methods

Data were collected from Oughtershaw Beck, a headwater tributary of the River Wharfe, northern England (54°13' N; 2°12' W). This 13.8 km^2 blanket peat catchment receives a mean annual precipitation of 1850 mm (Lane *et al.*, 2004). The catchment is underlain by Carboniferous Limestone and Millstone Grit that is covered with a glacial boulder clay deposit (Urquhart, 1987) which, in conjunction with the high annual rainfall and deforestation around 7 000 years ago, has resulted in the development of an acidic, blanket peat approximately 2 m thick (Winter Hill soil series: Avery, 1980). During the 1960s, a large proportion of the catchment was artificially drained via the installation of open-cut ditches. Some of the drain networks were blocked in 1999.

Three treatments were chosen within the catchment (intact peat, drained peat and drain-blocked peat). At each site there were two 60 m transects of 14 sampling points. Each of the sample points was instrumented with a crest-stage tube to measure overland flow (Holden and Burt, 2003); four piezometers (at depths of 5, 10, 20 and 40 cm) to measure pore water pressure; and one dipwell to measure the water table. Over the period January–May 2005, soil water solutions were extracted on a monthly interval from the crest stage tubes and piezometers using syringe filters housing Whatman WCN 0.45 μm filter papers. DOC was measured using a Thermalox Total Carbon analyser and water colour was assessed using a HACH DR/2010 spectrophotometer set at wavelengths of 400, 465 and 665 nm (Wallage *et al., submitted*). The colour to carbon (C/C) ratio of the samples was obtained by dividing the absorbance values at 400 nm (Abs^{400}) by the corresponding DOC concentrations, while the E4/E6 ratio was determined by dividing the absorbance at 465 nm (Abs^{465}) by that at 665 nm (Abs^{665}) for the individual samples. Full details of the sampling protocols used in this study can be found in Sykes and Lane (1996).

Results

There were significant (p<0.001) differences in DOC concentrations and water colour values between all three sites (Figure 1, Table 1). At all three sites DOC and Abs^{400} were significantly (p<0.001) and positively (>0.86) correlated. However, the median C/C ratio was significantly (p<0.001) lower for the intact and drained sites compared to that of the blocked site (Table 1). The higher C/C ratio at the blocked site highlights the fact that although this treatment has the lowest median DOC and Abs^{400} values, the DOC actually contains more colour per carbon unit than the two other sites.

DOC and Abs^{400} vary significantly with soil depth in each of the three treatments (Figures 2 and 3). At the intact site, DOC concentration increases steadily with soil depth (Table 2), whereas Abs^{400} increases significantly (p<0.001) with depth from 0 cm to 10 cm, but then remains relatively stable for the rest of the profile. This variability in the colour-carbon relationship is manifest in the C/C ratios presented in Figure 4. The amount of colour per carbon unit is clearly not stable within or between treatments.

At the drained site, Figure 2 indicates that there is a similar trend towards increased DOC concentration with depth, although there is a significant (p<0.001) decrease in DOC concentration between 20 and 40 cm depth. Assessment of the median Abs^{400} (Figure 3) values also shows a similar trend. However, analysis of the C/C ratio reveals a very different colour-carbon relationship at depth compared to the intact site (Figure 4). Furthermore, the differences between the C/C ratios for the sample subsets demonstrates that, per carbon unit, the DOC in overland flow on the drained site contains significantly less colour compared to the rest of the peat depths sampled.

At the blocked site, the differences in DOC and colour with increasing depth are less marked. While there is a significant (p<0.001) increase in DOC and Abs^{400} with soil depth, the lowest values are actually found at 10 cm (Figures 2–3). Furthermore, although the C/C ratio is more stable between depth categories at the blocked site (Figure 4), there is a significant (p 0.01) increase between depths of 10 and 20 cm.

Median E4/E6 ratios are significantly (p<0.001) different between the three treatments (Table 1). When overland flow is discounted (as it is likely to be a mixture of water from different depths due to the dominance of saturation-excess overland flow), all three sites show a general (yet significant (p<0.001)) decline in E4/E6 ratio

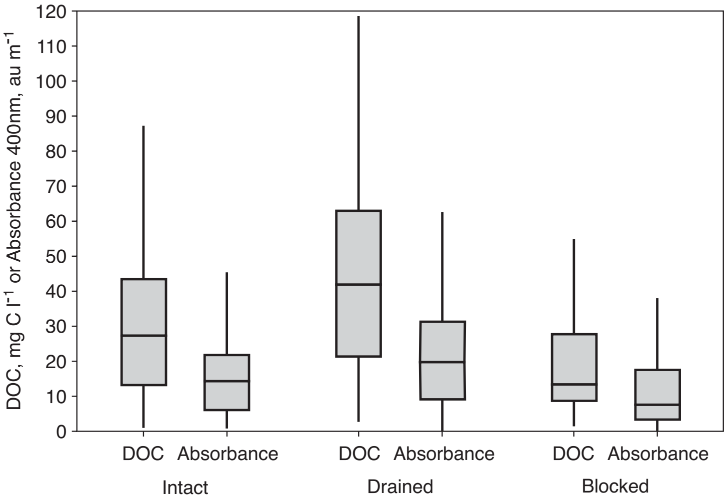

Figure 1 *Average DOC concentration and Abs^{400} for the three land management treatments, based on all samples from each site*

Table 1 *Descriptive statistics for the three treatments including median values of DOC, absorbance, C/C and E4/E6 ratios, and regression and correlation coefficients*

	Treatment		
	Intact	*Drained*	*Blocked*
Median DOC (mg C l^{-1})	27.6	42.9	13.3
Median Abs^{400} (au m^{-1})	14.6	19.8	7.6
Median Abs^{465} (au m^{-1})	5.9	9.0	3.6
Median Abs^{665} (au m^{-1})	0.9	1.7	0.8
Median C/C Ratio	0.49	0.49	0.55
Median E4/E6 Ratio	6.67	5.56	5.18
Correlation DOC v Abs^{400}	0.89	0.86	0.93
R^2	0.80	0.75	0.87
Regression DOC v Abs^{400}	DOC = 1.69 Abs + 5.13	DOC = 1.63 Abs + 9.02	DOC = 1.39 Abs + 3.51
n	277	148	161

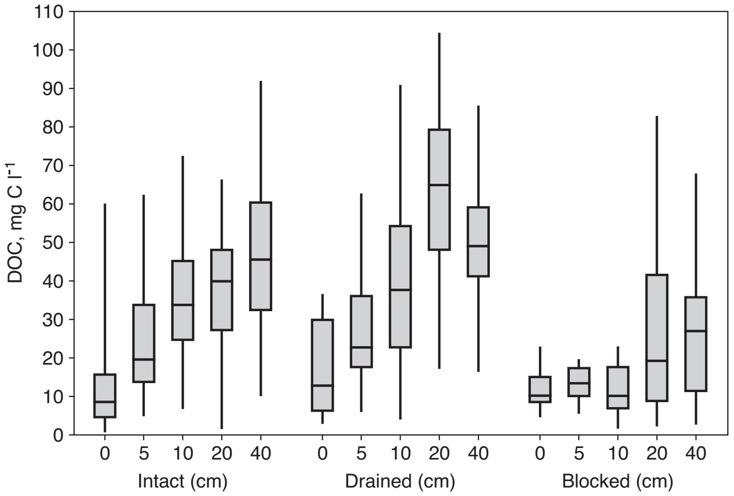

Figure 2 *DOC concentration by depth for each of the three land management treatments*

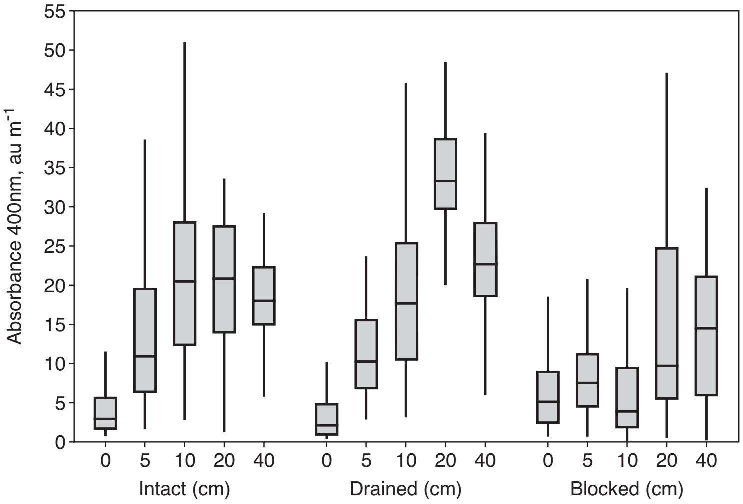

Figure 3 *Abs^{400} by depth for each of the three land management treatments*

Table 2 *Median values of DOC, absorbance, C/C, and E4/E6 ratios at varying depths for each of the three land management treatments*

	Intact					*Drained*					*Blocked*				
Depth of sample	*0cm*	*5cm*	*10cm*	*20cm*	*40cm*	*0cm*	*5cm*	*10cm*	*20cm*	*40cm*	*0cm*	*5cm*	*10cm*	*20cm*	*40cm*
DOC(mg C l^{-1})	8.53	19.50	33.65	39.90	45.30	12.55	22.70	37.75	65.00	49.00	10.20	13.30	9.94	19.30	26.90
Abs^{400}(au m^{-1})	2.98	11.00	20.50	20.84	18.04	2.14	10.32	17.78	33.20	23.20	5.12	7.52	4.08	9.90	14.68
Abs^{465}(au m^{-1})	1.14	4.64	8.56	8.24	7.24	0.88	4.56	7.42	15.38	10.20	2.28	3.48	1.58	4.70	7.16
Abs^{665}(au m^{-1})	0.26	0.64	1.22	1.20	1.16	0.28	0.76	1.24	2.76	2.12	0.36	0.64	0.32	1.20	1.68
C/CRatio	0.42	0.51	0.58	0.53	0.38	0.13	0.54	0.50	0.54	0.49	0.51	0.55	0.45	0.61	0.62
E4/E6Ratio	6.23	7.50	7.15	6.65	6.10	3.66	6.14	5.96	5.54	4.91	5.70	5.82	5.49	4.75	4.77
n	*60*	*53*	*56*	*47*	*61*	*18*	*36*	*20*	*38*	*37*	*35*	*29*	*28*	*34*	*35*

with depth (Table 2, Figure 5). The median E4/E6 ratio of overland flow is significantly lower than all other depths for both the intact and drained sites. However, the median E4/E6 ratio of overland flow for the blocked site is not significantly different to that in pore waters at 5 or 10 cm depths, which are significantly (p<0.001) higher than that of the deeper pore waters sampled at the site.

Discussion

The peat treatment with artificial drainage ditches had significantly higher Abs^{400} values than the intact peat. This corroborates well with the findings of Mitchell and McDonald (1992) who showed that catchments with moorland drainage tended to have more highly coloured

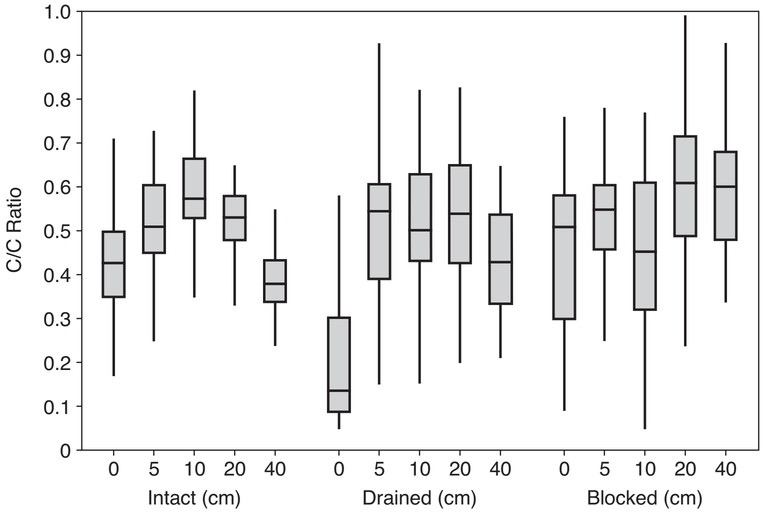

Figure 4 *C/C ratio by depth for each of the three land management treatments*

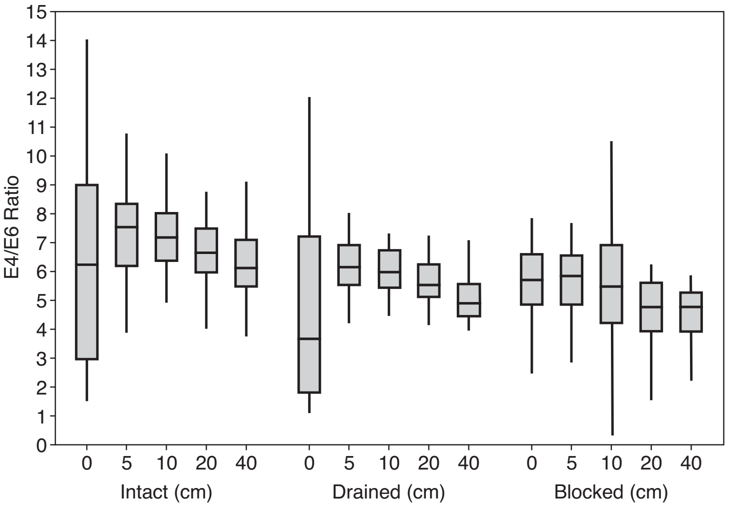

Figure 5 *E4/E6 ratio by depth for each of the three land management treatments*

river water than that of undisturbed peats. However, in addition, this paper has also investigated directly determined DOC concentrations, which were also found to be significantly higher at the drained treatment.

Water samples extracted from the drain-blocked treatment showed that this is a highly successful strategy for reducing both DOC and water colour values from drained blanket peats. Indeed, DOC and colour values at the blocked site were on average 69% and 62% lower than the drained site. Furthermore, DOC and colour values at the blocked treatment were found to be significantly lower than those at the intact peat, which suggests a store exhaustion process. However, the C/C ratio showed that, for every carbon unit, the DOC at the blocked treatment contained significantly more colour than per unit of carbon at the intact or drained sites. The high C/C and low E4/E6 ratios at the blocked site suggest the DOC is obtained from a more humified source than the intact site. This would be a source dominated by larger, more darkly coloured humic rather than fulvic acids, which implies some form of disturbance to the DOC production and/or transportation processes, such as sustained microbial activity at depth (e.g. Freeman *et al.,* 2001) or modified hydrological routing (e.g. Holden *et al.*, in press a). To gauge the likelihood of such mechanisms, it was necessary to assess how the composition of DOC varied at depth across the three treatments.

At the intact site, although there is a trend towards increased DOC and Abs^{400} with depth, analysis of the C/C and E4/E6 ratios indicated that the peat can be divided into two distinct layers: an upper layer consisting of depths 0 to 10 cm, and a lower layer comprising depths 20 to 40 cm. In the upper layer, both the E4/E6 and C/C ratios are significantly higher than the lower layer. This suggests that the upper layer is dominated by immature fulvic acids (from the newly decomposing plant litter), in which there is a relatively high level of microbial activity. Meanwhile, the reduced ratios in the lower layer imply that more mature, darkly coloured, humic acids and a reduced level of microbial activity dominate this part of the peat mass. The lack of activity and accumulation of humified organic matter in this lower layer suggests that this area is anoxic, which implies the water table does not normally exceed 10 cm depth in the intact peat. This was verified by water table measurements at the site, which are reported elsewhere (Holden *et al.*, in press b). The properties of the two layers identified here align with the traditional two-layered model of blanket peats that consists of an upper acrotelm layer and a lower catotelm layer (Ingram, 1978, 1983; Holden and Burt, 2003).

At the drained site, there was a spike in the data at 20 cm, where median DOC and Abs^{400} values were significantly higher than at other depths. When the intact and drained sites were compared, there were no significant differences in the DOC or Abs^{400} values at 0 cm or 5 cm depth. At 20 cm depth, however, the DOC and Abs^{400} values were 39% and 37% greater than the same layer of intact peat. This suggests that the greatest area of influence in elevating DOC and Abs^{400} values at the drained site occurs at around 20 cm depth. Assessment of the C/C and E4/E6 ratios at depth support this finding. The characteristics of the acrotelm layer (as determined by C/C and E4/E6 data for the intact site within the upper 10 cm) are apparent in the drained peat at 20 cm, for significant reductions in the C/C and E4/E6 ratios are not evident at this site until depths >20 cm (i.e. 40 cm). The apparent lowering of the acrotelm base from 10 to 20 cm depth (albeit a conclusion limited by sampling design) would suggest that a greater proportion of the soil body has been oxidised in response to a lowering of the water table. This, in conjunction with increased DOC and Abs^{400} values at 20 cm in the drained peat, suggests that there has been a stimulation of microbial activity at depth in response to a lowered water table (Freeman *et al.,* 2001).

At the blocked site, even though the values are significantly lower than the two other treatments, there is still a pattern of increasing DOC and Abs^{400} with depth. However, the values from 10 cm are significantly lower than those at all other depths in this treatment. The pattern of C/C and E4/E6 ratios for the blocked site suggest that the lower DOC and Abs^{400} values, particularly those at 10 cm depth, are the result of a flushing and subsequent modification of soil layers in response to a rising water table. For example, there was a significant reduction in the E4/E6 ratio between 10 and 20 cm depth, indicating that the base of the acrotelm has been raised in the blocked site to depths <10 cm, indicative of successful water table restoration. Schiff *et al.* (1998) suggested that above the maximum depth of the water table, the water flow is rapid enough to flush out DOC produced in surface layers. They hypothesised that within the catotelm the DOC production may be occurring at lower rates but, as the groundwater flow is much slower, DOC could still accumulate.

The apparent ‘flushing’ of DOC and Abs^{400} in the upper (<10 cm) peat layer, in addition to the significant reduction in the E4/E6 ratio between 10 and 20 cm, suggests the maximum water table depth may have been successfully restored at the blocked site. However, the C/C ratio actually remains significantly higher in the lower layer (>10cm) than the upper layer, which in conjunction with the elevated DOC and Abs^{400} values at such depths, suggests enhanced microbial activity and internal cycling of existing organic matter. This corroborates well with Freeman *et al.* (2001) and Worrall and Burt (2005) who suggest that the reduction in the concentration of phenolic compounds in response to the preceding oxygenation allows decomposition of organic matter to continue at depth, even after the water table has been restored.

Conclusion

Artificial drainage of blanket peat significantly increases DOC and colour values in soil water solutions compared with intact peat. Most of the additional DOC and colour produced came from peat deeper than 10 cm but shallower than 40 cm depth, with observed values at 20 cm enhanced by nearly 40% compared to those of the intact treatment. Assessment of the C/C ratios showed significant deviation from the intact site, specifically at a depth of 20 cm, which suggests the increased DOC and colour values result from modified DOC production and/or transportation processes operating within the peat, such as enhanced microbial activity via oxygenation following water table drawdown.

Drain blocking is recommended as a suitable technique to attempt to remedy the degradation and enhanced DOC and water discolouration associated with such peatland drainage. The drain-blocked treatment saw DOC and colour values successfully lowered by between 60 and 70% compared with the drained site. Furthermore, values at the blocked site were significantly lower than the intact treatment, suggesting some form of store exhaustion and flushing process operating in response to a rising water table. The C/C ratio was significantly higher at the drain-blocked site than either the intact or the drained treatments, whilst the E4/E6 ratio was significantly lower compared to the two other treatments. This indicates that, as well as reducing DOC and colour values, blocking also modifies the composition of DOC, such that darker-coloured humic substances dominate compared to the intact site. Furthermore, a heightened C/C ratio at depth compared to the intact site suggests continued disturbance to the DOC production and/or transportation processes, such as enhanced microbial activity and internal cycling of existing organic matter via an enzyme-latch mechanism.

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