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Research article

Removal of mesh track on an upland blanket peatland leads to changes in vegetation composition and structure

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ABSTRACT

Mesh tracks on peatlands are often granted permits on a temporary basis under the presumption that the tracks are either removed at the end of their permitted use or remain unused in situ. However, the fragility of peatland habitats and poor resilience of the specialist plant communities within them, mean that these linear disturbances may persist post-abandonment or post-removal. We removed sections of mesh track, abandoned five years earlier, from a blanket peatland using two different removal treatment methods (mown and unprepared) and studied a third treatment with sections left in place over a period of 19 months. On abandoned tracks, invasive species including *Campylopus introflexus* and *Deschampsia flexulosa* had established, while track removal led to extensive loss of *Sphagnum* species. Loss of surficial nanotopographic vegetation structures during track removal was extensive, and micro-erosion features were prevalent in both removal treatments. Abandoned sections of track performed comparably better across all metrics than removed sections. However, similarity between the vegetation assemblage of the abandoned track and the controls was <40% at the study outset, with NMDS (Non-metric Multidimensional Scaling) highlighting divergences. There was a mean species loss of 5 per quadrat for the removed sections. Bare peat was present in 52% of all track quadrats by the finish of the study. Our findings suggest that mesh tracks left in situ and track removal both present significant barriers to recovery and additional conservation interventions may be required after peatland tracks are abandoned.

1. Introduction

In recent years, an expanding human population coupled with the push for resources to support this growth and the desire to access ever more remote areas, has led to – often extensive – infrastructure networks being constructed in peatland areas. In the UK a study found a track density of 1.76 ($\pm$0.19) km km^{-2} on protected peatland sites (Clutterbuck et al., 2020a). In many cases, peatland roads and access tracks have been installed but their impacts are understudied (Williams-Mounsey et al., 2021). While some tracks are temporary in nature as either surfaced or unsurfaced linear features, their effects can be wide ranging, including influences on vegetation (Robroek et al., 2010), hydrology (McKendrick-Smith and Kathryn, 2016) and carbon cycling (Saraswati and Strack 2019). Tracks in peatlands represent an abrupt change to the habitat, creating a linear disturbance, with either a surface which is not normally part of the habitat or a flattening of the vegetation causing significant structural change related to vehicular passage. A study of seismic lines (unsurfaced resource exploration routes) between 3 and 4 years old, in Northern Alberta, found changes in vegetation structure up to 15 m from track edges (Dabros et al., 2017). An experimentally placed track at Moor House, northern England was found to have significantly reduced cover of *Sphagnum capillifolium*, *Calluna vulgaris* and *Eriophorum vaginatum* after commencement of vehicle passage (McKendrick-Smith and Kathryn, 2016). Powerline rights of way on peatlands in Southern Quebec acted as 'invasion pathways', encouraging the growth of both native and non-native invasives up to 250 m from track edges (Dube et al., 2011).

At the end of their use, unsurfaced tracks can simply be abandoned and allowed to revegetate gradually, although other studies of tracks have found that recovered assemblages can diverge significantly from those in areas without tracks (Caners et al., 2019; Dabros et al. 2022a, 2022b). Surfaced tracks and roads, however, present more of a challenge as there are concerns about leaving unnatural building materials, such as plastic mesh or tarmac, on site and concerns about the role of base-rich aggregates that may alter the chemical properties and functioning of peat (Lindsay, 2014). With a presumption to 'make good' on a track after

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use by removing it, temporary structures may often be pulled, dug out, or buried at the end of their life (Williams-Mounsey et al., 2021). However, studies on track removal impacts and mitigation measures are sparse (Elmes et al., 2021; Pouliot et al., 2021).

Mesh track has commonly been used as a reinforcer for mineral soil surfaces with grassy vegetation such as in temporary carparks. Plastic (HDPE) mesh is laid over existing vegetation allowing growth through the gaps, giving greater structural strength to the surface soil to reduce rutting and slow erosion rates. In the UK, the use of mesh track has increased over the past 10 years on blanket peatlands, facilitating access for agricultural and sporting purposes (McKendrick-Smith and Kathryn, 2016, Clutterbuck et al., 2020a; Williams-Mounsey et al., 2021). Permission from UK environmental regulators for temporary track use assumes that at the end of their useable life these tracks can then be removed, and the vegetation allowed to regrow. Peatlands, however, consist of large bryophyte communities which may experience lasting effects from tracks (Charman and Pollard, 1995). Some longer-term (decadal lag time) impacts of peatland roads with heavier usage have previously been identified (Sengbusch, 2015, Bocking et al., 2017) and peatlands can suffer long-lasting changes to a range of ecohydrological functions from even small perturbations (Emers et al., 1995; Holden, 2005; Robroek et al., 2010). Vegetation on peatlands helps form surficial structure such as hummocks, hollows and lawns. These most obvious structures are referred to as the microtopography, but Lindsay (2010) also suggested that finer-scale features could also be identified, denoted as nanotopography, including micro-erosion structures and intermediary ridges. This structure is integral to the hydrological functioning of the ecosystem (Branham and Strack 2014). It is therefore important to understand how the removal of temporary tracks influences the diversity of species and the nanotope structures that form the peatland surface (Lindsay, 2010; Clutterbuck et al., 2020b). This fine-scale assessment provides greater insight into disturbance impacts (Evans and Warburton, 2007; Lindsay, 2010; Graham et al., 2020,Williams-Mounsey et al., 2023).

The purpose of this study was to understand how blanket peatland vegetation responds in the event of a mesh surfaced track being abandoned and later removed from a site. The study was based at an established site in northern England where a track had been abandoned in place for five years. We hypothesised that there would be initial loss of vegetation with impacts lasting for at least the duration of the study period and that the removal of the track would lead to a reduction in vegetation height. Based on findings by Dube et al. (2011), we hypothesised that the loss of vegetation cover could lead to the former track acting as an 'invasion pathway' for fast growing species and those usually found on acidic mineral soils but not normally peat soils. Moreover, we expected that there would be a large amount of dead vegetation on lifted sections, but that *Sphagna* would regenerate from this. An edge effect on the vegetation was also hypothesised as a result of the track being constructed. The importance of microforms in peatland function has been previously highlighted (Branham and Strack 2014; Lovitt et al., 2018; Clutterbuck et al., 2020b). However, seismic lines have also been found to cause structural simplification of the peatland surface (Stevenson et al., 2019). The flattening of the microtopography has also been found to alter the vegetation community (Caners and Lieffers, 2014). We hypothesised that there would be differences in structure, including the frequency and distribution of these structures on the removed and remaining track study plots in comparison to control areas.

2. Methods

2.1. study site

The 1.5 km mesh track, installed in July 2013, originally as part of a hydrological investigation (McKendrick-Smith and Kathryn, 2016) is located within the Moor House National Nature Reserve (54°41′37.1″N, 2°22′25.2″W) in the North Pennines of northern England. The reserve is characterised by large areas of blanket peat across rolling headwater landscapes, many of which have not been subject to direct management for at least the past 80 years. There has been no artificial drainage in the vicinity of the experimental site. There have been numerous studies on the Hard Hill plots at Moor House which examine both vegetation diversity and structure (Clutterbuck et al., 2020b) but these focus on the influence of experimental burning and grazing, while the only track studies at Moor House are those carried out by McKendrick-Smith and Kathryn (2016). The climate is sub-Arctic oceanic, and over the period of 1931–2006 the mean annual temperature was 5.3 °C and mean annual precipitation measured in 1953–1980 and 1991–2006 combined was 2012 mm (Holden and Rose, 2011). The vegetation community is dominated by *Calluna vulgaris* and *Eriophorum vaginatum*, with the dominant *Sphagna* species being *Sphagnum capillifollium* and *Sphagnum medium*. The track is located at an altitude of ~600 m, and the topography undulates along the length of the track, with a recorded peat depth of between 1 and 3.2 m.

2.1. Experimental design

2.1.1. Track removal

Beginning in June 2020, a study of a 1.5 km long, 2.5 m wide specially designed, heavy duty Terram plastic mesh track with a total weight of 4 0.8 t, was undertaken to examine the ecohydrological effects of removing and abandoning sections of track using three different treatments. The primary focus was species diversity, relative abundance and surface microforms compared to control survey points. In the previous study different sections of the track received controlled numbers of vehicle passes (McKendrick-Smith and Kathryn, 2016). For our study, a 270 m section which had received 412 passes from an Argocat, with a weight of ~770 kg and ground pressure of ~0.15 kg/cm^2 was selected (Fig. 1).

In the UK, on protected sites, tracks are consented for periods of around five years, after which they should, in theory, be removed or a new consent sought to extend the usage period. However, there is no established protocol for the removal or abandonment of a mesh track. Therefore, we applied three treatments which were deemed feasible by conservation practitioners. During the removal process large amounts of vegetation fell off the track surface (Fig. 2). This mulch vegetation was left in place to study whether it would regenerate or aid regrowth. We

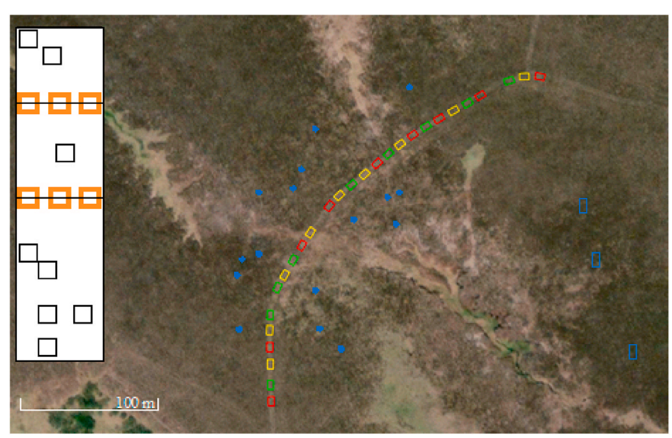

Fig. 1. Layout of plots (indicated by rectangles) along the track. Red plots indicate unprepared prior to removal (UR) treatment locations, green left in place track (LP) treatment and yellow mown prior to removal (MR) treatment. Blue dots represent individual random control quadrats and the blue rectangular plots contained 8 control quadrats each. The inset figure shows a schematic example layout of track quadrat points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 2. Removal of sections of mesh track from the study site showing digger set-up and the extensive surficial vegetation loss that occurred during the removal process.

monitored the changes in vegetation cover, bare peat, mulch, species assemblage, sward height, and nanotopographic structure over a two-year period with comparison to control plots.

Three treatments were applied to plots along the 270 m of track (Fig. 1) which were: i) track left in place (LP); ii) mown with a quad-pulled flail-mower prior to removal, the aim of which was to ease removal and leave a short functional layer (MR), and iii) no preparation (mowing or cutting) of vegetation prior to removal (UR). Nine replicates of each treatment type were created, with three of each kind on one of the following: top, mid or bottom of slope position, giving 27 plots in total plots were 7 m × 2.5 m (plot area 17.5 m^2). A total of 126 m of track was removed, and a 3 m buffer of track was left between each plot to minimise movement of overland flow sediment and debris between plots. 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 digger (Fig. 2). The digger was positioned to the side of the track to minimise disturbance to the experimental plots on the track, although disturbance to the surrounding vegetation occurred, which we discuss later.

2.1.2. *Survey plots*

Eight random survey points within each plot were selected using an online random number generator. The vegetation surveys and bare peat were carried out using 0.5 m^2 quadrats divided into 100 × 5 cm x 5 cm cells, giving a total of 70 possible locations for 0.5 m^2 quadrats within each plot. Random numbers were also used to select the location of two linear transects, to closely assess the impact of rutting on each plot (Fig. 1). Small overlaps between the random and linear quadrats were deemed acceptable on account that the overlaps were not complete and would therefore capture different data; 5 overlaps occurred. Each quadrat point was marked using a wooden stake fixed at the top corner of the survey point.

Vegetation and bare peat surveys were carried out before the track was removed on all plots to establish a baseline for each survey point; these took place approximately five years after vehicular use on the track ceased. Immediately after removal, the plots coincident with where the track had been removed were resurveyed. A 'lite' survey (involving four randomly selected quadrats from the full eight and all the linear quadrats) on all plots from the two treatments where track was removed was carried out in the following spring (2021) to assess for interim changes, followed by full surveys in autumn 2021 and mid-summer 2022 of all survey points including the control points. Three control plots mirroring the topography of the track were selected, situated on undisturbed blanket peat ~100 m from the mesh track area to avoid undue influence from the track (Fig. 1). A further 16 random control points sitting >10 m from the track edge on the up and down-slope sides were also selected (Fig. 1).

All 100 cells were assessed in each quadrat, and no subsampling was undertaken. To be counted as present in a quadrat cell, a plant had to be growing/rooted in said cell, accounting for plants such as *Calluna vulgaris* or *Eriophorum vaginatum* which may provide extensive canopy coverage while rooted only in a few cells. While each quadrat is divided into 100 squares this does not equate cleanly to a percentage cover, as multiple plants are often rooted in any given cell. Thus, the number recorded for each species equated to percentage of cells having the species of interest present. The exception was for bare peat, where only cells with minimal plant presence (i.e., diffuse strands of *Eriophorum* spp. or small seedlings) or entirely bare ground were recorded as bare.

In summer 2022, a survey of nanotope structures, following the method in Lindsay (2010), was carried out to establish the extent of structural alteration relevant to track edges in the post-removal period. Surveys were carried out on linear transects on each of the 27 plots, with nanotopes surveyed at 1 m intervals on each plot in the ruts and centres of the plots to give a total of 189 centre data points and 378 rut data points. An assessment of the 1 m edge transect was also carried out. A detailed table of nanotope descriptors is given in Appendix 1: Table S1. The codes used to classify the nanotopes, following Lindsay's classification, are as follows; EMB – bare micro-erosion, EMM – Non-*Sphagna* dominated moss micro-erosion, EMS – *Sphagna* dominated micro-erosion, TK – Tussock, T1- Low ridge, T2 – High ridge, T3 – Hummock. Nanotope types were allocated a number based on their average height above the water table to allow for statistical analysis: T3 – 65, T2 – 22.5, T1 – 8, TK – 5, EMS – 1, EMM – 0.5 and EMB– 0 (EM features are allocated values based on the hierarchical nature of each feature).

2.1.3. *Vegetation height*

Measurements of the vegetation height (hereafter referred to as sward height) on both the track and the downslope edge adjacent to the track were taken at intervals of ~6 months (autumn 2020, spring 2021, autumn 2021, and summer 2022). The upslope edge was used to access the track on foot during the study period, so measurements were not taken from this side, although the distance disturbed by the digger was measured. Sward heights involved three measurements taken across the track with one per wheel rut, and one from the centre (with the mean value calculated to give one measurement). There were also two off-track measurements of sward height: one at 1 m from the track edge and one at a control, 10 m from the track edge. An additional 25 measurements 5 m from the track edge were taken in autumn 2021, followed by a full set of 100 measurements in summer 2022 to test if there was a graduated effect corresponding to our observations on the sward height between the 1 and 10 m transects. The sward height measurements were taken ~3 m apart at 100 points along the line of the track, with measurements taken from both plots and the 3 m buffers between each plot. The height of the vegetation was measured without any extension, i.e. graminoids were measured at their natural height, and not when pulled straight upwards.

2.1.4. *Data analysis*

Data analysis was carried out using QED statistics (ver: 1.5.5.503) and Python (ver: 3.10) with Spyder (ver: 5.0.1). To explore differences in vegetation community between the treatments and controls in a 2D space, NMDS (Non-metric Multidimensional Scaling)was employed. The envfit function was used to highlight species driving more than 15% of the variation. NMDS was created using R (ver: 4.2.1) with RStudio (ver: 2022.12.0). Bray-Curtis dissimilarity was used to compare differences between treatments and controls. Non-parametric tests were used with all data except for sward height due to heteroscedasticity. Exploratory analyses using histogram and scatterplots were used to establish the suitability of tests. Bare peat data were analysed using Mann-Whitney U tests. Sward height was analysed using two-tailed t-tests. Two-tailed pairwise comparisons were carried out on nanotope data using Mann-Whitney U tests. Key seasonal species differences within treatments were analysed using Wilcoxon matched pairs, and between treatments using Mann-Whitney U tests. Spearman's rank correlation was used to explore the possible relationship between mulch and bare peat extent, and mulch and *Sphagnum capillifolium* regrowth.

3. Results

Precipitation, water-table depth, air and soil temperature data during the period of study are provided in Appendix 1: Fig. S1 for context. A two-month period of reduced rainfall and lowered water table occurred in June and July 2021.

3.1. *Changes in vegetation species assemblage and abundance across the treatments post-removal*

In the immediate period following the removal of the track, the make-up of the vegetation community changed significantly, driven by several key species (Table 1). Species losses were recorded across all removed quadrats in the following 19 months. *Calluna vulgaris, Eriophorum vaginatum* and *S. capillifolium* were the three most abundant species at baseline. Track removal led to reduced occurrence of the three most abundant species and their occurrence remained lower 19 months after removal in summer 2022. The mean species loss combined for both UR (unprepared removed) and MR (mown removed) was 5.03 species per quadrat with no significant difference between them ($p = 0.21$).

3.1.1. *Similarity in species assemblages and abundance over the study period*

The lowest levels of similarity between treatments and controls were recorded at the baseline (Table 2, full details of all surveys can be found in Appendix 1: Table S2) with all track plots <40% similar to controls. Fluctuations occurred in the community composition both spatially and temporally, as evidenced by the small changes in the similarity index over the survey period in the control plots (Table 2), and in the differences at baseline between the treatment plots pre-removal.

A total of 29 species were identified in the quadrats sampled in the undisturbed control plots, compared to 45 species in the treatment plots, with only two of these species in the controls being non-characteristic bog species (*Campylopus* sp. moss and *Polytrichum commune*) and both present at very low densities (<1% of total quadrat squares). While there is broad similarity in the assemblage between the controls and treatments, the driver for the low similarity found between the locations appears to be the abundance of the species. Non-metric multidimensional scaling (NMDS) using Bray Curtis distance provides visualization of these difference in vegetation assemblage composition between the control and treatment plots (Fig. 3) for baseline and summer 2022, stress = 0.21.

3.1.2. *Effect on key species abundance of the two methods of removal*

To assess the impact of track removal we analysed the differences in nine selected species (*Calluna vulgaris, Eriophorum vaginatum, Eriophorum angustifolium, Sphagnum capillifolium, S. medium, S. papillosum, Campylopus* sp.*, Hypnum jutlandicum* and *Polytrichum commune)*. These were selected as a mix of typical bog species and some indicative of disturbance, We applied a Wilcoxon matched pairs test to focus on the changes within each treatment between baseline and post-removal, and baseline and summer 2022 (19 months post-removal). Using Mann Whitney-U tests we compared the abundance of these same key species at baseline, post-removal and in summer 2022 for the two removal treatments (detailed analysis in supporting material; Appendix 1: Tables S3 and S4). We found that *C. vulgaris, E. angustifolium* and *H. jutlandicum* were all significantly more abundant in UR prior to removal ($p < 0.05$), while abundances of other species were not significantly different between treatments. Post-removal, *C. vulgaris* and *E. vaginatum* were more abundant in the UR plots ($p < 0.05$), representing a greater loss of *E. vaginatum* from MR. In the summer 2022 survey, *E.vaginatum* remained significantly more abundant ($p < 0.05$) in UR than in MR. Mature *C. vulgaris* plants showed a steady decline in abundance in UR between spring 2021 and summer 2022, although abundance remained significantly higher than in the MR plots ($p = 0.04$). However, the abundance of seedlings was not significantly different between UR and MR ($p = 0.12$). **3.1.3 Influence of track abandonment and removal on the prevalence of invasive or non-bog species.**

We aggregated the counts of seven key invasive or non-bog species (in the UK) and one kingdom (fungi - two species were identified – which we did not differentiate for the analysis), these were: *Galium saxatile, Deschampsia flexulosa, Festuca ovina, Nardus stricta, Sphagnum tenellum,*

Table 1
Mean quadrat squares (out of 100) occupied by key species on the track treatments (MR – mown removed, UR – unprepared removed and LP – left in place) for baseline (5 years post-abandonment) and summer 2022 (19 months post-removal).

Species	Baseline MR	Baseline UR	Baseline LP	Summer 2022 MR	Summer 2022 UR	Summer 2022 LP
Calluna vulgaris	28	40	39	9	11	13
Eriophorum vaginatum	85	86	75	32	30	53
Eriophorum angustifolium	5	2	2	3	2	2
Narthecium ossifragum	2	4	2	1	2	3
Sphagnum capillifolium	49	50	56	18	11	60
Sphagnum medium	8	5	10	0	0.5	10
Sphagnum papillosum	4	2	1	3	2	5
Hypnum jutlandicum	9	12	9	3	2	9
Campylopus spp.	9	6	4	9	5	2

Table 2
Summary of Bray-Curtis similarity index (a full version with corresponding dissimilarity can be found in Appendix 1: Table S2) between treatments; MR – mown removed, UR – unprepared removed and LP – left in place.

Compared treatments and time period	Bray-Curtis similarity index
All LP baseline, all MR baseline	88.7%
All LP baseline, all UR baseline	89.5%
All MR baseline, all UR baseline	89.5%
All LP baseline, all LP Summer 22	81.9%
All MR baseline, all MR Summer 22	57.6%
All UR baseline, all UR S22	48.5%
All UR S22, all MR Summer 22	85.8%
All LP S22, all MR Summer 22	56.0%
All LP S22, all UR Summer 22	52.2%
All UR baseline, controls baseline	36.8%
All LP baseline, controls baseline	38.2%
All MR baseline, controls baseline	37.6%
Controls baseline, controls Summer 22	85.9%
Controls A21, controls Summer 22	88.8%
Controls S22, all UR Summer 22	51.6%
Control S22, all MR Summer 22	47.0%
Control S22, all LP Summer 22	40.7%

Campylopus sp. and *Polytrichum commune*. Firstly, analysis was undertaken on the combined counts for all treatments by season, compared to the remote, undisturbed control counts at the same point. All track sections had significantly higher numbers of the key species at each survey than for the control plots ($p < 0.001$). Treatments were then analysed individually to assess if there was any difference between them in abundance of invasives/non-bog species at the baseline condition. MR contained significantly higher numbers of non-bog species than LP at baseline ($p = 0.02$), but in the final survey 19 months post-removal, there was no significant difference between any of the three treatments. Finally, analysis of invasives across all treatments was carried out comparing baseline to summer 2022, where we found no significant difference ($p = 0.50$).

3.2. *Impact of track abandonment and removal on sward height*

Sward height was variable both spatially and temporally. The lowest recorded mean height in the 10 m transect, 31.6 (±7.98) cm was in autumn 2021. In the 1 m transect the lowest mean height, 24.9 (±8.62) cm was recorded in summer 2022, and in the control quadrats the lowest recorded mean height, 19.8 (±7.11) cm was in autumn 2021. We found that sward height fluctuations occurred seasonally across all locations, with no clear trend. The mean sward height in summer 2022 was the lowest recorded for each of the track, 1 m and 5 m transects. A key driver for reduced sward height may be die-off of *Calluna vulgaris* which we recorded extensively on the track, but which was also observed across the site.

3.2.1. *Sward height effects by treatment and position on track*

The mean sward height for the treatment plots at baseline was 10.6 (±4.44) cm, and the mean sward height in the control quadrats was 22.1 (±6.07) cm. Baseline comparisons for the three treatments suggested that both the UR and MR plots had a significantly higher sward height than LP ($p < 0.01$). MR and UR plots did not differ significantly in sward height ($p = 0.34$), and control plots had sward heights that were greater than those for all track locations ($p < 0.001$). In the post-removal period, UR had a significantly higher sward height than MR ($p < 0.001$). However, the baseline sward of LP was higher than that for UR post-removal ($p < 0.001$), highlighting the effect of removal. Analysis of the random and linear quadrats showed that sward height also varied

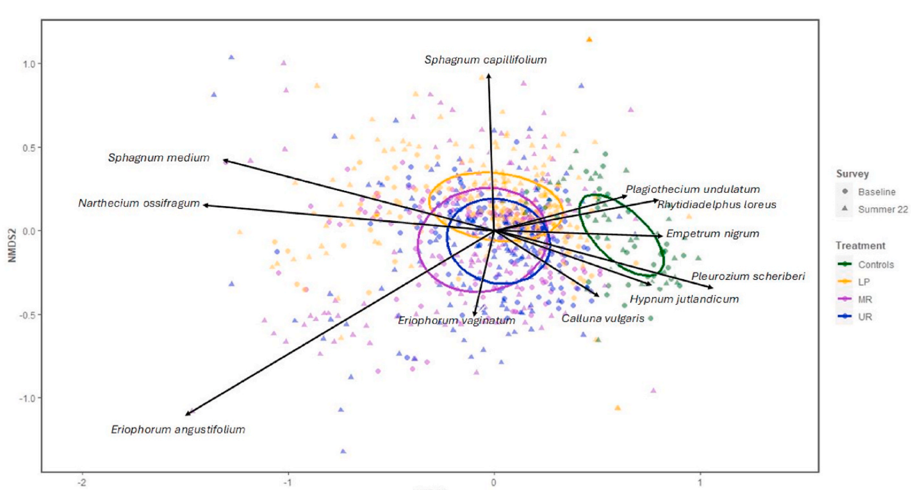

Fig. 3. NMDS using Bray Curtis distance showing differences and overlaps between treatments (MR – mown removed, UR – unprepared removed and LP – left in place) and control, highlighting the divergences in the assemblage, with the species acting as major drivers of variation highlighted.

independently of the removal process. Linear quadrats include the rutted sections, so this is likely indicative of lasting damage from previous vehicular use. When random and linear and quadrats from MR and UR were aggregated into two groups at baseline, random quadrats had significantly higher sward than linear quadrats ($p = 0.003$). In the post-removal period, there was no significant difference between random and linear quadrats ($p = 0.15$). By summer 2022, however, sward heights for random quadrats had increased significantly (mean = 5.9 (±3.00) cm; $p = 0.01$) in comparison to those for the linear quadrats (mean = 5.1 (±3.32) cm).

3.2.2. Edge influences on sward height

Sward height was found to be significantly lower for all sets of track measurements compared to the 1 m edge and 10 m control transects ($p < 0.001$). Both 1 m and 10 m transects had significantly different mean values over the survey period (mean 26.3 (±8.18) cm and 33.2 (±8.17) cm respectively) than the track values (Fig. 4). A significant difference ($p < 0.001$) between the 5 m and 10 m mean sward heights (mean 27 (±6.32) cm and 33.6 (±8.04) cm respectively) in summer 2022 was also found. Treatments played a role in reducing sward height on the track; but individual treatments did not significantly influence the edge transect sward height.

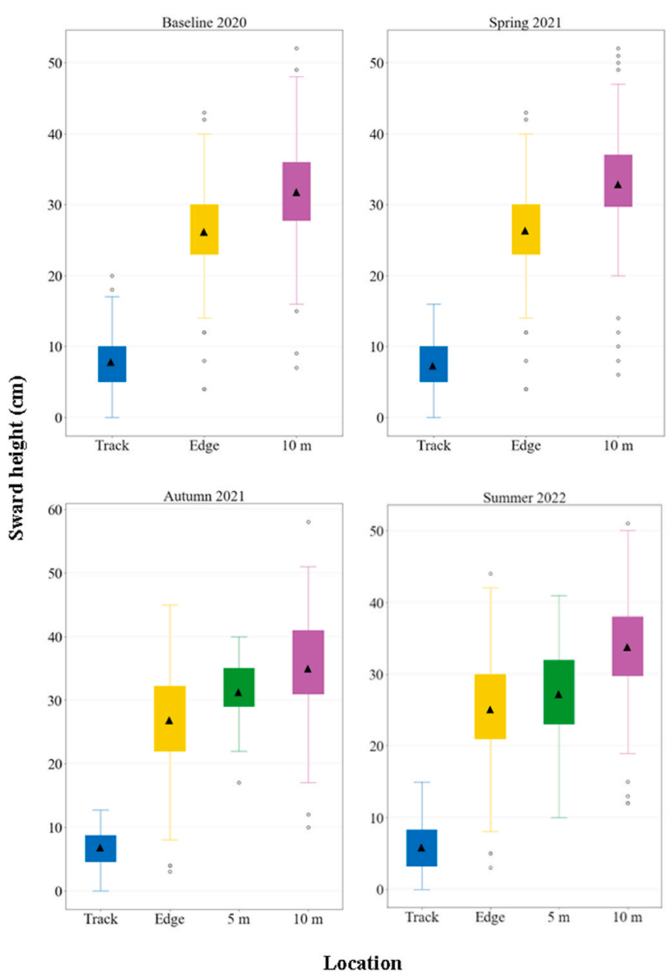

Fig. 4. Variation in sward height measured at three points; track, 1 m away from track edge and 10 m away from track edge, with an additional 5 m transect included in autumn 2021 and summer 2022. The median is represented by the black triangle, box ends represent IQ1 and IQ3, whiskers represent values up to 1.5 times the IQ range with fliers representing the extreme outliers.

3.3. Bare peat and mulch

With track removal, bare peat incidence increased almost threefold from being present in 18% of quadrats at baseline (68 quadrats) to 41% of quadrats immediately post removal. By 19 months post removal, in summer 2022, bare peat was present in 52% of quadrats. The mean bare peat coverage across track all quadrat locations (ruts, centre and random) and treatment types at baseline was 5.3 (±15.7)%, while in the plots selected for track removal it was 3.4 (±10.7) % at baseline. Broken down by quadrat location at baseline, linear quadrats (all treatments) had a mean of 6.5 (±17.8)% and random quadrats (all treatments) 4.4 (±13.9)% bare peat coverage. Bare peat was not recorded in any of the control plots or random control quadrats. Despite some variation there was no significant difference between the MR and UR treatment plots in extent of bare peat at baseline (Fig. 5). Further comparative analysis for the removed track treatments is shown in Table 3.

There was a significant difference in the extent of bare peat in the LP baseline random quadrats compared to the UR plots ($p < 0.05$), while no significant difference was found compared to the MR plots. As anticipated, immediately after the track was removed bare peat coverage had increased significantly in MR and UR treatments compared to baseline across all quadrats to a mean coverage of 35.8 (±31.4)% ($p < 0.001$).

Many quadrats lost their functional layer of vegetation, which was pulled off or severely damaged during the track removal process. This fallen vegetation was not readily identifiable but was left in place in place and counted subsequently as mulch, to assess whether it could regenerate or aid recovery. In summer 2022 (19 months post-removal) mulch had a mean cover of 7.8 (±16.8)%, and was found in 122 quadrats, representing 32% of all surveyed quadrats.

One-tailed Spearman's rank correlation was used to analyse the relationship between bare peat and mulch across all quadrats on all removed treatments plots, in each of the three main survey periods (post-removal, autumn 2021 and summer 2022). A significant negative correlation, albeit with a moderate to weak association was found between bare peat and mulch (post-removal $p < 0.001$ $r = -0.62$ and summer 2022 $p < 0.001$ $r = -0.27$). However, a positive correlation with a weak association was found between mulch cover and *Sphagnum capillifolium* regeneration, post-removal mulch cover correlated with the final summer 2022 growth ($p = 0.021$, $r = 0.15$).

3.4. Impact of removal and abandonment on nanotope structure

A nanotope survey on the track was carried out in July 2022, 7 years after the track was abandoned and 19 months post-removal. At the beginning of the recording period in 2020, nanotope structure was observed to be relatively uniform across the track yet simplified compared to the control areas and the track edges. These findings mirror those from the other abandoned tracks on the site (Williams-Mounsey et al., 2023). The bryophyte layer and associated features were extensively lost in the lifting process. *Eriophorum vaginatum* and *Trichophorum cespitosum (L.) Hartm* tussocks, although widely damaged in the initial post-removal period, were able to recolonise from the remaining individuals. In the ruts and centres of both removed treatments these tussock species were the dominant vegetated nanotope type with 118 of the recorded nanotopes being TK type (31% of the total 378 recorded nanotopes). EMB was the most common nanotope feature in the two removed treatments with 193 occurrences (51%). The LP treatment showed a more complex nanotope structure, with the T1 feature recorded 110 times (58% of the total recorded 189 features). Micro-erosion features on the LP treatment were fewer and mainly re-vegetated. A total of 53 occurrences were EMS or EMM type (28%) with 22 being EMB (12%), all but one of which occurred in the ruts. Between the two removed track treatments we found no significant difference in the nanotope structure which remained (Table 4).

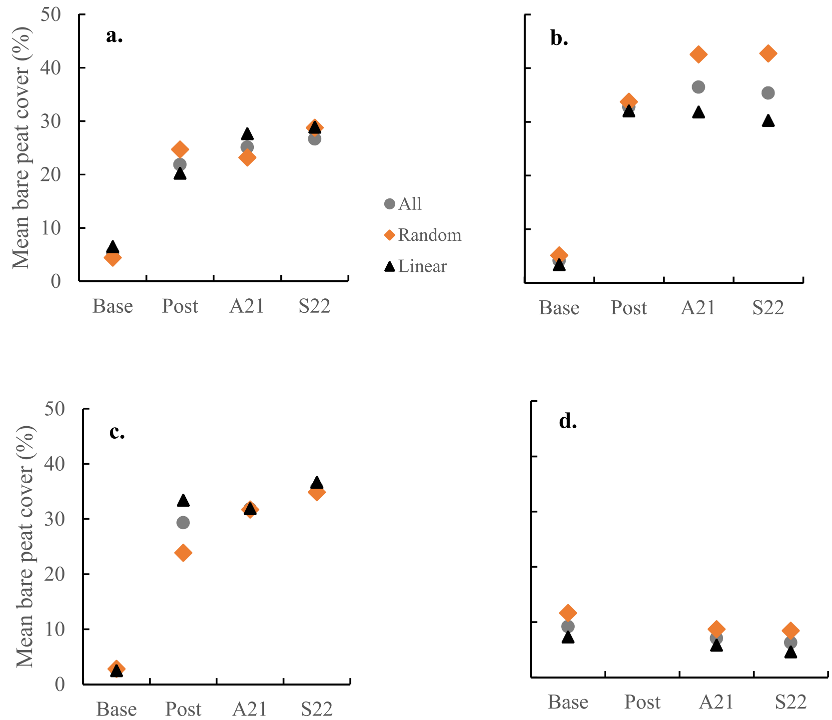

Fig. 5. Changes to the mean cover of bare peat across quadrat survey points at baseline (Base), post-removal (Post – Mown and unprepared removed – MR and UR - only), autumn 2021 (A21) and summer 2022 (S22).; **a.** all treatments combined **b.** MR **c.** UR and **d.** LP (left in place).

Table 3
Summary of descriptive statistics and Mann Whitney U pairwise comparisons for bare peat extent and changes to bare peat extent across the three treatment types (MR – mown removed, UR – unprepared removed and LP – left in place) on the track.

Survey period and quadrat type	LP plots median %	UR plots median %	MR plots median %	p-value
Baseline random	0	0	0	0.47
Baseline linear	0	0	0	0.32
Post-removal random	N/A	25	20	0.36
Post-removal linear	N/A	17	31	0.07
S22 random	0	32	26	0.07
S22 linear	0	35.5	42.7	0.18
Comparisons between surveys	**LP p-value**	**UR p-value**	**MR p-value**	
Baseline, S22 rando[a]	0.31	<0.001	<0.001	
Baseline, S22 linear[a]	0.22	<0.001	<0.001	
Post-removal S22 random	N/A	0.14	0.49	
Post-removal S22 linear[a]	N/A	0.01	0.03	

Codes: * - treatment with larger extent of bare peat, S22 – 19 months post-removal.
[a] – survey period with greater extent of bare peat.

Table 4
Summary of p-values for pair-wise comparisons of nanotope values for the three treatments (MR – mown removed, UR – unprepared removed and LP – left in place), (* denotes the treatment with the greater mean) with mean nanotope values below.

Treatments in comparison	Rut 1 p-value	Centre p-value	Rut 2 p-value	1 m p-value
MR, UR	0.47	0.15	0.41	0.44
MR, LP*	<0.001	<0.001	<0.001	0.37
UR, LP*	<0.001	<0.001	<0.001	0.42
Treatment	**Rut 1 mean**	**Centre mean**	**Rut 2 mean**	**1 m mean**
MR	13	22.2	17.9	257
UR	10.6	23.2	15.9	255
LP	27.1	48.1	34	250

4. Discussion

This study represents the first investigation of HDPE mesh track removal from blanket peatlands. Our results show that abandoned tracks, where left or removed, impact the species assemblage and abundance, increase instances of bare peat, reduce the sward height, and alter the surficial structures relative to undisturbed control plots. A greater diversity of species was recorded on the track in comparison to controls. However, a number of these species were non-bog species, including the non-native invasive *Campylopus introflexus,* supporting findings from Quebec, that track routes act as pathways for invasives to establish (Dube et al., 2011). Comparison to controls suggested that dissimilarity in abundance and assemblage along the track increased over time, an important consideration in deciding whether active restoration is required when tracks are no longer required. Similar lasting alterations to the composition of bog communities have been observed on seismic lines in Canada (Davidson et al., 2021; Dabros et al. 2022a, 2022b). We recorded reductions in sward height along the track supporting our hypothesis of a significant edge effect, with height reduction up to 5 m either side of the track. Both removal treatments caused significant alterations to the nanotope structure compared to the LP treatment. However, nanotopes for all treatments were simplified compared to the adjacent structure; findings supportive of both our hypothesis and an earlier nanotopographic study of all the abandoned tracks on the site (Williams-Mounsey et al., 2023).

4.1. Impact on vegetation community of leaving and removing tracks

Initial surveys at baseline (five years after abandonment, prior to removal) showed that the vegetation assemblage across all track plots was substantially dissimilar to control areas. At 19 months post-removal we found no convergence towards the control assemblage, we had hypothesised that recovery would not occur within the timeframe of this study, and this finding is supportive of that. These findings also suggest that tracks initiate changes in the assemblage that persist whether abandoned or removed, supporting findings from North American sites (Davidson et al., 2021; Dabros et al. 2022a, 2022b). We recognise, however, that there is a lag time on recovery in the post-removal period that is not fully captured within our study timeframe. In comparison to controls, we found that invasives or non-bog species were significantly more prevalent on all track locations. One further track of this type has been removed, on a comparable peatland area nearby in the North Pennines. Although the nearby track could not be studied in detail due to access restrictions, we periodically photographed it to document recovery (Fig. 6). Observations of this nearby track also suggest that restoration intervention is required after track removal as there is a large area of bare peat after 4.25 years.

Non-peatland species and non-native invasives were recorded on both the intensively studied removal plots and on the areas of abandoned tracks at Moor House (e.g. Appendix 1: Fig. S2). However, numbers were not significant enough to support our hypothesis that removal alone would lead to an increase. Introduction of exotic plants along access routes is a well documented phenomena even in remote habitats (Fiori and Zalba., 2003; Dube et al., 2011;Roberts et al., 2018). Non-bog graminoid species increased their abundance in the post-removal period; most notably *Deschampsia flexulosa* was well established on the site by summer 2022. We also recorded a 12-fold increase in fruiting bodies of fungi (including *Sphagnurus palustre* a parasite of *Sphagna*) 12 months post-removal. Additionally, the invasive non-native moss *Campylopus introflexus* was widely established across the track site. Prior to the commencement of the study by McKendrick-Smith and Kathryn (2016) *Campylopus introflexus* was recorded on just one area of the experimental site and not on the area under discussion here, yet by the end of the 2016 study it was recorded on all track areas. This ability for *Campylopus* sp. to rapidly colonise disturbed peatlands has been discussed in multiple studies (Żarnowiec et al., 2018; Noble et al., 2018). Our findings support those from peatland road study sites in Quebec (Dube et al., 2011) where invasives colonised along tracks and dispersed out into the surrounding vegetation, a pattern observed with *D. flexulosa*. Removal of these invasives or generalists may prove challenging once they are established and decision makers should consider this as part of the decision making process when creating a track.

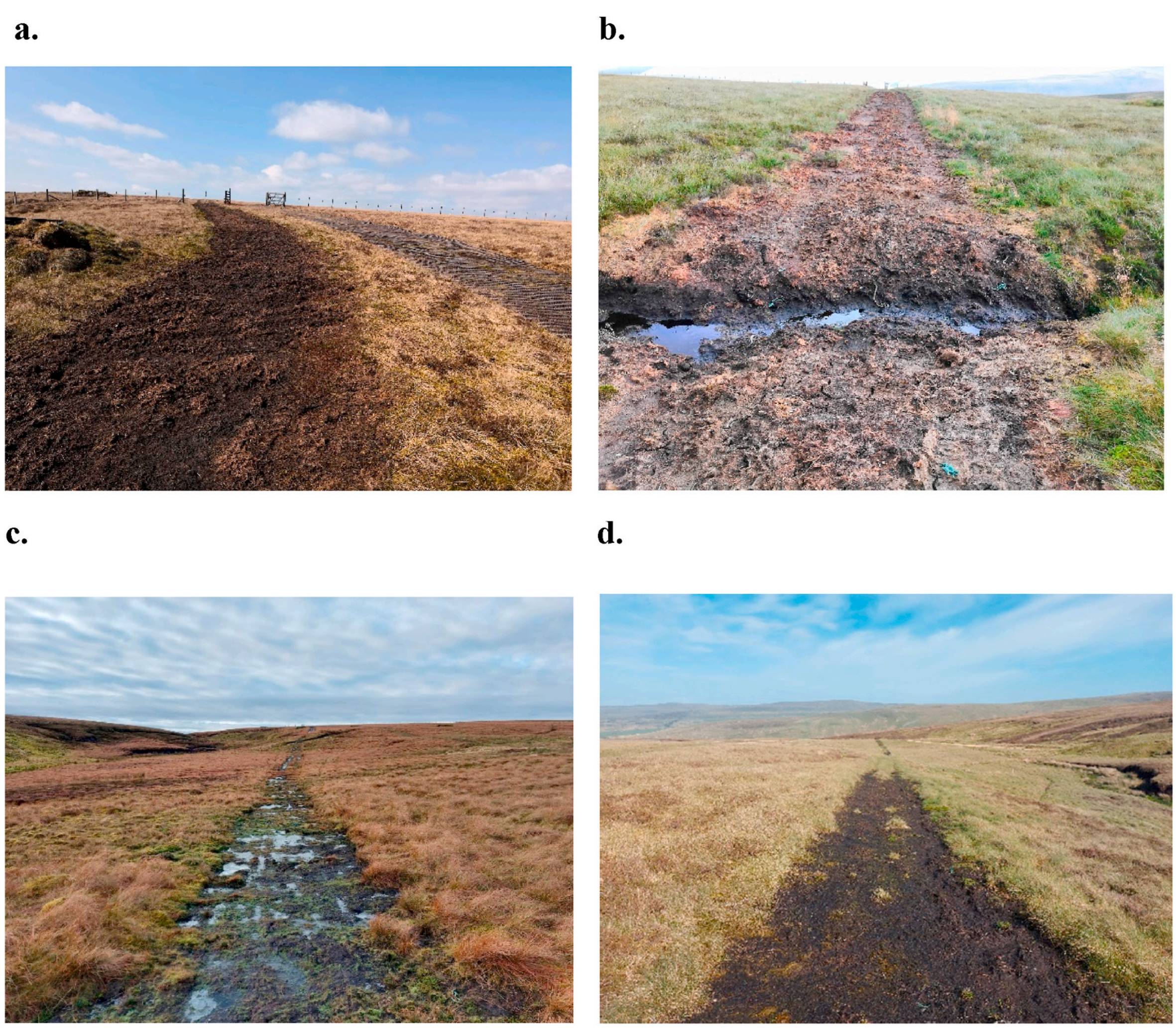

Fig. 6. Track removed from an estate in the North Pennines showing it at four different time intervals post-removal a. 15 months post-removal, April 2019 (left-hand track, a new track was laid adjacent) b. 18 months post-removal showing water eroded channel c. 3 years post-removal d. 4.25 years post-removal (shown on right of image parallel to the new mesh track).

4.1.1. Does leaving mulch in place support regrowth on removed tracks?

The mulch, composed largely of *Sphagna,* was left in place post-removal. However, our findings do not provide conclusive evidence to support our hypothesis that the mulch would benefit recovery. *S. capillifolium,* appeared to be regenerating most readily in the 19 months following the track removal. Research from three study sites in North America found that *Sphagna* were able to regenerate best when the capitula is intact, although *S. medium* and *S. papillosum* were able to regenerate from fragments up to 10 cm below the capitula (Rochefort et al., 2003). Studies highlighting the use of a straw cover layer suggest that improvements to recovery may occur where active restoration is undertaken (Price, 1996; Rochefort et al., 1997).In the most waterlogged plots where mulch presence was high in the post-removal period, a red alga established, smothering the vegetation layer which led to an increase in bare peat extent, and surficial cracking in dry weather. While attached algal communities have been found to increase in degraded peatlands under some conditions (Goldenberg Vilar et al., 2014) there has been no research into their impacts. The extent of bare peat increased significantly across all quadrats where the track was removed. This extent did not significantly decrease in the 19 months between track removal and the final survey, and mulch did not appear to support recolonisation. Damage to treated plots was extensive in the first instance, with large areas of bare micro erosion features visible (Appendix 1: Fig. S3). Our observations of the track in Fig. 6 suggest that bare peat dominance should be anticipated in ombrotrophic peatlands for at least four years post-removal. There is a risk that where changes to prevailing climate conditions occur, such as projected increases in UK rainfall (Rau et al., 2020), that the addition and removal of tracks could lead greater erosion rates where peat surfaces are exposed. Interventions such as transplanting of *Sphagna* or spreading of brash could help to protect and stabilise bare peat surfaces.

The intention of mowing the Moor House track (MR treatment) was to test whether shortening the vegetation to the level of the track would leave a functional layer of vegetation under the track that would allow faster recovery and leave less bare peat. In practice, tussocks had knitted through the mesh, and mowing did not remove enough of their structure to prevent them lifting the surrounding vegetation during track removal. While the LP treatment was more vegetated and structurally complex, bare peat area did not significantly alter over the 19 months following the baseline survey, representing a period of seven years since the initial track abandonment. These findings suggest that bare peat areas are likely to remain for significant time periods on abandoned tracks, particularly if restoration is not undertaken.

4.1.2. Edge effect on sward height

Edge effects are an important consideration, as they effectively extend the footprint of the track. Sward height showed significant variation throughout the study, not solely on the track but also in transects taken 5 m from the track edges. A significant edge effect was found extending out from the track with a maximum extent of 10 m (nanotope features and vegetation were at the upper end of the size scale at 10 m and therefore this was judged to be the limit of the track influence for our site). Our findings of edge effects are supportive of those of Dabros et al. (2011) and Willier et al. (2022) who found reduced cover in taller woody vegetation species along seismic lines in Boreal peatlands in Canada. McKendrick-Smith and Kathryn (2016) previously recorded a shallower downslope water-table depth along the track section we studied, particularly within the 1 m distance, while on the upslope side the water table was found to be deeper. A distinct visible vegetation line is observable in images (Fig. 7a and b) which may correspond with this variation, and is supported by research showing that water-table variations impact the make-up of the plant communities (Andersen et al., 2017). The removal process also led to depressed sward height post-removal on the upslope side of the track edge up to 7 m from the track (Fig. 7b).

4.2. Additional considerations

In early May of 2021, an illegal motorbike pass was made adjacent to and along the main track by trespassers on the nature reserve. The most severe part of the rut (Appendix 1: Fig. S4 a and b) was 4 m long and ~10 cm deep along its length, in August 2022 the rut remained clearly visible with an average depth of 4.3 cm. In April 2022, further illegal passes were made by at least two motorbikes over the track and the adjacent upslope area leading to further ruts. Livestock also used the track on several occasions, with poaching and hoof prints remaining visible for a number of months following; trampling also impedes vegetation regeneration (Watts, 2020). This suggests that even where a mesh vehicle track has been abandoned by the original owner, the visible route remains and therefore has the potential to become an established and preferred access route for both humans and animals. These temporary routes are necessarily side routes off larger permanent routes, and so it may be difficult to control access and thus further damage. The idea that usage is difficult to control, is supported by research which found that 36% of paths designated for pedestrian usage on UK blanket peatland sites had been used by vehicles (Clutterbuck et al., 2020a).

a. **b.**

Fig. 7. Images showing variation in the sward height along track sides, including a visible line where *C. vulgaris* growth occurs more vigorously, on the upslope side (a.) on the downslope side (b.) the effect is reversed with more vigorous growth beyond the 5 m. Damage from the removal digger is also highlighted.

Alternatively, leaving the track in place may provide surface protection. However, we have previously found that nanotope establishment is restricted by the presence of mesh tracks (Williams-Mounsey et al., 2023) due to potential spatial constraints and reduced light availability (Prusinkiewicz and Barbier de Reuille, 2010). Likewise, the sward height, although further reduced in the track removal process, was significantly lower on LP than the control areas. The baseline survey took place five years after abandonment, and we found that similarity was lowest between track plots and controls at this point compared to all subsequent survey periods. Charman and Pollard (1995) examined two abandoned tracks on Dartmoor where differences from the controls were recorded 25 years after abandonment and succession to dry-heath was occurring. Complicating the decision to leave a HDPE track in place is the lack of research on microplastic impacts in soil systems. There may be risk of pollution if a track constructed of HDPE is left in place (Rillig, 2012; Souza Machado et al. 2018; Rillig and Lehmann, 2020).

5. Conclusion

Our findings demonstrates that mesh tracks have impacts on the vegetation which are wide-ranging and significantly outlast the vehicular usage period of the track. While we present here a detailed chronological study of the vegetation after track removal, we were limited to the fine-scale study of one track with removal studied over a relatively short time scale of 19 months. We found that, where a track is abandoned in place, the vegetation assemblage and abundance patterns appear to increase in dissimilarity to the surrounding community. Conversely, removing the track by either first mowing or without preparation led to a loss of any recovering surficial structure and extensive exposure of the peat surface. Moreover, tracks whether removed or abandoned were found to be associated with a significantly lower mean sward height on the track and a graduated height effect along track edges. Invasives were able to establish along all treatment types, and while some did not gain a foothold, others were well established which would make their removal difficult and, in the right conditions, allow invasion into other parts of the habitat. Our findings strongly suggest that where the construction and subsequent removal of a track are entirely necessary, there must be a requirement for restoration intervention to be undertaken after track removal in order to prevent establishment of non-bog species, further damage to exposed surfaces, and the unintended establishment of access routes. Considering our findings, research into restoration techniques and longer term studies on removed track sites is urgently required.

Credit author statement

Jessica Williams-Mounsey: Conceptualization, methodology, investigation, software, validation, data collection data-curation, formal analysis, visualization, writing - original draft; **Alistair Crowle**: Supervision, funding acquisition, data collection, writing – review and editing; **Richard Grayson**: Supervision, visualization, validation, writing – review and editing; **Joseph Holden**: Supervision, validation, funding acquisition, project administration, writing review and editing.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117935.

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