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Blanket bogs exhibit significant alterations to physical properties as a result of temporary track removal or abandonment

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Abstract

Temporarily consented tracks made from high-density polyethylene (HDPE) mesh have been used to mitigate both the physical and ecological impacts on peatlands from low-frequency vehicle usage. However, the impacts of mesh track removal or abandonment at the end of the consented period remain poorly understood. Over a 2-year period, we studied replicate sections of abandoned mesh track which, at the start of the experiment, had been unused for approximately 5 years, on a UK blanket bog. Some sections were removed (using two treatment methods – vegetation mown and unprepared), whereas others were left in situ. Metrics were compared both between treatments and to undisturbed reference areas. Significant differences in surface soil moisture were found between abandoned and removed tracks depending on season. Control areas had higher volumetric soil moisture than track locations. Compaction was significantly higher across all track locations in comparison to controls ($p < 0.001$), but rarefaction was not recorded post-removal, suggesting long-term deformation. Overland flow events were recorded in rut sections for a mean of 16% of the time, compared to <1% in control areas. Sediment traps on the tracks collected 0.406 kg compared to 0.0048 kg from the control traps, equating to a per trap value of 7.3 g from track samplers and 0.17 g from control samplers. Erosion and desiccation features occurred on both removed and abandoned track sections. Both abandonment and removal of mesh tracks have a wide range of impacts on the physical properties of peatlands, suggesting that only where access is a necessity should such a track be installed.

KEYWORDS

degradation, ecology, hydrology, infrastructure, mire, peatland, wetland

1 | INTRODUCTION

Peatlands are a globally important organic wetland habitat found in over 175 countries, consisting of a minimum peat depth of 30 cm and with predominant forms being bog and fen (Xu et al., 2018). Peatlands store approximately 600 Gt carbon, representing over one-third of terrestrial soil carbon (Yu, 2012; Yu et al., 2010) across all biomes, and additional major peatland areas continue to be discovered

(Fatoyinbo, 2017). Human activities impact peatlands both directly and indirectly, with loss and damage frequently reported (Joosten et al., 2016; Parish et al., 2008). Pressure to access resources such as gas and oil, coupled with for leisure activities in some countries has increased the amount of road infrastructure being created in remote peatland areas. These roads may be designed to facilitate both vehicle and pedestrian access. Although there has been an increase in the number of studies into peatland road and track impacts in recent years, overall the effects of these tracks are still poorly understood (Williams-Mounsey et al., 2021). These infrastructure networks may be narrow, rudimentary linear unpaved track features such as single-use seismic lines or they may be wide, fully engineered surfaced roads with associated drainage features designed for regular usage (Elmes et al., 2021; McKendrick-Smith, 2016; Pilon, 2015; Williams-Mounsey et al., 2021). In some regions of North America, tracks and roads represent the largest form of human disturbance (Jorgenson et al., 2010). Effects may be wide-ranging: vegetation structure and composition may alter (Dabros et al., 2017; Echiverri et al., 2022; Kemper & Macdonald, 2009; Lampinen et al., 2015; Saraswati, Bhusal, et al., 2020), hydrological function may be impaired (McKendrick-Smith, 2016; Pilon, 2015; Saraswati, Petrone, et al., 2020), biogeochemical and physical processes may be altered (Saraswati et al., 2023; Saraswati, Bhusal, et al., 2020; Saraswati & Strack, 2019) and enhanced sensitivity to climate change may result (Sengbusch, 2015).

Much of our current knowledge concerning road and track impacts derives from the boreal and permafrost peatlands of Canada (Dabros et al., 2017; Jorgenson et al., 2010; Saraswati et al., 2023; Stevenson et al., 2019), yet effects on blanket bogs with high rainfall patterns have been less extensively studied. Blanket bogs are ombrotrophic peatland ecosystems, which form in high rainfall areas (typically >1,000 mm rainfall per annum) (Lindsay, 2016). In the UK alone, peatlands cover approximately 2.9 M ha representing around 10% of the total land area, the majority of which is blanket bog with some small areas of fen (IUCN, 2018). Up to 80% of UK peatlands are degraded to some extent (Artz et al., 2019; IUCN, 2018) through a combination of management practices such as afforestation, burning or livestock grazing. Blanket bogs occur on undulating terrain including slopes up to 20°. As such, track impacts might be quite different to those in other more gentle gradient peatlands. Blanket bogs are highly susceptible to erosion from overland flow if there is any damage to surface vegetation because slope, high rainfall and dominance of saturation-excess overland flow mean that surface incision can rapidly develop if ground-level vegetation cover is reduced. Rill development and larger-scale gullies and bank erosion are significant sources of sediment in degraded blanket bogs (Li et al., 2018). While erosion in single rainfall events is self-limited by the availability of sediment, on degraded and exposed peat, weathering processes such as needle-ice formation, rain splash, mud-crack-style plate formation and desiccation provide a continual source of new sediment to be dislodged in each subsequent rainfall event (Li et al., 2018, 2019). There is concern that tracks can act as channels, concentrating water flows, which enhance blanket bog sediment loss.

There has been a rapid expansion of both surfaced and unsurfaced track networks for resource access and leisure purposes, in what are nominally protected blanket bog areas in the UK, with a mean track density of 1.76 ± 0.10 km km^{-2} across peatland sites (Clutterbuck, Burton, et al., 2020) with greater densities associated with vegetation management for gun-sports.. Despite rapid growth of these peatland track networks, there are significant gaps in knowledge about the environmental impacts of tracks. Due to its high water content, peat has a poor engineering surface (Hobbs, 1986) and consequently road structures are vulnerable to sinking (Olszewska, 2018). Mesh (similar to that used as grass reinforcer) tracks have recently emerged in the UK and elsewhere as a potential solution, supporting the passage of low ground pressure vehicles such as Argocats. At present, there is little data beyond the work of McKendrick-Smith (2016) on the physical impacts of mesh tracks on peatlands. Peat is known to have complex patterns of consolidation and rheologic behaviour (Kazemian et al., 2011; Mesri & Ajlouni, 2007; Mesri et al., 1997; Warburton, 2020) and can exhibit bilinear stress–strain patterns (Edil et al., 1993). The lack of understanding about responses of peatlands to temporary tracks leaves conservationists, regulators and landowners facing difficult decisions when creating vehicular access routes on ecologically and environmentally important peatland sites, which can lead to tensions and conflicts, including, on occasion, resort to legal process. As temporary tracks have a short usable life by design and are consented accordingly, this lack of knowledge presents stakeholders and policymakers with difficult decisions regarding whether to leave or remove tracks at the end of their operational period.

This study aims to examine, for the first time, the physical impacts of both removing and abandoning temporary access mesh tracks in blanket bog. We employed a control treatment approach with comparisons made between track treatments and to reference areas which have not been subject to intensive management for approximately 80 years. We hypothesised that the mesh tracks with the lowest vehicular usage rates would experience reduced compression and that the mesh surface would attenuate the compression effects from vehicular usage. After removal, we hypothesised that there would be rarefaction of the peat, but that removal would lead to increased erosion, while areas where track remained would be less vulnerable to these processes. An unsurfaced track was also studied, and we hypothesised that this would suffer from greatest compaction due to the lack of surface protection. We hypothesised that there would be a drying effect at the surface of track edges with significantly reduced surfaced moisture levels compared to control areas and that the drying effect would be similarly observed in the centres of tracks. Conversely, ruts would have increased surface moisture because they would act as channels for surface water and be closer to the water table.

2 | METHODS

2.1 | Study site and timescale

The study site is located within an area of the Moor House National Nature Reserve (54°41′37.1″N, 2°22′25.2″W), managed by the governmental body, Natural England, and lies within the 7,400 ha North Pennines World Biosphere Reserve in northern England. The site is at

600 m altitude, characterised by extensive blanket bog with limited disturbance in the nature reserve for ~80 years. The area has a sub-Arctic oceanic climate with a mean annual temperature of 5.3°C and a mean annual precipitation of ~2,000 mm (Holden & Rose, 2011). Occult precipitation is characteristic, and the water table sits close to the surface, being within 5 cm of the surface for 83% of the time and rarely dropping deeper than 30 cm (Evans et al., 1999).

A HDPE mesh track, 1.5 km long and 2.5 m wide, and weighing 4,800 kg, with a tensile strength of ~13.99 kPa, was laid in July 2013 as part of a hydrological study of upland tracks (McKendrick-Smith, 2016). The topography underlying the track is undulating, reflective of a typical upland blanket bog. The track was subdivided into sections (Figure 1) which were driven over a controlled number of times between 2013 and 2015. We use the same nomenclature for track treatments as used by McKendrick-Smith (2016) to aid cross-referencing with the previous work, and full descriptions of the time-frame of usage are described in Table 1. The six treatments which were used in this study comprise five mesh-surfaced areas and one unsurfaced area. Our measurements took place over a 19-month period between March 2021 and October 2022, with the last dataset collected 23 months after the track was removed and ~7 years after the track was last driven over (Table 1). All of the track treatments remain clearly delineated (Figure 1) from the surrounding bog, as a result of the altered vegetation community and simplified nanotopographic structures. We looked at how the peat responded to the different track usage rates and also to the removal of the track using the following

TABLE 1 Summary of the track treatments all of which were abandoned in November 2015. Abbreviated codes used for the PDELAYED and UNSURFACED treatments in some tables and figures are shown in parentheses. The original experimental design included an outbound and return pass which counts as two passes.

Treatment name	Frequency of passes	Total number of passes
PWEEK.AH	2 per week (April–July 2014) 2 per week (October–April 2015) 10 per week (August–October 2015)	412[a]
EXP (sections experimentally removed)	2 per week (April–July 2014 2 per week (October–April 2015) 10 per week (August–October 2015)	412
PWEEK	2 per week (April 2014–November 2015)	156
PMONTH	2 per month (April 2014–November 2015)	38
PDELAYED (PDEL)	2 per week (February 2015–November 2015)	76
UNSURFACED (UNS)	2 per month (ended early in 2015 due to damage levels)	24

[a]Vehicle had an additional load of ~375 kg between July and October each year.

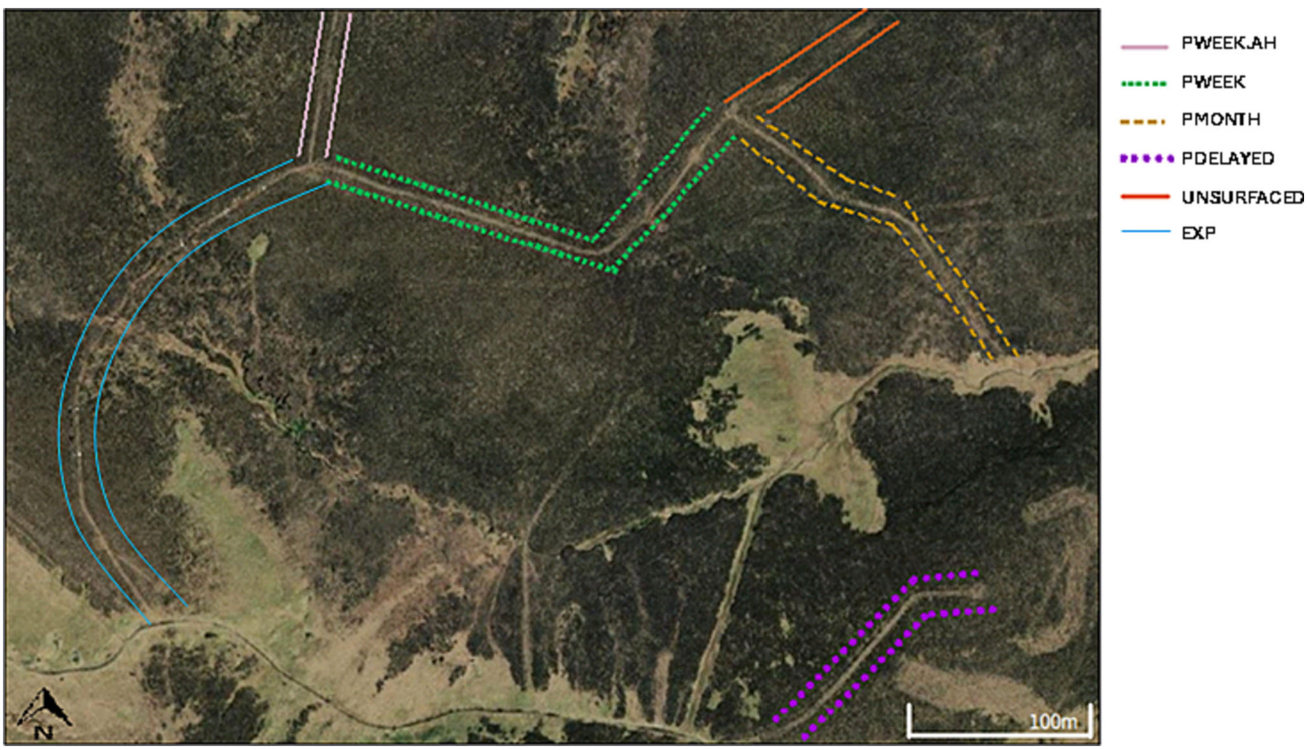

FIGURE 1 Map showing the locations of each of the track sections (centre of the image is at: 54.69298°N, 3.370061°W). The track routes can be seen in the centre of the paired lines which are used for illustrative purposes rather than indicating track widths. The aerial image was captured in 2022 approximately 7 years after the tracks had been closed to vehicles.

measures: soil moisture, compaction (determined using two methods) overland flow frequency and sediment loss. The data collected were a mix of continual time-series data and point-in-time data.

2.2 | Track removal and plot set-up

In the UK, on protected sites, tracks are consented for periods of around 5 years, after which they should be removed or a new consent sought to extend the usage period. However, at present, there is no established protocol for the removal or abandonment of a mesh track. For the EXP treatment a track section which had previously received 412 passes from an Argocat, with a weight of ~770 kg and ground pressure of ~14.5 kPa, was examined. The track was divided into 27 (numbered 1–27) plots each measuring 7 m × 2.5 m (plot area 17.5 m^2). One of three sub-treatments was applied to each plot, these were: i) track left in place (LP); ii) mown with a quad-pulled flail-mower down to the mesh surface prior to removal (MR) the aim being to try to leave a functional layer of vegetation to aid recovery and iii) no preparation of vegetation prior to removal (UR), replicating the most cost-effective way to remove the track. Nine replicates of each treatment type were created.

A total of 126 m of track was removed, and a 3 m buffer of track was left between each plot to minimise the movement of sediment between plots. A short-term pilot study and sediment collected from the track edges confirmed that the buffers acted to reduce sediment movement to a low amount (<5 g over 2 months). The track was cut manually using a Stihl circular saw, and sections were then lifted and removed using a modified clamp on a low ground pressure tracked excavator. Although the excavator was positioned to the side of the track to minimise disturbance, during a rest period the machine sat motionless for a period of 1 hour. This stationary period resulted in the unintended formation of two pools and will have tended to result in permanent plastic deformation of the peat compared with the temporary elastic deformation created while the vehicle remained in motion. We included the resulting pools in our penetrometer measurements and analysis, and they are referred to hereafter as 'digger pools'. All other track treatments remained unchanged.

Control transects for soil moisture, bulk density and cavity strength readings were located 10 m from the track edge, running parallel. Edge effects were also tested for using a parallel transect 1 m from the track edge. The transect locations on the track were in both ruts (Rut 1 and Rut 2 – Rut 1 is the right-hand rut and Rut 2 is the left-hand) and the centre (is provided in Figure S1). Measurements were also taken along the same transect setup within the plots on the EXP treatment.

2.3 | Measuring compression

A low-cost peat penetrometer was used to measure the compression of the peat (Clutterbuck, Lindsay, et al., 2020). Cavity strength is calculated using a low-speed projectile ballistics equation:

$$Yc = \frac{(mv)^2}{2AX_p}$$

where m is the mass of dropped weight, v is the velocity of the weight hitting the top plate, A is the cross-sectional area of the threaded rod and X_p is the penetration distance (in cm) of the threaded rod into the peat.

Cavity strength can be used as a measure of relative peat density or 'softness' – a commonly acknowledged but rarely measured characteristic of natural peat bogs. This is distinct from and should not be conflated with, dry bulk density, though the two share many characteristics. Readings were taken at 4 m intervals along each transect, giving 70 readings per transect. On the EXP track five readings were taken along the transects within each sub-treatment plot, this gave a total of 135 readings in each transect. An additional 20 measurements were taken from the digger pools. All penetrometer data were collected in May 2022. A further 48 bulk density samples were collected in July 2022 (to avoid disturbance before vegetation monitoring had ended) from the main experimental track (EXP). For each sub-treatment (MR, UR and LP), two plots were selected and eight samples were extracted from each plot (two per rut and four from the centres) giving a total of 16 samples per treatment,. A set of 20 control samples was also taken. Additionally, 20 samples were collected from ruts within the unsurfaced track (UNSURFACED, Table 1) as the penetrometer measurements suggested that the track was more compacted than the other tracks. Bulk density samples were taken using a standard 100 cm^3 bulk density ring and were heated in a laboratory oven at 105°C for a period of 24 hours to obtain their dry weight.

2.4 | Sediment collection

Sediment traps (Figure 2), adapted from a design by Li et al. (2019), were installed to capture sediment over the track area. A small nylon mesh bag was attached to a rigid 110 mm diameter pipe which was placed horizontally on the peat surface and secured in place with a metal U peg. Trapping efficiency was calculated at 96%, as obtained by creating a solution using 38.09 g (dry weight) of peat. A trap was suspended over a tray, and the peat and water solution was poured in and allowed to run out into the tray. After a 24-hour period, the solution was dried, and the remaining peat was weighed: 1.57 g was lost.

Sampling was stratified, with areas on mid-slopes selected for sediment collection, and traps placed in a linear set-up to capture ruts and centres. Sediment was not purposefully 'directed' into the traps, and it is assumed for the purposes of this study that the track sediment captured is wholly from the track sections, and not the edges. Sediment traps were placed on a total of eight mid-slope

FIGURE 2 In situ set-up of overland flow sediment traps. The inset panel shows a basic schematic plan of the experimental layout, with squares representing the sediment traps in the ruts and centre.

plots, including two LP plots and three of each of the MR and UR plots. Three traps were placed on each track section, one in each rut (Rut 1 and Rut 2) and one in the centre. One control trap was placed adjacent to each sampled plot between 10 and 15 m from the track edges. Sediment was collected over a continuous period from March 2021 to September 2022, with new samplers inserted at the beginning of collection periods as follows: March 2021–August 2021, August 2021–November 2021, November 2021–May 2022, May 2022–September 2022. Samplers were removed at the end of each period, after which sediment was oven-dried in the laboratory for a period of 24 hrs at 105°C and weighed. Some samplers were moved or added where plots became waterlogged or where new flow pathways were observed to form. This was in order to capture the dynamic erosion that occurred over the post-removal period on the MR and UR plots. The additional sets of samplers were added to EXP plots 3 and 4 for the last two sample periods as the bare peat area was observed to increase on these plots due to mulch loss. A set of samplers from plot 11 was removed after the first sample period due to waterlogging, and data from these were excluded from the analysis. In conjunction with the sediment traps, we also employed overland flow sensors based on a design adapted from Goulsbra et al. (2009) with the field set-up described in Appendix 1: S2 and S3.

2.5 | Soil moisture

A Delta-T ML3 theta probe, 5 cm long, was used to collect soil surface moisture data. To avoid sampling voids or excessive vegetation, it was necessary in some places to part vegetation to reach the peat below. Peat volumetric water content can be highly variable even within sites. It is therefore appropriate to calibrate the outputs from the theta probe by location rather than by calibrating to just one site sample. Three samples were collected, selected from a rut, the track centre and a control. The calibration graphs and full details of the process are provided in Appendix 1: S4 & S5. Readings were taken in mV and calibrated according to the linear regression line equation generated by the drying of samples. As we did not find significant compression relative to the controls in the peat in the 1 m transect, and vegetation was structurally comparable to controls, these readings were calibrated with the control sample values. Soil moisture data were collected at 50 points spaced 5 m apart at four locations for each track treatment – within each rut, at the centre and 1 m away from the track. Data were collected in May 2022 (dry conditions after lower rainfall period) and October 2022 (wet conditions). A further 50 control readings per survey date were taken along a parallel linear transect 10 m from the track mirroring track topography.

2.6 | Statistical analysis

Analysis of data was carried out using QED statistics (ver: 1.5.5.503) and Python (ver: 3.10) with Spyder (ver: 5.0.1). Cavity strength data were transformed using log 10 transformation for homoscedasticity, as checked using the Shapiro–Wilk test and then analysis was carried out using one-way ANOVA with Bonferroni correction. Within-treatment comparisons of cavity strength data were carried out using *t*-tests. Two-tailed Kendall's τ coefficient was used to test for correlation between the number of passes and cavity strength, as aggregated data were heteroscedastic. Two-tailed Wilcoxon matched pairs were used to analyse soil moisture data within each track between seasons, and Mann–Whitney U tests were used to compare tracks to one another within seasons: these tests were selected due to data heteroscedasticity. Pairwise comparison of bulk density samples was carried out using balanced *t*-tests with equal variance, f-testing showed equal variance between samples. Sediment data were analysed using Mann–Whitney U tests. Explanatory variables included the number of passes, seasonality and removal method. Response variables were compaction, overland flow and soil moisture.

3 | RESULTS

3.1 | Impacts on compaction of track abandonment and removal

Two methods were employed to assess compaction on the tracks, the penetrometer and bulk density results both demonstrated a significant compression effect resulting from track usage and that these effects lasted well into the post-abandonment period. The removal of the track did not lead to rarefaction during the study period. We found that the novel penetrometer method yielded comparable results to traditional bulk density sampling, except for at the UNSURFACED treatment. Bulk density on the UNSURFACED treatment was significantly higher than for the controls, but it was lower than the values obtained from the other track plots. The penetrometer recorded highest cavity strength in the Rut 1 transect of the UNSURFACED treatment with a mean value of 8,417 Nm^{-2}, whereas the lowest mean cavity strength value was 3,607 Nm^{-2} obtained from the controls. The aggregated mean cavity strength values for the transects were: Rut 1 = 6,461 Nm^{-2}; Rut 2 = 6,168 Nm^{-2}; centres = 5,541 Nm^{-2}; 1 m = 3,844 Nm^{-2} and digger pools = 4,619 Nm^{-2}.

3.1.1 | Peat density from penetrometer by location

Across the six track treatments – Rut 1, Rut 2 and centres, a 1 m edge transect parallel to each track, the controls and the separate digger pools – a total of 1,688 measurements were collected. Of these, 14 were excluded from analysis due to anomalously high values (accounting for <1% of the measurements), with the most likely cause being heather roots. One plot from the EXP treatment (number 11) was excluded due to excessive waterlogging. Significant differences in cavity strength were found across all tracks compared to controls (Table 2), with most locations showing greater cavity strength relative to the control values, except for the PMONTH treatment in both ruts and the UNSURFACED treatment in the centre (Figure 3).

T-test comparisons for the EXP treatment transects, with the UR, MR and LP plots aggregated, showed that all track locations (Rut 1, Centre, Rut 2) had significantly higher cavity strength compared to the controls ($p < 0.001$ for all locations). One-way ANOVA comparisons for UR, MR and LP treatments separated found no significant differences between any of the transects between treatments ($F = 0.76$, $p > 0.05$).

All Rut 1, Centre and Rut 2 surfaced track measurements were aggregated into a single measurement to test for a correlative effect with the number of passes and controls were included within each category as having zero passes. Determination of Kendall's τ coefficient suggested a weak, but significant, association with the number of passes in all three categories with Rut 2 showing the strongest relationship of the three transects ($\tau = 0.33$, $p < 0.001$), with the other transects showing weaker relationships (Rut 1 $\tau = 0.23$, $p < 0.001$; Centre $\tau = 0.19$, $p < 0.001$).

3.1.2 | Compaction measured by bulk density

Mean bulk density was greater relative to controls on all sampled track locations (Figure 4): controls = 0.093 g cm^{-3}, UNSURFACED ruts = 0.105 g cm^{-3}, EXP ruts = 0.122 g cm^{-3} and EXP centre = 0.124 g cm^{-3}. For the three treatments on the EXP treatment, the rut and centre values were aggregated, with mean values of UR = 0.128 g cm^{-3}, MR = 0.129 g cm^{-3} and LP = 0.113 g cm^{-3}. Pairwise analysis of Controls, UNSURFACED, EXP ruts and EXP centre showed that mean bulk density was significantly higher on the track areas compared to controls: UNSURFACED ($p = 0.012$), EXP ruts ($p = 0.002$), EXP centre ($p = 0.002$). No significant difference was observed between EXP ruts to EXP centre ($p = 0.815$) which mirrored findings from the penetrometer data. Comparisons for the individual treatments UR, MR and LP were not made due to the relatively small sample sizes.

3.2 | Influence of tracks on surface peat moisture

Rainfall and water-table data are provided in Appendix 1: S6 for the study period and the year prior to commencement to give an

TABLE 2 ANOVA results for penetrometer readings from each location (aggregated) compared to control values with post hoc Bonferroni correction highlighting treatments where significant differences are recorded.

Location	***F*-value**	***p*-value**
Ruts 1	7.77	<0.001
Ruts 2	5.34	<0.001
Centres	7.40	<0.001
1 m	0.79	0.429
Treatments which differed from controls in *post hoc* testing		**Significance level used for *post hoc* test**
Ruts 1 UNSURFACED, PDELAYED, EXP, PWEEK, PWEEK.AH		$p < 0.01$
Ruts 2 UNSURFACED, PDELAYED, EXP, PWEEK, PWEEK.AH		$p < 0.01$
CentrePMONTH, PDELAYED, EXP, PWEEK, PWEEK.AH		$p < 0.05$
Location	***F*-value**	***p*-value**
Ruts 1	7.77	<0.001
Ruts 2	5.34	<0.001
Centres	7.40	<0.001
1 m	0.79	0.429
Treatments which differed from controls in *post hoc* testing		
Ruts 1 ($p < 0.01$)	UNSURFACED, PDELAYED, EXP, PWEEK, PWEEK.AH	
Ruts 2 ($p < 0.01$)	UNSURFACED, PDELAYED, EXP, PWEEK, PWEEK.AH	
Centre($p < 0.05$)	PMONTH, PDELAYED, EXP, PWEEK, PWEEK.AH	

overview of the antecedent conditions. A period of low rainfall was experienced in July 2022 during a UK-wide heatwave.

Significant spatial and temporal variability in peat surface moisture was observed (Table 3). Controls were found to have significantly higher θ values in October compared to May ($p = 0.0016$), while the Rut 2 location (all tracks aggregated) was found to have significantly higher θ values than Rut 1 in both May and October surveys, although the effect size was relatively small (May: $p = 0.02$, $r = 0.08$; October: $p < 0.001$, $r = 0.12$). The majority of θ values were significantly lower on the track than those of the controls across both survey periods, with the exceptions being in the May survey where the Rut 2 and 1 m transects were not found to be significantly different (Table 3). Analysis between treatments of the track locations determined only a limited number of significant differences between treatment types. The Rut 1 transect in the PWEEK treatment had significantly higher θ values ($p = 0.008$ and 0.018 in May and October, respectively) than the PMONTH treatment. The PMONTH treatment had significantly higher Rut 1 θ values ($p = 0.0015$) in autumn than the PDELAYED treatment. However, despite the lower number of vehicular passes, there was no significant difference between the two in May. The Rut 2 transect was only significantly different between PWEEK and PMONTH in October (PWEEK θ value was larger in October, $p = 0.037$). While all treatment θ values were lower than those of the controls in the centre transects, the effect size was largest in the centre of the UNSURFACED treatment, where the θ value was found to be significantly lower than the controls in both May and October ($p < 0.001$ for both periods May $r = 0.37$ and October $r = 0.47$). A significant difference was found between the Rut 1 and Rut 2 and centre transects on the UNSURFACED treatment where the θ value was found to be lower in the centre (May: $p < 0.01$ for Rut 1 and Rut 2, $r = 0.26$ for Rut 1 and Rut 2; October: Rut 1 $p = 0.037$ $r = 0.18$; Rut 2 $p < 0.001$, $r = 0.35$).

The EXP transects from the two removed treatments, UR and MR, were compared to the PWEEK.AH track (same number of vehicle passes as the EXP track, albeit with a periodically weighted vehicle). We found that for all transects (Rut 1, Rut 2 and centre) in May the PWEEK.AH treatment had significantly higher θ values ($p < 0.05$ for all transects), except for the MR centre where there was no significant difference. In October, however, an opposite pattern was observed whereby the removed treatments had significantly higher θ values ($p < 0.01$) for all transects except UR Rut 2 where there was no significant difference. The effect size was found to be greater in October, with a mean $r = 0.39$ compared to a mean $r = 0.27$ in May.

3.3 | Patterns of overland flow erosion on removed and abandoned treatments

The overland flow sensors showed that overland flow occurred throughout the year, with the tracks having the highest occurrence of flow. Only two prolonged overland flow events were recorded across all controls, the longest event occurring in September 2021 recorded by a top slope logger for a period of approximately 12 hours, or 0.7% of the operational time for the logger. The track areas, by contrast, experienced prolonged periods of overland flow during and after rainfall events, with some lasting for, or recurring, over several days (Appendix 1: S7). Ruts across all treatments experienced the most

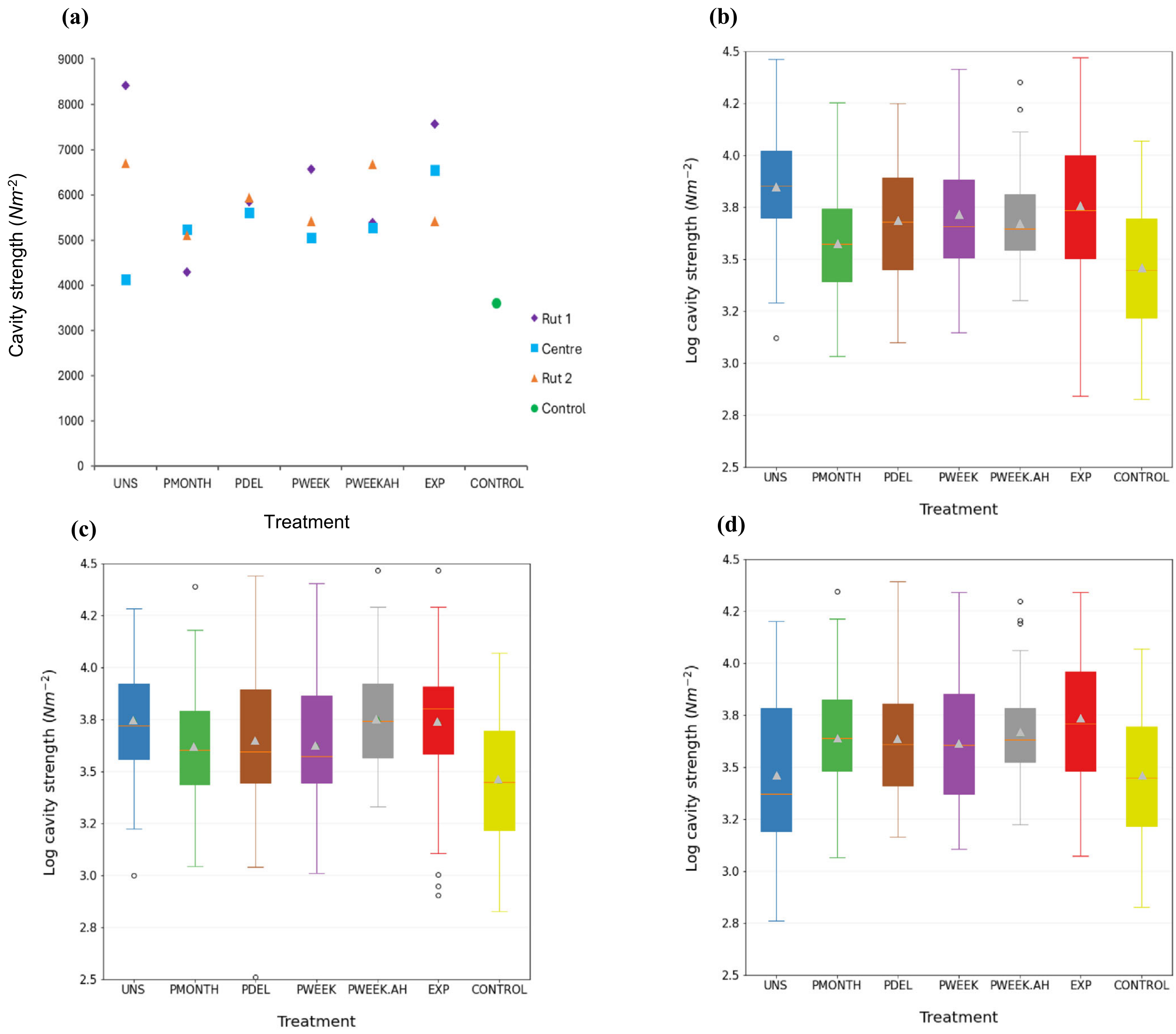

FIGURE 3 Cavity strength plots for comparison of treatments and locations. (a) Mean cavity strength values for the six treatment types and three transect locations. Boxplots for: (b) Rut 1, (c) Rut 2 and (d) centre, with controls included for each as comparisons. Data in boxplots are log-transformed for consistency with the analysis. The mean and median are represented by the grey triangle and orange line, respectively, box ends represent IQ1 and IQ3, whiskers represent values up to 1.5 times the IQ range with fliers representing the extreme outliers.

frequent flow, with sections where the track was exposed or where vegetation was very short recording overland flow events for a mean of 16% of the recording time, compared to a mean of 3.6% for the track centres. The removal of the track did not appear to lead to an increase in the occurrence of these events, as the most sustained overland flow events were logged on areas where the track was present (Appendix 1: S7).

Over the four collection periods, a total of 0.406 kg of sediment (dry weight) was collected from the 56 traps placed on the track, whereas in the 28 control traps a total of 0.0048 kg of sediment was collected. This gives a per trap value of 7.25 g from the track and 0.171 g from the controls. The total loss from all periods for the individual treatments was as follows; UR = 0.138 kg, MR = 0.209 kg and LP = 0.059 kg. There was no significant difference between the median sediment loss for the UR and MR treatments ($u = 356$, $p = 0.08$). The median sediment loss of the UR treatment was significantly larger ($u = 154$, $p < 0.001$, $r = 0.49$) than for the LP treatment, whereas there was no significant difference in the median sediment loss values of MR and LP treatments ($u = 267$, $p = 0.052$). The loss aggregated for all track treatments for the two autumn–spring periods was 0.270 kg and for the spring–autumn periods was 0.136 kg.

The total sediment loss from ruts of all tracks across all collection periods was 0.354 kg. For the centres, the total loss was 0.0519 kg, with the median value for the ruts significantly larger ($u = 473$, $p = 0.0016$, $r = 0.32$). The median sediment loss for both ruts and centres was significantly larger than the controls (ruts – $u = 230.5$,

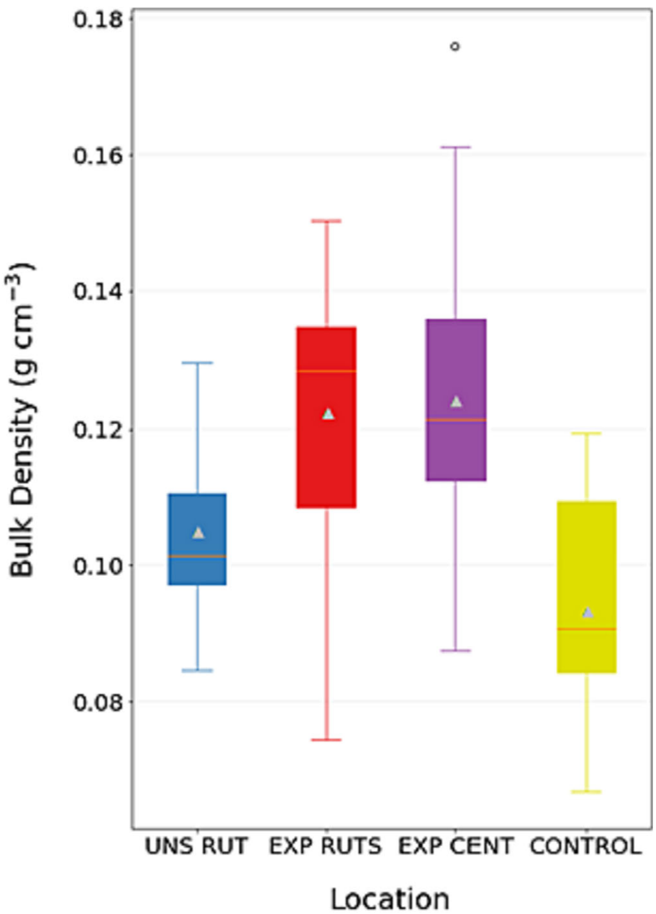

FIGURE 4 Boxplots comparing bulk density for the four sampled locations. The mean and median are represented by the grey triangle and orange line, respectively, box ends represent IQ1 and IQ3, whiskers represent values up to 1.5 times the IQ range with fliers representing the extreme outliers.

$p < 0.001$, $r = 0.57$; centres – $u = 265$, $p = 0.02$, $r = 0.33$). Calculated values for r represent a moderate effect size between locations.

TABLE 3 Pairwise comparisons for soil moisture in the four surveyed locations compared to all controls and between seasons.

Comparisons between track locations and all controls (* denotes location with higher θ)	*p*-value	Effect size (*r*) (where significant)
Controls*, all Rut 1 May 2022	0.02	0.10
Controls, all Rut 2 May 2022	0.08	N/A
Controls*, all centre May 2022	0.004	0.13
Controls, all 1 m May 2022	0.24	N/A
Controls*, all Rut 1 October 2022	<0.001	0.30
Controls*, all Rut 2 October 2022	<0.001	0.21
Controls*, all centre October 2022	0.02	0.10
Controls*, all 1 m October 2022	<0.001	0.16
Between seasons comparisons by location (* denotes period with higher θ)		
Ruts 1 May 2022, October 2022*	<0.001	0.53
Ruts 2 May 2022, October 2022*	< 0.001	0.62
CentreMay 2022, October 2022*	<0.001	0.46
1 m May 2022, October 2022*	0.006	0.14
Controls May 2022, October 2022*	<0.01	0.31

4 | DISCUSSION

4.1 | Main findings

Our study represents the first examination of the physical impacts of mesh tracks on blanket bogs. We identified a complex set of impacts suggesting that mesh tracks do not provide suitable protection of a peat surface against vehicular disturbance. Significant impacts were observed across all metrics from the tracks in comparison to the controls. Given the period since abandonment where no driving or walking occurred on the track, this suggests that even in the absence of vehicular passage the physical impacts on both surfaced and unsurfaced tracks are persistent. We found that compaction from driving, even after long periods of no activity on the area, was long-lasting, suggesting that peat may experience plastic deformation which is not recoverable. This supports findings from studies showing that patterns of deformation in peat soils are bi-linear in nature (Edil et al., 1993) which results in a period of secondary consolidation after a lag period (Berry & Poskitt, 1972; Mesri et al., 1997). The small-scale heterogeneity of the peat-forming surface gives rise to similar heterogeneity of the resulting peat, while the fibrous and decomposed vegetation components of peat are also subject to fluctuations with changing environmental conditions so these rates of consolidation can alter (Barber, 1981; O'Kelly & Pichan, 2013). We found the highest levels of compaction in the ruts of the UNSURFACED treatment in comparison to other tracks and also to controls. However, as cavity strength data act as a proxy for density (Clutterbuck, Lindsay, et al., 2020) it should be noted that the bulk density readings were comparably lower than suggested by the penetrometer readings for the UNSURFACED treatment (see Section 4.2) – possibly reflecting the differing influence of fibres on the actions of the penetrometer and bulk density apparatus. We also found that the mesh tracks increased the footprint of the disturbance compared to the UNSURFACED treatment, by creating significant levels of compression across the track.

Peat moisture patterns in the upper 5 cm of the profile were altered spatially over the track itself. We identified a potential drying effect influenced by the presence of the mesh track, where soil surface θ values were unexpectedly lower in October than plots where the track had been removed. We found that moisture levels were highest in control areas where the lowest cavity strength and bulk density values were obtained, suggesting that compaction may be influencing peat surface moisture content.

We found that where the track was removed the greatest amount of sediment was collected. Although the mesh track provided some protection to the peat surface, sediment traps from unremoved sections still collected more sediment than the control areas. We did not identify a significant seasonal effect on the sediment collection, suggesting that the track remains vulnerable to erosion processes throughout the year, consistent with findings on peat erosion from Li et al. (2018). Waterlogging in bottom slope areas of the track sections was found to hamper the regrowth of vegetation on the track and led to filamentous algal growth in summer (Williams-Mounsey, Crowle, Grayson, & Holden, 2023). We also observed the formation of several erosion features on the track areas during the project.

4.2 | Does the mesh surface protect the peat surface from compaction?

We found that compaction, 5–7 years after abandonment, was lower under mesh in the ruts than where no mesh surface was present prior to driving. The UNSURFACED treatment had higher cavity strength values in the ruts than all other treatments, in spite of vehicle usage being up to 17 times greater in the PWEEK.AH and EXP treatments. Compaction levels determined by bulk density, however, were lower for the UNSURFACED treatment than the EXP treatment. The driver of this is most likely due to areas with a higher content of fibrous plant material, particularly graminoids such as *Eriophorum vaginatum* or *Tricophorum germanicum* which are problematic to sample using the bulk density ring. We found that it was not possible to push the ring into areas where denser tussocking or high deposits of graminoid matter occurred. This led to the exclusion of these areas, therefore introducing bias which the penetrometer was able to overcome. We suggest, therefore, that data from the penetrometer more robustly reflect the compaction of the peat in the UNSURFACED treatment. We found that although the cavity strength was greater in the UNSURFACED treatment in the ruts, compared to both controls and centre, the centre of the treatment was not significantly different from control values for the cavity strength measure. On the mesh track treatments, however, compaction was not confined to the ruts and was significantly higher than control values measured by bulk density and cavity strength. Bulk density and cavity strength across treatments were also not significantly lower in the centres than for the ruts. This suggests that whilst the mesh surface decreases compaction in the ruts when compared to where there was no mesh on UNSURFACED, the overall disturbance footprint is increased by compaction across the full width of the track. The mechanism for this appears to be a product of the elasticity of the mesh, as it is pulled down from the ruts, it pulls down on the peat across the centre. Compaction can also occur as a result of altered hydrological regimes (Hobbs, 1986; Holden et al., 2004; Liu & Lennartz, 2019) and therefore the track may have a two-fold effect; the initial vehicular compaction could be followed by drainage into rutted areas creating further compaction to the centre from an ongoing drying effect. We identified some significant variations between the ruts and the centres in the May 2022 moisture readings. However, variation was not consistent in October 2022 where the centre had higher θ values than in the Rut 1 transects and was not significantly different than the Rut 2 θ values, and effect sizes were small. This suggests that the major driver of the compaction is the vehicular action and that the mesh surface provides a level of protection, particularly at very low usage levels.

The abandoned track sections were found to have broken mesh in several areas at the commencement of the study, most commonly at the bottoms of slopes where high waterlogging had occurred (Figure 5). The assumption is that waterlogged peat is unable to provide support in the same way that a natural *Sphagnum* hollow or pool would have no bearing capacity. In this case, it led to fatigue failure of the mesh with repeated vehicular passage. Rutting was noticeably worse in these areas, although the damage was localised and confined to the higher usage tracks (EXP, PWEEK.AH and PWEEK). The breakdown of the track is likely to leave peat vulnerable to greater levels of erosion, and, on tracks still in use, further increase compaction.

Track removal did not lead to significant recovery over the duration of the experimental period when comparing the abandoned track to controls for penetrometer and bulk density data. While a study from a fen in Canada found that significant decrease in bulk density, with values comparable to controls, had occurred 3 years after track removal (Elmes et al., 2021) we were not able to conclude, at this

FIGURE 5 Area of failed track in a rutted section.

stage, that removal of mesh tracks on blanket bog will lead to rarefaction. Our findings suggest that further research into deformation of peat resulting from vehicular usage is required to establish the maximum number of vehicular passes that can be made over a peat surface before plastic deformation occurs, which would build on previous work looking at peat tensile strengths (Dykes, 2008). Indentation testing in situ or in a lab could help to establish an upper tolerance level for the number of passes that can be made over mesh-protected peat before damage is observed. It would also be useful to compare any observed compression in an alternative experimental surface with the experimentally used track in our study to establish the timeframe over which secondary consolidation may occur.

4.3 | How removal or abandonment of tracks influences surface moisture patterns and erosion processes

The removal of the track led to extensive bare peat areas with an increase in the mean bare area from 5% at the commencement of the study, to 30% by July 2022 (Williams-Mounsey, Crowle, Grayson, & Holden, 2023). Large amounts of sediment were washed down the track as a result. Both rill formation, overland flow and desiccation were observed and recorded on both the removed and abandoned tracks (Figure 6).

We recorded the loss of plant cover, including *Sphagna*, and nanotope structures after track removal (Williams-Mounsey, Crowle, Grayson, Lindsay, & Holden, 2023), or the simplification of nanotope structure across the abandoned track sections, across the experimental site. The long-term loss of surficial structure has also been documented along seismic lines (Stevenson et al., 2019). Vegetation and the nanotopographic structures that the plants form are integral to the hydrological functioning of peatlands (Branham & Strack, 2014; Waddington et al., 2010). The loss of *Sphagna*, in particular, has been shown to lead to increased overland flow velocities and hydrograph shapes (Grayson et al., 2010; Holden et al., 2008). While the end fate of the sediment on the Moor House track site is unclear because the adjacent vegetation acts as a buffer, the rates of erosion were comparable to other studies of eroding catchments (Li et al., 2019). On tracks which truncate with other tracks at the downslope junction or where water courses intersect them, however, there exists greater potential for sediment loss to the stream network. We suggest that losses of both peat physical structure and vegetation cover observed on our study site are major contributors to the enhanced sediment loss and altered patterns of surface soil moisture that we have identified.

Tracks were drier at the surface than control areas along all three transect locations (Rut 1, Rut 2 and centre) with lower θ for all track locations in both surveys. Based on observations of the presence of higher quantities of *Eriophorum vaginatum* tussocks and *Calluna vulgaris* that we have previously recorded in track centres (Williams-Mounsey, Crowle, Grayson, Lindsay, & Holden, 2023) we hypothesised that the centres may suffer from lower moisture levels than controls and ruts. We found that this was the case when rut data were aggregated, with the exception of Rut 2 in October where there was no significant difference to the centre θ value. The UNSURFACED track centre, however, was found to have significantly lower θ than the controls and each of the rut transects in both survey periods with a moderate effect size in both seasons. The reason for this effect in the UNSURFACED treatment may be because the ruts are more depressed relative to the centre, thereby acting as channels, leading to water running off more rapidly into them.

We found that the tracks were drier under the mesh in October (after a prolonged dry spell over summer) than for locations where the

FIGURE 6 Formation of cracks and rills at the track edges and in the removed track areas, with overland flow accumulating in the ruts.

tracks were removed or absent (moderate effect size). Some of these impacts may be driven by the sheltering effect of the track. The mesh-to-hole ratio on the track is 1:1. The dark colour of the track may also lead to increased solar gain at the peat surface causing increased evaporation during warmer periods, hence the seasonal variability. Tracks are manufactured in lighter colours, and a heavier-density track in a lighter colour could ameliorate some impacts.

4.4 | Additional considerations

Vehicle usage on the track in our experiment was tightly controlled, whereas in practice, it is more much challenging to enforce usage guidelines on roads designed for access. The extensive nature of surfaced (with a variety of materials including wood, gravel and mesh) and unsurfaced road networks in the UK uplands alone, with some 6,000 km identified (Clutterbuck, Burton, et al., 2020), is some cause for concern in the light of findings highlighted by our study. Our experimental site is well-vegetated and in relatively healthy condition adjacent to the track. However, where vegetation has been managed through burning, grazing or cutting, rates of overland flow may increase, and higher erosion rates may result. This means that a track or its removal may represent an additional pressure in the context of other management pressures.

FIGURE 7 Digger pools photographed in August 2021.

While the cavity strength values for the PMONTH Rut 1 and digger pools were not significantly different from those of the controls, it is worth noting that the digger pools had an approximate depth of 10 cm and remained filled with water throughout the study, remaining visible 24 months after track removal had occurred (Figure 7). Pools are a natural feature of peatlands and so these features may become beneficial over time. However, the issue of deformation from vehicles has wider applicability, such as when peatland restoration work may require the use of vehicles on site. It seems prudent to suggest that vehicles remaining stationary or passing over the same area multiple times should be avoided, but that further study may also be useful.

We found that a temporary mesh surface can attenuate some of the effects of vehicular usage, particularly at lower usage rates. Where mesh track was laid, and then left until plants had partially grown through the mesh prior to the commencement of driving (McKendrick-Smith, 2016), we found that nanotopographic structures displayed greater complexity (PDELAYED treatment) (Williams-Mounsey, Crowle, Grayson, Lindsay, & Holden, 2023) than on tracks where driving commenced immediately. We did not find any evidence, however, that delaying usage of the track had led to significant differences in levels of compaction or higher θ values than the other tracks, suggesting that the physical properties of the peat subsurface have a long recovery time.

5 | CONCLUSIONS

This study represents an important step in growing our understanding of the long-term impacts of tracks on blanket bogs. Our study demonstrates that mesh tracks have significant impacts on the physical properties of peatlands and that these outlast the useful life of the track. Where bare peat areas were left exposed by track removal or vehicular damage, we found that there were large movements of sediment on the track, being most prevalent in the ruts. While a drying effect was identified in the track centres, particularly on the unsurfaced track, an anticipated edge effect was not identified. Moisture was increased in ruts relative to the centres, but the hypothesis that they would have higher wetness in comparison to the controls was not supported by our analysis. We identified significant compaction of the peat across the majority of track transects. The unsurfaced track suffered from high levels of compaction in the ruts, despite the low number of passes made over the track, while the centre was unaffected by compaction. The number of passes over the mesh tracks was broadly indicative of the compaction, with the lowest pass tracks showing the lowest compaction. We did not find rarefaction of the peat where track sections were removed. Our findings on surface compaction support conclusions that peat is an inherently unsuitable substrate to support heavy vehicle usage and that while mesh tracks provide some protection against compaction, they increase the footprint over which it occurs and alter moisture patterns. More research is needed to establish the nature of deformation after vehicular usage, how tracks and track removal impact overland flow processes, and whether vegetation or microtopographic restoration on peat where tracks are removed could attenuate these impacts.

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CONFLICT OF INTEREST STATEMENT

Joseph Holden has also received funding for peatland research in the last 5 years from Defra, Yorkshire Water, The National Trust, Forest Research, Peak District National Park Authority, Natural England and the Environment Agency, while both Richard Grayson and Joseph Holden are currently funded to undertake peatland research by the EU's Horizon 2020 programme. Richard Lindsay has received funding for peatland research in the last 5 years from the IUCN UK Peatland Programme and Natural England and is currently funded through the UK Centre for Ecology and Hydrology to undertake peatland research through the UKRI's Greenhouse Gas Reduction - Peatland Project.

DATA AVAILABILITY STATEMENT

Data will be available in White Rose Repository upon publication.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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