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Sediment and fluvial particulate carbon flux from an eroding peatland catchment

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Abstract

Erosion and the associated loss of carbon is a major environmental concern in many peatlands and remains difficult to accurately quantify beyond the plot scale. Erosion was measured in an upland blanket peatland catchment (0.017 km^2) in northern England using Structure-from-Motion (SfM) photogrammetry, sediment traps and stream sediment sampling at different spatial scales. A net median topographic change of –27 mm yr^{-1} was recorded by SfM over the 12-month monitoring period for the entire surveyed area (598 m^2). Within the entire surveyed area there were six nested catchments where both SfM and sediment traps were used to measure erosion. Substantial amounts of peat were captured in sediment traps during summer storm events after two months of dry weather where desiccation of the peat surface occurred. The magnitude of topographic change for the six nested catchments determined by SfM (mean value: 5.3 mm, standard deviation: 5.2 mm) was very different to the areal average derived from sediment traps (mean value: –0.3 mm, standard deviation: 0.1 mm). Thus direct interpolation of peat erosion from local net topographic change into sediment yield at the catchment outlet appears problematic. Peat loss measured at the hillslope scale was not representative of that at the catchment scale. Stream sediment sampling at the outlet of the research catchment (0.017 km^2) suggested that the yields of suspended sediment and particulate organic carbon were 926.3 t km^{-2} yr^{-1} and 340.9 t km^{-2} yr^{-1} respectively, with highest losses occurring during the autumn. Both freeze–thaw during winter and desiccation during long periods of dry weather in spring and summer were identified as important peat weathering processes during the study. Such weathering was a key enabler of subsequent fluvial peat loss from the catchment.

KEYWORDS: erosion; Structure-from-Motion; topographic change; desiccation; wetland

Introduction

Peatlands cover approximately 4.23 million km^2 (2.84%) of the world's land area (Xu et al., 2018b). They store an equivalent of around two thirds of carbon stored in the atmosphere (Yu et al., 2010). Peatlands in the UK are highly valued because they provide a wide range of ecosystem services such as water supply (Xu et al., 2018a), biodiversity and recreation (Holden et al., 2007, Bonn et al., 2009) and the largest terrestrial carbon pool (Cannell et al., 1993, Milne and Brown, 1997). Though peatlands form an important carbon reserve, they can be degraded under a wide range of internal and external pressures (Parry et al., 2014). Numerous studies have suggested that peatlands can be both sinks and sources of carbon to the environment (Clay et al., 2012, Holden et al., 2007). Land management practices and pollution have led to disturbance of peat surfaces, resulting in large areas being extensively eroded (Li et al., 2016b, Li et al., 2018a) or under increasing erosion risk (Li et al., 2016a, Li et al., 2017) in many peatlands of the UK. The physical disturbance of peat by weathering processes (e.g., freeze–thaw and desiccation) and erosive forces (e.g., water and wind) has the potential to considerably affect the ability of peat to sequester carbon (Evans and Warburton, 2007).

Fluvial organic carbon fluxes in both particulate and dissolved forms are important links between terrestrial peatland carbon stores and the ocean carbon sink (Hope et al., 1997, Goulsbra et al., 2016, Stimson, 2016). Fluvial carbon is also subject to oxidation representing an important link between terrestrial and atmospheric carbon pools (Pawson et al., 2012, Shuttleworth et al., 2015). While dissolved organic carbon (DOC) fluxes have been well studied (e.g., Worrall et al. (2003), Worrall et al. (2009), Evans et al. (2006)), particulate organic carbon (POC) losses from peatlands has been much less studied (Pawson et al., 2012, Billett et al., 2010). In less severely eroded or intact peatland systems, POC is usually 5–50% of the total organic carbon load (Hope et al., 1997, Dawson et al., 2002). However, for eroding headwater catchments the POC flux represents an even larger proportion of fluvial organic carbon export (Pawson et al., 2008, Evans and Warburton, 2005). For example, Pawson et al. (2008) reported that POC flux from an eroding site in the English Peak District represented over 80% of the total organic carbon fluxes (107 g C m^{-2} yr^{-1}) from the system. A similar magnitude of POC flux has been historically reported from other eroding peat systems in northern England (Crisp, 1966, Evans and Warburton, 2005). In headwater systems, active erosion forms such as gullies typically export large amounts of POC to peatland streams (Evans et al., 2006, Evans and Warburton, 2007, Evans and Lindsay, 2010). Assessing the temporal patterns of POC from eroding peatlands has the potential to provide insight into the controls on fluvial carbon flux from these systems (Pawson et al., 2012, Shuttleworth et al., 2015). It can also provide important baseline data to assess effects of restoration projects on carbon fluxes in the fluvial system.

Weathering processes such as frost action and desiccation play an important role in supplying erodible peat particles for fluvial transport (Shuttleworth et al., 2017, Li et al., 2018a). Frost weathering - resulting from the freezing and thawing of water between peat particles - is common in cool, high latitude or high altitude climates which support many peatlands. This frost action plays a vital role in breaking up the peat surface during winter months (Francis, 1990, Labadz et al., 1991, Li et al., 2018b). A major form of frost weathering on peat is needle-ice which is important in producing eroding peat faces (Tallis, 1973, Luoto and Seppälä, 2000, Grab and Deschamps, 2004) with ice crystal growth gradually weakening and finally breaking peat soil aggregates and the subsequent warming and thawing weakening or loosening the fractured peat. The growth of needle ice can lead to a ‘fluffy’ peat surface that is loose and granular and vulnerable to being flushed off by overland flow events (Li et al., 2018b, Evans and Warburton, 2007). Surface desiccation during extended periods of dry weather is another important weathering process for producing erodible peat (Burt and Gardiner, 1984, Evans et al., 1999, Francis, 1990, Holden and Burt, 2002). Francis (1990) monitored erosion in a mid-Wales blanket peat catchment (Plynlimon) during two drought years (1983–1984) and found that frost action appeared to be of relatively little importance; and instead summer desiccation was far more significant. Li et al. (2016a) modelled the effect of future climate change on UK peatlands and found that peat desiccation is likely to become more important in blanket peatlands as a result of warmer summers. However, additional field monitoring data is required to parameterize models of the temporal dynamics of peat erosion and their responses to climate change (Li et al., 2017).

Different peat erosion processes are active at different spatial scales (Li et al., 2018a). For example, rainsplash, interrill and rill erosion are the dominant erosion processes studied at fine scales (erosion plots) (Holden et al., 2008, Li et al., 2018c, Li et al., 2018b, Holden and Burt, 2002, Grayson et al., 2012). For larger hillslopes and small and medium-size catchment scales (1000 m^2 – 1 ha), gully erosion and mass movements become more important, yielding large quantities of sediment (Evans and Warburton, 2007, Evans et al., 2006, Evans and Warburton, 2005). At the large basin scale (> 1 ha) long-term (> 1 year) erosion and sediment deposition processes are potentially more important due to large sediment sinks (footslopes and floodplains) (De Vente and Poesen, 2005). Further research is needed on the role of streams as sediment sources and (temporal) sinks. Multi-scale studies to facilitate spatial upscaling of erosion rates and provide data on the spatial connections between different units at each scale are necessary.

This paper addresses the key knowledge gaps by assessing the hydrosedimentary dynamics of a peat-dominated catchment over the course of a year. The specific objectives are to: (i) measure fluvial suspended sediment and POC fluxes from an eroding headwater peatland system; (ii) describe the dynamics of suspended sediment transport at different temporal scales (seasonal and monthly); and (iii) compare peat erosion rates measured by different techniques (sediment traps, SfM photogrammetry, sediment sampling) at different scales (plot, mini-catchment and catchment).

Materials and methods

Study area

Extensive peat erosion in the UK occurs across many upland systems but particularly in the Pennine region of England (Bower, 1960b, Bower, 1961, Evans and Warburton, 2007). Fleet Moss (54°14´55´´N, 2°12´53´´W) is an area of approximately 1.0 km^2 with blanket peat deposits of up to 2m depth, at an altitude of 550–580 m in the Yorkshire Dales National Park in North Yorkshire, England (Figure 1). The vegetation is dominated primarily by Eriophorum vaginatum, Calluna vulgaris and Empetrum nigrum. The research catchment (0.017 km^2) within Fleet Moss (Figure 2) has a large area of exposed bare peat covering 60% of the catchment, as estimated from aerial images. There are a range of erosion forms (interrill and rill erosion and gullying). There are well developed and connected Type 1 and Type 2 gully systems as classified by Bower (1960a). On the flatter interfluve areas (slopes less than 5°), Type 1 dissection usually occurs with gullies branching and intersecting in an intricate dendritic network. On steeper slopes (exceeding 5°), Type 2 dissection dominate s with a system of sparsely branched drainage gullies incised through the peat and aligned nearly parallel to each other.

< Figure 1 is here >

Data acquisition: monitoring and sampling

Data on climate parameters, discharge, sediment, POC and topographic changes were collected between October 2016 and November 2017. Discharge, sediment and POC were measured at the outlet of the research catchment (1.7 ha). For a 990 m^2 area within the 1.7 ha catchment, sediment was collected by traps and SfM surveys were conducted.

Climate data

Rainfall was logged every 15 minutes with a tipping bucket raingauge during the course of the study. Temperature for the air and soil was measured using Tinytag Plus 2 loggers (resolution 0.01 ºC) at 10-minute intervals from 26/10/2016 to 20/07/2017 after which a logger failure meant data collection ceased. The air temperature sensor was housed in a radiation shield approximately 1.5 m above the ground surface. The soil temperatures sensors were located at surface, 5 cm and 10 cm depths.

Topographic change measured by SfM photogrammetry

SfM photogrammetry is a technique that is low cost and quick to use in terms of data acquisition and post-processing and thus was used to measure topographic change. Over the study period (26/10/2016–02/11/2017), a mini-catchment (990 m^2) was surveyed six times (Table 1). Since weather conditions during field campaigns significantly influence data quality (Snapir et al., 2014, Stöcker et al., 2015), image acquisition was arranged under conditions with no rain, no snow cover or no sunny weather to avoid producing strong shadows on images. Areas near the catchment boundary were subject to poorer quality SfM data (point clouds were sparse with large empty areas or vegetated points). Therefore, the SfM data analysis focused on a 598 m^2 central part of the catchment (yellow boundary shown in Figure 2).

< Figure 2 is here >

< Table 1 is here >

Abundant high-quality images were taken at positions and angles that have sufficient coverage of the peat erosion features of interest. In specific erosion features (i.e. gully heads, peat hagg), the density of images from additional perspectives was increased for further detailed reconstruction. The camera used was a Sony ILCE-6000 24 mega pixel digital camera with a 16 mm focal length. Camera settings varied based on light conditions, with exposure between 160 and 320 ISO, F-stop between f/4 and f/4.5 and exposure time between 1/160 and 1/80 second. Fourteen permanent Ground Control Points (GCPs) made of rebar (0.5–1.0 m in length) with a painted white top (high contrast with the dark peat surface) were placed around and within the feature of interest. The rebar was hammered deep into the substrate below the peat. A geodimeter was used and full surveys of the relative coordinates of all the GCPs were carried out at the start of the monitoring period.

Images acquired were processed using the commercial software Agisoft PhotoScan, to produce a dense point cloud based on the workflows described in Li et al. (2019). Poorly located GCPs were excluded; however, a minimum of six GCPs that were well distributed over each site remained (Fonstad et al., 2013, Smith et al., 2014). Point-cloud quality was evaluated by summarizing residual errors using root mean squared error (RMSE) (Smith et al., 2014), and mean georeferencing uncertainty was 40.5 mm (Table 1). The derived dense point clouds contained both bare peat surface and vegetation points. Vegetation was filtered through selecting vegetation points based on RGB values embedded in the point cloud and the filtering was conducted in the open source CloudCompare software. Cloud-to-cloud differencing was computed using the Multiscale Model to Model Cloud Comparison (M3C2) algorithm that quantifies 3-D distance between two point clouds along the normal surface direction and provide a 95% confidence interval based on the point cloud roughness and co-registration uncertainty (Lague et al., 2013). M3C2 requires two main user-defined parameters: i) the normal scale D, which is used to calculate a surface normal for each point and is dependent upon surface roughness and registration error; ii) the projection scale d within which the average surface elevation of each cloud is calculated. In this study, the normal scale D for each point cloud was estimated based on a trial-and-error approach similar to that of Westoby et al. (2016) and was fixed at 0.5 m. The projection scale d was specified as 0.1 m and this scaling was enough to average a minimum of 30 points sampled in each cloud (Lague et al., 2013). M3C2 output was subsequently masked to exclude points where change is lower than level of Level of Detection (LoD) threshold for a 95% confidence level ($\text{LoD}_{95\%}$), which is defined as:

$$LOD_{95\%}(d) = \pm 1.96\left(\sqrt{\frac{\sigma_1(d)^2}{n_1} + \frac{\sigma_2(d)^2}{n_2}} + reg\right) \quad (1)$$

where σ_1 and σ_2 represent the roughness of each point in sub-clouds of diameter d and size n_1 and n_2, and reg is the user-specified registration error which is assumed to be isotropic and spatially uniform across the dataset (Lague et al., 2013). The surface-to-surface Interactive Closest Point algorithm implemented in CloudCompare was used to align a patch of two inactive point clouds. The registration error was estimated by a series of tests and it ranged from 7.0 to 8.0 mm for the field models. Data analyses were conducted between individual survey dates with dates and intervals presented in Table 1. Between 26/10/2016 and 02/11/2017 the 6 repeat topographic surveys yielded 5 survey intervals (e.g., 2–1; 3–2), and a long-term survey interval (6–1) which was selected to represent potential large topographic changes.

DEMs were derived from the dense point clouds gridded at 0.01 m. The DEM data used a relative coordinate system, with the point clouds georeferenced using local GCPs. Two transect profiles (Figure 2) were selected to extract data from the DEMs to reveal the changes in relative coordinates.

Peat eroded through fluvial processes

A series of sediment traps (Baynes, 2012, Fewings, 2014) were used to measure the quantity of peat eroded by fluvial processes from different parts of the catchment from 04/11/2016 to 21/08/2017 (Figure 2). The traps were made of weaved polypropylene bags which allow water to drain through the sack, but ensure any peat transported in suspension is trapped. The trapping efficiency was assessed in the laboratory by pouring 1 L peat solution (100 g L^{-1}) into a polypropylene bag over a plastic box and allowing water to seep for 24 hours. The collected solution was poured into weighed beakers, oven-dried, and weighed. The trapping efficiency of the sacks determined by this experiment was 91.7 ± 0.5 %. In the field the trapped peat materials were weighed as field moisture weight. Five subsamples were collected and sealed in plastic bags, returned to the laboratory, oven-dried, and weighed. The moisture contents of the subsamples were calculated, then averaged and multiplied by the field moisture peat weight, allowing the estimation of field dried peat weight. The traps installed in the field were renewed periodically.

Stream discharge and catchment sediment yield

Steam discharge (Q) was monitored at a cross-section with a ‘U’ shape at the outlet of the research catchment (1.7 ha) using automatic pressure sensors. Unfortunately the water level data collected by the logger could not be used as the shallow nature of the channels resulted in poor quality data due to issues with temperature compensation. Therefore daily discharge data were interpolated from the rainfall-runoff relationship (rainfall x study area). Previous studies in UK headwater blanket peatlands have shown the runoff coefficient to be > 80% (Evans et al., 1999, Holden et al., 2012, Marc and Robinson, 2007, Holden et al., 2017). Evapotranspiration is expected to be low over the research catchment used in this study due to large areas of bare peat. The runoff coefficient was therefore assumed to be 0.9 in this small headwater peatland catchment.

An automatic pump sampler (ISCO 6712C) was used to take samples once per day at 13:00 (UTC +2) from 26 October 2016 to 01 November 2017. Samples were filtered through Whatman GF/F 47 mm (0.7 µm) circle filter papers in the laboratory. Total suspended sediment concentrations (SSCs) were measured by oven-drying at 105 ℃ to constant weight. All water samples contained both inorganic and organic fractions. POC was determined by first conducting loss-on-ignition tests in a muffle furnace at 375 ℃ for 16 hours to give organic matter content that was then converted to POC using the method of Ball (1964).

The suspended sediment yield (Q_s: kg d^{-1}) was calculated by $Q_s = SSC \times Q$, where SSC (kg m^{-3}) and Q (m^3 d^{-1}) are suspended sediment concentration and discharge, respectively. The values of suspended sediment yield Q_s were regressed against discharge Q using measured daily data for different months and the total study period. A power function, $Q_s = aQ^b$, widely used to estimate transport, where a and b are empirical constants, was applied to form a Q_s fit for different events and months. The POC yield (Q_{POC}: kg d^{-1}) and the rating curve for Q_{POC} were calculated in the same way with Q_s.

Data analysis

Peat loss obtained from SfM was converted to an estimate of weight loss using peat bulk density values from the study site. Regression analysis was used to identify the relationship between SS or POC loads and daily discharge. Test results were considered significant at $p < 0.05$. The area-specific sediment yields measured from plots, a series of nested mini-catchments, and stream sampling measurements for the whole study area were compared.

Results

Peat surface topographic change measured by SfM

M3C2 differences above Level of Detection threshold at 95% confidence level ($LoD_{95\%}$) over different survey intervals are given in Table 2. The spatial distribution and histogram of M3C2 differences for different comparisons are shown in Figure 3. M3C2 distances ranged from negative values marked with red colour to positive values marked with blue colour. In this study the ‘positive M3C2 distance’ more accurately reflects topographic change that could be caused by both deposition and swelling processes; while ‘negative M3C2 distance’ could also be attributed to both erosion and shrink processes (Grayson et al., 2012, Evans and Warburton, 2007, Glendell et al., 2017).

< Table 2 is here >

From 04/11/2016 to 02/05/2017, there were large areas of the peat surface (69%) showing significant change (i.e. M3C2 distance > $\mathrm{LoD}_{95\%}$). Net topographic change was –18 mm, with a high variability as shown in the large root mean square (RMS) of the M3C2 distance which was 85 mm (Table 2). The magnitude of the negative topographic change yielded a median change of 65 mm, which was much greater than the median positive topographic change (50 mm) (Table 2). This period had the greatest total rainfall but low rainfall intensity and 57 days of temperatures below 0 ºC. These conditions may cause surface expansion due to freezing. The spatial variability of the changes showed that negative topographic change mainly occurred on hillslopes along the main stream networks (Figure 3 (a)), with 52% of the total area that is above the $\mathrm{LoD}_{95\%}$ (Table 2). In contrast, positive topographic change was found predominantly on the north-east, north-west and southern edge areas of the catchment (Figure 3 (a)) where overland flow paths were not connected and bare peat areas are surrounded by dense vegetation cover (Figure 2).

The next survey interval (Model 3–2: 02/05/2017–13/06/2017) experienced greater topographic changes in both magnitude (median = –29 mm) and extent (77% of the total area = 461.8 m^2) (Table 2) than the first survey interval (Model 2–1). The positive topographic change was observed in the upper stream areas, i.e. north-east and south parts of the catchment (Figure 3 (b)). Model 4–3 (from 13/06/2017 to 21/08/2017) had a longer time interval (70 days) than the previous interval (Model 3–2, 43 days), but displayed smaller areas with significant topographic changes (72%) within the catchment (Table 2). Positive topographic change was more extensive (60% of the area), leading to a net positive topographic change (Table 2 and Figure 3 (c)). A small zone of negative change was evident in the central-south part of the study area (Figure 3 (c)). For Model 5–4 (21/08/2017–27/09/2017), 73% of the area is above the $\mathrm{LoD}_{95\%}$, among which 60% of the area is dominated by negative topographic change. Finally, the survey interval from 27/09/2017 to 02/11/2017 (Model 6–5) demonstrated 73% of the catchment area had significant change.

< Figure 3 is here >

The topographic change between the first survey (04/11/2016) and last survey (02/11/2017) (364 days, Model 6–1) was significant over 69% of the area. Positive topographic change was present in 42% of the area above the $\mathrm{LoD}_{95\%}$ while negative topographic change was dominant in extent (58%). The median negative topographic change rate was 71 mm, which was greater than the median positive topographic change rate (50 mm). Zones of intense negative topographic change were observed on the hillslopes, while there was a clear zone of deposition visible along the main drainage lines (Figure 3 (f)).

Two example transects were examined over the catchment where topographic changes were significant. Figure 4 shows the vertical difference between a series of surface elevation profiles across the profile AA’ and BB’. For profile AA’ the elevation was initially high at approximately 2.0 m, 3.1–4.0 m and 9.5 m distance along the profile on 04/11/2016 (Figure 4 (a), grey line), however, these sections experienced pronounced negative topographic changes during the subsequent field surveys. The maximum vertical displacement was about 500 mm at 3.2 m along the transect. For the sections between 0 and 1.8 m and 4.0 and 5.5 m along the transect, the surface elevation surveyed on 04/11/2016 was significantly lower than for the later surveys, indicating positive topographic changes occurred after the first field survey. For profile

BB', there was significant surface lowering at a distance 9.0 to 10.0 m along the transect with a maximum vertical displacement of ~700 mm. The survey on 13/06/2017 recorded surface elevation significantly higher at 5.0–7.0 m along the transect than those of the other surveys.

< Figure 4 is here >

Sediment production measured by sediment traps

Loss measured by sediment traps on the tributaries

Over the 10-month period of sediment trap observation, they captured 30.75 kg of peat (oven-dry weight). The sediment trapped during the intervals 13/06/2017–21/08/2017, 04/11/2016–23/03/2017 and 23/03/2017–07/04/2017 were 10.71 kg, 9.60 kg and 8.53 kg, respectively (Table 3). In contrast, the sediment trapped between 07/04/2017 and 13/06/2017 was significantly lower ($p < 0.05$) than for other survey periods, with a value of 1.91 kg. Among the six sediment traps T3 and T5 generally collected more sediment than other traps (Table 3), indicating that source areas of T3 and T5 were more actively eroding.

< Table 3 is here >

Over the full monitoring period T3 had the highest peat loss rate of 0.6 g m^{-2} d^{-1}, followed by T6 (0.5 g m^{-2} d^{-1}) and T1 (0.4 g m^{-2} d^{-1}) (Table 3). The total sediment captured by T2 was lowest, with 0.1 g m^{-2} d^{-1}. Among the different monitoring periods the interval 23/03/2017–07/04/2017 had the highest peat loss rate; while 07/04/2017 to 13/06/2017 had the smallest peat losses (Table 3).

Comparing SfM and sediment trap data

The sediment trap data allowed a comparison of ground recession to be made with SfM measurements. The peat loss data, expressed in kilograms and surface change (mm), derived from both the sediment traps and SfM is shown in Figure 5. The peat loss (dry weight) rate measured by the sediment traps ranged from 0.0 kg to 4.7 kg, with a mean value of 1.8 kg (standard error of mean is 0.3 kg) however this does not take into account any deposition that may take place. In contrast, the SfM measurements indicated both positive and negative values, allowing not only areas of erosion and deposition to be identified but also periods of time. At the catchment scale, the SfM method resulted in an estimated mean peat deposition rate of 93.3 ± 55.5 kg (5.3 ± 5.2 mm), compared with a mean peat loss rate of 1.8 ± 0.3 kg (0.3 ± 0.1 mm) derived from the sediment traps across the catchment (Figure 5). From the M3C2 distances and histogram of differences (Figure 3), there were both erosional and depositional areas within the catchment and these features were captured by SfM.

< Figure 5 is here >

Stream discharge and suspended sediment loads

Empirical suspended sediment-transport rating curves

A power law ($Q_s = aQ^b$) performed well in describing the relationship between suspended sediment yield (Q_s) and discharge (Q). However, the sediment rating curves differed between different months (Figure 6). High uncertainty with a low coefficient of determination (R^2) of the regression equations was found from February to June 2017. The values of coefficients a and b, which indicate erodibility and erosive power of flow respectively, varied considerably among different months. The regression curve for the whole study period was $Q_s = 49505Q^{1.0441}$ ($n = 176$, $R^2 = 0.6817$, $p < 0.05$).

< Figure 6 is here >

Stream discharge and suspended sediment (SS) loads

Mean daily stream discharge estimated by the rainfall-runoff relationship for the 12-month monitoring period was 0.0013 $m^3 s^{-1}$ (Table 4). Flows ranged over two orders of magnitude, with a minimum mean discharge of 0.0001 $m^3 s^{-1}$ and a maximum mean discharge of 0.0021 $m^3 s^{-1}$. There were 53 days when discharge exceeded 0.0021 $m^3 s^{-1}$ during the study period (Figure 7). The majority of high flows occurred in the autumn months (September and October) and early spring 2017 (March).

Suspended sediment (SS) loads ranged from 0.002 to 6.236 t with a total value of 14.822 t (Table 4). Despite some breaks in the record, some seasonal patterns can be identified. Both SS and POC loads were low during late spring months (April and May) and increased in the late summer and autumn and were highest in October. For most of April to June 2017, discharge was maintained at a low level and very little sediment was transported to the catchment outlet. However, there were two high flow events (daily mean discharge rate > 0.006 $m^3 s^{-1}$) in late May and June which mobilised a considerable amount of sediment (Figure 7).

< Table 4 is here >

< Figure 7 is here >

Particulate organic carbon loads

The relationship between POC load (Q_{POC}) and discharge (Q) was well described by a power law ($Q_{POC} = aQ^b$) (Figure 8). Similar to the SS rating curves, the POC rating curves had high uncertainty from February to June 2017. The values of coefficients a and b varied significantly among different months. The regression curve for the whole study period was $Q_{POC} = 15776Q^{1.0061}$ (n = 144, $R^2 = 0.6245$, $p < 0.05$). POC loss ranged from 0.000 to 2.444 t per month, and the total POC flux was 5.454 t which accounted for 36.8% of the total suspended sediment load.

< Figure 8 is here >

Scale effect of sediment production in headwater peatlands

The relationship between sediment yield and area is shown in Figure 9 also illustrating which data were derived from the different approaches at the study site. At the fine scale with area ranging from 1×10^{-5} to 1×10^{-3} km^2, sediment yield generally decreased with increasing area. Spearman's Rank correlations between sediment yield and area showed that the relationship was significant at p = 0.052 at the fine scale (i.e. only marginally beyond a standard 95 % confidence level). The sediment yield at the outlet of the whole study area was highest. Spearman's Rank correlations between the sediment yield and area showed that the relationship was not significant (p = 0.693).

< Figure 9 is here >

Discussion

Temporal evolution of eroding headwater peatlands

The study winter (Dec/Jan/Feb) had a mean temperature of 2.3 ^oC. For northern England the MetOffice (2018) reported that the study winter was warmer than the 1981-2010 mean for winter. A total of 55 freezing days occurred between 26/10/2016 and 07/04/2017. Diurnal freezing was common in November 2016 with temperature frequently fluctuating above and below zero and needle ice was formed (Figure 10 (a)), causing expansion of the peat surface. The large amount of peat material captured by the sediment traps during the period 23/03/2017–07/04/2017, compared to the rest of the study period, may have been related to a period of heavy rainfall from 30 to 31 March which occurred on the peat surface preconditioned by freeze–thaw weathering. During the dry period from April to May 2017, hillslope peat exhibited substantial desiccation (Figure 10 (b)). Surface desiccation also affected deposited peat within the river channels and overbank areas. Field observations showed that on the desiccated peat surface the upper dried crust was generally concave in shape and detached from the intact peat below, a feature also reported by Evans and Warburton (2007). Cracks often connected in the form of polygons and were up to 12 cm deep. The peat loss rate measured by sediment traps during the period of 07/04/2017–13/06/2017 was the lowest during the study due to low rainfall (Table 3). However, the sediment trapped during the subsequent period with higher rainfall totals (13/06/2017–21/08/2017) was the highest observed (Table 3). These results are in agreement with those reported in other blanket peatland environments, surface desiccation during extended periods of dry weather has been shown to be an important weathering process for producing erodible peat (Burt and Gardiner, 1984, Evans et al., 1999, Francis, 1990, Holden and Burt, 2002). Similar seasonal patterns of sediment capture have also been reported by Francis (1990) and Labadz et al. (1991) who found little peat sediment removed during the summer or late winter/spring, with the majority captured in the autumn and early winter.

< Figure 10 is here >

Scale effect of sediment production in headwater peatlands

Peat erosion decreased with increasing area at the fine scale for areas less than 1 × 10^{-3} km^2 (Figure 9) where erosion processes are dominated by rill and interrill erosion (Li et al., 2018a). This scale effect on peat erosion values could be explained by decreasing sediment delivery ratios with increasing area (Walling and Webb, 1996). The fact that sediment yield was highest for the whole study area (0.017 km^2) suggests that gully erosion, channel bank erosion and flushing of deposited materials could be important sediment sources at larger scales. A number of previous studies have shown that bank erosion (Small et al., 2003), gully erosion and mass movements (Evans and Warburton, 2007, Evans et al., 2006) form an important part of the catchment sediment budget in upland peat catchments. At larger scales erosion and transport of mineral materials might become even more important, with mineral sediment accounting for 63.2% of the total sediment yield at Fleet Moss. Mineral sediments in these upland systems may be loosened and mobilized in different ways and may not require freeze-thaw and desiccation to make them available for transport.

This study has shown that peat loss measurements at one scale are not representative of sediment yield at another scale level. Therefore, direct extrapolation of plot scale interrill and rill erosion rates up the catchment scale can be problematic. Different erosion processes are active at different spatial scales, and different sediment sinks and sources appear from plot to catchment scale (Li, 2019). More monitoring, experimental and modelling studies are needed as a basis for scaling erosion rates from one specific area to larger or smaller areas. In addition, it is suggested that monitoring of peat erosion processes should utilize standardized procedures to allow comparisons of data obtained from different study areas.

Sediment production estimated from topographic change measured by SfM and sediment traps

The error obtained during the manual registration of the SfM point clouds (mean value of 41 mm) (Table 1) is within the range of registration errors (i.e. 11–291 mm, mean 46 mm) found in a previous study in natural terrain (Glendell et al., 2017). Although both positive and negative net topographic changes were observed over different survey intervals, the net topographic change observed over the whole monitoring period was –27 mm (Table 2). This value is in agreement with data from other UK sites where topographic change rates (-24 ± 8 mm yr^{-1}) were measured using erosion pins (Evans and Warburton, 2007, Grayson et al., 2012); and those (–286 mm to +31 mm yr^{-1}; mean value of –33 mm yr^{-1}) measured using SfM (Glendell et al., 2017).

Peat erosion measurement using sediment traps and SfM have different applications. For many applications mass loss captured by sediment traps or estimated by river sediment yield studies is a key parameter of interest; while for other applications surface change is used as a proxy for erosion. It should be noted from mass balance principles that all things being equal, the estimates of mass loss using different methods should be comparable. However, in this study peat loss data estimated from the sediment traps and SfM techniques did not match well with each other (Figure 5). Deposition-related change measured by SfM was 93.3 ± 55.5 kg (5.3 ± 5.2 mm), in comparison with erosion-related change derived from the sediment traps of 1.8 ± 0.3 kg (0.3 ± 0.1 mm). The discrepancy could be explained by two reasons. The first explanation is associated with wind erosion, oxidation loss of the peat and shrinkage of the peat by compression that can cause topographic change captured by SfM but not by sediment traps. For example, 30–81% of surface lowering has previously been attributed to peat wastage in upland peat environments (Francis, 1990, Evans and Warburton, 2007, Evans et al., 2006) though it is thought that this estimate probably includes both oxidation loss (i.e. true wastage) and compression of the peat associated with loss of water and collapse of the pore structure leading to higher bulk density values. In addition, eroded peat is loose and less compact than when it was in situ and so re-deposition of such loose peat materials could result in positive topographic change which is well captured by SfM. However, such changes to peat bulk density would not often be accounted for in stream sediment sampling or sediment trap data which examines dry mass loss.

Loss of organic sediment from the catchment

The estimated annual total suspended sediment load leaving the catchment was calculated as 14.8 tonnes per year, equivalent to 926.3 t km^{-2} yr^{-1}. This value at Fleet Moss is much greater than those reported from other upland blanket peatlands (generally less than 200 t km^{-2} yr^{-1}, cited in Li et al. (2018a)). The estimated POC load was 5.5 t yr^{-1}, equivalent to 340.9 t organic carbon km^{-2} yr^{-1} and accounted for 36.8% of the total suspended sediment load. The POC flux is greater than those reported (0.12–38.9 t C km^{-2} yr^{-1}) in other peatland catchments in the UK (Francis, 1990, Labadz et al., 1991, Hutchinson, 1995, Dawson et al., 2002, Dawson et al., 1995, Holden, 2006, Worrall et al., 2003). It is recognised that the discharge from the catchment was not continuously gauged due to instrument errors and that continuous gauging combined with storm event sediment sampling would improve the stream sediment flux estimates for Fleet Moss. In this study, daily stream sampling for sediment concentrations was used but this technique may miss important sediment transport events such as storms, which could be important as peat systems often have flashy regimes. Sediment concentration-discharge hysteresis can occur during events meaning that the sediment-discharge rating equation can vary (Li et al., 2018a). Thus our estimates of catchment sediment yield are approximate. Nevertheless, the evidence presented using multiple data sources suggests that there is a very high erosion and organic carbon loss rate from the system and high localized rates of topographic change measured in only 12 months (i.e. 500–700 mm in some places). Thus Fleet Moss is rapidly eroding, exporting large amounts of sediment and particulate carbon and could be a hot spot target for restoration intervention to stabilize the peatland and reduce future erosion.

Conclusions

The net topographic change for the studied catchment within Fleet Moss derived from SfM was negative during the 12-month monitoring period. A comparison of topographic changes for a series of nested small watersheds derived from SfM and sediment traps showed significant differences with a positive topographic change determined by the SfM and a negative topographic change from the sediment traps. This difference indicates that it is problematic to directly interpolate peat erosion rates measured by local net topographic change that can be as high as 500–700 mm into sediment yield at the catchment outlet, without considering sediment sinks within the catchment budget. Desiccation and freeze–thaw processes were identified as playing key roles in breaking up the peat surface prior to removal by fluvial processes. The greatest sediment and organic carbon losses occurred during the autumn following a two-month period of dry weather in spring during which desiccation was observed and summer period when bare peat was exposed to warmer weather and more desiccation. Frost action played an important role in providing available sediment during the winter months via needle-ice formation and thaw. Peat loss measured at the hillslope scale was not representative of that at catchment scale within which bank erosion, mass movements and transport of eroded mineral sediment could also be important.

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Tables

Table 1. Summary of georeferencing errors (i.e. RMSE on control points) for the field surveys.

Survey date	No. of images	No. of GCPs	Georeferencing RMSE (mm)
04/11/2016	197	6	43.9
02/05/2017	166	6	33.3
13/06/2017	104	6	42.8
21/08/2017	197	6	49.2
27/09/2017	165	6	37.1
02/11/2017	208	6	36.8

Table 2. Summary of the median net, positive and negative topographic changes (mm) with root mean square (RMS) (mm) for comparisons over different survey intervals. The long-term survey intervals are highlighted with bold.

Model[a]	Differencing epoch	Mean temperature (℃)	Rainfall (mm)	Net change			Positive change			Negative change		
				Median	RMS	Area (m^2 and %[b])	Median	RMS	Area (m^2 and %[c])	Median	RMS	Area (m^2 and %**)
2–1	04/11/2016–02/05/2017	3.7	720.4	–18	85	414.3 (69%)	50	82	198.1 (48%)	–65	88	216.2 (52%)
3–2	02/05/2017–13/06/2017	11.2	225.4	–29	66	461.8 (77%)	46	71	229.8 (32%)	–43	64	349.3 (68%)
4–3	13/06/2017–21/08/2017	13.5	457.0	21	66	431.9 (72%)	39	65	299.0 (60%)	–41	69	243.4 (40%)
5–4	21/08/2017–27/09/2017	–	226.4	–21	62	438.5 (73%)	38	65	245.3 (40%)	–36	59	310.8 (60%)
6–5	27/09/2017–	–	396.4	24	64	433.6	40	64	300.8 (63%)	–40	63	232.8

	02/11/2017					(73%)						(37%)
6–1	**04/11/2016–02/11/2017**	**–**	**1997.4**	**–27**	**90**	**413.3** (69%)	**50**	**84**	**205.5 (42%)**	**–71**	**95**	**302.6 (58%)**

[a] Model refers to difference between a survey of late date and a survey of earlier date.

[b] Percentage of the area above the LoD$_{95\%}$.

[c] Percentage of the area with significant changes.

Note: RMS is the square root of the arithmetic mean of the squares of a set of values.

Table 3. Summary of peat loss rates and net topographic change measured by sediment traps. '–' indicates not reported. Peat loss obtained from sediment traps was converted to an estimate of net topographic change using peat bulk density values from the study site.

Monitoring interval	**Sediment traps**	**Peat loss rate (kg)**	**Peat loss (g m^{-2} d^{-1})**	**Net topographic change (mm)**
04/11/2016–23/03/2017	T1	1.24	0.4	0.3
	T2	1.01	0.1	0.1
	T3	2.27	0.4	0.5
	T4	0.84	0.1	0.1
	T5	2.65	0.2	0.2
	T6	1.59	0.3	0.3
	Total	**9.60**		
23/03/2017–07/04/2017	T1	0.87	2.5	0.2
	T2	0.62	0.5	0.0
	T3	2.40	3.4	0.6
	T4	1.26	1.6	0.1
	T5	1.65	1.2	0.1
	T6	1.73	3.3	0.3
	Total	**8.53**		
07/04/2017–13/06/2017	T1	0.41	0.3	0.1
	T2	0.13	0.0	0.0
	T3	0.37	0.1	0.0
	T4	–	–	–
	T5	0.77	0.1	0.0
	T6	0.23	0.1	0.0
	Total	**1.91**		
13/06/2017–21/08/2017	T1	–	–	–
	T2	1.17	0.2	0.1
	T3	3.21	1.0	0.4
	T4	2.35	0.7	0.3
	T5	2.83	0.5	0.2
	T6	1.15	0.5	0.2
	Total	**10.71**		

Table 4. Summary of suspended sediment load and POC load during different months, seasons and whole monitoring period.

	Mean discharge ($m^3\ s^{-1}$)	SS load (t)	POC load (t)
November 2016	0.0006	0.069	-
December 2016	0.0006	0.204	-
January 2017	0.0005	0.150	-
February 2017	0.0011	0.323	0.114
March 2017	0.0012	0.592	0.194
April 2017	0.0001	0.002	0.000
May 2017	0.0005	0.002	0.000
June 2017	0.0014	1.100	0.400
July 2017	0.0012	2.237	0.838
August 2017	0.0009	1.475	0.550
September 2017	0.0012	2.431	0.912
October 2017	0.0021	6.236	2.444
Winter 2016	0.0009	0.677	0.114
Spring 2017	0.0008	0.596	0.195
Summer 2017	0.0017	4.813	1.788
Autumn 2017	0.0023	8.667	3.357
Whole monitoring period	0.0013	14.822	5.454

Figures

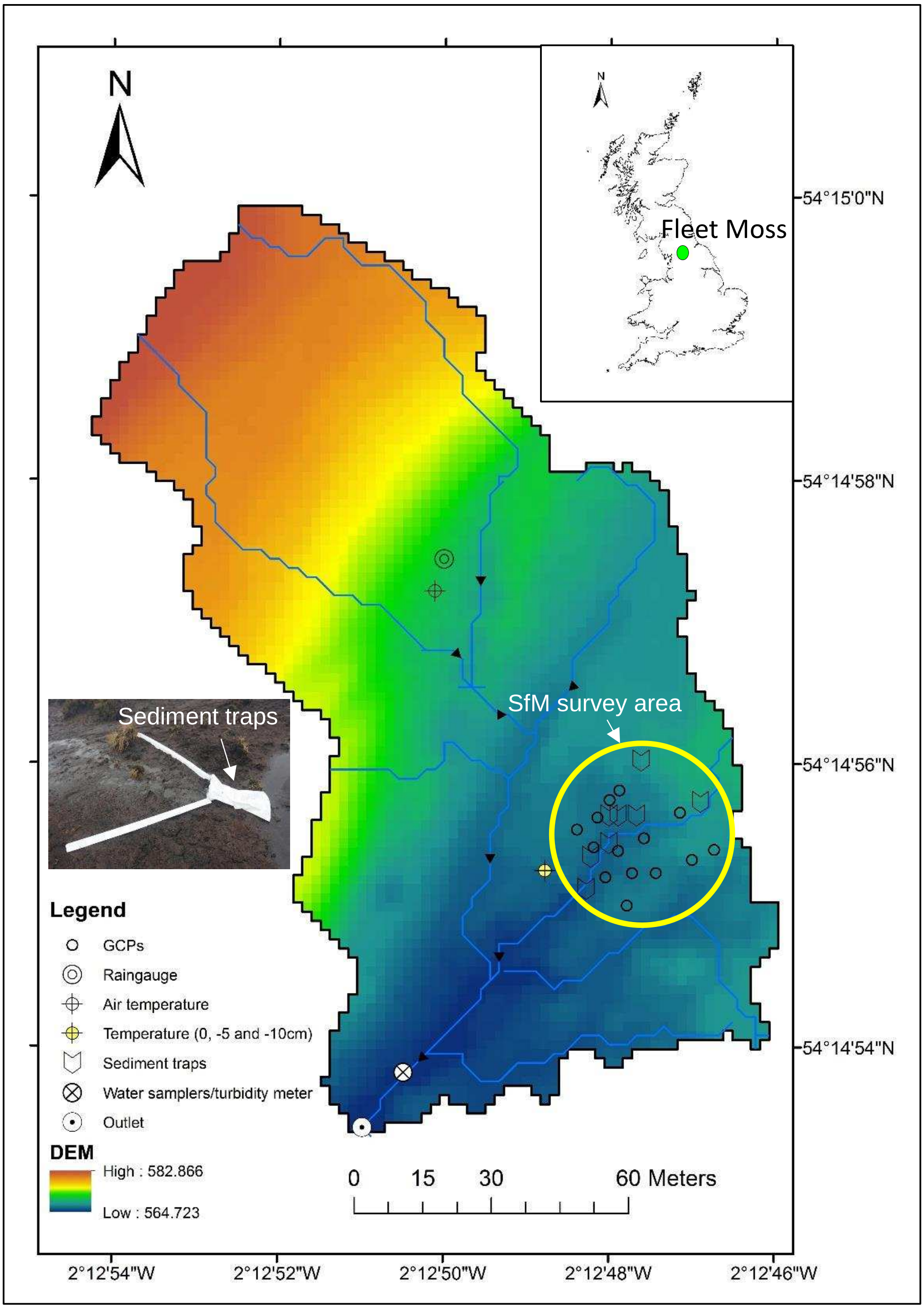


Figure 1. Map showing the position of Fleet Moss within the UK and the locations of field instruments in the research catchment (1.7 ha). Within the catchment there was a mini-catchment (990 m^2) where sediment traps were distributed and SfM surveys were conducted. An example sediment trap is shown in the inset photograph.

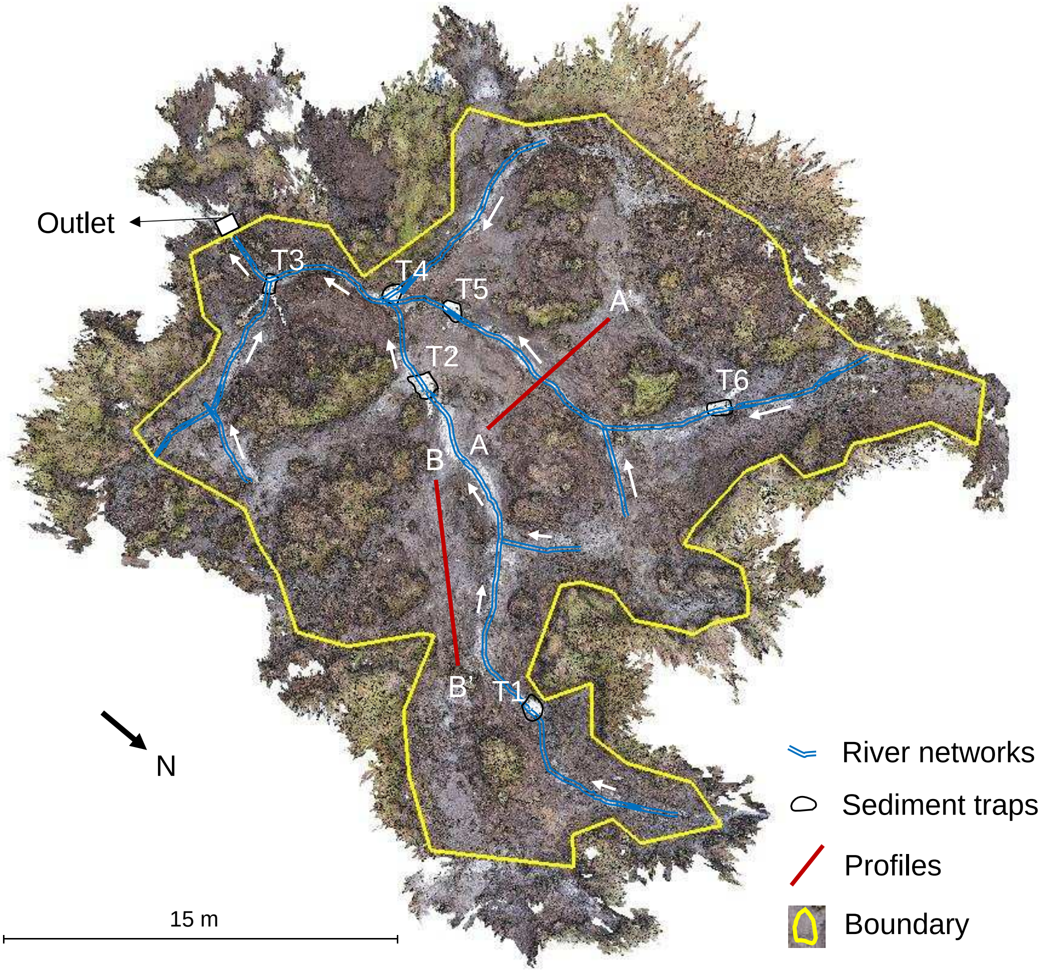


Figure 2. Orthophoto of the small-catchment (990 m^2) and the SfM focus area (with boundary outlined with yellow) (598 m^2). The sediment traps are numbered T1–T6. While the transect profiles are labelled A-A’ and B-B’ shown by the red lines.

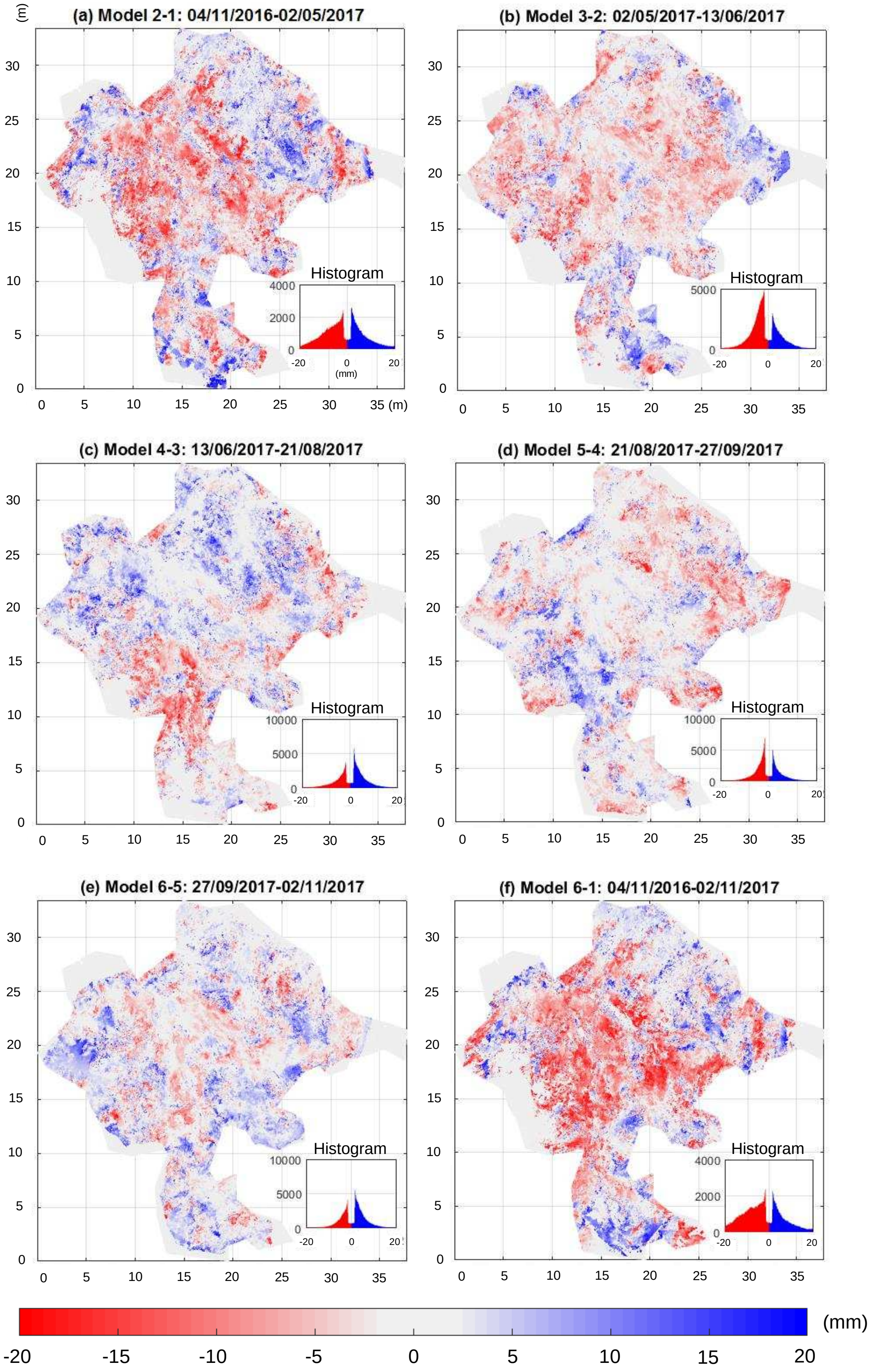

(a) Model 2-1: 04/11/2016-02/05/2017
(b) Model 3-2: 02/05/2017-13/06/2017
(c) Model 4-3: 13/06/2017-21/08/2017
(d) Model 5-4: 21/08/2017-27/09/2017
(e) Model 6-5: 27/09/2017-02/11/2017
(f) Model 6-1: 04/11/2016-02/11/2017
(m)
0
5
10
15
20
25
30
35 (m)
Histogram
4000
2000
5000
10000
-20
0
20
(mm)
-15
-10
-5
5
10
15

Figure 3. SfM determined M3C2 distances and histograms over different survey intervals (a–f) for the studied catchment. Grey areas have non-significant changes. Blue colours indicate positive topographic change and red colours show negative topographic change.

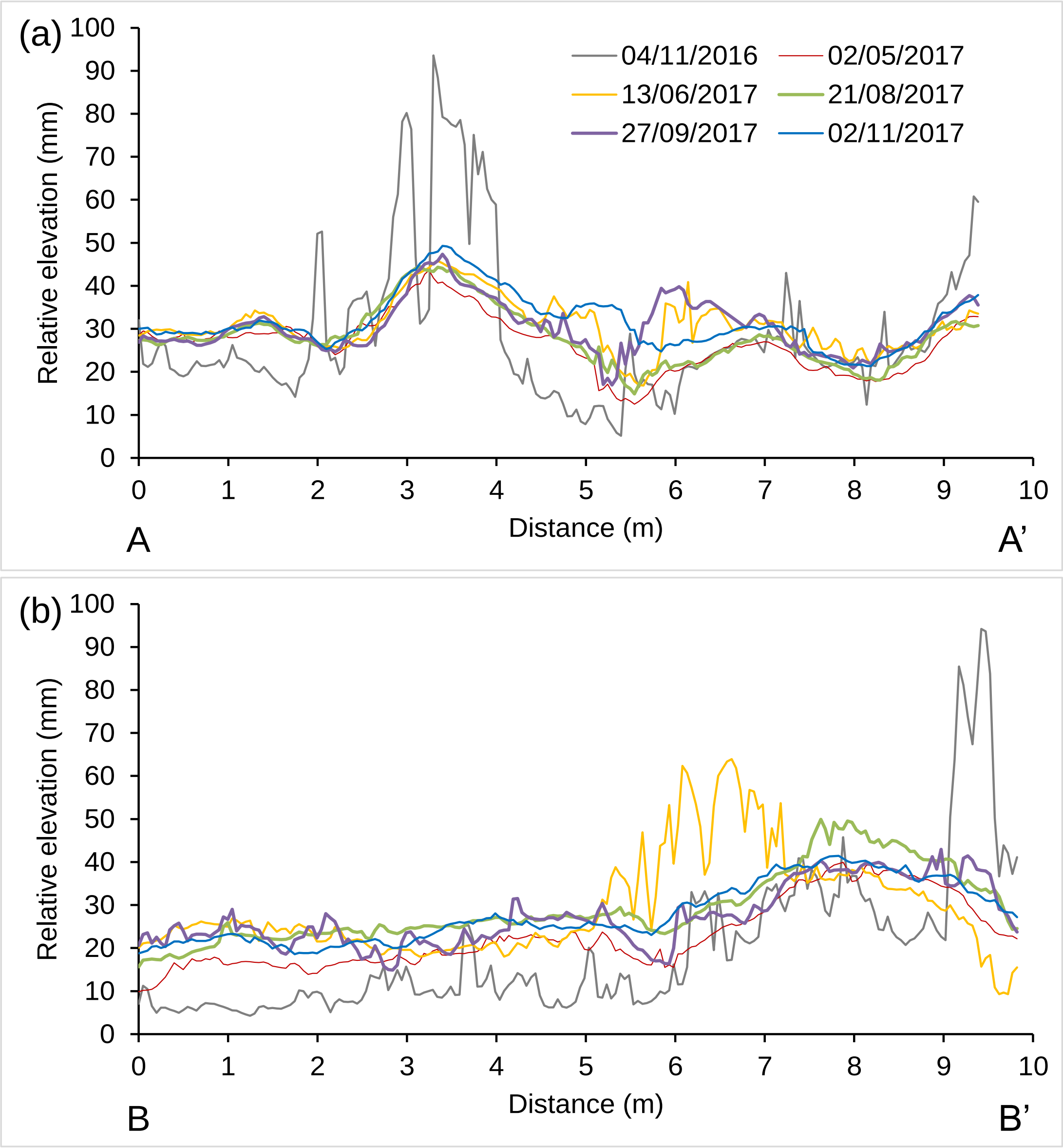


Figure 4. SfM measured 2-D peat profiles of (a) AA’ and (b) BB’ revealing topographic change over the monitored period. For the location of the cross-sections, see Figure 2.

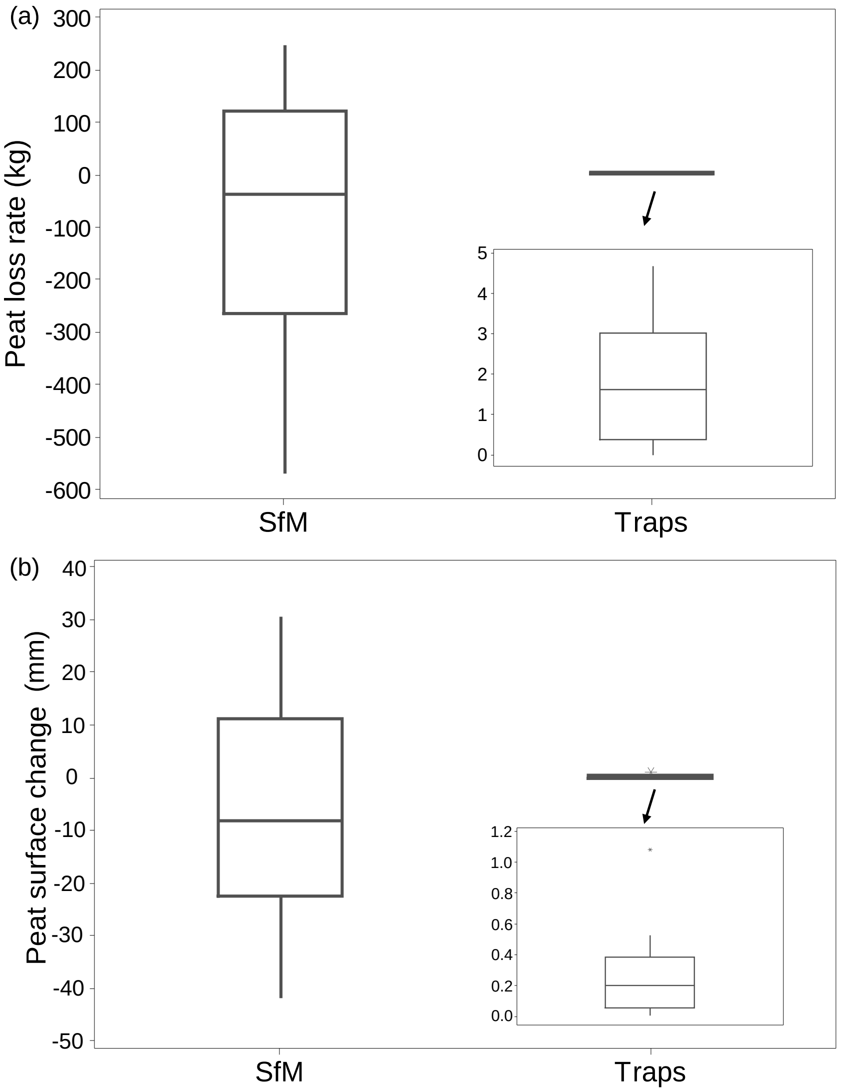


Figure 5. Summary of (a) peat loss (positive values show erosion; negative values show deposition) and (b) surface change (positive values show deposition; negative values show erosion) measured by SfM and sample trap methods.

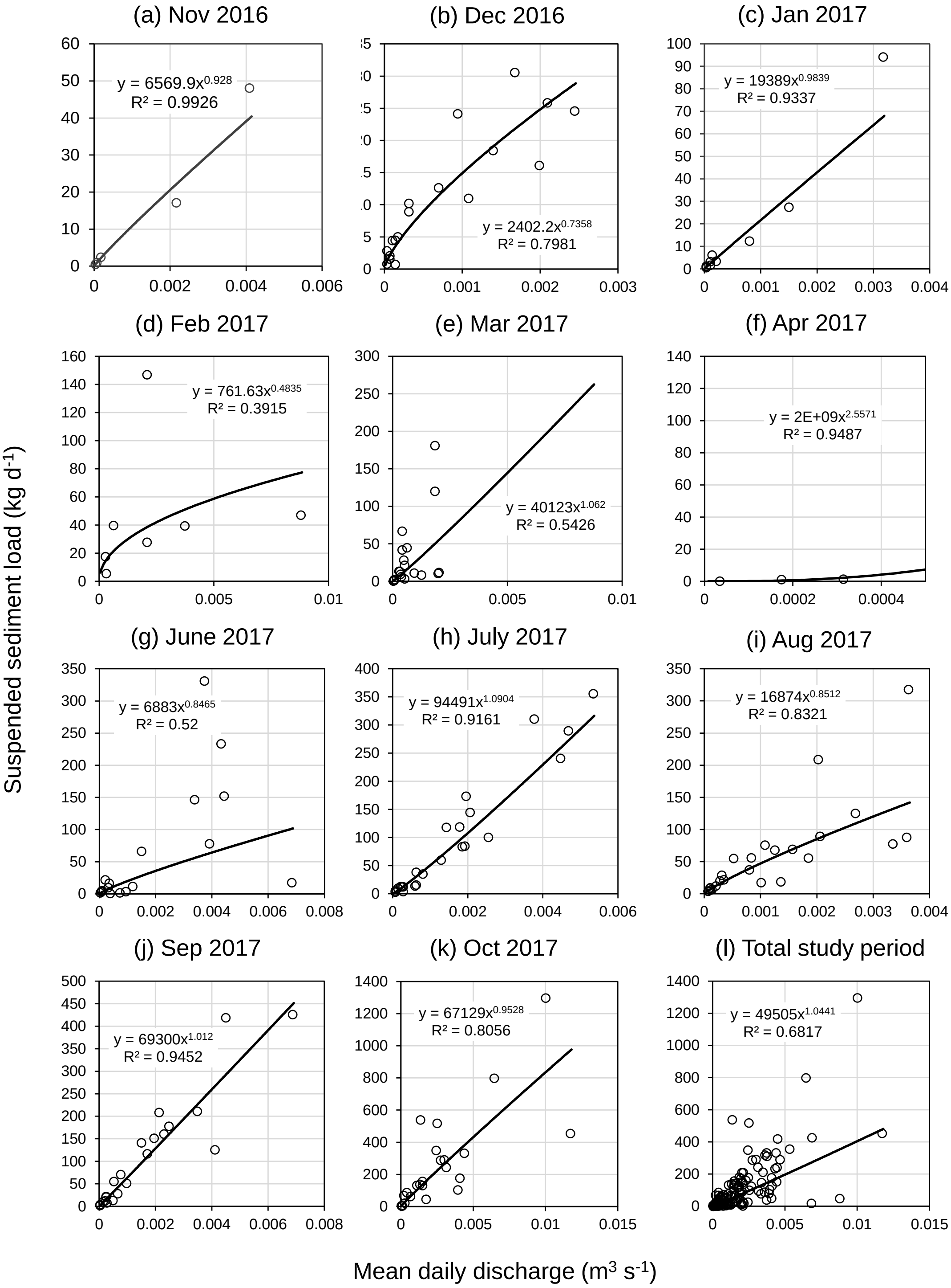


Figure 6. Stream-based suspended sediment rating curves, measured using autosampler data and laboratory determinations, for each month from November 2016 to October 2017 and for the full study period.

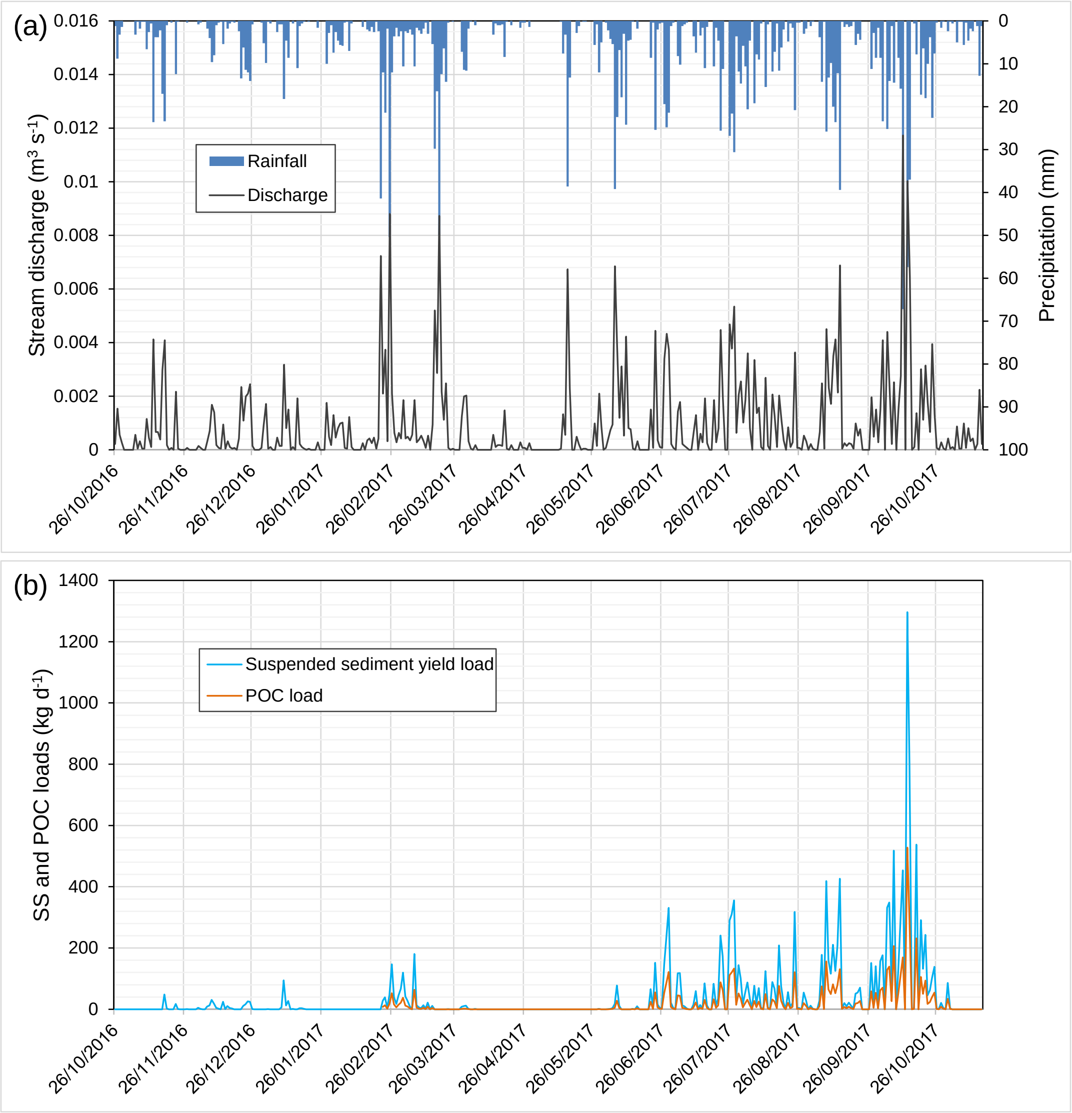


Figure 7. Daily rainfall, discharge, suspended sediment and particulate organic carbon loads during the monitoring period of 26/10/2016–15/11/2017 from the catchment outlet.

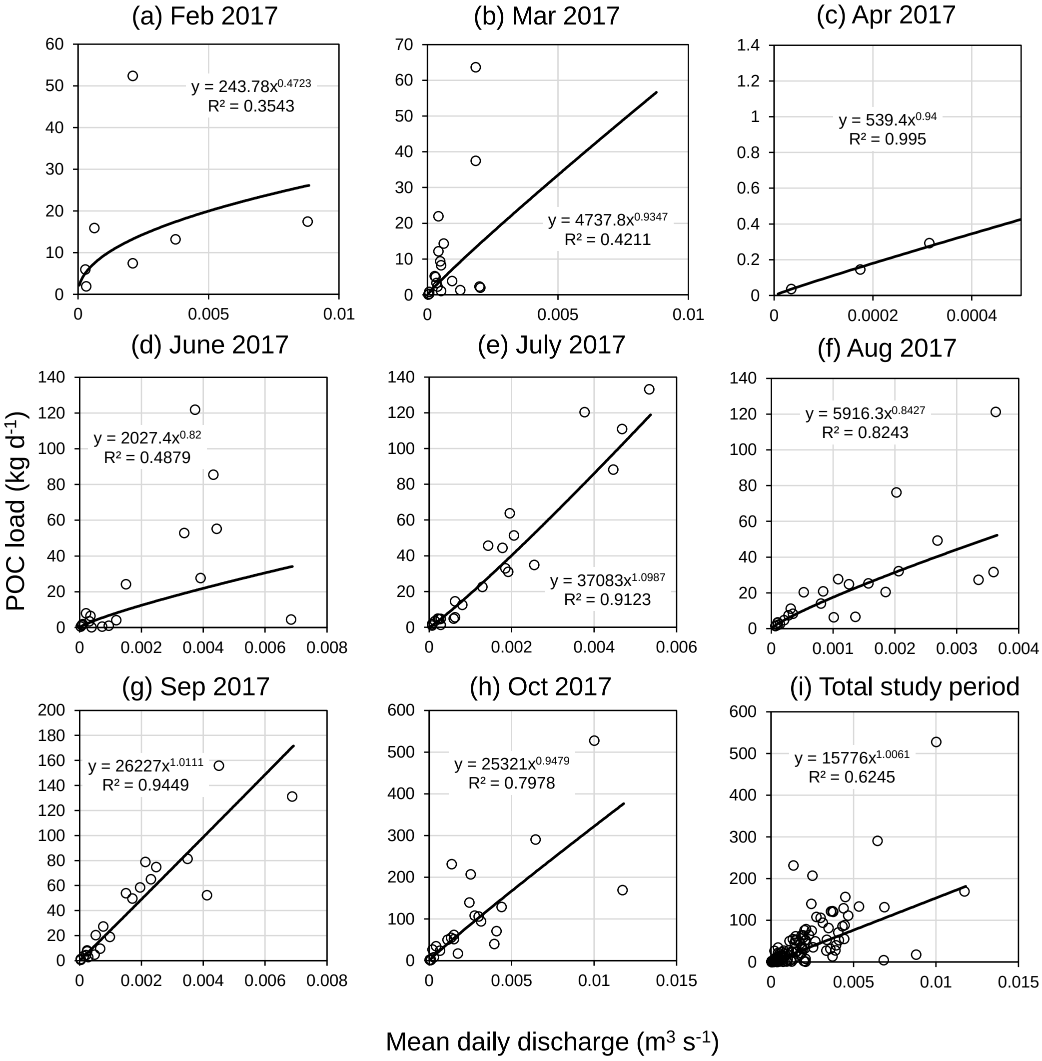


Figure 8. Stream-based POC rating curves, measured using autosampler data and laboratory determinations, for each month from February 2017 to October 2017 and for the total study period.

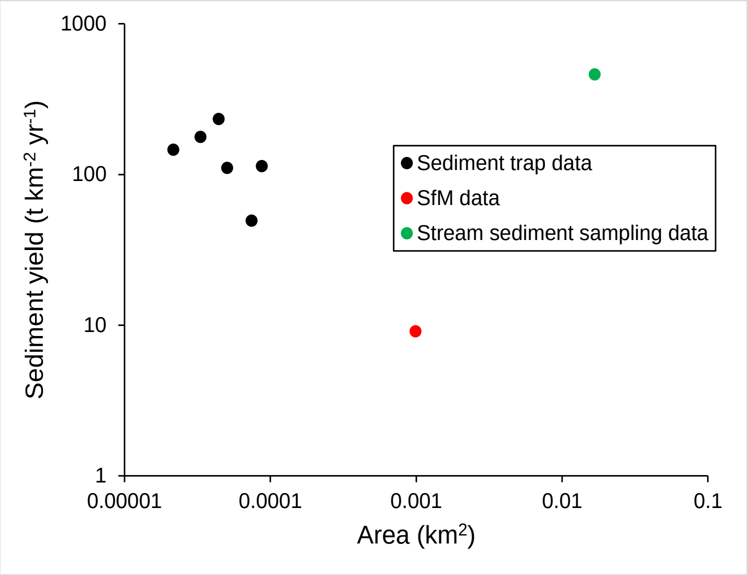


Figure 9. Area-specific sediment yield estimates over the 12-month monitoring period at Fleet Moss, showing the data collection technique used to derive each value.

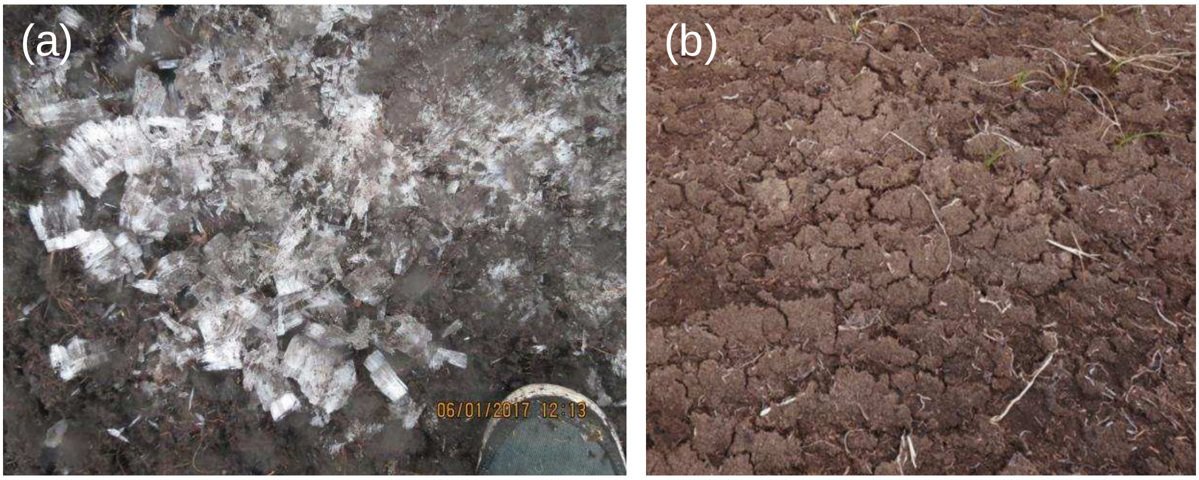
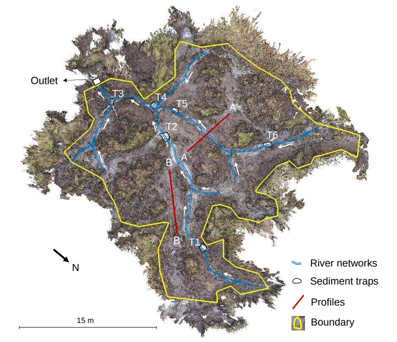


Figure 10. Needle ice formation (a) and surface desiccation (b) observed at the field site.

Graphical abstract



We measured erosion in an upland blanket peatland catchment (0.017 km^2) in northern England using Structure-from-Motion (SfM) photogrammetry, sediment traps and stream sediment sampling. A net median topographic change of –27 mm yr^{-1} was observed over a year by SfM surveys for a small peat catchment. Stream suspended sediment and particulate organic carbon yields were 926.3 t km^{-2} yr^{-1} and 340.9 t km^{-2} yr^{-1} respectively, with highest losses during autumn. The important peat weathering processes were determined.