Effects of wind farm construction on concentrations and fluxes of dissolved organic carbon and suspended sediment from peat catchments at Braes of Doune, central Scotland

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SUMMARY

This paper assesses the impacts of disturbance associated with the construction of a wind farm on fluxes of dissolved organic carbon (DOC) and suspended sediment from a blanket peat catchment in central Scotland during the period immediately following completion of construction. Six streams draining the site were sampled on six dates from October 2006, when construction was completed, and an additional three control streams to the west of the site were sampled on the same dates. Turbidity and stage were recorded semi-continuously in the two largest streams (one disturbed and one control), which were also sampled during storm events. Absorbance (400 nm) and DOC concentrations were determined on all samples, and suspended sediment was determined on the event samples. Absorbance and DOC were closely correlated in both the disturbed and undisturbed streams, with slightly greater absorbance per unit DOC in the disturbed streams. DOC concentrations in disturbed tributaries were always greater than those in undisturbed streams, with mean differences ranging from 2 to around 5 mg L^{-1}. DOC and stage were positively correlated during events with maximum concentrations in excess of 30 mg L^{-1} at peak flow. Suspended sediment concentrations were markedly elevated in the disturbed stream with maximum concentrations at peak flow some 4–5 times greater than in the control. The colour of the sediment suggested that it was highly organic in nature at peak flow, and suspended particulate organic carbon represented a further loss of C from the site. Using flow-weighted mean DOC concentrations calculated for the storms monitored in autumn 2007, dissolved carbon losses can be estimated for the catchments of the disturbed and control streams. From these data the additional DOC loss related to disturbance associated with the wind farm is estimated at 5 g m^{-2}.

KEY WORDS: disturbance, peat soil, terrestrial carbon storage, water quality, turbidity.

INTRODUCTION

Soils in Scotland are amongst the most highly organic in Europe (Towers *et al*. 2006). The largest concentrations of soil organic matter are found in the highlands and southern uplands, where the cool and wet climate (> 1500 mm annual precipitation) inhibits decomposition. However, even in the central lowlands with warmer temperatures and annual rainfall generally less than 1500 mm, organic soils are widespread on isolated hill masses. In Scotland as a whole, organic soils (peats, peaty gleys and peaty podzols) cover approximately 50% of the land area (Scottish Executive 2007). Runoff from catchments dominated by such soils often has high concentrations of dissolved organic matter (Aitkenhead *et al*. 2007).

Peat soils contribute significantly to terrestrial carbon storage both globally and in the UK. Organic and organo-mineral soils in Scotland store a total of 2,735 Tg of carbon (Scottish Executive 2007), which amounts to approximately 55% of the UK's terrestrial carbon store. Recent studies suggest that the carbon storage function may be under threat. Bellamy *et al*. (2005) reported significant reductions in percentage organic carbon in soils in England and Wales following re-sampling of National Soils Inventory sites. The reductions were greatest for upland peat soils where the mean rate of decline was 2% per year. However, such losses cannot be directly equated to losses of total soil carbon without knowledge of whether bulk density and soil depth have changed over the same time period (Scottish Executive 2007). Direct evidence of loss of organic carbon from peat soils has also been inferred from the increased concentrations of dissolved organic carbon (DOC) in streams draining upland catchments. Worrall *et al.* (2004b) reported a statistically significant increase in DOC concentrations within the last 2–3 decades at 77% of 198 sites in the UK. The mean annual increase in DOC concentrations was 0.17 mg L^{-1} yr^{-1}. Recent ^{14}C measurements suggest, however, that DOC is generated from relatively young carbon sources in the soil (Evans *et al*. 2007, Harrison *et al*. 2008).

The reported increases in DOC concentrations have been attributed to increased decomposition due to greater mean temperature or changes in hydrology associated with recent climate change (Freeman *et al*. 2001, Evans *et al.* 2002, Tranvik & Jansson 2002). However, such explanations have recently been challenged (e.g. Worrall *et al*. 2004a, Freeman *et al*. 2004, Monteith *et al*. 2007). Reduced deposition of acid sulphur compounds following mitigation measures in the 1980s is one possible contributory factor, as the solubility of humic compounds is pH-sensitive and increased acidity and ionic strength have been shown experimentally to reduce DOC concentrations in laboratory experiments (Evans *et al*. 2006, Monteith *et al.* 2007).

Other pressures drive change in upland peat carbon storage. Glatzel *et al.* (2003) found that DOC fluxes from harvested peatlands in Canada were approximately twice those from natural peatlands. Major construction projects such as wind farms impose similar disturbance to harvesting and might therefore drive increases in carbon fluxes. Disturbance arising from the construction of access roads, drainage channels, turbines, pylons and borrow pits lead to exposure and dewatering of peat, and hence probably to enhanced decomposition rates. Given the reported reductions in percentage carbon in organic soils in England and Wales over the last three decades, further catchment land use activities that might exacerbate the problem need to be identified.

The loss of carbon and sediment to watercourses may also be problematic in terms of ecological impacts on stream systems. Discolouration of water reduces light levels in the water column and on the stream bed, and this may affect primary productivity and feeding of heterotrophic organisms. Moreover, siltation of spawning gravels by fine sediment can reduce the reproductive success of salmonids. Assessment of such ecological impacts is, however, outside of the scope of this paper.

The aim of the work described here is to quantify the impacts of disturbance due to construction of a wind farm on the fluxes of dissolved organic carbon and suspended sediment in streams draining an upland peat site in central Scotland during the immediate post-construction phase.

METHODS

The study area is located on the Braes of Doune, some 15 km north of Stirling in central Scotland (56° 17′ N, 4° 04′ W). The site lies between 370 and 540 m altitude (Figure 1) and mean annual precipitation is approximately 1600 mm. The geology of the site consists of sandstones and conglomerates of lower Devonian (Old Red Sandstone) age which are overlain by glacial tills. Soils have been mapped as blanket peat with depths of up to several metres on the upper slopes. These peat soils showed evidence of fluvial erosion prior to construction of the wind farm, with extensive gullies and wet flush communities on the gully floors (Land Use Consultants 2002). The River Teith (within whose catchment the site lies) is a Special Area of Conservation for its salmon and lamprey populations and Loch Mahaick, some 3 km south of the wind farm, is designated on the basis of its aquatic and fen vegetation as a Site of Special Scientific Interest (SSSI).

Construction of the wind farm was completed in late 2006 and the site was formally opened in February 2007. The wind farm consists of 36 turbines of capacity 2 MW located within a 400 ha site with 20 km of newly laid dirt roads. The site is drained by the south-flowing streams Allt na Criche, Allt a' Bheith and Garvald Burn together with several smaller un-named streams (Figure 1). Significant adverse impacts during construction were reported by a local action group (Friends of the Braes 2007). Those relevant to this paper include siting of quarries within 500 m of watercourses, storage of peat within these quarries, water discolouration, and sedimentation downstream.

Water samples ('tributary samples') were collected from six streams draining the wind farm site in October 2006 and on six dates from July 2007 to February 2008. Three control streams to the west of the wind farm were sampled on the same dates. In September 2007, the largest disturbed stream (Garvald Burn, catchment area 4.5 km^2) and the largest control stream (Annett Burn, catchment area 3.5 km^2) were instrumented for more intensive sampling during times of high flow, when dissolved organic carbon and suspended sediment concentrations were likely to be greatest. Automatic water samplers (ISCO 3700) collected 'event samples' at three-hour intervals during storm events, and at other times at twelve-hour intervals in order to sample from a wider range of flow conditions over longer time periods.

Stream flow was monitored semi-continuously using a Global Water WL16 pressure transducer to record river stage at 15 minute intervals and turbidity was monitored semi-continuously using a Greenspan TS200 turbidity probe (0–1000 NTU), also recording at 15 minute intervals.

All samples were filtered through oven-dried Whatman GF/C filters (nominal pore diameter 0.8 μm) on return to the laboratory. Suspended sediment concentrations were determined on the event samples from the increase in mass of the filters after two hours of oven drying at 105°C. For the filtered samples, colour was determined as absorbance at wavelength 400 nm (Watts *et al*. 2001) using 4 cm quartz cells, and dissolved organic carbon (DOC) was determined using a Shimadzu TOC analyser.

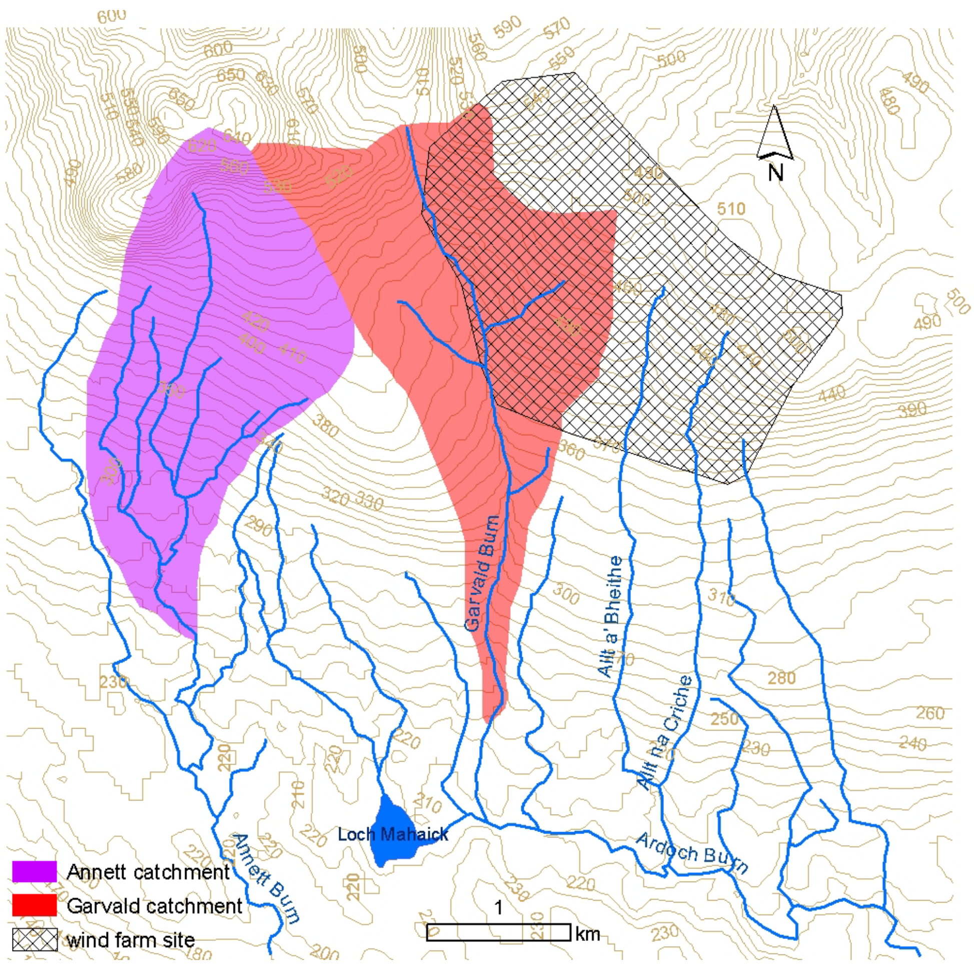


Figure 1. Map showing the location of the Braes of Doune Wind Farm site in relation to the catchments of the Annett (control) and Garvald (disturbed) Burns and other streams. Contour heights are in metres above sea level and the contour interval is 10 m.

RESULTS

Figure 2 shows absorbance *versus* DOC relationships for samples from all nine tributaries (tributary) and from the automatic samplers on the two largest streams (event). There is a strong correlation between the two variables and the linear regression of DOC on absorbance for the combined data set is

$$DOC = 0.5 + 34.2\ Abs_{400} \qquad [1]$$

(r^2 = 0.929, p = 0.000, df = 186), indicating that DOC can be determined reliably from simple measurements of absorbance in these streams. However, in both the tributary (Figure 2a) and event (Figure 2b) samples, there is a difference between the relationships for the undisturbed and disturbed streams. Both relationships are curvilinear and the slope is noticeably steeper for the disturbed streams. The major differences between disturbed and undisturbed streams are seen at DOC concentrations greater than *ca*. 15 mg L^{-1}.

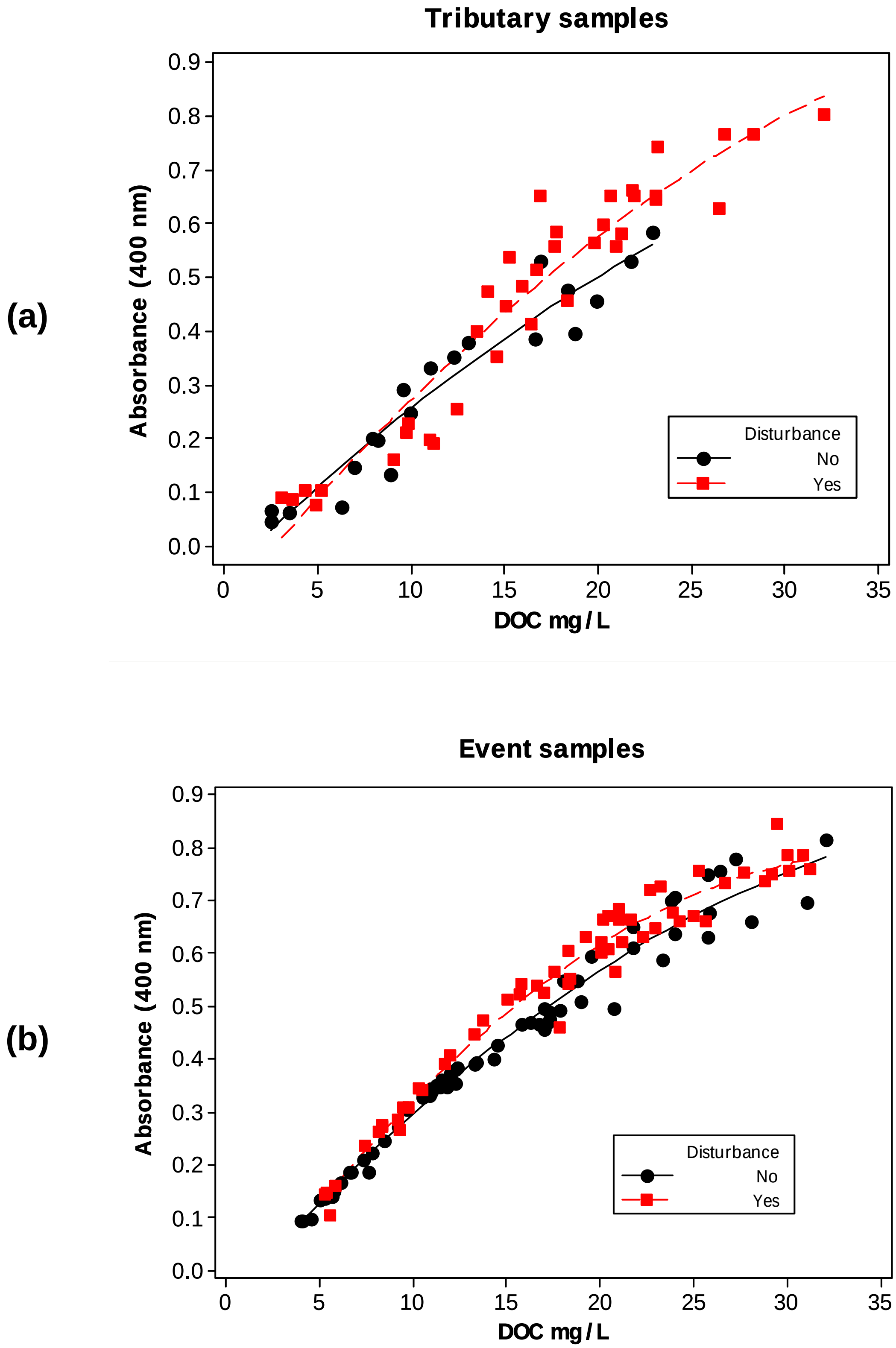


Figure 2. Relationships between DOC and colour for (a) tributary and (b) event samples.

Figure 3 shows the differences in DOC concentrations between the (disturbed) streams draining the wind farm site and the control streams. The disturbed tributaries usually had greater mean concentrations than the undisturbed control streams, with differences ranging from 2 to 9 mg L^{-1}. The differences were tested using a two-way analysis of variance, with disturbance and time of sampling as the "treatments". Both disturbance and time of year had significant effects on DOC concentrations ($F_{1, 45} = 29.0$ and $F_{6, 45} = 40.4$ respectively, $p < 0.001$), but there was no significant interaction between disturbance and time suggesting that the disturbance effect did not change over time. Visual examination of the data in Figure 3 also indicates that there is no evidence that the difference in DOC concentrations between disturbed and control sites is decreasing through time.

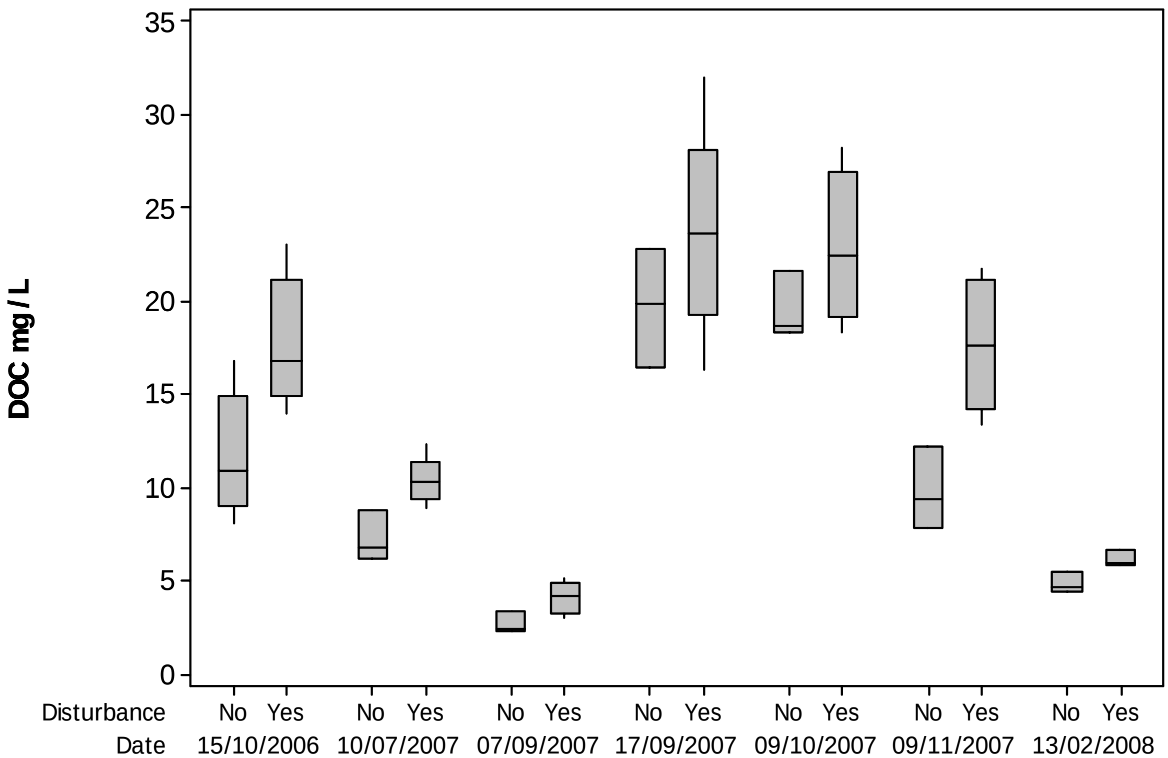
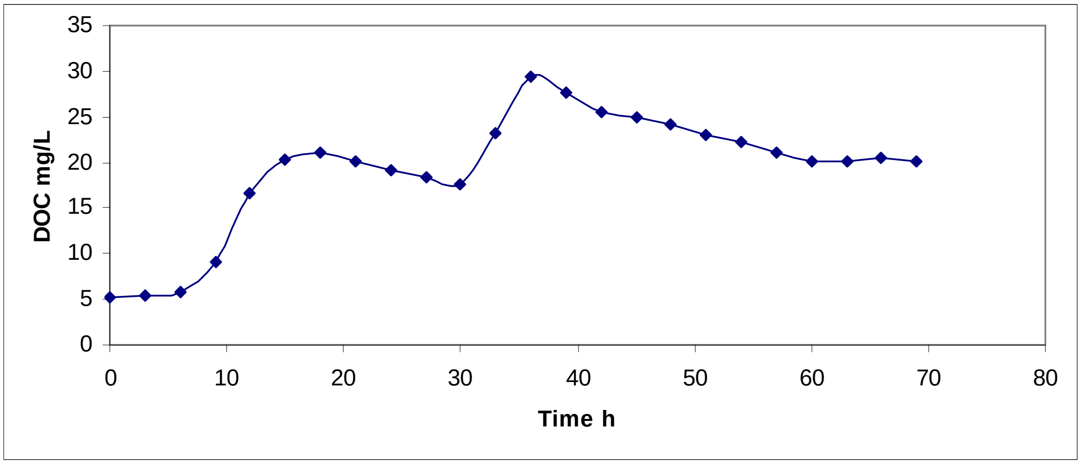


Figure 3. Box-and-whisker comparisons of DOC concentrations in disturbed and control streams at different sampling dates.

Figure 4 shows the variations in DOC and stage over time during a complex storm event in the (disturbed) Garvald Burn during October 2007. Pre-event baseflow concentrations of DOC were approximately 5 mg L^{-1}. The small increase in stage approximately nine hours after the sampler was triggered coincided with an increase of DOC to a peak of more than 20 mg L^{-1} and the later rise in stage at around 40 hours coincided with a rise in DOC to more than 30 mg L^{-1}. DOC concentrations at peak flow were not, however, markedly different in the control and disturbed streams.

Figures 5a and 5b compare DOC and suspended sediment concentrations in the (disturbed) Garvald Burn and the (control) Annett Burn for a sequence of samples collected at twelve-hour intervals under variable flow conditions in November 2007. DOC in the disturbed stream was always greater than that in the control stream. The difference in concentration between the disturbed and control streams for most of that time was approximately 5 mg L^{-1}, or 25–50% of the control stream DOC. These differences decreased with increasing flow, and concentrations near the peaks of the hydrographs were similar.

(a)



(b)

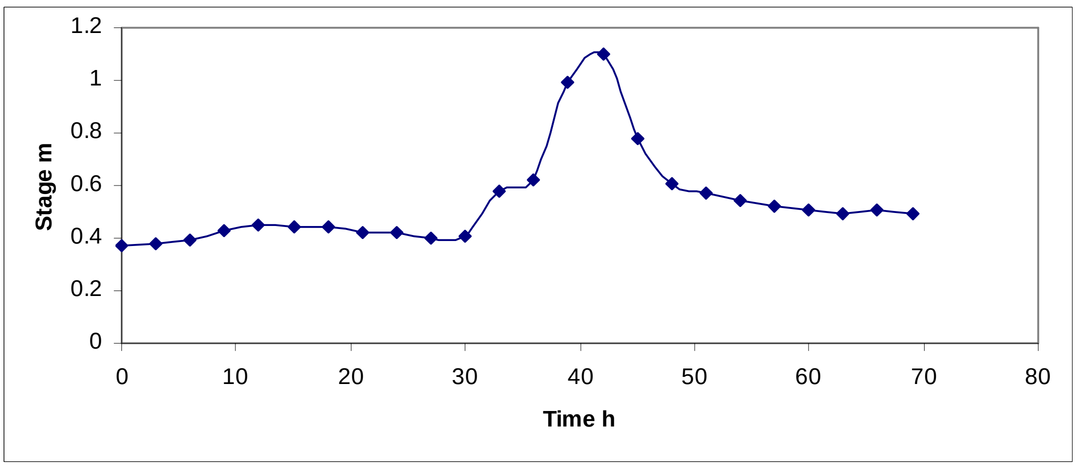


Figure 4. Variations in DOC concentration (above) and stage (below) in the Garvald Burn (disturbed stream), 26–29 October 2007.

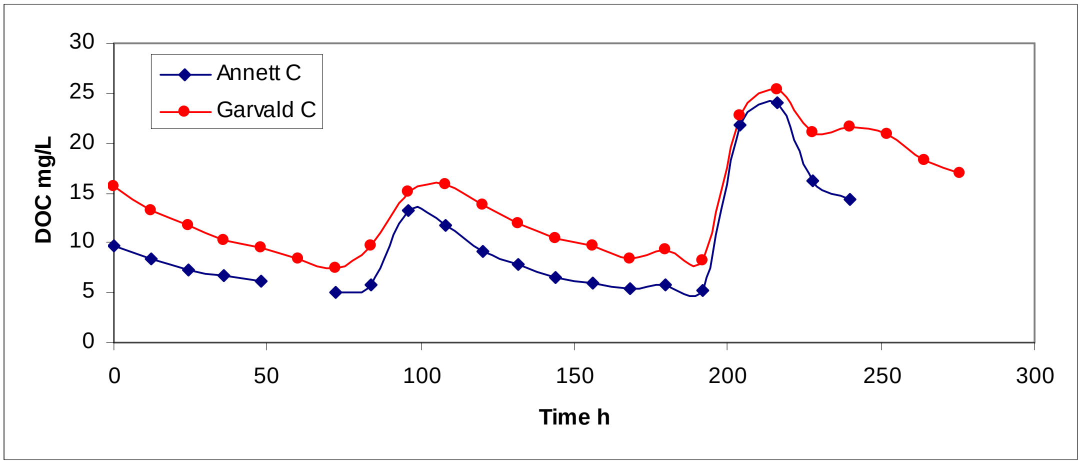
Direct measurements of discharge in the intensively sampled streams were not available. In order to calculate discharge-weighted mean DOC concentrations, discharge was estimated from stage measurements. Stage was measured in near-rectangular, bedrock-controlled sections of each stream and it was assumed that discharge was related to stage by the same power function ($stage^{1.5}$) as for a rectangular flume. Discharge-weighted mean DOC was calculated as:

$$\frac{\sum DOC \times Q}{\sum Q} \qquad [2]$$

where Q represents the estimated discharge. Discharge-weighted mean DOC for the samples collected between September and November 2007 was 16.24 mg L^{-1} in the control stream and 20.53 mg L^{-1} (i.e. 4.3 mg L^{-1} or 26% higher) in the disturbed stream.

Figure 5 also shows that peak suspended sediment concentrations were generally greater in the disturbed stream, with concentrations during high flow around 4–5 times those in the control stream. The maximum suspended sediment concentration measured over the sampling period was 70 mg L^{-1} in the disturbed stream. Turbidity and suspended sediment concentrations were strongly correlated (r = 0.91) and the difference in sediment concentrations between the two streams at high flow over a longer time period is evident from the turbidity graphs for both streams (Figure 6). These data indicate a smaller difference between streams, with the maximum values recorded in the disturbed Garvald Burn (100 NTU) only some 2 times the

(a)



(b)

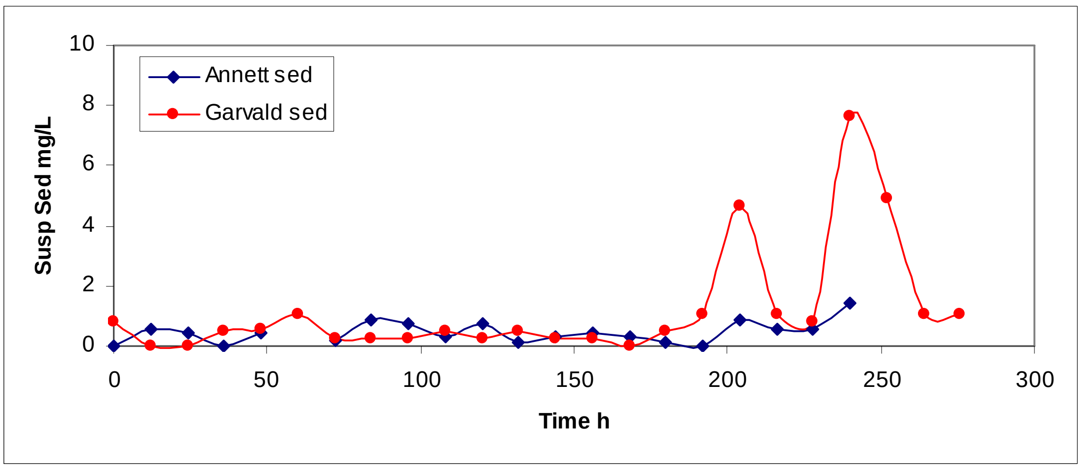


Figure 5. DOC (C) and suspended sediment (sed) concentrations in the Garvald Burn (disturbed stream) and the Annett Burn (control stream), 9–21 November 2007.

maxima in the Annett Burn (40 NTU). Peak turbidities were very short lived in both streams and some discharge peaks were not matched by turbidity peaks, suggesting that exhaustion of the sediment supply occurred on some occasions. Turbidities at low flow were very low in both streams with no evident disturbance effects.

Fluxes of DOC as kg ha^{-1} can be estimated from the discharge-weighted mean DOC concentrations calculated for the storms monitored in autumn 2007. Mean annual precipitation for the Braes of Doune site is 1600 mm (Land Use Consultants 2002) and actual evapotranspiration for Scotland is typically between 350 and 400 mm per annum (Soulsby *et al.* 2002). Annual runoff is therefore likely to be approximately 1200 mm, or 1200 L m^{-2}, per annum. Multiplying runoff by the discharge weighted DOC concentration for the disturbed Garvald Burn catchment (20.5 mg L^{-1}) gives an annual carbon loss as DOC of 24.6 g m^{-2}. For the control burn discharge-weighted mean DOC was 16.2 mg L^{-1}, giving an annual carbon loss of 19.5 g m^{-2}.

DISCUSSION

The strong correlation between absorbance and DOC indicates that the DOC is the major cause of the discolouration of the streams draining this area in the summer and autumn months, although the decrease in slope of the relationship at DOC concentrations greater than 25 mg L^{-1} suggests that increases in DOC above that concentration may not produce proportional increases in colour. The small

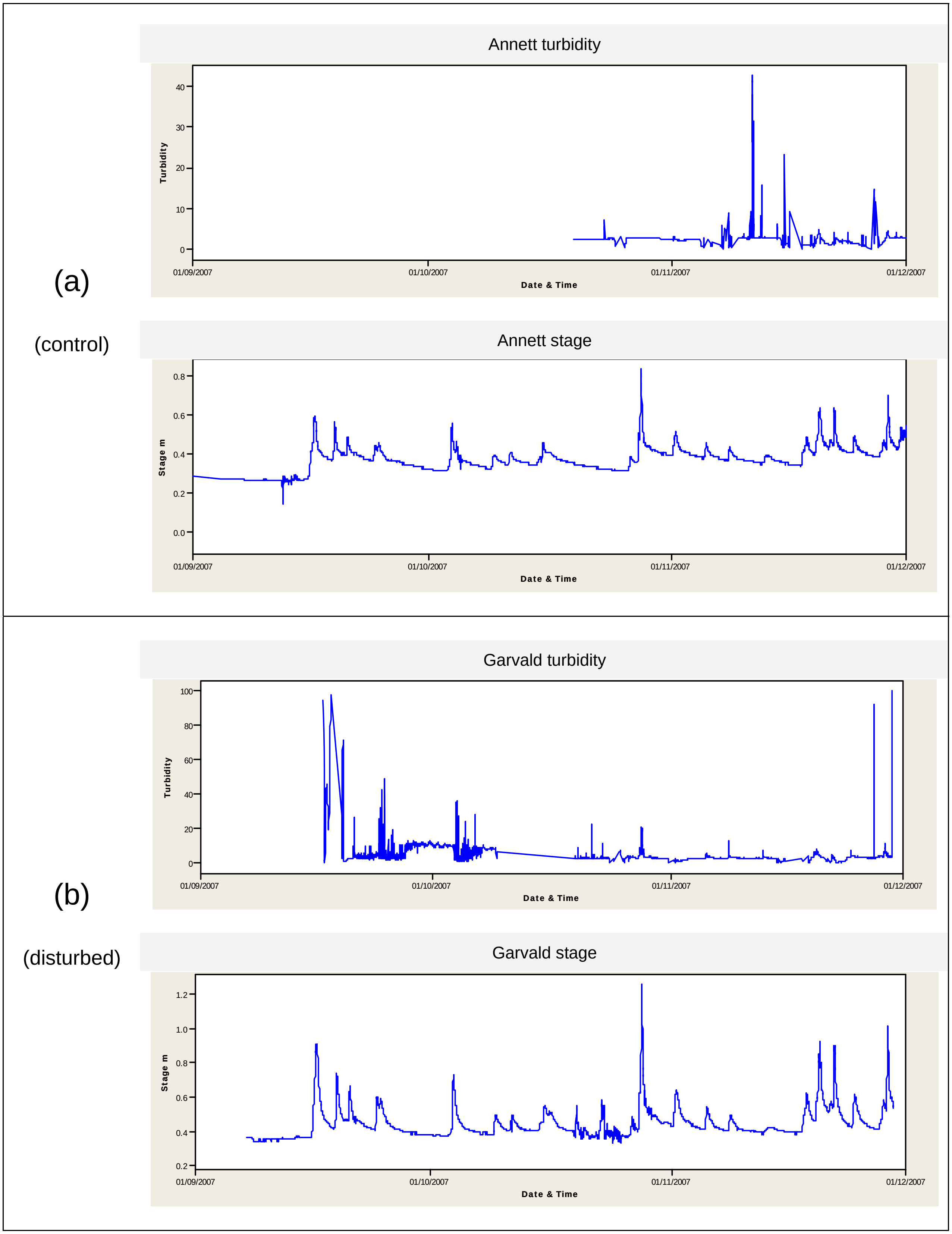


Figure 6. Continuously recorded turbidity (NTU) and stage for events in the two streams.

differences between the disturbed and control streams in the slope of their regression lines indicate that the disturbed streams are more strongly coloured per unit of DOC than the undisturbed streams. These differences are consistent with the greater specific UV absorption and aromaticity found in drainage waters from disturbed peatlands (Kalbitz *et al.* 1999).

The data presented in Figure 3 suggest that disturbance of the peat within the catchments of the streams studied is associated with an increase in DOC concentrations and more coloured waters. The magnitude of these differences is rather less than the increases in DOC concentration found by Glatzel *et al*. (2003) in streams draining catchments with peat disturbed by harvesting, but the disturbance associated with harvesting is likely to be much more widespread within the catchment than the disturbance in the present study. Stream discharge differed between the different dates of sampling in the tributaries, and these dates also represent increasing time since construction activities ceased. The lack of interaction between disturbance and time of year indicates that that neither discharge nor time since construction ended affected DOC differences between the disturbed and undisturbed streams. Figure 3 also suggests that, even a year after construction activities ended, the differences between the disturbed and undisturbed streams was not decreasing with time.

Sampling during storm events showed a clear relationship between stream flow and DOC concentrations (Figure 4). The positive correlation indicates that concentrations of DOC were greatest during storm events when the majority of flow was derived from near-surface quickflow (Grieve 1994). The vast majority of DOC in peat catchments is generated within the acrotelm (Worrall *et al*. 2002), and positively charged surfaces in the mineral subsoils also adsorb DOC thereby reducing baseflow DOC concentrations (Evans *et al*. 2006). The larger (by 26%) discharge-weighted DOC concentration in the disturbed stream relative to the control stream is consistent with previous studies of disturbance effects on DOC fluxes (Glatzel *et al*. 2003).

Semi-continuous sampling showed that annual losses of dissolved organic carbon from the disturbed and control catchments were 24.6 and 19.5 g m^{-2} (246 and 195 kg ha^{-1}) respectively. These losses are larger than the range of values found for temperate forest, moorland and boreal forest catchments in the UK and Europe (Hope *et al*. 1994, Dawson & Smith 2007) and also larger than losses from forested catchments on similar soils and at similar altitudes in west-central Scotland (Grieve 1994). However it should be noted that in the present study sampling was carried out principally during the times of year when DOC concentrations are greatest, and these figures may therefore over-estimate annual fluxes.

The difference in exports between the two burns of 5 g m^{-2} represents the best estimate of the impact of disturbance on annual DOC fluxes in streams draining this wind farm site. The total increase in DOC exports from the disturbed Garvald Burn catchment which can be attributed to disturbance can be estimated by multiplying the 5 g m^{-2} additional loss by the catchment area of 4.5 x 10^6 m^2. These data suggest that the additional annual loss of carbon attributable to disturbance at the 400 ha wind farm site is of the order of 22.5 Mg, many orders of magnitude smaller than the carbon savings claimed for wind farms when compared to electricity generation from non-renewable sources. However disturbance may also increase losses of C in other forms, including gases and particulates.

The mass of sediment trapped on the filters was insufficient to allow determination of its organic content. Nonetheless, the dark brown colour of the sediment collected on the filters suggests that sediment collected at peak flows is highly organic in nature. If this is the case, particulate organic carbon (POC) would represent a further loss of C from the site, in addition to the DOC losses. However, even assuming that all the sediment was organic (i.e. 50% C), the maximum concentrations of particulate C would be approximately 30–35 mg L^{-1}. Therefore losses of C as POC are likely to be substantially less than losses as DOC, since the high POC concentrations were sustained for much shorter periods of time than were the maximum DOC concentrations.

The increased losses of DOC due to disturbance in the catchments are most likely linked to increases in decomposition rates of soil organic matter in the large areas of peat which have been disturbed, exposed and have not re-vegetated during and since construction. Blanket peatlands in the UK uplands are generally regarded as a net carbon sinks sequestering between 10 and 20 g m^{-2} carbon annually (Holden 2005). Peatlands in the Pennine hills in northern England which have been subject to excessive grazing and erosion over many centuries can, however, be net carbon sources, with annual losses of 11 g m^{-2} reported (Worrall *et al*. 2007). These authors also indicate that net carbon losses could double due to changing climate over the next decade. The increase of 5 g m^{-2} in losses of dissolved organic carbon attributed to disturbance by this wind farm development in central Scotland represents between 25% and 50% of net annual carbon sequestration in peatlands, and so adds significantly to the potential impacts of climate change on the status of blanket peat soils as carbon sinks or sources.

CONCLUSIONS

Significantly increased concentrations of DOC and sediment were observed in the streams draining the wind farm site, although the overall impact on carbon losses from the site *via* dissolved organic carbon fluxes in streams (20 Mg) is likely to be small in comparison to carbon savings associated with the wind farm. However, the increase in carbon exports estimated at 5 g m^{-2} a^{-1} for this development represents a significant flux within the net peatland carbon balance. The impacts of greater DOC and sediment concentrations on the stream systems are also likely to be significant through discolouration, reduction of light transmission through the water column and siltation of salmonid spawning gravels.

Suspended sediment losses continue to be significantly elevated, even after construction activities at the site have ceased. Wash of fine sediments into and from the road network on the site and ineffective provision for trapping this sediment probably explain the continued high losses.

Monitoring and sampling over the next few years will help to ascertain whether the losses observed in the short term are sustained and/or the level of reduction with time as vegetation is re-established on disturbed areas of peatland.

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