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A review of the effects of vehicular access roads on peatland ecohydrological processes

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Abstract

An increasing demand for resources, coupled with technological advances which make remote exploration possible and economically viable, have led to a human push into previously inaccessible areas, including peatlands. In spite of the unsuitable nature of peat as a substrate for engineering projects there has been a growth of vehicular access networks on peatlands. However, there is a lack of understanding about how such networks impact peatland functioning. We found that research trends on peatland access track studies have changed from a concern largely with the physical properties of peat and its suitability as a substrate for building, to study of vegetation recovery, microbiological functioning and carbon cycling processes. Some recent research has examined vehicular access route impacts on peat ecohydrological processes showing that biogeochemical processes are affected, and that vegetation recovery is significantly impeded in post abandonment periods. Sizeable knowledge gaps which could form the focus of future research include the effects of roads on tropical peatlands, influence of plastic, erosion and pipe formation processes, the hydrological effects of seismic trails, ecotoxicological effects of plastic tracks and chemical pollutants on peatlands resulting from vehicular access, the ecohydrological recovery process after temporary roads are removed from peatlands.

Keywords: Wetlands, fen, bog, degradation, hydrology, ecology, mire, tracks, infrastructure

1. Introduction

Peatland is a globally important wetland habitat found in nearly every country on Earth (IUCN, 2017). Peat is an organic soil composed largely of partially decomposed plant remains preserved within a waterlogged environment. Peat can often be 90% water by mass (Hobbs, 1986), but this also means it can be a poor substrate for built infrastructure. The surface of a peatland can move up and down with wetting and drying cycles (Howie and Hebda, 2018) and the surrounding peat material can often wobble when traversed even by light foot passage. Waterlogging largely restricts microbial metabolic activity to anaerobic pathways (Hobbs, 1986; Parry *et al.*, 2014; Kettridge *et al.*, 2016; Olszewska, 2018). The near absence of aerobic activity means that deep peat deposits can grow over time. Peatlands are globally important carbon stores; while they account for < 3% of the global land surface (Xu *et al.*, 2018b) they contain more than a third of the world's soil carbon (Yu *et al.*, 2010; Yu, 2012).

Globally, the largest loss of peatlands has resulted from agricultural conversion which has involved extensive drainage and burning. Denmark and The Netherlands have lost almost the entire extent of their peatlands, while in tropical regions such as Malaysia and Indonesia conversion to palm oil plantations has been the major driver of loss (Parish *et al.*, 2008). Timber forestry for fuel and export has also caused extensive losses in both northern and tropical peatlands and peat extraction for horticultural purposes and fuel remains problematic in places (Joosten, 2016). Across many peatlands of Africa, and parts of Asia including Mongolia and China, overgrazing has caused large scale degradation (Parish *et al.,* 2008). Studies have projected that in the combined face of human activity and climate pressure, many peatlands may not continue to persist across their current extent (Moore, 2002; Gallego-Sala and Prentice, 2012) with some predicting large reductions by the middle of the 21st century (Gallego-Sala and Prentice, 2012). Globally, around 80% of peatlands are still in a natural state. However, where there is a high population density, often much peatland nearby is degraded or lost (Joosten, 2016). There is currently a great deal of interest in the ecosystem services which are provided by peatlands, particularly in respect of their role in mitigating climate change and in provision of drinking water supplies (Williamson *et al.*, 2017; Xu *et al.*, 2018a), and how these might be affected under environmental change.

With growing demand for resources there have been corresponding increases in access demands on peatlands. These demands are frequently linked to fossil fuel exploration in different regions of the world (Hernandez 1973; Jorgenson *et al.,* 2010; Plach *et al.,* 2017) or palm oil plantations and logging in tropical locations (Osaki and Tsuji, 2016; Sumarga, 2017). Roads, herein referring to frequently used or more permanently surfaced access routes, and tracks, referring to lightly or temporarily used unsurfaced or temporarily surfaced routes, take different forms. In northern peatlands, fossil fuel exploration tracks have been created for use by seismic exploration vehicles, with exploration mainly occurring during winter months when the ground is frozen, supporting a single pass on an unmade track (Jorgenson *et al.* 2010). More permanent roads for fossil fuel access - particularly oil sand mining – and mineral deposit extraction have also been created by removal of trees and scraping of the top layer of peat in order to create a more solid road bed to support the heavy axle vehicles used for excavation and transport (Campbell and Bergeron, 2012). In the UK, peatland vehicle track and road networks serve both sporting and energy expansion purposes (Bonn, 2009). Such roads and tracks have been constructed from aggregate infill after peat removal, aggregate placed directly on top of the peat, plastic mesh and even articulated wooden materials (e.g. Figure 1). While there is a diversity of road and track types there is also a diversity of usage and a range of peatland types and habitats. All of these factors may influence the impacts that roads or tracks have on peatland functioning - but we know little about these interacting effects.

a.

b.

c.

d.

e. f.

Figure 1. Example road and track types which may be encountered on peatlands: a. plastic mesh on deep peat; b. close up of terram heavy duty mesh commonly used for peatland tracks in the UK; c. aggregate track on deep peat with drainage ditch; d. unmade track on shallow peat; e. wooden articulated track for heavy vehicular access; f. single pass track in northern England on deep peat.

Although research into access infrastructure on peatlands dates back to the 19th century (Mullins, 1846) there was little research into the effects of road and track disturbance on ecohydrological processes, even during the main part of the 20th century (Mackenzie, 1948; Pollett, 1967; Hernandez, 1973). Research priorities have changed rapidly as awareness of the value of peatlands has grown and the pressures of climate change have come to the fore in scientific discourse. Using the terms ‘peatland roads’, ‘peatland tracks’, ‘peat roads’, ‘roads on peat’, ‘tracks on peat’, ‘peatland infrastructure’, ‘peatland development’ and ‘peatland disturbance’, the prefixes ‘bog’ and ‘fen’ were then added to all terms, and the following databases were searched on 29-31st May 2020, repeated on15th November 2020; Web of Science, Google, Google Scholar, Scopus, University of Leeds library, ScienceDirect. Figure 2 breaks down the results of this search indicating the number of published research outputs on peatland roads, indicating both the shifting topics of research and the overall increase in research in this field. It should be noted that there is a more limited amount of available research in databases for material published prior to 1970, so the figure is indicative rather than exhaustive. The late 20th century and early 21st century have seen a clear emergence of research which is concerned with ecohydrological effects of roads on peatlands, mirroring the rapid expansion of road networks in these regions in recent decades (Emers *et al.*, 1995; Alamgir *et al.*, 2019; Clutterbuck *et al.*, 2020).

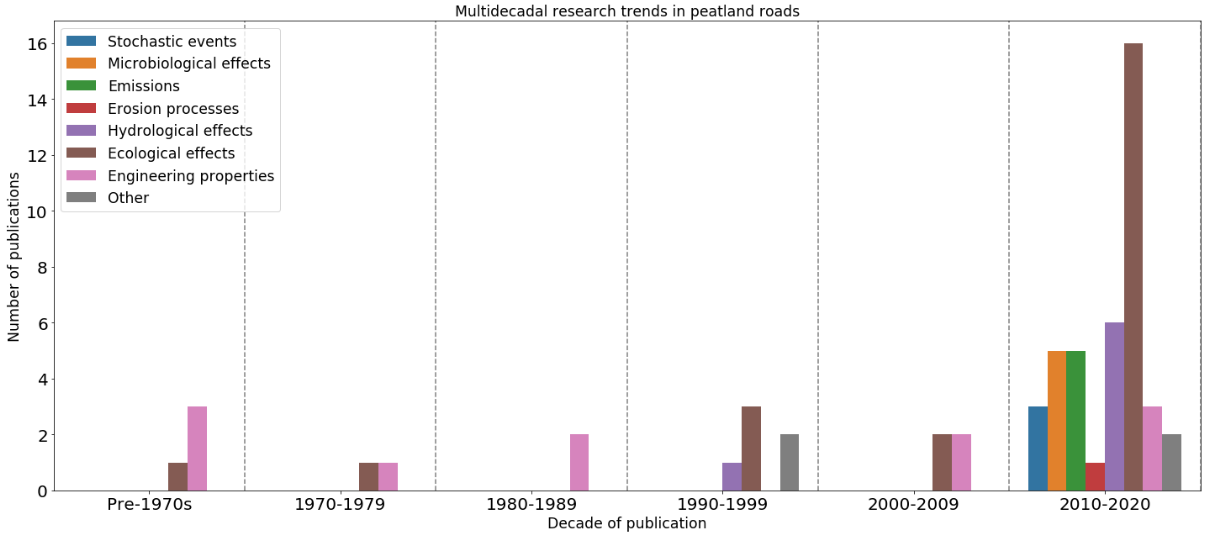

Figure 2. Published papers on peatland roads grouped by field and by the decade of publication based on search terms and databases as described in the main text.

Our review seeks to synthesise current knowledge on ecohydrological impacts of road access infrastructure on peatlands and highlight where there has been progress in recent years. There will be a focus on northern peatlands, noting that the largest body of research has been undertaken in the UK, US (specifically Alaska) and Canada. Nevertheless, we will also cover tropical peatlands and peatlands elsewhere when relevant information is available. It is notable that there has been increasing anthropogenic pressure on the boreal to Arctic peatlands in Russia due to oil and gas exploration expansion, but there is a dearth of papers on peatland impacts from this region in at least the English-speaking scientific literature. We begin with an outline of key peatland properties and within this context we then outline the focus subject of the review; roads on peatlands. We then review current research on peatland roads and tracks including hydrological and biogeochemical impacts, vegetation responses to road and track installation including delayed effects and microhabitat feedbacks We will then turn to the problems associated with track and road removal or abandonment before concluding with suggested priorities for future research.

2. Key peatland properties

There are two major categories of peatland: fen and bog (Gore, 1983). Bogs are acidic in nature, and predominantly rain fed, with specialist plant communities often, in the northern hemisphere, characterised by a dominance of *Sphagnum* mosses (Williamson et al., 2017). Because rain water contains only small amounts of nutrients, bogs are also oligotrophic in nature (Pippen and Keough, 1984; Rothwell *et al.*, 2009). Fens are typically alkaline –

although there are some acidic fens ('poor fens') - and their water is often mainly supplied from groundwater sources although surface flow can also feed these systems (Gore, 1983). The characteristic fen plants are grasses, sedges and reeds with rich fens being brown moss dominated (Gore, 1983; Hobbs, 1986; Charman, 2002). Within these two overarching categories there are sub-categories of peatland, and these can be classed variously by shape, chemistry, plant species composition, vegetative structure, or a combination of these (Gore, 1983). Both bogs and fens have in common that they are nutrient limited and therefore the specialised vegetation found in these systems is highly sensitive to nitrogen deposition and climate perturbation (Hedwall *et al.*, 2017). While the majority of peatland area is in the northern high latitudes – comprising ~3.18M km^2 or around 75% (Xu *et al.,* 2018b), there are also extensive peatlands – both bog and fen - in tropical regions. For example, around 20 million ha of peatland is found in Indonesia (Osaki and Tsuji, 2016) and approximately 145.5 million ha in the Congo basin (Dargie *et al.*, 2018).

Hydrology, ecology and climate are closely linked in peatlands and disturbance of one of these can result in a shift of the peatland ecosystem. In high latitude peatlands the combination of shallow water tables and low soil temperatures often results in a slow decay rate of the plant detritus but there are important feedbacks between plant communities, water dynamics, peatland development and decay (Belyea and Baird, 2006). The plant community composition is important in the formation of peat which, in turn, may influence hydrological functioning. Hydrological variability in peatland habitats is intimately tied to both the accumulation of the peat itself and the ability of peat to act as a carbon sink (Holden, 2005; Rennermalm *et al.*, 2010). Temperature is also crucial for peatland hydrological function and carbon cycling (Wu *et al.*, 2012) and changes in plant cover can also impact peat temperature (Brown *et al.*, 2015). As hydrological changes can also cause alterations in temperature which impact the thermal properties (Williams *et al.* 2013) there exists potential for positive feedback loops to develop driving further change. Mosses from the genus *Sphagna* are currently thought to form half of the world's peat (Turetsky, 2003) although it is worth noting that peat can still be produced in the absence of *Sphagna* (Bacon *et al.*, 2017). *Sphagnum* creates acidic, nutrient poor and decay-resistant conditions which the flora develop unique adaptations to survive in (Bu *et al.,* 2013) such as the insectivorous *Drosera* species. *Sphagna* store around 90% of their water content externally between their leaves and branches, which means variations in soil water content can have a significant impact on *Sphagnum* species as they have no roots and therefore are entirely reliant on passive water transport (Thompson and Waddington 2008), further demonstrating how disturbance to the hydrology might lead to significant ecosystem change. However, *Sphagnum* may also protect the underlying peat in times of drought by reducing evaporation and enhancing albedo (Bragg and Tallis 2001).

Water movement occurs both through and over the peat in a number of different ways and is an essential component of peatland integrity. Surface runoff can occur either as a result of infiltration-excess overland flow or saturation-excess overland flow. Infiltration-excess overland flow occurs when the rate of precipitation exceeds the infiltration capacity of the soil (Bevan, 2004). Saturation-excess overland flow does not need high levels of precipitation, rather it occurs because the soil is already saturated and thus has no further capacity to store water and is most common on peatlands (Holden and Burt 2003b). The rate of flow over the surface may depend on the topographic roughness, vegetation roughness, the flow depth and the slope (Holden *et al.*, 2008). Subsurface flow can occur through small pore spaces, macropores and pipes. The hydraulic gradient and hydraulic conductivity (K) will combine to determine the rate of subsurface flow. Even if a peatland has high K, if it is relatively flat then total subsurface flow could be small. If a peatland is steep, but has low bulk K (i.e. the sum across pipes, macropores and micropores), then the total subsurface flow could also be small. Research has shown that tropical peatlands, in contrast to high-latitude peatlands, may have high K – similar to that of coarse sand – which can leave them vulnerable to rapid decay when drained (Baird *et al.*, 2017). Vertical water movement through the peat column was found to be significant where underlying soils are permeable (Reeve *et al.*, 2000) but the addition of a road surface may impede this movement causing alterations to the hydrology of the peat: understanding the role of roads in this respect would therefore be useful.

Degraded peatlands can act as a net source of carbon as oxidation processes release the stored carbon into the atmosphere as CO_2 (Page and Baird, 2016). Globally, wetlands are the largest natural source of methane (Zhang *et al.*, 2017) and as the global climate warms methane release rates may increase (Gedney *et al.*, 2019). However, overall it is thought that global peatlands have acted as net carbon sinks and with a net global cooling effect on climate during the Holocene (Stocker *et al.*, 2017).

From an engineering point of view, peat is a poor foundation soil with characteristics which may lead to localised sinking of infrastructure built on it (Tan, 2008, Olszewska, 2018). The low shear strength makes peat vulnerable to slope failure (Warburton *et al.*, 2004). Hillslope variability is important in the stability of blanket bogs, as the relatively steep slopes on which blanket bogs tend to occur can increase the risk of slope failure (Warburton *et al.*, 2004). Peat also has a very low stiffness and high compressibility resulting from high water content (Olszewska, 2018) which means that infrastructure can suffer from subsidence and other movements, particularly if vehicles are driven across the peat system. Thus many peatlands have been drained to enhance their stability for infrastructure (Rahman *et al.*, 2004).

3. Roads within peatlands

While infrastructure construction on peatlands is not a recent occurrence, improved technology is spearheading a rapid push into remote areas, making research into the effects of this infrastructure creation a priority. Tropical peatlands are frequently cleared for oil palm plantations and logging (Osaki and Tsuji, 2016), whereas in Alaska, Russia and Canada oil sand mining is prevalent along with forestry and mineral exploration and extraction. In the UK, forestry, agriculture, sporting interests and wind farms are the main threats to peatland integrity (Holden *et al.*, 2007). All of these activities give impetus to the creation of vehicular access routes into peatlands, and while their peatland specific impacts remain a burgeoning area of study, that road networks have the potential to impact ecohydrological processes is broadly accepted (Forman and Alexander, 1998).

A recent study on the density of tracks across the UK found that, in an example 6855 km^2 of blanket peatland survey area, there was around 5700 km of vehicular track, with large lengths in ‘protected areas’ (Clutterbuck *et al.*, 2020). Many of these tracks were mapped in areas where land management for the purpose of game shooting often takes place. The prevalence of these sizable track and road networks in nominally protected areas suggests the need for more robust data-driven regulation of consent to construct tracks (Clutterbuck *et al.*, 2020). In some countries there may be little regulation for infrastructure and very limited studies on impacts, meaning that roads may be built with little or no consideration given to the potentially detrimental effects of such construction (Alamgir *et al.*, 2019; Lilleskov *et al.*, 2019).

In large areas of Alberta, Canada, there has been an intensifying push towards mining for oil sand in addition to timber harvesting (Turchenek, 1990; Plach *et al.*, 2017). It has been projected that oil sand mining will lead to a loss over 29,555 ha of boreal peatlands in the region (Rooney *et al.*, 2012). Prior to the mining process itself there is a period of exploration known as 'seismic exploration'. It has been shown that roads and tracks on peatlands, including lightly used footpaths, can have effects over a multi-year period after use has ended (Robroek *et al.*, 2010). For seismic exploration these effects are far greater; in the 1940s the exploration on unsurfaced peat was carried out at various times of year, resulting in scars which were still visible over 50 years later as result of induced thawing of the permafrost. As a result of this impact, exploration moved to winter, greatly reducing damage (Hernandez, 1973; Jorgenson *et al.*, 2010). There has been an increase in the creation of seismic trails since the turn of the century and on the Alaskan tundra this has created the largest footprint of all human activities combined (Jorgenson *et al.,* 2010). Canada, likewise, has seen significant expansion of these trails (Schneider *et al.*, 2003).

Consideration must also be given to the role of changing climate and peatland management practices as these have the potential to act 'in-combination' with infrastructure, either when the infrastructure is added or in the period after infrastructure is removed. These in-combination effects occur when multiple factors exert pressures on the system such as those linked to carbon cycling or stochastic events (Armstrong *et al.* 2015; Sengbusch, 2015). A further example from the North West Territories of Canada showed that canopy removal for track creation led to an increase of ~20 cm in the active layer depth; the resultant wetter conditions led to more extensive permafrost thaw (Williams *et al.* 2013). These interactions are particularly important in the context of peatlands where small-scale perturbations can have long-lasting impacts (Holden, 2005).

3.1 The influence of roads and tracks on peatland hydrology, physical properties and biogeochemistry

The addition of roads or tracks and associated infrastructure to peatland ecosystems can lead to alterations in the hydrology of these systems. Plach *et al.* (2017) found impeded groundwater movement in Alberta around a road system and CO_2 sequestration was lowered on the down slope side of the road and there were variations in vegetation across the sides of the roads (Plach *et al.* 2017). Similar to the observations from Alberta, roads in the Puna peatlands of Peru were found to cause impeded groundwater movement around mining sites (Salvador *et al.*, 2014). Shrinkage and compression resulting from mining activities were found to reduce volumetric water storage of peat by 3.5% over a season at Lac St Jean, Quebec (Price and Schlozhauer, 1999). Clearance of trees for seismic trail creation in boreal peatlands near Fort Simpson, Northwest Territories, was found to increase incoming thermal radiation by 11% (Williams and Quinton, 2013). Although the authors concluded that this did not appear to effect change in the permafrost, woody debris piled on the trail and increased evaporation led to increases in soil moisture. A further study in this region examined seismic lines which cut across from bogs to fens over permafrost peat plateau, finding that seasonal thaw lowered the permafrost table sufficiently that a flow pathway between the bog and the fen was created, allowing enhanced runoff into the wider catchment (Braverman and Quinton, 2016). McKendrick-Smith (2016) surveyed 29 peat roads and tracks across northern England. With stone roads, peat on the downslope side was found to have lower volumetric water content probably due to upslope compression reducing water flow through the peat. Such an effect was not found with the use of plastic mesh tracks (McKendrick-Smith, 2016). Studies from North America have demonstrated that roads have the ability to act as dams on peatlands – with flooding occurring locally upslope from the road and drying occurring on the downslope side (Ferrell *et al.*, 2007; Chimner *et al.*, 2017). This is particularly problematic where roads run perpendicular to the gradient (Chimner *et al.*, 2017). Culverts may address this barrier to water flow by reducing the damming effect. For example, a study in Alberta, Canada found that culverts had considerable efficacy in reducing – although not eliminating – variations in hydrological states (Saraswati *et al.*, 2020). The siting of culverts can be important with the most significant reductions in effects – including depth to water table - observed where culverts were situated <2m from study transects (Saraswati *et al.*, 2020). However, we have observed in the field that in some cases road culverts can focus turbulent water flow leading to peat incision and even gullying. To minimise hydrological disruption, roads on peatlands are best situated parallel to slope gradients (Chimner *et al.*, 2017; Saraswati *et al.*, 2019) and some peatland restoration projects are rebuilding roads which promote more diffuse sheet flow (Chimner *et al.*, 2017).

Due to the damming effects of the roads themselves or the fact that peatland roads can be subject to significant overland flow, drainage ditches often accompany road and track installation (Bradof, 1992; Chimner *et al.*, 2017). Drainage and other management practices alter peat properties through a combination of compaction, drying, oxidation and the addition of minerals (Hobbs, 1986; Mustamo *et al.*, 2016). The process of draining peatlands has been shown to cause subsidence through oxidation of the peat (Williamson *et al.* 2017) which occurs due to the loss of water normally retained in the peat pores (Bragazza *et al.*, 2013; Rezanezhad *et al.*, 2016), leading to desiccation and structural shrinkage of the peat mass

(Grzywna, 2017). The drying effects have been recorded leading to up to fourfold increases in surface plant biomass (Miller *et al.*, 2015) while the construction of aggregate roads can introduce base minerals onto acidic peat soils (McKendrick-Smith, 2016; Pouliot *et al.*, 2019).

In blanket peatlands, ditch drainage has been associated with enhanced macropore and pipe development through the process of desiccation, which in turn can lead to gully erosion. (Holden, 2005; Holden *et al.*, 2006). Even single ditches when dug perpendicular to the slope can have a significant drying effect on the peat immediately downslope (Holden and Burt, 2003a; Holden and Burt, 2003b; Holden *et al.*, 2006; Chimner *et al.*, 2017). Ditch erosion can also occur with the flowing water carrying away increasing amounts of peat. The bare floors and walls of drains can be vulnerable to summer desiccation and winter freeze/thaw processes that further enhance peat loss (Holden *et al.*, 2007). The contribution of roads and tracks to erosion and pipe formation processes is currently unknown.

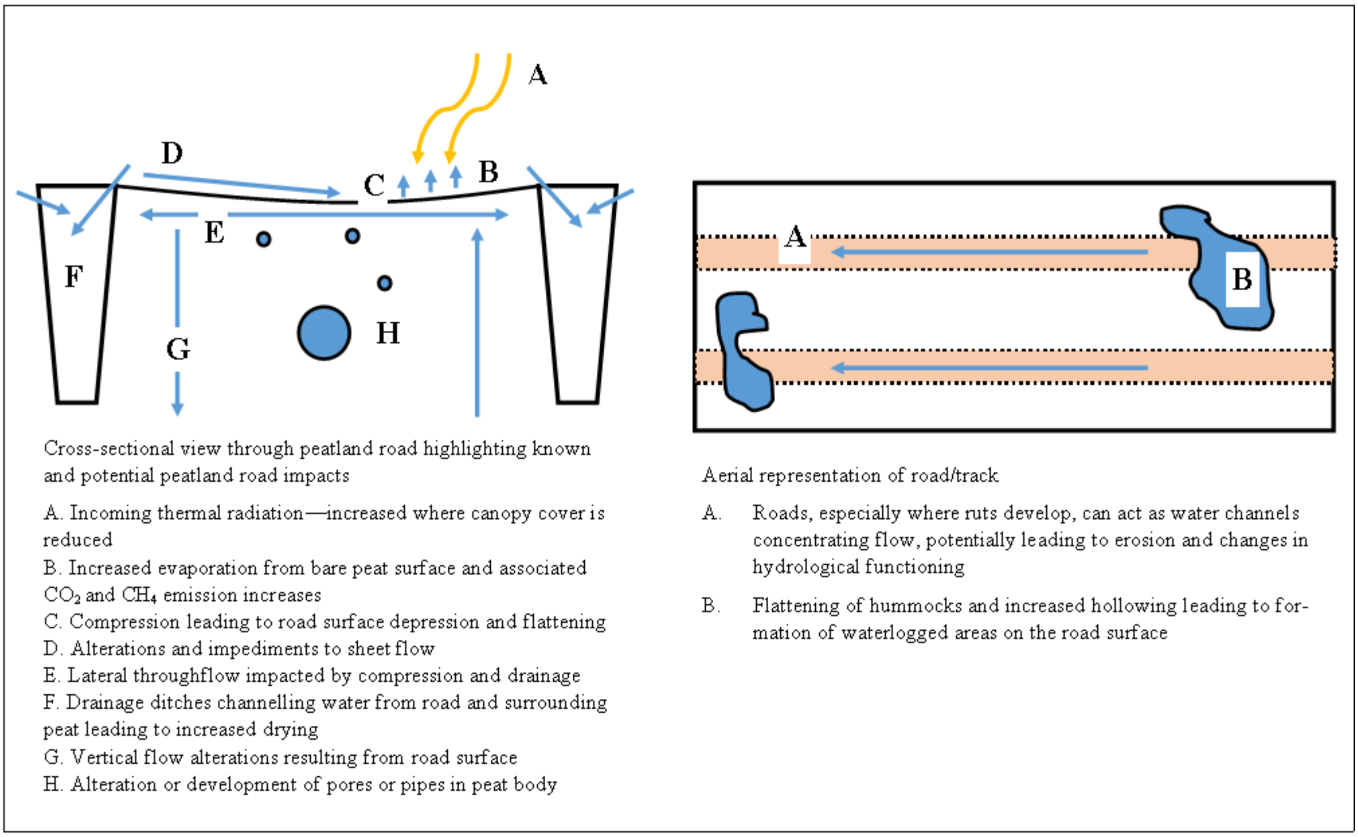

Figure 3. Simple visual summary of some of the key ecohydrological effects of peatland roads and tracks which have been recorded or merit further study.

Roads can also alter peatland ecohydrological and biological processes. A study in bog and boreal fen peatlands of Alberta examined alterations in enzyme activities after a road had been constructed (Saraswati *et al.*, 2019). These enzyme activities were used as indicators of changes to hydrological processes. There were significant increases in two out of six studied enzymes in areas where disturbance had occurred compared to undisturbed areas. There were complex interlinked patterns which caused these alterations including the oxidation of the peat as a result of disturbance (Saraswati *et al.*, 2019). Significant alterations in temperatures adjacent to roads have also been observed. For example, over a two year period, a temperature rise of 1°C was recorded in a naturally forested bog and 1.2°C in a shrubby fen compared to the control plots situated ~50 m from the road (Saraswati and Strack, 2019). Such temperature increases may enhance methane release. . Over a 1900 km^2 area used for petroleum exploration an additional 4.4-5.1 kilotonnes of methane emissions were calculated per year above that found in the undisturbed regions (Strack *et al.*, 2019). Boreal peatlands in Russia could contribute up to 69% of European methane emissions, with emissions found to be higher when the peat was warmer and drier (Schneider *et al.*, 2016) However, there is a lack of research focused on Russian peatland disturbance, but with growing resource exploitation this is an important region representing some of the world's most extensive boreal peatlands.

In light of the importance of peatland carbon cycling processes and gas release a growing area of research is attempting to quantify peatland management impacts on these processes. However, road and track impact studies which address carbon cycling are lacking. Fen peatlands in the Western boreal plains of Alberta, were found to have subtly altered rates of productivity and respiration where tracks were installed which led to lowered CO_2 sequestration rates (Plach *et al.* 2017). A Scottish windfarm development was found to have a small but still significant negative effect on pH, alkalinity and acid neutralising capacity in the immediate area surrounding the windfarm. However, the study area only had small areas of deep peat and further down the catchment in the streamwater these effects were negligible (Millidine *et al.*, 2015). In a national park area of the Krkonoše Mountains in Czech Republic, significant changes to soil chemistry were found where roads were constructed of base rich gravel leading to an increase in soil pH from 3.9 to 7.6 with associated changes in the plant community (Müllerová *et al.*, 2011). A poor fen site in Maine intersected by a four-lane asphalt road was found to have year round base nutrient enrichment as a result of salt application: cations of Ca, Na, K and Mg were detectable up to 200-300m from the road (Pugh *et al.*, 1996). Further work is recommended to test for such effects elsewhere.

Management influences can cause peat slides or bog bursts, and higher slope angles tend to present a higher risk (Long *et al.*, 2011). These mass movements, whether natural or arising from human activity, can result in expensive remedial work to damaged infrastructure (Long, Jennings and Carroll 2011). Five slides which were examined in the North Pennine valleys of Teesdale and Weardale in England found that open moorland drains – which often accompany aggregate roads on peat – had played a role in the slides (Carling, 1986). At Ballincollig hill in Ireland, previous cutting for domestic fuel had destabilised the peat, to the point where road construction then resulted in a bog slide (Long *et al.*, 2011). While there is little research into the influence of roads or vehicle vibrations in causing peat slope failure, in Scotland, windfarm track construction applications must consider whether peat stability will be affected by their construction (Lee and Giles, 2020).

A topic on which there is limited published research, is on the potential effects of chemicals produced by vehicles driving across peatlands. For example, there may be fuel leakage, nutrient deposition from vehicle emissions, dust from brakes, and heavy metals, rubber or plastics from vehicle abrasion and wear. There may also be degradation of materials used in road and track construction which could contaminate the peat and alter biogeochemical processes. Some studies have looked at such issues in similar ecosystems such as non-peat wetlands and heaths and these maybe useful in extrapolating potential impacts. In the Bakken region in North Dakota and Montana, dust loading from a nearby road into a wetland area increased by 335% at 10 m from the road edge, but recorded impacts of the dust compared to unaffected controls were minimal (Creuzer *et al.*, 2016). At heathland sites in the New Forest, UK increased numbers of vascular plants including *Calluna vulgaris* and graminoid species were recorded along roads thought to be the result of nitrogen enrichment from exhausts (Angold, 1997). Road sites on shallow peaty soils in the Alaskan Arctic tundra were found to have suffered similar effects to those recorded in the Angold (1997) study, with large increases in graminoids and the vascular plant *Rubus chamaemorous* and loss of most *Sphagna* within 5 m of roadsides (Myers-Smith *et al.*, 2006). It is known from the archaeological literature that decay of organic deposits can be accelerated when chemical characteristics of water sources change (Holden *et al.*, 2006; Howard *et al.*, 2008). However, such studies have not been undertaken to examine peatland specific road effects on chemical interactions with nearby peat deposits. Plastic tracks, which may or may not be removed after use, may also break down by photodegradation or abrasion into microplastic particles but it is unknown whether this effect occurs and whether it is important for biogeochemical functioning of peatlands.

3.2. The influence of roads and tracks on peatland vegetation

Roads or tracks may create abrupt boundaries between habitats. Linear human features such as roads can produce so-called ‘edge effects’. Edge effects can be defined as ecological phenomena which occur where two habitats meet that do not occur in either habitat in isolation; amongst individuals this may be behavioural changes and in a population it is changes in abundance (Potts *et al.*, 2016). These edge effects may be particularly pronounced in areas of high biodiversity such as are found in many tropical peatlands where edge effects may include increased human disturbance and exploitation, structural changes to habitats and changes in microclimates (Poor *et al.*, 2019). A study from Kalimantan in Indonesia looking at tree diversity in a degraded peatland habitat found a 32% reduction in forest biomass on edge plots compared to interior plots (Astiani *et al.*, 2018). Research which took place at Moor House in England over a period of ~ 2 years also found that *Calluna vulgaris, Eriophorum vaginatum and Sphagnum capillifolium* all decreased in abundance along the line of a 1.5km plastic mesh track when compared to undisturbed areas (McKendrick-Smith, 2016). Two sites in Southern Quebec – one bog, one fen – which were intersected by powerline rights of way (ROW) were found to have higher levels of both native and non-native invasive species along ROW (Dube *et al.*, 2011). The fen appeared more susceptible to invasion than the bog with invasive species found up to 250 m from the edge of a ROW in the bog and 31 m in the fen In northern Alberta, 3-4 year old low impact seismic trails across boreal peatlands were found to have detectable impacts on vegetation up to 15 m from the edge of the track (Dabros *et al.*, 2017). A problematic species in European peatlands is the invasive *Campylopus introflexus,* a moss which readily colonises disturbed, drier areas of peat (Żarnowiec *et al.,* 2019). Our own fieldobservations from Moor House and the Yorkshire Dales suggest that the species is resistant to high levels of disturbance and is abundant along tracks. The nature of edge effects in regard to peatland roads is a topic which merits further research.

Attempts to reduce the negative impacts of access routes on peatlands have included use of plastic mesh tracks and wooden articulate tracks (figures 1a, b and e). McKendrick-Smith (2016) studied an experimental mesh track in northern England. In line with statutory body guidelines at the time the site was prepared by mowing and the track then laid. The track was driven over in varying driving patterns for different treatment sections over a two-year period. The study found some strong effects on vegetation composition and that tracks affected the surface elevation profile through lowering the peat surface directly under the track. Some effects were found to be topographically linked, suggesting that careful consideration be given to the siting of tracks. Impacts were not correlated with the frequency of vehicle usage on the track on any of hydrological processes considered in the study. There were significant changes to vegetation over the period of study including increases in bare peat, alterations to species composition and reductions in both *Calluna vulgaris* and *Eriophorum vaginatum*. Where regeneration occurred on the track it was at the edges with the worst effects observed in rutted sections. Vegetation height was significantly impacted on the highest use track, although occurrences of bare peat were low.

There can often be a time delay between a management intervention on a peatland, and observation of significant change to ecosystem function (e.g. Holden *et al.,* 2006; Holden, 2005). A study on Ennersbacher Moor in the Black Forest of Germany found that the construction of a road some 30 years earlier (in 1983) on a mountain bog was associated with changes to the surrounding vegetation but that these changes were not significant until two decades after road construction. The road had been constructed with the intention that road-salt contaminated water in winter be conducted away from the bog, but it had also restricted the flow of water to the centre of the bog. Over the period from 1998 to 2014 there was a gradual change in the vegetation on the bog with an increase in the size of the trees (bog pine), cover of dwarf shrubs and composition of *Sphagna.* Between 2009 and 2011 there were a series of droughts and the observations from Ennersbacher Moor suggested this triggered a succession by the bog pine. The pH of the bog showed little change, but there was greater fluctuation in the water-table depth and the peat became more humified after 2002 (Sengbusch, 2015). Analysis of tree rings in a boreal peatland in Canada after the construction of a road in 1977, showed that all trees < 83.5cm there had suffered a mass die off in 1989 after the single culvert which had been built to allow water to flow under the road became blocked causing inundation of the surrounding peatland (Bocking, 2015; Bocking *et* *al.*, 2017). These time-delayed effects of road construction suggest that long-term monitoring is required in peatlands to adequately assess the impacts on peatland processes and functioning.

Winter *trails* are tracks used for single passes by convoys of heavy-axled vehicles, whereas, winter *roads* allow multiple passes of these vehicles and provide access for heavy haulage vehicles (Campbell and Bergeron, 2012). Winter trails rely upon frost and snow to bear the load of the vehicles. Roads, in contrast, have their woody vegetation cleared and a load bearing road-bed is created (Campbell and Bergeron, 2012). These trails and roads range from 4 m to 50 m in width, and often form a grid pattern across the areas they are used to explore. Seismic exploration vehicles which are used on the trails can exert a ground pressure of up to 0.73kg/cm^2 (Jorgenson *et al.,* 2010). Winter trail use has been found to have an effect on peat compaction where soil moisture levels were initially high while drier sites experienced bare patches with re-colonisation delayed by almost 10 years on the most disturbed site (Emers *et al.*, 1995). Winter trails have been found to effect the depth of the active layer with highly disturbed sites suffering from insulation from plant detritus leading to a shallower permafrost layer (Emers *et al.*, 1995). The most significant effects, however, have been observed on the plant communities found in these areas (Emers *et al.,* 1995; Kemper *et al.,* 2009). Alaskan peatlands had clear patterns with disturbed sites all showing a reduction in some species associated with seismic trails (Emers *et al.*, 1995). Other studies in the region have shown significant differences in the composition of plant communities between the seismic trails and the reference tundra, but that there was no difference in diversity or richness (Kemper and MacDonald, 2009a).

While the species make-up is an important consideration, they also form unique meso and micro topographic features which play a role in the hydrology and ecological diversity of peatlands. These features can include the small characteristic hummock formations of species such as *Sphagnum capillifollium* to larger pools containing *Sphagnum cuspidatum.* The presence of vascular plants in moderate quantities has been shown to support hummock development, the characteristic domed shape which some species of *Sphagna* form (Pouliot *et al.* 2011). Research has shown hummocks to be important in the movement of water over and through peatlands, as their shape adds surface roughness which is useful in slowing runoff (Branham and Strack, 2014). This surficial microtopography creates a range of microclimates which are important for birds and insects (Lindsay *et al.*, 2014). Flattened microtopography has been recorded on low impact seismic trails on boreal peatlands in the Northwest Terriorities and northern Alberta regions of Canada with increased hollowing and mean surface depression of 2 cm and 8 cm respectively (Lovitt *et al.*, 2018; Stevenson *et al.*, 2019). The impacts of both surfaced and unsurfaced roads on peatland micro and mesotopography and associated ecohydrology is an area which would still merit furthur study.

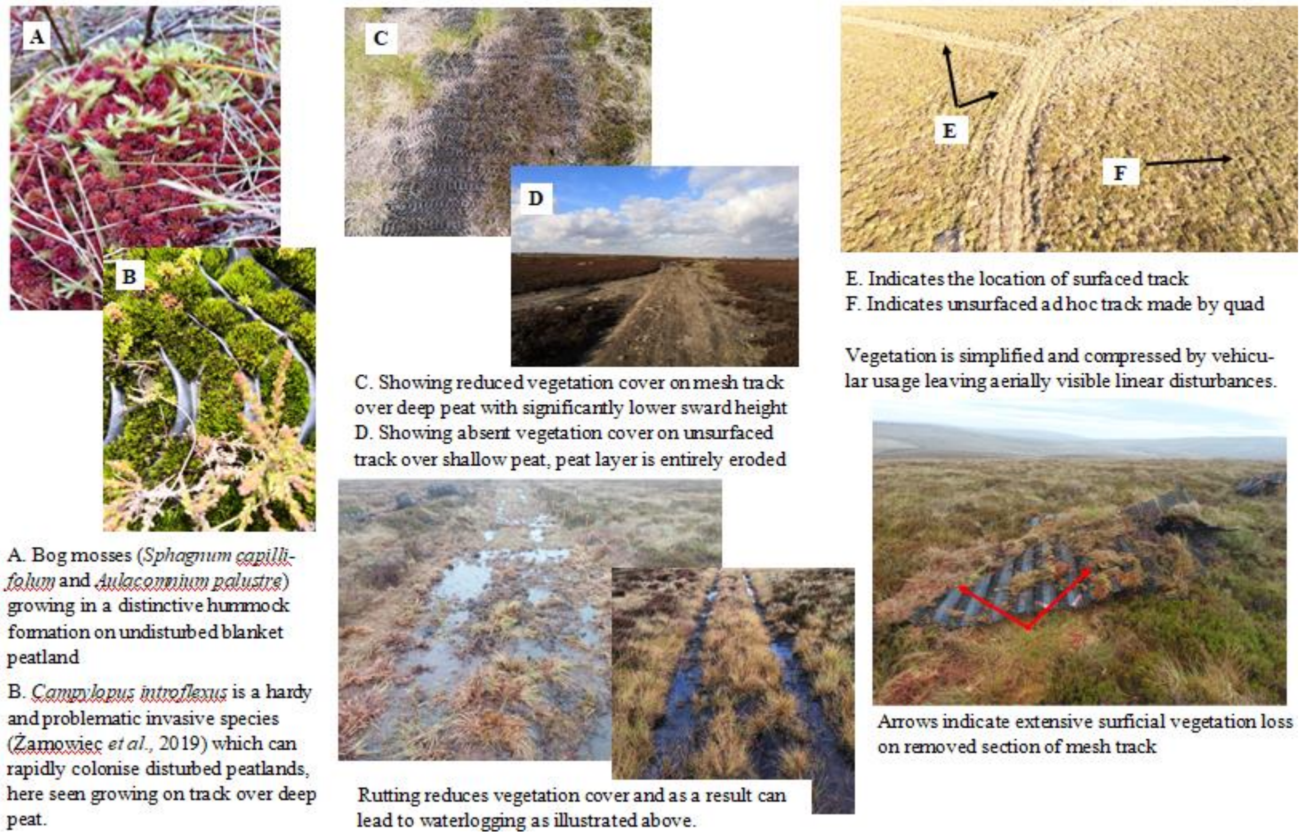

Figure 3. A photographic summary of some of the effects discussed in section 3.2. Vegetation impacts as a result of peatland tracks are variable in their extent - corresponding with usage levels and surface types. A common theme emerges, however, that effects are often clearly visible.

3.3 Recovery in the post abandonment period

The statutory body in England (Natural England) which consents the addition of tracks to upland areas produced an evidence review (Grace *et al.*, 2013) which found large gaps in knowledge which could hinder the confidence with which they could make a judgement of ‘no significant effect’ in the UK consenting process. At present there is only a requirement for consent in order to construct a (temporary) track on UK protected sites (those with legally designated Special Scientific Interest status). Given that most consents are for temporary tracks it is essential that there is some understanding of the impacts of track removal, since there is an underlying assumption that temporary tracks are removed at some point. The image in Figure 4 from the North Pennines of England illustrates the issue. The image is of a section of track that had been removed 12 months previously. Vegetation recovery over the time period had been slow and there are waterlogged and desiccated areas forming along the length of the track. Although the image appears to show an extensive area of damage, the lack of research means we have little understanding as to whether or how other peatland ecohydrological processes have been impacted by track removal.

Figure 4. A track on an area within the North Pennines, which sits within the Moor House Cross Fell Site of Special Scientific Interest: the right-hand track shown was surfaced between 2011 – 2018. The mesh track was then removed from this area (image taken 15 months post removal) and new track was laid in 2018, shown to the left-hand side of the image.

There are few studies which have attempted to quantify the recovery in the post track removal/abandonment period (Pilon, 2015). The question of removal is important, as projects - such as windfarm construction - may require temporary access or utilise materials to construct tracks which may be unsuitable for leaving in place in the long term due to the risk of degradation and ecotoxicological effects. Tracks may also be abandoned due to their use only being intended for short periods (as is the case for seismic trails) or if the ground becomes too damaged to continue being used. It is also important to understand what happens to the ecosystem after road and track removal, particularly as many sites where roads and tracks are constructed may be of high ecological value.

A study of two blanket bog sites with tracks that had been abandoned for over 25 years in Dartmoor National Park in southwest England showed very little similarity in vegetation community makeup when compared to the controls; moreover there was evidence of succession to dry heath (Charman and Pollard, 1995). A study of the influence of military vehicles travelling over different soil types from Estonia found that, although on the initial pass peat had the deepest rutting evident, by 10 passes the grassland was found to have suffered a greater increase in rut depth than the peat. The study concluded, however, that there was a need for greater research into the effect of 'wheeling' on peat soils (Vennik *et al.*, 2019).

A study of recovery after use of winter trails used for diamond and base metal mining in the James and Hudson Bay areas has shown that while plant cover may recover rapidly, the diversity of species is still lower than in undisturbed areas, several years later, with graminoids showing greatest resilience (Campbell and Bergeron, 2012). In boreal peatlands tree species have also been shown to suffer delayed recovery along abandoned seismic trails, due to the loss of microtopography (Lieffers *et al.,* 2017; Filicetti and Nielsen, 2020). Roads on Finnish boreal peatlands were found to cause lowering of the water table on the downstream side due to damming effects, this led to changes in vegetation up to 100m from the road edge (Miller *et al.,* 2015).

A number of studies have recorded the recolonization of disturbed areas by species from the genus *Polytrichum;* this is of importance as *Polytrichum* species may outcompete *Sphagnum* mosses in some ecological conditions (Groeneveld and Rochefort, 2002; Toet *et al.*, 2006; Benscoter, 2006; Bu *et al.*, 2013; Bu *et al.*, 2017). Some species are more susceptible to this competition than others (Bu *et al.*, 2011) and this may be attributable to the stronger allelopathic effect that *Polytrichum* species possess when compared to *Sphagnum* species which can inhibit *Sphagnum* germination (Bu *et al.* 2017). A study in Norway found that *Polytrichum* species cover increased by over 30% in plots which had been restored after road construction compared to cover of 1% on the undisturbed plots. The same study showed that abundance of other peatland species was reduced with increasing depth of *Polytrichum* hummocks (Johansen *et al.*, 2017). Campbell and Bergeron (2012) found that in plots which were disturbed by seismic vehicles in Hudson Bay, Canada, the species *Polytrichum strictum* was found in three times more of the quadrats than those sampled from the control plots. The study at Ennersbach Moor in Germany found that between 1999 and 2013 *Polytrichum* coverage in the studied plot of 80m^2, went from being absent, to constituting 1-2% of the vegetation (Sengbusch, 2015). Studies which have looked at the impact of prescribed rotational burning in peatlands have found that *Polytrichum* is a species which recovers rapidly in the post burn period (Benscoter, 2006; Johansen *et al.*, 2017). However, it should be noted that *Polytrichum* has been found to be a useful nursery plant for a variety of peatland species in both boreal and open peatland ecosystems, particularly where microclimates may be harsh (Groeneveld *et al.*, 2007). *Polytrichum* hummocks have been found to create a more humid environment which favours *Sphagnum* growth (Groeneveld *et al.*, 2007) and spruce seedlings have also benefitted from enhanced root growth stimulated by *Polytrichum* (Groeneveld and Rochefort, 2002). Sewn *Polytrichum* carpets on a domed bog site at Rivière-du-Loup, Québec were found to reduce the occurrence of frost heave (Groeneveld and Rochefort, 2005), a finding which may be relevant to reducing needle ice erosion on bare peat areas. Monitoring the influence of *Polytrichum* on vegetation diversity and erosion proccesses on both fen and bog peatlands in the post track recovery period may be useful.

Graminoid species, particularly *Eriophorum vaginatum,* have often demonstrated a greater ability to recover after usage of roads has ceased, whereas dwarf shrubs, lichens and some bryophytes including *Sphagnum* species appear less resilient (Emers *et al.*, 1995; Kemper and MacDonald, 2009a; Kemper and Macdonald, 2009b). This is further supported by a number of studies which have recorded large increases in graminoid cover on abandoned winter roads (Strack *et al.*, 2018) while Goud et al. (2018) found graminoid increases in the poor fen areas of Mer Bleue after disturbance. Graminoids are more resistant to disturbance than both bryophytes and shrubs and can rapidly colonise highly disturbed areas post abandonment (Emers *et al.* 1995). Upland sites in the UK and North America have shown resistance to initial disturbances but after long-term usage there are long recovery rates once tracks are abandoned (Charman and Pollard, 1995; Robroek *et al.*, 2010; Campbell and Bergeron, 2012). *Eriophorum vaginatum* and a number of *Carex* species seem to be not only resilient to disturbance but are stimulated by it (Hernandez, 1973; Campell and Bergeron, 2012). Caution must be taken to avoid the generalisation that suggests that all graminoids are tolerant of disturbance, however. Campbell and Bergeron (2012) showed *Eriophorum angustifolium* showed poor recovery along seismic trails post abandonment. At Moor House in northern England, within a year of abandonment of tracks used by researchers *Eriophorum angustifolium* had shown little recovery (Robroek *et al.*, 2010). Figure 5 shows a mesh track at Moor House, England illustrating surficial effects of vehicle passage – again, *Eriophorum* *vaginatum* is seen to be the dominant species here.

Figure 5. Re-colonisation state of a rutted section on the experimental plastic mesh track at Moor House four years after last vehicle usage as part of the McKendrick-Smith study (2016). The surrounding area has a diverse blanket bog flora.

Given the importance of bryophytes in peat building, it is important to consider the effects of roads on *Sphagnum* health and diversity. A functional *Sphagnum* layer had re-established on a walking track at Moor House after abandonment (Robroek *et al.*, 2010). All *Sphagna* showed recovery in the Hudson Bay study by Campbell and Bergeron (2012), but at different rates, and they also observed that this recovery was slower when conditions were dry. As Moor House is a high rainfall site receiving ~2000 mm per year (Holden and Rose, 2011) the retarded response to dry conditions observed at Hudson Bay (Campbell and Bergeron, 2012) may not have been an issue at Moor House, but indicates that seasonal timing of track removal could be important. Rochefort (2000) suggested that there is also scope for research into competition interactions between *Sphagnum* species in the re-establishment process.

Alterations to abiotic factors such as water-table depth, atmospheric and surface temperatures, the addition of chemicals and seasonal changes can all favour different species (Rydin, 1993; Corradini and Clément, 1999; Robroek *et al.*, 2007; Breeuwer *et al.*, 2008; Pouliot *et al.*, 2011; Purre and Ilomets, 2018). This is particularly important when considering the removal process for a track which has been placed onto peatland as there may be bare areas left which will gradually be recolonised, so there is a need to understand which species may be able to colonise more readily and whether this may have longer term implications for ecosystem function. These factors may help inform the selection of intervention techniques for restoration. Investigation of bryophyte relationships on a restored peatland in northern Estonia suggested that a low peat moisture content led to a domination of *Polytrichum strictum* and that the ratios of nitrogen to potassium or nitrogen to phosphorous were influential in the establishment of both *P. strictum* and *Aulacomnium palustre* (Purre and Ilomets, 2018). There is also scope for addition of mulch cover to the surface to create a humid environment and prevent surface drying and desiccation. Bare peat sites in East Estonia covered with straw mulch had a mean vegetation cover of between 40-57% within a 5 year period, compared to control area coverage of just 2% (Triisberg-Uljas et al., 2018).

There are potential avenues for mitigation of some road and track impacts on peatlands, although relatively few studies have explored the development of best practice. Pouliot *et al.* (2019) examined ways to mitigate the effects of surface-placed mineral roads on peat. Using a peat inversion technique (PIT) the peat was excavated and the mineral added ~40cm below the active surface, with the aim of confining nutrient enrichment. One site showed a high rate of success using the PIT with *Sphagnum* cover at ~50% of the control site, while the other site showed a more limited *Sphagnum* recovery at ~5%; however, the second site had an initially lower water table from adjacent ditching (Pouliot *et al.*, 2019). PIT is a technique that would benefit from further study. Culverts are used to reduce ponding and allow passage of water (Saraswati *et al.*, 2020) and the alignment of roads perpendicular to the slope has also been shown to reduce the effects of roads on the water table and peat temperature (Saraswati *et al.*, 2019). Studies looking at unsurfaced seismic trails have attempted to promote the recovery of trees through intervention techniques such as mounding soil in order to create a drier area for saplings to establish (Filicetti and Neilsen, 2020). However, care must be taken with restoration projects as increased carbon losses resulting from microbial activity due to mounding exposure of soil were recorded on abandoned seismic trails at Fort McMurray, Canada (Davidson *et al.*, 2020). Remote sensing is a useful tool to identify sites for restoration which are regenerating slowly. In Canada, LiDAR has been used to identify seismic trails where tree growth height remained under 3 m within a 10 year timeframe, indicating that waterlogged ground conditions may have stunted growth (van Rensen *et al.*, 2015).

4. Conclusion and areas for further research

While research on peatland road impacts has increased considerably in the past decade, there remain sizeable gaps in the literature. There has been a shift in the focus of research, particularly in the past five years as our understanding of the value of peatlands in the provision of ecosystem services has improved. There is, however, an imperative for research which will target the research gaps, particularly as road networks are expanding rapidly into remote regions. These priorities are diverse and global in scope. There is scope to use remote sensing tools to make it faster and more cost-effective to identify vulnerable areas and target restoration efforts (Carless *et al.* 2019).

From our review of the literature we suggest the following areas as key future research areas:

- There is an urgent need for studies looking at the effects of roads on tropical peatlands specifically - there is a very limited body of work looking at these regions and much of the existing literature focuses on wildlife behavioural changes and biodiversity loss rather than the direct effects on the peat.
- Erosion and pipe formation processes as they relate to roads have not been studied at present, and as they can be major drivers of peatland loss this is a key area for research.
- The majority of the focus regarding seismic trails has been on vegetation recovery following disturbance with fewer studies looking at how this intertwines with hydrological change. These interactions could usefully be explored in light of expanding oil sand exploration in Canada and Alaska.
- Russia contains extensive peatlands with accelerated resource exploitation. However, the effects are poorly documented and research is needed in the region to give a more complete picture of infrastructure effects on boreal peatlands.

- As tracks may be constructed of materials which are not biodegradable (e.g. plastic mesh) there is a case for examining the potential for ecotoxicological effects of track materials. There are currently no published studies on the presence or effects of microplastics in peatlands, so new work is required to provide an evidence base.
- Vehicular access tracks may enhance chemical pollution of peatlands from passing vehicles but there has been no research on the issue. Therefore, new work is required to investigate such impacts both within the peat column and in peatland water bodies such as pools and streams.
- Studies which look at what happens to ecohydrological processes - such as runoff, vertical water movement, degradation of the peat, vegetation and microtopographic damage/loss and carbon and methane cycling - if/when an abandoned surfaced track is removed are currently unavailable: therefore, we recommend this as an important research avenue.
- Vegetation studies constitute a large volume of the road/track-related peatland research to date. However, there are still sizeable research gaps including inter-species competition between *Sphagna* and the influence of *Polytrichum* mosses on diversity in track abandonment recovery periods.
- In light of the oft slow recovery times of vegetation layers and the risk of underlying peat loss, there is a pressing need for research into restoration techniques with specific focus on roads following abandonment or removal.

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