Journal of Environmental Management 325 (2023) 116561

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Surface structure on abandoned upland blanket peatland tracks

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ARTICLE INFO

Keywords:
Wetlands
Bog
Nanotope
Erosion
Sward height
Roads

ABSTRACT

Temporary permissions are often granted for track use on peatlands. However, even when peatland track designs attempt to minimise environmental impacts via use of mesh systems, such linear disturbances may have persistent impacts. We evaluated the surface peatland structure of five abandoned tracks (four with a mesh surface, one unsurfaced) with varying past usage frequencies, at an upland site in northern England. Simplification of the surface nanotopography was found on all tracks compared to surrounding control areas, with increased micro-erosion patterns in rutted areas, and invasive species on some treatments. The frequency of previous usage was not found to be a significant factor controlling nano-topographic loss. Edge effects and hillslope position were influential in places, but these effects were not consistent across treatments. Nano-topographic recovery was found to be inhibited when track usage commenced within a short time frame after track construction. Mesh tracks appear to create a spatial constraint leading to poor development of plants and a reduced ability to form characteristic structures which are integral to mire function.

1. Introduction

Peatlands are a distinctive and important wetland habitat, which in healthy condition may be composed of up to 95% water (Charman, 2002). Peatlands are present in almost every country covering ~4.23 million km^2 (Xu et al., 2018) and containing ~600gt of carbon, around one third of the global total (Yu et al., 2010) and around 40% of the total stored across all wetland habitats (Nahlik and Fennessy, 2016) placing their preservation at the forefront of debates around climate change mitigation. Road networks are being established globally on peatlands for diverse reasons including access for utilities such as windfarms, oil sand exploration and subsequent exploitation, agricultural access, and leisure and sporting activities. Such access networks may be temporarily surfaced or unsurfaced tracks or permanent engineered roads (Williams-Mounsey et al., 2021). Much of our current knowledge about the effect of road construction over peatlands has been generated from more general engineering reviews, particularly that provided by Hobbs (1986), from individual case studies such as Nichol and Farmer (1998), or specialist conference proceedings such as Long et al. (2007). Far more extensive information is available for lowland wooded fen areas of Alaska or Canada driven by the prevalence of seismic exploration lines in these regions (Adam and Hernandez, 1977; Lee and Boutin, 2006; Campbell and Bergeron, 2012; Strack et al., 2018; Elmes et al., 2021). A smaller number of studies such as those from German (Sengbusch, 2015) and UK peatlands (Charman and Pollard, 1995; McKendrick-Smith, 2016) focus on upland bogs, a markedly different habitat in terms of structure and composition. Many of these studies suggest there are long-lasting impacts of linear disturbances from tracks and roads (Charman and Pollard, 1995; Robroek et al., 2010).

Blanket peatlands in the UK form in high rainfall regions, mainly in the uplands, on generally gentle slopes of up to 20^o., however blanket peat has been recorded on 35^o slopes (Lindsay, 2016). While UK studies of the effects of peatland roads and tracks are limited, this is not reflective of the prevalence of these structures. A recent upland peatland mapping study examining ~5% of mainland UK upland sites found a mean track density of ~1.1 km km^{-2}. The study found no evidence that sites with protected status were immune to the development of often extensive track/road networks, in particular, managed heather and grassland sites on these protected areas were strong predictors of track presence (Clutterbuck et al., 2020a). In the UK, many upland peatland sites are formally protected as Sites of Special Scientific Interest and therefore the creation of a surfaced road or other structure is controlled

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https://doi.org/10.1016/j.jenvman.2022.116561
Received 23 June 2022; Received in revised form 3 October 2022; Accepted 16 October 2022
Available online 2 November 2022

on these sites by government advisory bodies such as Natural England (England only) through a process of assessment and consent. Mesh tracks have been put forward and accepted for approval in some peatland areas as a lightweight and potentially less damaging alternative to heavier engineered tracks in order to facilitate access for lighter weight vehicles (such as Argocats), to remote peatland sites. These mesh tracks are generally deemed as temporary in nature and therefore best practice decisions need to be made around their abandonment and removal, but there is very little evidence to guide these decisions (Grace et al., 2013). At present there are only a small number of studies which focus specifically on the recovery of peatlands after roads have been removed (Elmes et al., 2021; Pouliot et al., 2021) while a few studies have considered recovery on abandoned unsurfaced tracks or paths (Charman and Pollard, 1995; Robroek et al., 2010). Where vegetation is considered, the major focus of these studies has been the composition of the vegetation community.

More generally, studies considering impacts of human activity on plant ecology in peatlands have often focused on the composition of the vegetation community as the marker for recovery (Charman and Pollard, 1995; Emers et al., 1995; Dabros et al., 2017) or signs of invasion as indicators of detrimental effects (Dube et al., 2011; Żarnowiec et al., 2018). However, peatlands have a unique microtopographic structure usually characterised as hummock-hollow, which is formed by differing growth forms of the vegetation. This highly distinctive microtopography is recognised for its importance in, among other things, the ecohydrological functioning of peatlands (Lindsay, 2010; Branham and Strack, 2014) and reduction of erosion (Evans and Warburton, 2007). A hummock-hollow system of classifying microtopography is used in many countries such as Sweden and Canada in order to assess health of the peatland. In the UK, assessments have more traditionally been reliant on the vegetation diversity (Lindsay et al., 2014; Moore et al., 2019). Despite the significance of hummock-hollow landforms, there are few studies which include detailed examination of these features at the finer 'nanotope' scale, particularly in relation to peatland recovery (Lindsay et al., 1985, 1988; Branham and Strack, 2014; Stevenson et al., 2019; Clutterbuck et al., 2020b). Detailed nanotopographic classification represents an expansion of the binary, and widely used microtopographic hummock-hollow system, and this expansion beyond the binary is supported by other research (Graham et al., 2020). Whereas microtopographic features are larger in size often forming networks or structures easily distinguishable from a distance of a few metres, nanotope features are individual forms, and as such are frequently much smaller – in some cases a few centimetres (Evans and Warburton, 2007). These small features form 'complexes' that make up the broader microtopography, and their characterisation requires close examination, similar to vegetation survey. These structures can change in nature and number over time (Belyea and Baird, 2006) so caution should be exercised when comparing structure between bogs, but comparisons of detailed nanotopography at the fine scale within a bog site could be useful in assessing changes over time or degradation around smaller features such as tracks, grazed or burnt plots compared to control areas. The application of a fine-scale holistic approach integrating vegetation diversity and detailed structural survey, as proposed by Lindsay (2010), could provide greater understanding of how disturbances impact peatland ecohydrology (Lindsay, 2016).

This study sought to implement an extensive survey of the nanotope forms - using the Lindsay (2010) classifications - and related vegetation composition on a 1.25 km long blanket peatland track, which had a range of former treatment sections, abandoned six years previously. The site is situated in the North Pennines of northern England and the overarching aim was to quantify and understand the effects of track features and track abandonment on peatland structure over different spatial and temporal scales. We hypothesised that the combined actions of past vehicular usage (including frequency and duration of use) and the constraining action of the mesh track would lead to a consistent simplification or loss of complex nanotopography, and an increase in micro-erosion features in the short term. This initial loss coupled with the slow growth rates of peatland plants would lead to a long timeframe for recovery of these features compared to controls. Additionally, we hypothesised that the track would create an edge effect impacting the adjacent nanotopography. We also hypothesised that, in tandem with structural loss, the vegetation types which formed the structures would differ from the surrounding control areas and finally, that there would be an observable significant difference in the structure that would clearly delineate the track from the surrounding habitat. In the UK context there is only one report which has quantified nanotope features as a function of peatland vegetation recovery (Clutterbuck et al., 2020b), and this was a limited spatial study focusing on the impact of burning and grazing. A single study from Canada assessed microtope simplification along single use seismic lines in boreal peatlands using an altimeter (Stevenson et al., 2019). Our study represents the first assessment of nanotopographic structure on tracks and along their edges, constituting an extension to the existing research on both nanotopes and peatland tracks and contributing to an understudied research topic (Williams-Mounsey et al., 2021).

2. Methods

2.1. Study site

A 1.5 km length of 2.5 m wide HDPE plastic mesh track was installed onto a pre-mown area of undulating blanket peatland at an altitude of ~600 m at Moor House National Nature Reserve (54°41′37.1″N, 2°22′25.2″W) in the North Pennines in Northern England in July 2013 as part of an earlier research project (McKendrick-Smith, 2016). A further 200 m section of adjoining unsurfaced track was also included in this study. The surrounding area is dominated by blanket bog habitat and smaller areas of acid and calaminarian grassland. The track was situated wholly on the blanket bog. The absence of prescribed burning combined with very low-density livestock grazing on the site for the past 80 years has resulted in a more botanically diverse bog in active condition compared to sites in the surrounding regions. The site experiences high rainfall (with mean annual precipitation in excess of 2000 mm) (Burt and Holden, 2010) and is frequently exposed to strong winds characteristic of the sub-Arctic oceanic climate of the site (Manley, 1939). Dwarf shrubs (predominantly *Calluna vulgaris*) and graminoids (primarily *Eriophorum vaginatum*) dominate the vascular plant system while the *Sphagna* are dominated by three species: *Sphagnum capillifollium, Sphagnum papillosum* and *Sphagnum medium* The sections of track included in this study were driven over by vehicles but abandoned in autumn 2015, have only been walked over occasionally in the intervening period, and no management or restoration of these sections has taken place.

2.2. Experimental design

The primary goal of our study was to determine the nanotope status on an abandoned surfaced peatland track. Such information could be important in determining what should happen to an abandoned track at the end of its useful life, such as whether it should be removed or whether the peatland surface structure would satisfactorily recover if the track were left in place. From November 2021 to February 2022 we undertook a comprehensive survey of nanotope structure along ~1.25 km of abandoned track at Moor House using the system outlined by Lindsay (2010) and used in Clutterbuck et al. (2020b). During a study by McKendrick-Smith (2016), the track was subjected to a controlled number of vehicle (Argocat, for up to 6 passengers with a weight of ~770 kg and ground pressure of ~2.1psi) passes along sections, over a two-year period (Table 1). The locations of these treatments along the track are indicated in Fig. 1. To allow cross referencing we employ the same nomenclature throughout for the treatments as those used by McKendrick-Smith (full details can be found in S1).

Table 1
Summary of treatments used by McKendrick-Smith (2016) on the tracks which were then abandoned in November 2015. Abbreviated codes used in some tables and figures are included in parentheses. The number of passes is the total of passes in each direction (vehicles drove down the track, turned at the bottom and returned, making two passes).

Treatment Name	Average number of passes per week	*Frequency*
PWEEK.AH (412)	2 (April – End July 2014 and October–April 2015) then 10 (End July–October 2015)	412 (vehicle had additional load of ~375 kg July–October each year)
PWEEK(156)	2 (April 2014–November 2015)	156
PMONTH(38)	0.5 (April 2014–November 2015)	38
PDELAYED (DEL)	2 (Feb 2015–November 2015)	76
UNSURFACED (UNS)	0.5 (Trial ended early in 2015)	24

The nanotopes were assessed at 3 m intervals along linear transects (S1) running down the length of each track and fixed markers were placed in the following locations: Rut 1, Centre, Rut 2, 1 m (henceforth referred to as 'edge' transect) from the track edge away from the track, and 10 m (henceforth referred to as 'control' transect) from the track edge away from the track, on each of the five track treatment types indicated in Fig. 1. The transects located 10 m away from the track acted as the controls, as vegetation and sward height at this distance were comparable to areas in other undisturbed locations. Sward height was measured at 2 m intervals along each track for the five measured locations (Rut 1, Centre, Rut 2, Edge and Control). A total of 100 measurements were recorded in each location for the PWEEK, PMONTH and UNSURFACED treatments and 92 and 90 for the PWEEK.AH and PDELAYED tracks, respectively, due to their slightly shorter length.

Nanotopes were classified at the point directly under the transect line in a diameter of approximately 10 cm to ensure the feature was representative (i.e., a very small bare patch on an otherwise moss-covered patch would be EM moss – Table 2). The starting point was taken at 3 m from the anchor to ensure there was no measurable effect on the nanotopes caused by excessive trampling when initially anchoring and laying the transect line. The line was moved and re-anchored to cover a total distance of 200 m. Two of the tracks (PWEEK AH and PDELAYED) were slightly shorter than 200 m. Ttherefore, the full length of available track was surveyed; this equated to 62 and 60 survey points respectively for each transect on these tracks. The nanotope features (Table 2) were allocated an abbreviated code and a feature description along with the range of heights above the water table at which each feature can be found.

As the tracks were originally designed to capture topographic variation, the track sections included top, mid and bottom slope areas. In

Table 2
Descriptions of nanotope types used for classification (Clutterbuck et al., 2020b).

Nanotope type	Description (measurement in relation to water table)
T1	1–15 cm low ridge
T2	15 cm–30 cm high ridge
T3	30 cm-1 m hummock
TK – Tussock	Hard grass tussock of Eriophorum or Trichophorum
EM Bare	Bare earth micro-erosion
EM Moss	Micro-erosion dominated by non-Sphagnum mosses
EM Sphagnum	Micro-erosion dominated by Sphagnum mosses

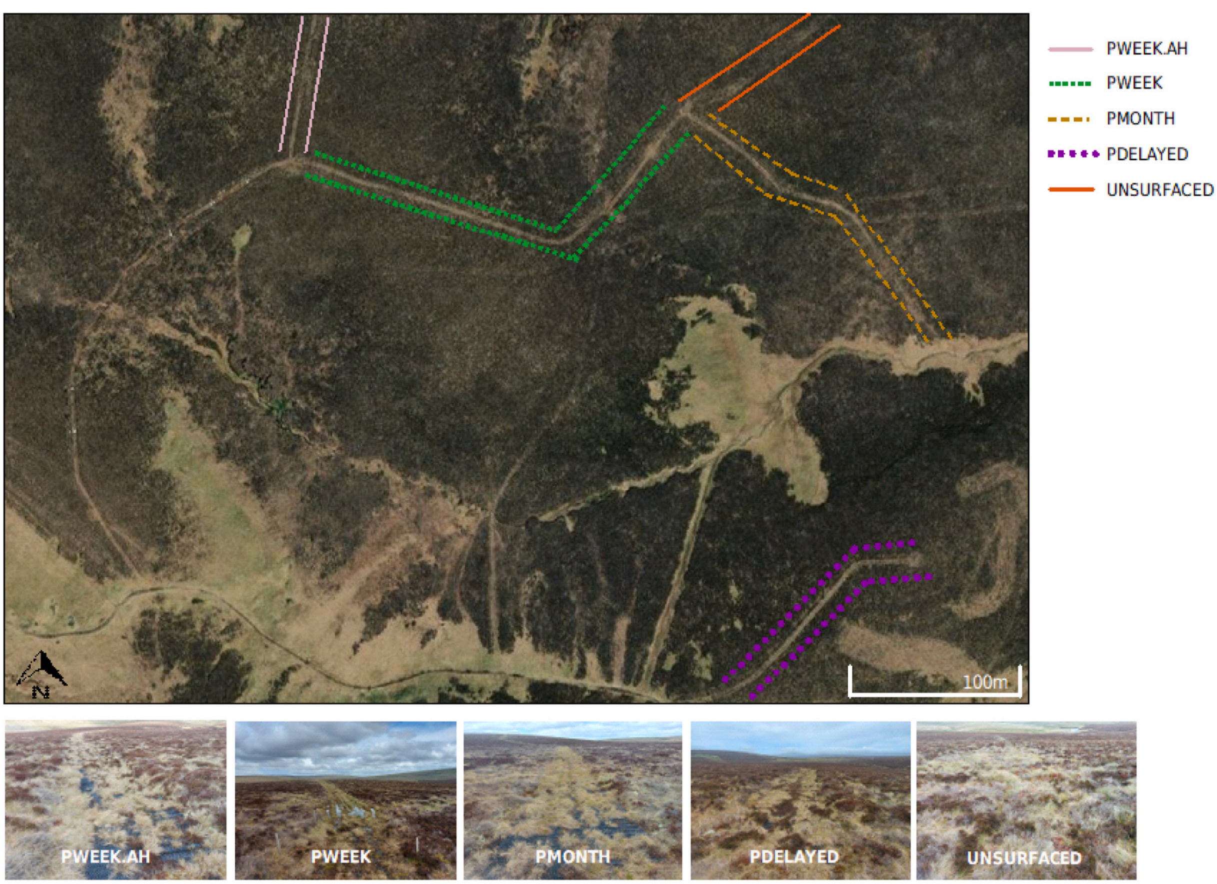

Fig. 1. Locations of the treatments on an aerial image from 2022 of the track sections (centre of image is at: 54.69298°N, 2.370061°W). Ground photographs of example sections of treatments are also shown, the track route can be seen in the centre of the paired lines, these are not indicative of the track width. The mean gradient of the tracks is 7.5%, although for PDELAYED the mean gradient is 5.0%.

addition to the classification of the nanotopes, the nanotope vegetation was surveyed for the full length of each track treatment and the full 200 m of the edge and two of the control transects to assess whether condition was 'favourable', 'recovering' or 'degraded' (descriptions can be found in S1). The vegetation survey took the form of a walk-over survey along the length of the track using a system designed by Lindsay (2010) which is based on the presence of key indicator species for blanket peatland habitats on each feature type as outlined in Table 2. Tables 2 and 3 are not intended to be definitive lists of all nanotope types and their corresponding vegetation types, as mounds and gullies were not recorded on the study site, and hollows were recorded in only two locations, a complete list is available in Lindsay (2010).

To allow statistical analysis and comparison of nanotope data for each track location, the nanotope types were allocated a number based on their average height above the water table: T3 – 65, T2 – 22.5, T1 – 8, TK – 5, EM Sphag – 1, EM Moss – 0.5 and EM Bare – 0 (EM Moss was allocated a score of 0.5 and EM Sphag a score of 1 to reflect the hierarchical nature of these two features – EM Moss tends to precede the recolonisation by *Sphagna*). Pairwise analysis of ruts, centres and edges was carried out within and between treatments using Mann Whitney U tests (two-tailed) while the edge and control track transects were compared using Kruskal-Wallis H tests. Mann Whitney U tests were also used to assess differences in nanotope data between slope position categories. Track regions were split into two halves for the slope analysis; top slope to upper-mid slope and lower-mid to bottom slope. Count data were aggregated by location from each track (e.g., Rut 1, Centre and so forth) and these were analysed for correlation between feature types using Kendall's τ coefficient (two-tailed). The association between features and the number of passes was analysed using Spearman's rank correlation coefficient (both one and two-tailed). Non-parametric tests were used as data were heteroscedastic and/or ordinal. All tests were performed using QED statistics version 1.5.5.503.

3. Results

3.1. Frequency and distribution of nanotopes

A total of 1600 nanotope measurements were made on five different track treatment types along 25 linear transects. A summary nanotopes by location and frequency of occurrence is displayed in Fig. 2. Aggregating the three major categories of feature for all locations, we recorded 1057 T features (66.1% of features), 389 micro-erosion (EM) features (24.3%) and 154 tussocks (9.6%). T features, particularly T2 and T3, were found predominantly in the edge and control transects adjacent to each track. In total, 509 T2 and T3 features were recorded in these locations, with an additional 52 T1 features, which accounted for 53% of T features recorded. In contrast, EM features were recorded predominantly on the track areas; 334 were recorded in total on the tracks, accounting for 86% of the total count. We found the occurrence of T features and EM features in the control transects to be consistent across all locations with no significant differences ($p = 0.76$). Likewise, we recorded no significant difference between T and EM features in edge transects ($p = 0.50$). Tussocks were most strongly associated with track locations: of 154 tussocks counted, 131 were located on the tracks (85% of the total). Tussocks were also more frequent in the centres of tracks where 76 (58%) of the tussocks were found. On two of the tracks with lower numbers of passes, the 38 pass (PWEEK) and 76 pass (PDELAYED) tussocks were the most frequently recorded nanotope type along the centre transects. On the 156 pass (PWEEK.AH) track the tussock count was lower in the centre than in all other locations.

Micro-erosion features (aggregated into one category for analysis) in the ruts (R2) adjacent to the edge transect were positively correlated

Table 3
Walk over survey for feature condition assessment by vegetation type.

	Favourable condition species	*Recovering condition species*	*Degraded condition species*
Feature type			
T3	Sphagnum fuscum,[a] *Sphagnum papillosum,* *Sphagnum magellanicum,* *Sphagnum/Eriophorum,* *Sphagnum austinii,* *Sphagnum/Molinia,* *Sphagnum capillifolium* Dwarf shrubs over *Sphagnum*	*Hypnoid* mosses, *Sphagnum subnitens,* Dwarf shrubs/*hypnoid* mosses, *Polytrichum commune,* *Hypnoid/Polytrichum* mosses	*Racomitrium languinosum,* *Leucobryum,* Hypnoid mosses/lichens Lichens dominant, Short mosses/bare peat Dwarf shrubs/no moss, Bare peat
T2	*Sphagnum/Rubus chamemorus,* *Sphagnum papillosum,* *Sphagnum fuscum,* *Sphagnum/Erica tetralix,* *Sphagnum austinii,* *Sphagnum magellanicum,* *Sphagnum/Molinia,* *Sphagnum capillifolium,* *Sphagnum/Eriophorum,* *Sphagnum*/Dwarf shrubs	*Hypnoid* mosses, *Sphagnum subnitens, Calluna* with some *Sphagnum,* *Eriophorum vaginatum,* Dwarf shrubs/*hypnoid* mosses *Hypnoid/Polytrichum* mosses,	Dwarf shrubs/no moss, *Eriophorum vaginatum*/no moss, *Sphagnum compactum* Lichens dominant, Bare peat/dwarf shrubs Bare peat/*Trichophorum germanicum* Bare peat
T1	*Sphagnum papillosum,* *Sphagnum/Erica tetralix,* *Sphagnum magellanicum,* *Sphagnum/Eriophorum,* *Sphagnum/Drosera,* *Sphagnum*/Dwarf shrubs	*Hypnoid* mosses, *Sphagnum fallax,* *Sphagnum capillifolium* dominant, *Eriophorum vaginatum,* *Sphagnum tenellum* dominant,	Dwarf shrubs/no moss, Dwarf shrubs/Hypnoid mosses Lichens dominant, Bare peat/dwarf shrubs Bare peat/*Trichophorum germanicum* Bare peat
TK	*Sphagnum* over *Eriphorum vaginatum* tussock, *Sphagnum* over *Molinia* tussock, *Sphagnum* over *Trichophorum* tussock	*Eriophorum vaginatum* with some *Sphagnum,* *Molinia* with some *Sphagnum,* *Trichophorum* with some *Sphagnum*	*Molinia caerulea* *Deschampsia flexulosa* *Tricophorum germanicum*
EM Sphagnum		*Sphagnum* moss	
EM Moss		Mixed moss sward/no *Sphagnum*	*Hypnoid* mosses *Campylopus* type mosses
EM Bare			Bare peat/*Eriophorum angustifolium* Bare peat/*Carex panicea* Bare peat

[a] Species are listed in order of importance by feature for each state 'favourable' and 'recovering'. Species or features indicative of degraded condition run from top to bottom as least degraded to most degraded.

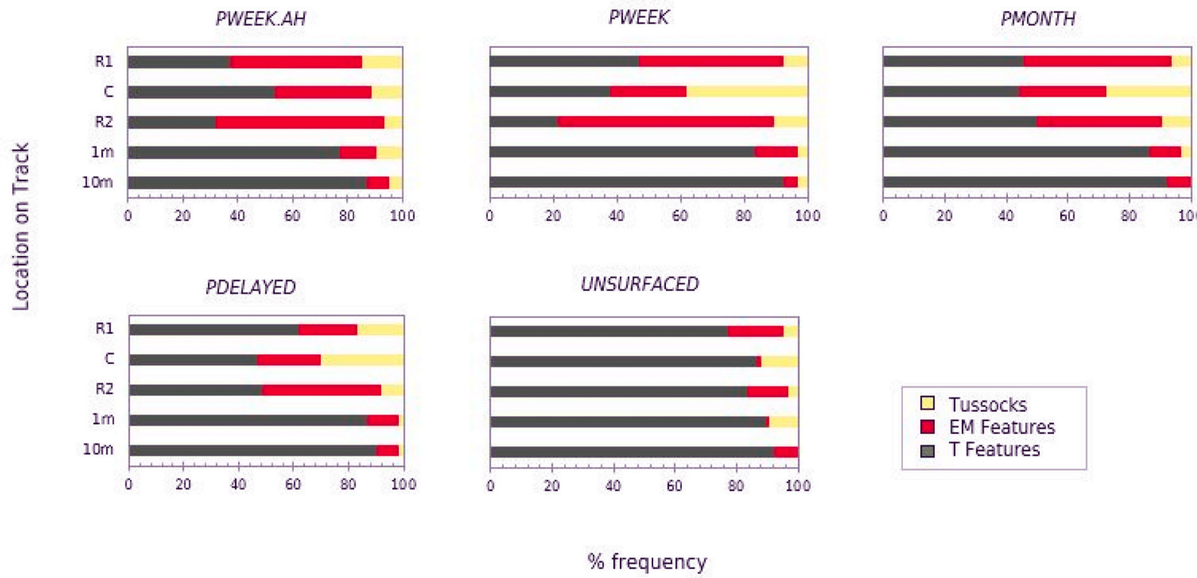

Fig. 2. Frequency occurrence of nanotope by location and treatment type on the study site.

with the micro-erosion frequency in R2 (τ = 0.949, p = 0.020). Micro-erosion presence in the ruts (R2) was found to be negatively correlated with T2 features in R2 (τ = −1, p = 0.014) and in the ruts (R1) micro-erosion was negatively correlated with T3 features (τ = −0.88, p = 0.03). Tussock growth did not correlate with a significant increase or decrease in any of the feature types.

3.2. Effect of slope position on nanotope recovery and formation

Analysis of the nanotope types from top to bottom of slope did not show a significant effect of slope position on the scores for most of the tracks. There were three exceptions: for the centre of the 412 pass track (PWEEK.AH) treatment (p = 0.001), micro-erosion features were prevalent at the top of the track; PDELAYED had a significant difference between the top and bottom slope scores in R2 (p = 0.001) and the centre (p = 0.011) track; EM features dominated at the bottom of the

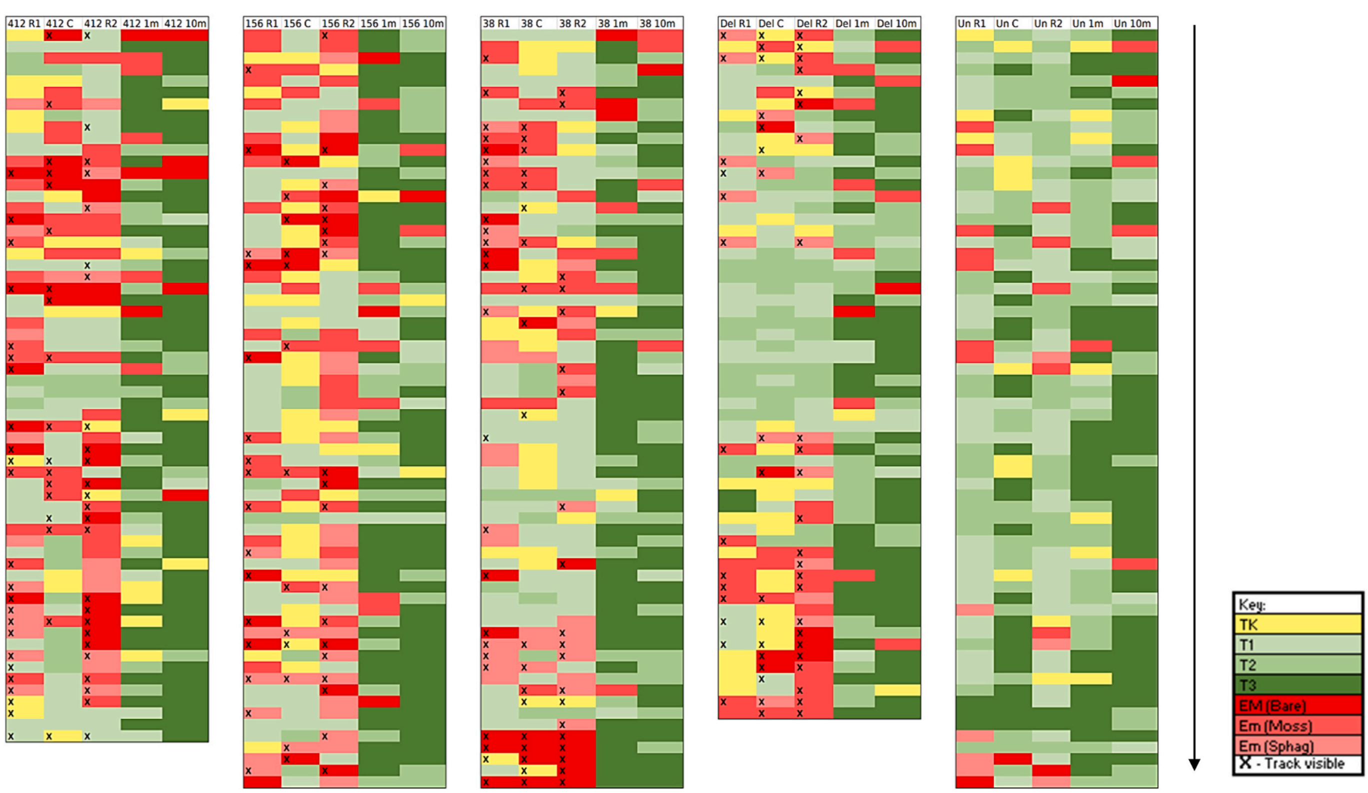

Fig. 3. Schematic maps showing nanotope types identified at each survey point; Rut 1 (R1), Centre (C), Rut 2 (R2) along abandoned track sections and 1 m and 10 m transects. From L–R: 412 passes (PWEEK.AH), 156 passes (PWEEK), 38 passes (PMONTH), 76 passes with delayed driving start (PDELAYED) and 24 passes with no surface mesh (UNSURFACED), from top to bottom of slope (arrow). Key code descriptions are provided in Table 2.

track. Some variation was also observed in the edge transects of the PMONTH and UNSURFACED treatments with bottom slopes having significantly higher nanotope scores than the top slopes, equating to fewer micro-erosion features at the bottom of the track ($p < 0.05$). The control transects on the PWEEK and UNSURFACED treatments both followed the pattern of bottom slopes having significantly higher nanotope scores ($p < 0.05$). For PMONTH and UNSURFACED, micro-erosions were dominant on the upper slope, with higher T feature counts on the bottom slope ($p < 0.05$). Some variation in the tussock-forming species was also observed along the slopes, with a transition from *Eriophorum vaginatum* to *Tricophorum germanicum* on PMONTH and PWEEK.AH in particular, reflecting the wetter nature of downslope areas on these treatments. Although the type of nanotopes did not differ significantly between the top and bottom slopes on most of the tracks, moss and *Sphagnum* micro-erosions or T1 features were more sparsely vegetated and frequently had mesh track showing through them (Fig. 3), or (in the case of some micro-erosions) the vegetation was growing under the track. While there was no significant difference in the nanotope scores between the top and bottom of the PMONTH slope, the wettest part of this track at the bottom suffered from extensive bare micro-erosion occurrence across all three track transects: 28 of the 64 instances of visible track on this section were recorded in the bottom 40 m of the track. This pattern held for the (100 m) mid-bottom slope transects of all track locations on all treatments; 44 of the 67 instances in the PWEEK.AH treatment, in the PWEEK treatment 29 of the 48 instances, and in the PDELAYED treatment 34 of the 55 were recorded in this location (Fig. 3). The highest occurrences of visible track were recorded in the rut transects, except for the PDELAYED treatment where the R1 transect had a lower amount of visible track than the centre and generally higher occurrence of T features: this was the only rut transect where no EM bare features were recorded (Fig. 3).

3.3. Impact of usage frequency on nanotope recovery

Despite vehicular access to all mesh tracks having ceased in November 2015 all tracks remain clearly visible both on the ground and from aerial imagery as of September 2022 (Fig. 1). Statistical analysis of the variation between nanotope scores reveals that there is high variability in these features between tracks and controls which is likely to be a key driver of this phenomenon. Spearman's rank correlation was used to investigate the relationship between the frequency of use and the nano-topographic structure score. Analysis of all treatments combined showed a significant negative correlation in the R1, R2, centre transects ($p < 0.001$ for all locations), suggesting that a higher number of passes may lead to reduction in T features in the post abandonment period. No significant correlation (positive or negative) was found between frequency of use and nanotope scores on the mesh surfaced PWEEK.AH (412 passes), PWEEK (156 passes), or PMONTH (38 passes) treatments in the R1 and centre transects. However, a significant negative correlation was identified for the R2 transect nanotope scores ($p < 0.01$). The PDELAYED treatment had a greater nano-topographic score than the three other mesh track treatments. Comparing PDELAYED to the PMONTH treatment which had the lowest vehicle use (38 passes) of the mesh surfaced tracks, the frequency of use for PDELAYED (76 passes) was positively correlated with occurrence of T features in the R1 ($p < 0.001$) and R2 ($p < 0.05$) transects, but no significant correlation (positive or negative) was found for the centre transects of the treatments. This suggests that the delay in usage, despite the higher frequency of use, resulted in increased formation of T features in the ruts. Fewer micro-erosions were recorded on the UNSURFACED treatment in comparison to PDELAYED. There were significant negative correlations between the R2, and centre, transects of the UNSURFACED and PDELAYED treatments, and no significant correlation for the R1 transect (Figs. 2 and 3 show the pattern of low micro-erosion in R1 PDELAYED). No significant correlations were found between the number of passes and a reduction in nanotope scores for the adjacent edge transects (Table 4).

Table 4
Spearman's rank correlation for vehicle use frequency and nanotope score for each treatment and transect location.

Tracks in comparison	Transect location	p-value	r
All treatments	Rut 1	<0.001	−0.26
All treatments	Rut 2	<0.001	−0.52
All treatments	Centre	<0.001	−0.2
All treatments	Edge	0.28	−0.03
PWEEK.AH, PWEEK, PMONTH	Rut 1	0.67	−0.03
PWEEK.AH, PWEEK, PMONTH	Rut 2	<0.01	−0.20
PWEEK.AH, PWEEK, PMONTH	Centre	0.73	0.03
PWEEK.AH, PWEEK, PMONTH	Edge	0.19	−0.1
UNSURFACED, PDELAYED	Rut 1	0.07	−0.16
UNSURFACED, PDELAYED	Rut 2	<0.001	−0.56
UNSURFACED, PDELAYED	Centre	<0.001	−0.32
UNSURFACED, PDELAYED	Edge	0.52	−0.06
PMONTH, PDELAYED	Rut 1	<0.001	0.28
PMONTH, PDELAYED	Rut 2	<0.05	0.15
PMONTH, PDELAYED	Centre	0.98	0.002
PMONTH, PDELAYED	Edge	0.13	−0.14

Pairwise comparisons were carried out using the Mann Whitney *U* test. The PWEEK.AH, UNSURFACED and PDELAYED treatment edge transects had a significantly lower value for the nanotopes than the control transects ($p = 0.008$, <0.05 and < 0.05 respectively). For PWEEK and PMONTH there were no significant differences in nanotope scores for the edge and control transects. No significant differences in nanotope scores were observed between the centres of the mesh tracks for any of the four treatments. When compared to the UNSURFACED treatment all four treatments showed significantly reduced values in the nanotopography of the centre transects ($p < 0.001$). The least disturbed of the mesh track treatments was PDELAYED. Therefore, an additional comparison was carried out between the rut transects (R1 and R2) of this treatment and those of the UNSURFACED treatment. PDELAYED R1 had a significantly larger nanotope value than UNSURFACED R1 ($p = 0.043$) while the opposite was true for the R2 transects, where the UNSURFACED transect had a significantly larger nanotope value ($p < 0.001$). For the UNSURFACED treatment the R1, R2 and centre transects showed significantly lowered nanotope values when compared to the control, most significantly in the ruts (R1 $p < 0.001$ and R2 $p < 0.001$). The centre nanotope value, although higher than the rut values (both R1 and R2 $p < 0.001$), was still significantly lower than for the control transect value ($p = 0.009$).

3.4. Effect of tracks on sward height

Tracks exerted a clear influence on sward height compared to the controls and there was a prevalent edge effect on the PWEEK.AH, PWEEK and PMONTH tracks ($p < 0.001$; Fig. 4). Analysis using Kruskal-Wallis H tests showed that there was no significant difference between the median sward heights of any of the control transects. We then compared the other four transects individually within treatments using Mann Whitney Utests.

Comparison across treatments suggested that all R transects compared to centres had shorter sward ($p < 0.001$) and all track transects across all treatments had significantly lowered sward compared to both edge and control transects (p 0.001). The PDELAYED and UNSURFACED treatments were found to have no edge effect on the edge transect compared to the control ($p = 0.07$ and $p = 0.09$ respectively).

3.5. Vegetation community patterns

To assess the dominant vegetation patterns across the entire track area, walkover surveys of all treatments were carried out. In addition, all edge transects and two of the control transects were assessed. Tussocks were predominantly formed of *Eriophorum vaginatum,* and this was

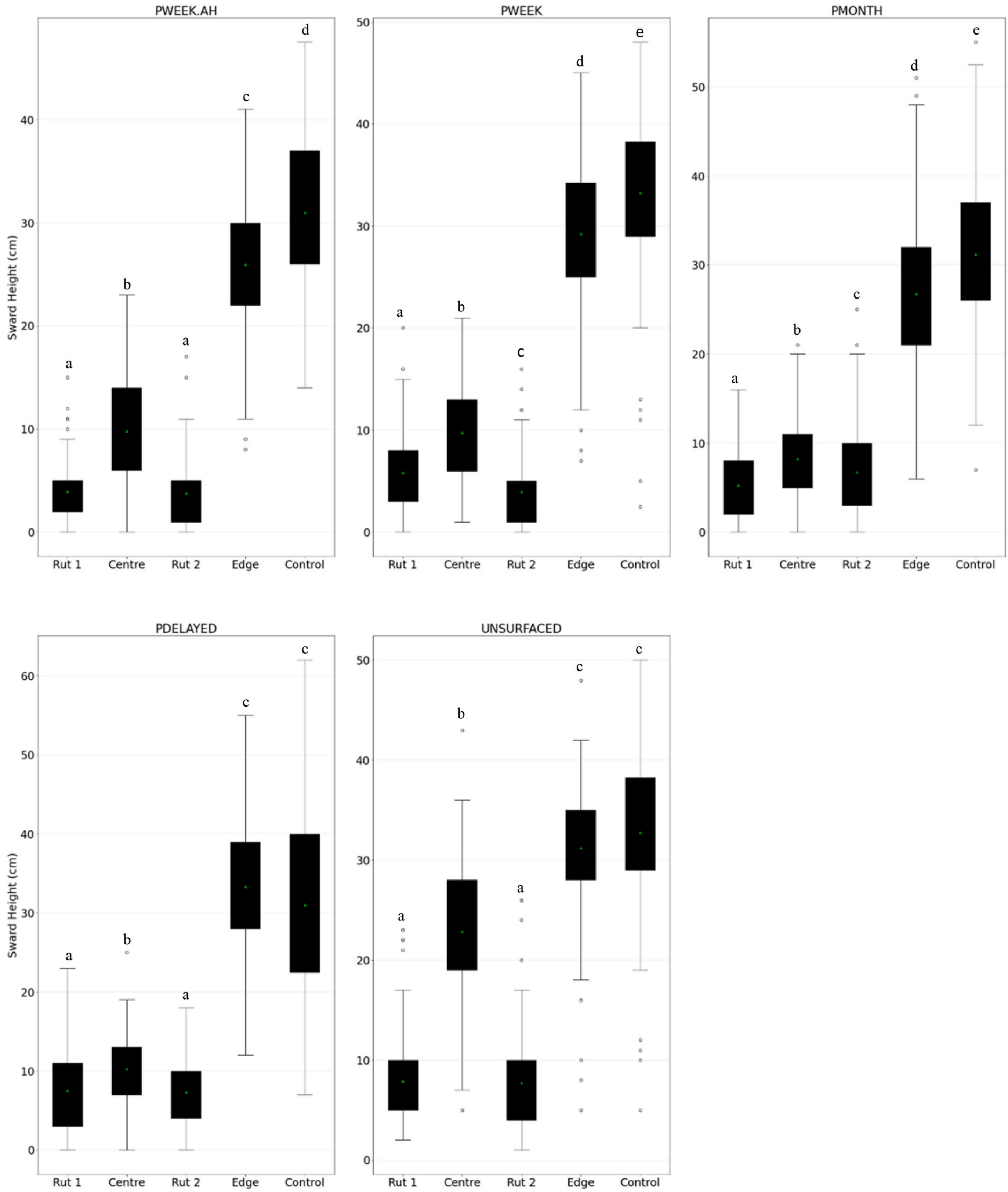

Fig. 4. Boxplots for sward heights in the five measured locations across the five treatments. Analysis was carried out within treatments. Boxes with the same letter codes are not significantly different within each treatment. The p-value used for significance was $p < 0.05$.

consistent across all tracks with the exception of the bottom slope areas of the PMONTH and UNSURFACED treatments where conditions were wetter. For these bottom slope locations there was a dominance of *Tricophorum germanicum* as the main tussock forming species. Tussocks on the UNSURFACED treatment covered the full range of states (favourable, recovering and degraded) as indicated in Table 3. In the centre of the UNSURFACED treatment, greater amounts of *Sphagnum* mosses were growing over the tussocks. In contrast, hard tussocks dominated in the rutted areas of UNSURFACED and one instance of the graminoid *Molinia caerulea* was identified, which is not characteristic of the peatland community at Moor House. *Nardus stricta* and *Festuca ovina* were found on the PDELAYED treatment, which are predominantly acid-grassland species. One instance of *Sorbus acuparia* was also recorded. On three of the four mesh track treatments, tussocks were most prevalent in the centres of tracks, on the PWEEK and PDELAYED treatments they were the most frequently recorded feature. On the PWEEK.AH treatment distribution of tussocks was more even across all track areas and higher levels of hard unyielding tussock features with lower *Sphagnum* overgrowth occurrence were found. One instance of the non-bog herbaceous species *Cerastium fontanum* was also recorded on the PWEEK.AH treatment.

All track T features were dominated by *Sphagnum capillifolium* or the moss varieties *Hypnum jutlandicum* or *Campylopus* spp. Low ridge T1 features were the dominant T features on the mesh track treatments (also classified in the literature as 'lawn' features). T features in centre track locations were in better condition overall than those occurring in ruts. However, we found the features on all mesh tracks were dominated by non-Sphagnum moss species, which can be indicative of drying of the peat or dominance of dwarf shrub species and bare peat areas which, in turn, are indicative of a degraded condition. The exception was the PDELAYED treatment which had the highest levels of structural regrowth, and while *Sphagnum capillifolium* dominated the *Sphagna*, *Sphagnum papillosum* was also recorded in the T2 features on this treatment. The UNSURFACED treatment had a range of species across all states, and many of them indicated favourable condition, particularly in the track centre. Lichen dominance by the species *Cladonia portentosa* was recorded on some of the T1 features and T2 features on the UNSURFACED treatment, but this was not recorded on any of the mesh treatments. The T3 (hummock) features were only found in significant numbers on the track for the UNSURFACED treatment, where they hosted many of the favourable indicator species, with fewer instances of degradation indicators and no areas of bare peat. However, *Cladonia portentosa* dominated a small number of the T3 features. The edge and control transects for all treatments were dominated by T2 and T3 features (Fig. 3). Large (up to 1 m tall) well-formed and diverse T3 hummocks of *S. capillifolium* and *S. papillosum* with *Eriophorum vaginatum, Vaccinium oxycoccos* and *Calluna vulgaris* were recorded in both edge and control transects. However, T3 features in these transects were still most frequently dominated by *Hypnoid* mosses and *Calluna* canopy. In places, a predominantly *Hypnoid* regrowth over old-growth *Calluna* had formed hollow-hummock-like features with bare peat interiors. Where this 'hollowing' was severe, we recorded these as EM Moss to reflect the lack of interior vegetation. If only *Calluna* were present with no understory, EM Bare was recorded. These hollow features were infrequent, accounting for 35 (5%) of the recorded features across all five of the edge and control transects. Hollowing was not recorded on the track areas and was slightly more prevalent on the edge transects than on the control transects, with 57% recorded in the edge transects. In the edge transect alongside the UNSURFACED treatment, two waterfilled mud-bottom hollow features were recorded in a degraded bare condition, but these were the only hollow features recorded.

EM (micro-erosion) features were most strongly associated with the mesh track treatments, although they were present in all surveys carried out. However, as detailed above, in the edge and control transects these features were most frequently observed below *Calluna vulgaris* canopies where mosses had failed to establish or had been lifted off the surface; they did not form the same interconnected erosion networks observed on the track areas. Of the EM features, EM Moss and EM Sphag were the most recorded, showing a likely recovery progression from EM bare areas. EM bare areas were most frequently completely devoid of vegetation, but in wetter areas of the PWEEK.AH and UNSURFACED treatments, *Eriophorum angustifolium* was present in some places, an important species in binding damaged peat and moving towards the recovering state. EM Moss features across all tracks were most frequently dominated by *Hypnum jutlandicum* or *Campylopus introflexus,* an invasive moss that was not recorded in any significant quantity along either the edge or control transects. In the EM Sphag feature, *S. capillifolium* was the dominant species with *S. fallax, S.medium, S. papillosum* all recorded. Some instances of *S. tenellum* were also recorded and this species is associated with disturbed areas on blanket peat, favouring an open canopy.

4. Discussion

4.1. Main findings

Our study is the first to examine surface nanotope structure on abandoned blanket peatland tracks. Our data were collected ~7 years after the tracks were initially abandoned. Therefore, we are not presenting change over time, rather assessing difference relative to controls, and our findings should be viewed in this context. Where possible it would be optimal to apply this method temporally to understand how nanotopes develop over time in post-disturbance periods. Our walkover vegetation surveys and quantification of the nanotopes themselves suggest long-term effects persisting years after abandonment. This is consistent with other studies which have also identified similar lasting impacts to peatland edges, vegetation and micro-structures (Adam and Hernandez, 1977; Charman and Pollard, 1995; Emers et al., 1995; Lee and Boutin, 2006; Jorgenson et al., 2010; Robroek et al., 2010). We found that all frequencies of usage, on both surfaced and unsurfaced tracks, caused a significant loss of complex nanotopes compared to the controls. Delaying usage of a mesh track, or using an unsurfaced track both led to increased nanotope scores. However, scores still differed significantly to those for both the edges and controls. Our findings suggest that recovery of nanotope structure to control levels is a slow process with significant time periods required for the structures to regenerate. This supports research findings from cutover peatlands in Canada and Estonia, where recovery of the microtopography was comparable to control levels in 10–20 years, but only where restoration interventions were undertaken. Principal components analysis of a spontaneously revegetated peatland from the same study was found to have dissimilarity in microtopography over 70 years later, suggesting long recovery times before they are comparable to undisturbed areas (Pouliot et al., 2011). Studies of Canadian boreal seismic lines also showed that loss of surface structure is persistent over decadal timeframes (Lee and Boutin, 2006; Stevenson et al., 2019).

It should be noted that our study was carried out on a long-term experimental site, where track usage was tightly controlled and extensively documented. Moor House also represents a site that is protected as a nature reserve, and therefore the vegetation community was largely undisturbed immediately prior to the initial study although had been subject to a range of impacts prior to designation as a National Nature Reserve in the 1950s. Recovery patterns may differ for tracks on already disturbed or heavily managed sites which may have higher use frequencies. Therefore, future nantope studies on more intensively used sites would be useful.

4.2. Effect of track surface and usage on long-term nanotopographic development post abandonment

Only in the case of the R2 transect was there a significantly greater amount of micro-erosion features between the highest usage treatments

(PWEEK.AH and PWEEK) – which received 412 passes (including some weighted) and 156 passes respectively, and the least used (PMONTH), receiving 38 passes. This was not anticipated at the start of the study, where we hypothesised that higher frequencies of use would consistently result in greater occurrence of the three EM features. However, McKendrick-Smith (2016) found no clear pattern in sward height reduction resulting from the number of passes on the PWEEK.AH, PWEEK and PMONTH treatments. Of the five treatments, the highest number of T features were recorded in the UNSURFACED treatment, although it was only used for a short time. The UNSURFACED treatment had lower numbers of EM features across all transects compared to the mesh treatments. Despite its low usage this section of track remains clearly visible from the air and ground (Figs. 1 and 5a) and EM bare features, where recorded, had minimal colonisation (Fig. 5c). Of the mesh tracks, the greatest recovery compared to the control transect was observed in the PDELAYED track, which was given a 19-month period to allow vegetation regrowth prior to usage, and this recovery was despite double the number of passes than that of the PMONTH track. Laying of the track in July may have limited the ability of the vegetation to recover from mowing prior to the commencement of driving. In contrast, allowing a full growth season prior to driving commencement improved resilience in the PDELAYED track.

As the tracks were laid on the surface, the underlying topography resulted in an uneven track surface (slope and camber) both along their entire length and locally as a result of underlying topography. This variability may have an influence on the recovery of nanotopography, particularly in the rutted sections of the treatments where uneven loading and subsequent mechanical compression may be important influencing factors. We had hypothesised that waterlogging at the bottom of tracks (bottom slope areas) would lead to poorer recovery on these sections and observationally there was more visible track on lower slopes. However, the nanotopes were only significantly different on the PDELAYED treatment, which also had a gentler slope than the other treatments. Where significant differences were found (PWEEK.AH), erosion was worse at the top of the slope. Overall, we found that slope position is not a reliable predictor of nanotope recovery. However, greater variation might be seen in longer or steeper tracks than those we studied.

Relatively high densities of graminoid tussock and *Calluna vulgaris* growth were found in the centres of tracks, which could indicate a drying action caused by the ruts acting as channels along either side of the centre ridge, draining water away and favouring dry adapted species (Fig. 5a). Lichen dominance was recorded on some hummocks on the UNSURFACED treatment (Fig. 5c). Lichen growth has been found to reduce rates of peat deposition, limit growth of *Sphagna* and increase bulk density (Harris et al., 2018). Tussocks were the dominant feature recorded in the centres of the PWEEK and PDELAYED treatments, and their occurrence was also high in the PMONTH treatment. Over time, tussocks may be overgrown by *Sphagna*. However, the mesh track has allowed prolific dense growth of tussock-species foliage at their bases, which may act as a limiter on the ability of other plants to compete (Prusinkiewicz and Barbier de Reuille, 2010). In contrast, for the rutted sections of the track, EM and T1 ridge features were the dominant nanotope types. Water flow was observed in the ruts on the mesh tracks during periods of high rainfall (Fig. 5b) which may contribute to micro-erosion persistence.

Despite significant sward height differences between the edge and control transects, this did not represent a significant difference in the makeup of nanotope types between these two transects, However, nanotopes fall within a size range, and our analyses found that sward height was lower in the edge transects suggesting that nanotopes in the edge transect fall at the lower end of the scale. T features were found to be negatively correlated with micro-erosion features in the R2 transects (which are adjacent to the edge transect on all treatments) of the aggregated data from all treatments, demonstrating an edge effect in areas directly adjacent to track. This aligns with studies along the edges of powerline rights of way and seismic lines in Canada where alterations to both composition and structure have been recorded (Dube et al., 2011; Dabros et al., 2017). The PWEEK.AH track had a significantly impacted nanotopography in the edge transect, and the R2 transect value was lower than those recorded for the PWEEK and PMONTH. The PWEEK.AH treatment received a higher number of vehicular passes towards the end of the McKendrick-Smith (2016) study, when it was also heavily loaded. It is not possible, however, to determine whether both factors combined, the extra passes, or the additional weight were responsible for these differences.

4.3. Implications for removal or abandonment of tracks

Our findings suggest that mesh track constrains nanotope recovery when compared to undisturbed controls, in the post usage period. This is supported by research into how plants grow under spatial constraint. Alterations to plant form and competition are both functions of space. Where available growing space is reduced then plants may not be able to

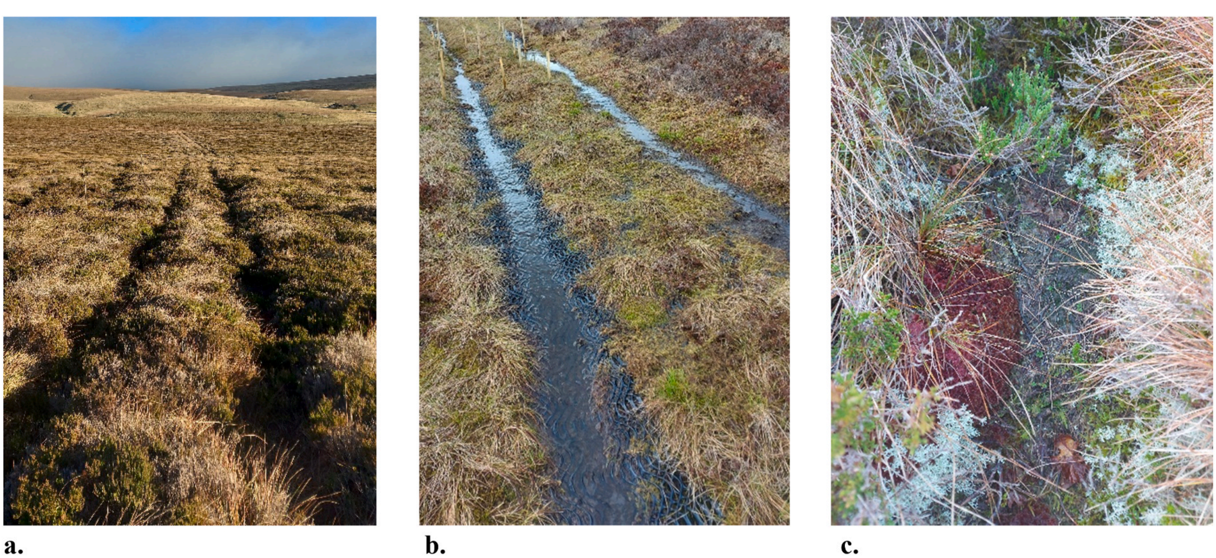

Fig. 5. Appearance and detail from the study sites: **a.** the unsurfaced track showing greater development in the track centre; b. mesh track showing pooling; **c**. detail of the rut in a section of the unsurfaced track, highlighting microerosion and lichen growth in these areas.

assume normal growing form and/or be subject to increased competition (Prusinkiewicz and Barbier de Reuille, 2010). The mesh track itself presents a significant spatial constraint; the mesh has small gaps to allow growth but for each hole we measured an equivalent amount of mesh (i. e. a ratio of 1:1) (S2) The extent to which mesh surfaces restrict growth could be a fruitful area of future research.

The presence of the mesh track also acts to reduce the light reaching plants growing under it. When the plants have re-established, this light reduction is less problematic, but during recovery, it may adversely impact growth. As peat dries, a shrinking effect can lower the peat surface (Price, 2003), meaning the mesh track can then be elevated above the surface during some summer periods, increasing shading at key points in the growth cycle. We also observed pooling of water on the PWEEK.AH, PWEEK and PMONTH tracks. This occurred in areas of depressions or bottoms of tracks. The smaller bryophytes are also less able to grow up through the track when it is elevated, and plants growing under the track are generally less well developed when compared to those above the track. This cyclical effect may impact plant recovery, and the ability of these plants to form hummock nanotopography over the long term. Therefore, leaving a track in place after use may not be an acceptable solution. However, at another peatland in the North Pennines where access for our study was restricted, a mesh track was removed in 2018 and aerial imagery and ground level photos of this site (S3a and b) show poor recovery of nanotopography, invasion by acid grassland and non-native mosses, and extensive areas of bare peat. Our walk-over recordings on the track at Moor House found non-native moss colonisation in micro-erosions and establishment of non-bog grasses such as *Deschampsia flexulosa, Festuca ovina* and *Nardus stricta,* all of which were absent or rare in control transects. Our identification of non-blanket bog species supports the findings of Dube et al. (2011) where tracks were found to increase the presence of invasive species in southern Québec. Pouliot et al. (2011) proposed that restoration intervention may speed up the nanotope recovery process. Restoration interventions may thus help recovery of peatland function where a track is removed. However, further work is required to determine the efficacy of such treatments.

Surficial structure is an important component of peatland function (Branham and Strack, 2014; Lovitt et al., 2018; Stevenson et al., 2019; Clutterbuck et al., 2020b). Early work by Ratcliffe and Walker (1958) dividing the surficial structure into four vertical levels has been expanded over the years, most recently by Clutterbuck et al. (2020b) to allow description of a greater range of hummock, ridge, pool, hollow and erosion patterns. Our study found that this most recent methodology was extremely useful in capturing the impacts of track usage that may not be possible using a smaller number of classifications. Detailed classification of the nanotope types at short intervals on the tracks allowed for a fine-scale study with more detail than the classic two-feature hummock-hollow approach. The nanotope survey method is relatively easy for practitioners to undertake and allows for the collection of more data points than vegetation surveys alone. As such, it offers a rapid way to assess bog ecosystem health and provides an important tool with which to plan conservation and restoration of disturbed sites. The limitations to our study could be addressed with future research in this area. We suggest that monitoring of nanotopes during usage periods of tracks would help to identify when alterations to nanotopes occur and additionally, where practical, long-term monitoring of abandoned tracks would lead to greater insights into the timeframes for nanotope re-establishment.

5. Conclusions

Our study shows that temporary mesh tracks, even when no longer used, can exert a significant influence on the re-establishment of natural micro-topographic features – particularly the T structures – on blanket peatlands. Usage commencing within a relatively short period of time after installation of a mesh track was a major contributor to micro-erosion formation and ridge/hummock loss. However, given our findings with regards to delaying usage, further research in this area could help to establish a timeframe within which usage should not occur post construction. While vegetation diversity may appear recovered in counts or walkovers, with many species re-establishing quickly, nanotope re-establishment, however, is a slow accumulation of growth. Consequently, we suggest that a holistic approach combining height measurement, structural and vegetation survey is more robust when assessing influence of disturbance such as tracks on peat bog ecosystems. The frequency of vehicular passage over the tracks in their 'active usage' period was not found to be a strong influence on the recovery of complex surface structure. This highlights the fragility of the ridges and hummocks, with loss occurring at even low usage levels. As the importance of nanotopography is widely recognised in the ecohydrological functioning of peatlands, any loss of, or alteration to, these structures should be considered problematic. As our study finds significant, lasting impacts to the nanotopography, we suggest that the addition of a surfaced mesh track on a peatland should be carefully considered. We feel that there is space for a broader discussion around the nature of what should be considered temporary, and that this could usefully be supported by further research into the biogeochemical, spatial and hydrological effects of surfaced tracks on the nanotopography to fully understand the drivers of loss and constraints on recovery.

Credit author statement

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

Funding

This work was supported by the UK Natural Environment Research Council (grant code: NE/R007527/1) and Natural England.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Jeffrey Thomas for assistance in recording nanotopes, Jennifer Christelow for assistance in collecting sward height data, and Ben Clutterbuck for support in training.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116561.

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