THE IMPACT OF TRACKS ON BLANKET PEAT ECOHYDROLOGY

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ABSTRACT

Peatlands are subject to multiple uses including farming, forestry, sites for renewable energy (wind farms) and recreation (including gun sports). To facilitate access, roads and tracks, both constructed and unsurfaced, are becoming an increasingly common feature in Northern peatlands. The impact that these linear features have on peatland ecohydrological functioning is poorly understood, especially within blanket peatlands which, unlike other peatland types, often occur on slopes. There is concern that disturbances could negatively impact important physical, hydrological and ecological peat properties, and consequently the wider functioning of these systems. Indeed, the ability of peatlands to capture and store carbon could be compromised following possible reductions in vegetation cover and a deepening of the water table. Likewise, the role of peatlands in flood management could be affected as a result of peat compaction and enhanced surface runoff. With respect to practical applications, the current lack of understanding and evidence for decision-making has made granting permission for track installation problematic.

In this thesis, the first comprehensive study of track impacts on blanket peat is presented. A two strand approach was used to investigate the impact of tracks on blanket peat ecohydrology, involving (i) a regional survey of 29 track reaches (aggregate and plastic) across seven sites in the North Pennines and Cheviots of northern England and (ii) an intensive study over two years, covering 1.5 km of plastic mesh track, 30 m of articulated wooden track and 200 m of unsurfaced track located at Moor House in the North Pennines. Key properties for peatland ecohydrological functioning were measured including soil moisture, bulk density, hydraulic conductivity, water-table depth, overland flow occurrence and vegetation composition. The influence of track type, frequency of use and topographic location were considered, in addition to the spatial extent of track impacts.

The regional survey found higher volumetric moisture content on the upslope side of stone tracks compared with the downslope side. Such an effect was not found around plastic tracks, where the upslope-downslope gradient was indistinct or did not exist, due to the orientation of the track to the contours. Topographic location and track age influenced spatial patterns in moisture content for stone tracks. Such effects could not be tested for plastic tracks. The influence of distance was considered for the stone tracks however no clear effect was observed.

Findings from the intensive study showed variation in the responses to the tracks from the selected key properties for blanket peatland ecohydrological functioning. Clear impacts were observed for surface profile elevation and vegetation characteristics. Following track use a lowering of surface peat elevation directly under the track was recorded for all three track types and at all topographic locations. Compared with before disturbance data, reduced cover in *C. vulgaris*, *E. vaginatum* and *S. capillifolium*, a lowering in the height of the vegetation, and increased bare peat occurrence, were found 22 months after track installation and 13 months after the commencement of driving. These impacts were closely associated with the installation process of the tracks. Track type was a key influential variable in the magnitude of impact observed for both surface peat elevation and vegetation composition and height. Topographic location was influential for vegetation composition but not surface profile elevation. Track frequency of use had minimal influence on the responses of all of the properties measured in the intensive study.

Expected impacts to bulk density, hydraulic conductivity, water-table depth and overland flow occurrence were found to occur under some conditions. The intensive study was undertaken over a two year period with 18 months of continuous monitoring (water-table depth and overland flow). The variation in the responses of a number of the key properties measured suggest a need for long-term studies (5+ years) to fully capture the impact of disturbances such as tracks.

The results from this study will be used to inform decision-making with respect to the siting and use of tracks in blanket peatland environments. With better informed decision-making the future impacts of track installation and use can be mitigated against; resulting in healthy peatlands, where their multiple functions including carbon sequestration and flood alleviation can be maintained and supported.

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CHAPTER 1: INTRODUCTION

1.1 Introduction and Rationale

1.1.1 Peatlands: The Global Context

Peatlands are masses of partially decayed organic matter which have built up over time under wet conditions which restrict decay. They cover approximately 3 % of the earth's terrestrial surface (Gorham, 1991) and play a key role in regulating the global carbon cycle, with current estimates suggesting peatlands store 500 ±100 gigatonnes of carbon (Yu, 2012).

Peatland ecosystems are therefore of international importance, and in addition to climate regulation support numerous ecosystem services (Kimmel and Mander, 2010). Peatlands are regarded as both water stores and sources of fresh water for potable supply. The storage of water, however, is dependent upon the peatland type and hydrological regime (Quinton and Hayashi, 2005, Holden, 2006). In the UK, it is thought that between 50 and 70 % of drinking water originates in peat covered catchments (Bonn et al., 2009). Consequently, there is potential for peat to impact water quality (Martin-Ortega et al., 2014). Peatlands also support many unique organisms (Charman, 2002) and a higher number of characteristic species (5-20 %) are found in peatlands compared with other terrestrial ecosystems (Parish et al., 2008). This gives peatland biodiversity a high conservation value.

Peatlands around the world face increasing pressure from natural and anthropogenic sources. A changing climate, warmer temperatures and change in rainfall patterns have the potential to alter the functioning of peatlands and their response and resilience to further disturbance (IPCC, 2014). Such disturbances can result from the economic development of peatlands, in addition to their use for recreational activities (Erwin, 2009). Economic activities in peatlands include: agriculture, peat extraction for fuel and horticulture, growth and harvesting of palm oil plantations and accessing sites of oil sands (Joosten and Clarke, 2002). In association with these is increased demand for vehicular access to the peatlands.

Often the multiple uses of peatlands have led to their degradation through drainage, erosion, and compaction; resulting in deeper water tables, exposed peat surfaces, loss of key species, and changes to the natural functioning of these ecosystems. The upper layers of peat are important zones for the movement of water and biological activity (Ingram, 1978, Limpens et al., 2008). Hence, disturbances to the peat surface and upper peat layer may affect flow pathways, impacting on water quality and the cycling of carbon. Deeper water tables can enhance peat decomposition, leading to an increase in the release of carbon dioxide (CO_2) (Strack and Waddington, 2007, Chivers et al., 2009), and upon rewetting, dissolved organic carbon (DOC) (Worrall et al., 2007b, Strack et al., 2008). However, deeper water tables can also reduce methane (CH_4) release (Moore and Roulet, 1993). Consequently, the management of peatlands can result in conflict between the use and economic development, and protection and conservation (Joosten, 2016).

1.1.2 Peatlands: The UK Context

Peatlands in the UK are an important resource and support many ecosystem services, including storing approximately 50 % of the UK's soil carbon (Milne and Brown, 1997). Blanket peatlands are the dominant type found in the UK (Baird et al., 2009), accounting for approx. 87 % of peatland cover. Blanket peat forms in locations with a hyperoceanic climate, in waterlogged, reducing environments where rainfall exceeds evapotranspiration (Tallis, 1998, Gallego-Sala and Prentice, 2012). Typically, for blanket peatlands to form, rainfall exceeds 1200 mm per year and the mean temperature of the warmest month is below 15°C (Lindsay et al., 1988). Unique to blanket peatlands are their formation on steep upland slopes (up to 15°) and ridges, a result of the impermeable substrates and climatic conditions which create the waterlogged conditions (Charman, 2002). In the UK, these conditions are primarily found in the north and west (Tallis, 1998). The specific environmental parameters required for development means blanket peatland is highly sensitive to change and disturbances, both natural and anthropogenically driven (Bragg and Tallis, 2001).

Blanket peat formation and functioning is driven by hydrology (Holden, 2005b). Water-table depth is often used as an indicator of blanket peatland health (Bragg and Tallis, 2001), an important control on the balance of accumulation and decomposition and therefore the stability of a peatland (Holden et al., 2004). Intact blanket peatlands are known to have flashy regimes, dominated by high water tables and saturation-excess overland flow. Short and longer term studies on a North Pennine blanket peatland found the water-table to be within 5 cm of the peat surface for more than 75 % of the study periods (Evans et al., 1999, Holden and Burt, 2003b). In addition, the steep slopes that characterise blanket peatlands mean that there is greater potential for hillslope scale topographic controls on hydrological functioning and dominant flow pathways, when compared with other peatland systems (Holden and Burt, 2003c). Hydrological responses in blanket peatlands have also exhibited spatial variation with the ecology. Hydrological processes have been found to differ between *Sphagnum* dominated, *Eriophorum* dominated and bare peat plots (Holden and Burt, 2002b), highlighting the occurrence of feedbacks between vegetation and hydrology in peatlands.

The uplands of the UK have multiple uses and hold economic value (Sotherton et al., 2009). In the past the use has been intensified for agriculture (sheep and cattle grazing), while current uses include: game sports (red grouse and deer); the water industry (sources of potable water); afforestation; peat extraction; military use; recreational activities and wind farm construction

(Tallis, 1998, Done and Muir, 2001, Holden et al., 2007). Disruption to natural processes has occurred as a result of these land management conditions. In an attempt to make peatlands more profitable, use of artificial drainage increased after the second world war with the aim of deepening the water table (Holden et al., 2004). Such a deepening of the water table did not occur on a wide scale, however, and instead resulted in a deeper water table immediately around and predominantly downslope of a drain (Stewart and Lance, 1991, Holden et al., 2011). In addition, alterations to the hydrological regime of small catchments were observed, with faster responses of peak flow to rainfall in drained catchments compared with intact catchments (Conway and Millar, 1960, Holden et al., 2006). Livestock grazing in the uplands has been linked with peat erosion (Evans, 2005), change in vegetation composition (Grant et al., 1985), decrease in carbon stores (Ward et al., 2007) and alterations to the hydrology (Meyles et al., 2006, Clay et al., 2009). Trampling by livestock can also compact the peat however, reducing infiltration and increasing the hydrological connectivity of a hillslope (Zhao, 2008).

1.1.3 Tracks and Peatlands

The many uses of the uplands have led to growing pressure to provide easier access to remote areas of blanket peatlands. Consequently, tracks are an increasingly common feature of peatland environments. Tracks can be constructed where material is added to the peat, or unconstructed, where vehicles drive directly over the peat surface. Different methods are used to construct tracks on peat; in some cases the peat is removed down to the mineral layer and the cavity is backfilled ('Cut and Fill'). A top layer of aggregate is added to create the driving surface (Munro, 2004, SNH, 2013). Depending on the depth of the peat, and the volume of the cavity that is backfilled, this can leave exposed peat faces on either side of the road. This is a common feature when tracks are cut into hillslopes (Munro, 2004, SNH, 2013). In comparison, floating roads are also constructed on peat. Here, the road is constructed upon the peat surface and does not require any excavation. In some cases a geotextile is placed under the aggregate prior to road construction to provide additional strength to the peat surface and spread the weight of the load (Munro and MacCulloch, 2006).

To date, research into the impacts of tracks and roads on peat has been limited and predominantly focused on constructed roads. Road construction has been linked to peat failures in the form of bog bursts and slides (Tomlinson and Gardiner, 1982, Dykes et al., 2008, Long et al., 2011), a result of the unusual geotechnical properties of peat (Hobbs, 1986). Additional observed effects have included: reductions in hydraulic conductivity in the peat surrounding stone tracks (Ruseckas, 1998), and increased compression of peat below road embankments (Van Seters and Price, 2001). Spatial impacts to water-table depth have been recorded in a small number of studies; investigating the impact of a constructed track across a low lying peatland in Japan (5 m a.s.l.) (Umeda et al., 1985) and a heavily damaged patterned peatland in Minnesota, where the track was installed constructed with drainage channels on either side (Bradof, 1992). In both studies the width of the track was > 7 m. Military vehicle manoeuvres on blanket peat in the south of England have resulted in reduced vegetation cover and slow recovery to pre-disturbance conditions (Charman and Pollard, 1995), whilst changes in vegetation composition, runoff characteristics and water chemistry have been found following human trampling on blanket peat (Robroek et al., 2010). There does not appear, however, to have been any long-term monitoring of impacts to blanket peat ecohydrology from driving and track construction.

It has been suggested that constructed tracks could have a similar impact as drainage channels to blanket peat hydrology (Lindsay and Bragg, 2005). Drainage channels on peat, especially where they run parallel to the contour, interrupt the natural flow pathways and redirect water that would have originally reached the downslope side of the drain (Holden et al., 2006). Depending on the nature of construction, tracks not only have the potential to redirect overland and near surface flow, but also to impede throughflow (SNH and FCE, 2010, Pilon, 2015), leading to a potential drying of the downslope side of a track relative to the upslope side.

Constructed aggregate tracks have been used to access peatlands for a long time. In recent years, however, there has been an increase in the installation of plastic mesh tracks for use with low-ground-pressure vehicles. There is debate between moorland users and environmental managers regarding the impacts that tracks can have on blanket peat ecohydrology. Frequently, land owners are required to obtain permission from regulatory bodies to install tracks on peatlands and at present the evidence base is severely lacking. In order to justify planning decisions on the placement of tracks, it is important to understand the impact of tracks on blanket peatlands. Decisions on access in the UK uplands need support, yet maintaining the health of peatlands is paramount as well.

The thesis addresses some of the gaps currently existing in our knowledge of the impact of tracks on blanket peat ecohydrology, studying common track types including constructed aggregate tracks and those created by driving directly over the vegetation and also newer untested tracks, with a particular focus on plastic mesh tracks. The results presented here will enable more informed decision-making for the use of tracks in the UK uplands.

1.2 Research Aim

The **primary** aim of this project was to understand the impact that tracks, constructed and unmade, have on the functioning of blanket peatland hydrology, physical properties and vegetation. This was broken down into four key questions and the rationale for their selection is outlined below.

1.2.1 What Is The Influence Of Track Type?

Track types on blanket peatlands vary by construction method and the vehicles which use them. Constructed stone tracks for use with heavier vehicles have been linked with causing considerable peat compression (Barry et al., 1992). It is possible that tracks created by driving directly on the peat surface could cause similar compression, as has been identified in studies on non-peat soils (e.g. Braunack, 1986a, Hutchings et al., 2002). In previous research, the influence that track type could have on peatland properties and processes has been overlooked, and it is not straightforward to draw comparisons of different track types between existing studies due to differences in experiment set-up or site location. This study will consider the impact of a range of different track types through a regional survey and intensive monitoring at a single site on a long stretch of experimental track laid specifically for the purposes of this project. The intensive monitoring will be focused on the impact of three types of tracks: a plastic mesh suitable for low-ground-pressure vehicle use, an articulated wooden track suitable for 4x4 vehicles and an unsurfaced track.

1.2.2 What Is The Spatial Extent Of The Track Impact?

Disturbances resulting from tracks can extend beyond the immediate track footprint (Robroek et al., 2010). For example, there are anecdotal suggestions that impacts can be observed more than 50 m away from constructed tracks (Dale et al., 2005, Lindsay, 2007). In addition, the steep slopes which characterise peatlands could exacerbate the extent of spatial impacts observed. To date these impacts have not been empirically tested. Unsurfaced tracks are a common feature on blanket peatlands and there has been increasing use of plastic mesh tracks in recent years; however, the spatial impact of these track types also has not yet not been addressed.

1.2.3 Is There A Difference In Impacts At Different Topographic Locations?

There is spatial variability in the hydrology and hydraulic properties of blanket peatlands (Holden et al., 2001, Holden and Burt, 2003a, Holden and Burt, 2003c, Holden, 2005a). It therefore follows that there could be a difference in the extent of impacts at different slope positions. Results are conflicting from track studies on non-peat soils, some find greatest impacts on the steepest slopes (Pickering et al., 2011), whilst others observed that impacts were greatest where the soils were wettest, i.e. runoff collecting areas (Alakukku, 1996a). It is therefore important to cover a range of topographic locations in order to discern whether there is a difference in the magnitude of impact.

1.2.4 What Effect Does Frequency Of Use Of The Track Have?

Access requirements in upland areas vary throughout the year. With particular reference to grouse shooting, the frequency of visits to moorland areas is greatest in the shooting season, from the 12th August through to the end of October. The majority of studies into vehicle use or trampling on non-peat soils found greatest impact on the most frequently used tracks (Braunack, 1986a, Racine and Ahlstrand, 1991, Ahlstrand and Racine, 1993, Alakukku, 1996b, Pickering et al., 2011). Understanding how the frequency of use can impact on the magnitude of impact will aid more informed decision-making as to how and when tracks can be used.

Figure 1.1 illustrates the connectivity between the components of this thesis, outlining how the four key research questions relate to the properties being measured. In addition the potential feedbacks between the properties are also shown.

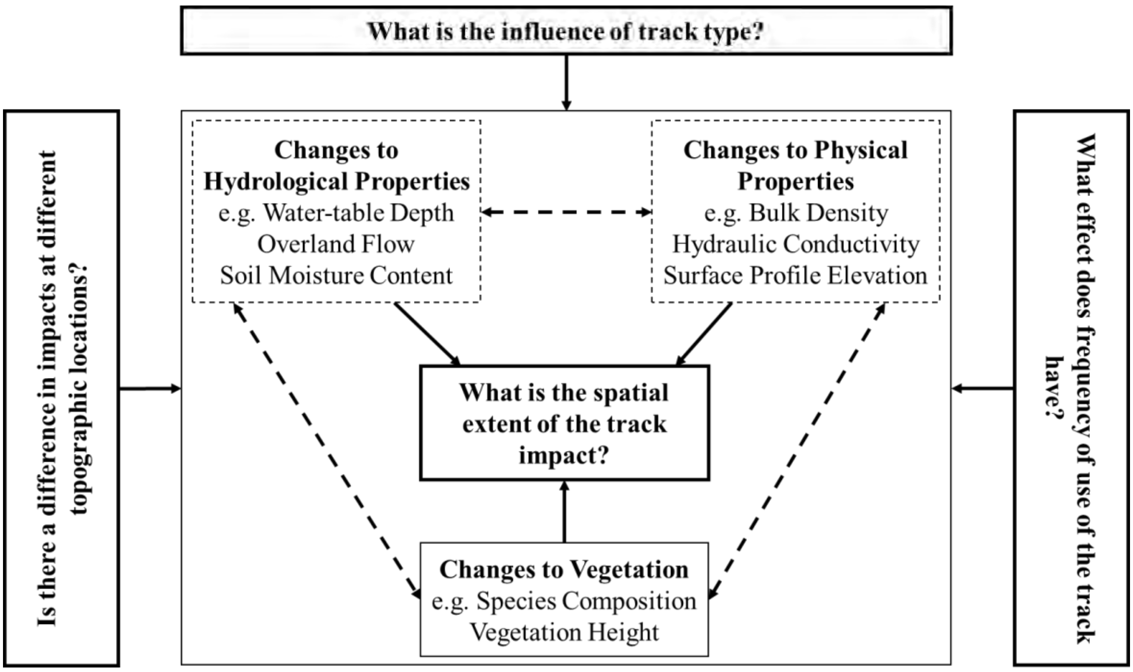

Figure 1.1 Conceptual diagram illustrating the connectivity between the different elements of the research. The research questions to be addressed (bold boxes) and the properties which will be measured in line with existing research in blanket peatland environments (dotted boxes). The potential for feedbacks between properties is highlighted by dotted lines between the boxes.

1.3 Thesis Structure

The purpose of this thesis is to provide an insight into the impact that different types of track under varying frequencies of use and at different topographic locations can have on peatland properties, which in turn impact on the functioning of these systems. This thesis is comprised of eight chapters. A review of the existing literature is presented in Chapter 2 which is split into three main sections. The first section will explore what peat is, how it forms and its functioning, with a particular focus on the hydrology of blanket peatlands. The second section will examine current understanding of the impacts to blanket peatland functioning from disturbances including drainage, to enable us to understand the potential impacts that tracks may have and to place these into a wider disturbance context. The final section will focus specifically on the current knowledge surrounding the impacts of tracks, predominantly in peatland environments but also considering organo-mineral soils. An overview of the methods used in determining the experimental track route and explanation of the site-set-up, in addition to a description of the study sites forms Chapter 3. Chapter's 4 to 7 comprise the results section of the thesis. Each of these chapters contains descriptions of any specific methodologies applicable to data presented in them and a discussion of the findings is also included. A two strand approach was adopted for this project: (i) a regional survey of tracks, and (ii) intensive monitoring of tracks at a single site. The results of the regional survey carried out in the North Pennines and Cheviots are presented in Chapter 4. This provides context for the intensive study which was undertaken on Moor House National Nature Reserve (NNR), in the North Pennines of England. The further three results chapters (5-7) will present results specific to this site. Chapter 5 presents the results of the measurement of 'before and after' impacts to peat properties, including bulk density, peat surface profile and hydraulic conductivity. The results of the routine monitoring of water table (manual and automated recordings) and overland flow will be presented in Chapter 6. The findings of vegetation surveys undertaken before and after driving are presented in Chapter 7. The concluding chapter of the thesis (Chapter 8) comprises a synthesis of the key findings and their implications and also makes recommendations for further work with respect to the impact of tracks on blanket peat ecohydrology.

CHAPTER 2: PEATLAND ECOHYDROLOGY AND THE RESPONSE TO DISTURBANCE

2.1 Understanding Peatlands

2.1.1 The Basics

2.1.1.1 What Is Peat and How Does It Form?

Formed from partially decomposed organic matter (Egglesman et al., 1993, Clymo et al., 1998), peat has low bulk density, high porosity and high water content ranging between 75-98 % by volume (Hobbs, 1986). Peatlands can feature microtopographic variation including drier raised hummocks, and wetter flatter hollows and lawns. The occurrence of these features is influenced by the vegetation composition at the time of peat formation, the associated organic inputs and resultant peat growth, leading to spatial variation and patterning in the peatland (Baird et al., 2016). Further discussion of the variation in peat formation associated with hummocks, hollows and lawns is provided in section 2.1.1.2. Ultimately, for the accumulation of organic matter to occur biomass production must be greater than the rate of decomposition (Clymo, 1984, Charman, 1992). During peatland initiation this balance between production and decomposition is controlled by the decomposition rate and the occurrence of anoxic conditions (low oxygen) where anaerobic decomposition exceeds aerobic decomposition. The creation of such conditions is primarily a function of the hydrological balance, and secondarily temperature and water chemistry (Charman, 2002). Five main factors influence the positive hydrological balance needed for peat initiation, including: (i) climate, (ii) topography, (iii) underlying geology and soils, (iv) biogeography, and (v) human influences (Charman, 2002).

Climate influences the balance between precipitation and evaporation, and therefore the availability of excess water, and is seen as a central factor to peat formation (Clymo, 1984). The initiation of peatland growth in some locations has been attributed solely to shifts in climate creating favourable conditions (e.g. Page et al., 2004). However, the initiation of peat at a particular location is often the result of a combination of some or all of these influential factors (Charman, 2002, Robichaud and Bégin, 2009). Within a landscape there are areas that collect water (basins and valleys) and those which shed water (hillslopes). Areas collecting water are therefore preferential locations for peat formation through the creation of waterlogged conditions (Moore, 1987). In addition to favourable areas in the topography, peat will preferentially form on impermeable substrates where the water loss is slow and a positive water balance can be established.

Feedbacks exist between vegetation and the hydrological balance. Consequently peat may form at a location because of the presence of a particular species, which creates favourable conditions. Some types of species have been found to be more resistant to decay, e.g. selected *Sphagnum* spp., meaning the organic matter is not decomposed as readily (Johnson et al., 1990). If there is a shift in environmental conditions and vegetation is removed or reduced, the hydrological balance of a system can be altered through a reduction in evapotranspiration; in addition, with a shift in climate to wetter conditions, there is potential to create favourable conditions for peat formation. Evidence suggests that an increase in human activity such as burning and deforestation could also have influenced the initiation of peat formation (Moore, 1993, Solem, 1986, Tallis, 1991, Charman, 1992).

2.1.1.2 Peat Growth and Structure

Following initial formation, the subsequent growth and development of a peatland is the result of positive feedbacks which vary across spatial and temporal scales (Belyea and Baird, 2006). Plant material will initially decay in aerobic conditions on the surface, with newer vegetation continuing to grow above this decaying layer. As the vegetation decays the structure of the plant material changes, a result of chemical and biological processes. In addition to this, the weight of the newer vegetation above leads to a collapse of the original structure. The collapse in structure results in an increase in the bulk density of the peat and a decrease in pore space. This in turn reduces the permeability (saturated hydraulic conductivity) of the peat, causing a rise in the level of the water table as both vertical and lateral flow is reduced. The rising water table then covers the decaying organic matter, shifting it from aerobic to anaerobic conditions which then limits further decay (Clymo, 1984). The collapse in peat structure, increase in bulk density and decrease in hydraulic conductivity maintain conditions needed for further peat development.

The pattern of growth is not consistent across a peatland and is influenced by small scale variation in microtopography. Peat formation is lowest in pools and high hummocks, and highest in lawns and low hummocks. Larger scale external forcings also have an influence; such as changes in atmospheric deposition or climate (Belyea and Baird, 2006). In addition to vertical growth, a peatland will also expand laterally (Charman, 2002). The lateral expansion of a peatland is influenced by topography, often determining the rate and direction of expansion (Charman, 2002).

2.1.1.3 The Acrotelm-Catotelm Model

Traditionally, peat has been seen to have a diplotelmic (two layer) structure, comprised of the acrotelm (upper layer) and the catotelm (lower layer). This was first classified by Ivanov in 1953 and further explored by Ingram (1978). Table 2.1 outlines the characteristics typically associated with the two layers. The acrotelm-catotelm model has been used extensively to explain the structure of peatlands and the differences in processes. However, as understanding of peatland functioning and the interactions between the ecology and hydrology of peatlands have developed, limitations of the acrotelm-catotelm model have become apparent (Holden and Burt, 2003b, Belyea and Baird, 2006, Morris et al., 2011, Baird et al., 2016).

Table 2.1 Overview of key characteristics associated with the acrotelm and catotelm

Acrotelm	Catotelm
• Water-table depth fluctuates within the acrotelm, resulting in changes in peat moisture content.	• Permanently saturated with little change in the peat moisture content.
• High hydraulic conductivity and movement of water is fast relative to the catotelm. A gradient of hydraulic conductivity from high to low exists between the surface and deeper in the acrotelm layer.	• Hydraulic conductivity can be three to five orders of magnitude lower than in the acrotelm. Water movement is typically very slow and moves at a constant speed.
• Deeper water-tables allow for air entry into this layer.	• Conditions are anaerobic due to its saturated state.
• High presence of aerobic bacteria and therefore aerobic respiration and faster rates of decay.	• Only anaerobic bacteria are present leading to low microbial activity and low rates of decay.

Ingram (1978) suggested the boundary between the acrotelm and catotelm was at the level of the mean deepest water table below the surface. Other suggestions are that the boundary is at the depth of a rapid change in bulk density (Charman, 2002). As Morris et al. (2011) discuss, differences exist in the depth of these boundaries according to the properties used to classify it. Whilst the use of the current acrotelm-catotelm model allows for general comparison between peatlands, it does not take into consideration the complexity of peatland environments, nor the flexibility needed to accommodate the spatial heterogeneity of properties, such as hydraulic conductivity, in these systems (Morris et al., 2011). Further consideration will be given to the spatial heterogeneity of properties later in this chapter. Morris et al. (2011) therefore suggested a hotspot/coldspot classification approach may be more appropriate to describe and understand the structure of peatlands and distribution of processes occurring within them. Morris et al. (2011) defined hotspots as zones of faster processing with multiple feedbacks between processes, and coldspots as zones where processing is slower and feedbacks may be limited.

2.1.1.4 Peatland Type

Peatlands differ according to their water and nutrient sources and are typically classified as ombrotrophic or minerotrophic (Charman, 2002). Ombrotrophic peatlands are characteristically nutrient poor and acidic, receiving almost all of their water and nutrient inputs from the atmosphere in precipitation; they include raised bogs and blanket peatlands (Bragg and Tallis, 2001, Charman, 2002). In contrast, minerotrophic peatlands receive their water and nutrient inputs from groundwater and surface runoff, originating outside the boundary of the peatland. Fen peatlands are minerotrophic, with their nutrient status ranging from nutrient-poor fens to alkaline, calcium rich fens (Charman, 2002). They can be further categorised as topogenous or soligenous. Topogenous fens form in depressions in the landscape where there are no inlets or outlets. Consequently, water inputs are from groundwater upwelling or runoff from the basin edges. In comparison, soligenous fens are valley peatlands, forming on the lower slopes or valley bottom where there is a dispersed flow of water through them (Charman, 2002).

2.1.1.5 Blanket Peatlands

The research presented in this thesis is located in a blanket peatland environment; consequently a more detailed review of blanket peatland characteristics is provided in this section. Blanket peat forms in hyperoceanic environments, where year round rainfall totals are high and summer temperatures low (Moore, 2002, Gallego-Sala et al., 2010). Due to excess water availability, blanket peatlands are not as restricted by topography for their formation and can form on water shedding sites, i.e. hillslopes (Moore, 1993). Forming on all but the steepest slopes (>15°) (Holden, 2005b), blanket peatlands are unique from other peatland types (Gallego-Sala et al., 2010). Their dependence on high water tables, however, does make them especially sensitive to changes in the hydrological balance, and consequently changes in climate (Ellis and Tallis, 2000).

The initiation of blanket peat formation has been attributed to both a shift in climate to wetter conditions around 8000 BP (Conway, 1954) and, in some places, human activity (Charman, 1992). Contention exists over the dominant influences on blanket peat initiation however, especially in Northern Europe. Paleoecological evidence shows deforestation, grazing and burning could have altered the hydrological balance in addition to a changing climate to create conditions suitable for blanket peat growth, with examples from the UK (Tallis, 1991, Charman, 1992) and Norway (Solem, 1986). Peat initiation on the Faroe Islands, however, pre-dates the first human settlement and does not appear to have been influenced by climate change either (Lawson et al., 2007), suggesting that peat initiation was the result of another process such as paludification.

Blanket peatlands are predominantly found at high latitude, oceanic fringe locations (Charman, 2002). Their global coverage includes the UK, Ireland, Iceland, Norway, Faroe Islands, Nova

Scotia, Quebec, southern Labrador, Newfoundland, Alaska (Pacific coast), Falkland Islands, Patagonia, the Paramos of Ecuador and Colombia, Kamchatka, Hokkaido, New Guinea (high elevations), western Tasmania and New Zealand (Gallego-Sala and Prentice, 2012).

The dominant peatland type in the UK (Gallego-Sala et al., 2010), blanket peatlands account for around 87 % of UK peat cover (Baird et al., 2009). Table 2.2 outlines the extent of blanket peat cover in the UK relative to other peatland types. The table is indicative of present day conditions and it should be noted that a few hundred years ago there were much greater expanses of other peatland types in the UK. However, many of the lowland raised bogs and fens in the UK have been destroyed by agriculture, abstraction and drainage (Darby, 1956). Blanket peat is predominantly found in the north and west of the UK, where rainfall totals are highest (ave. > 1200 mm per year) and summer temperatures are low (highest ave. < 15 °C) resulting in soil moisture excess (Moore, 2002).

Table 2.2 Area coverage of different peatland types in the UK. Data from Baird et al. (2009)

Peatland Type	Area (km^2)	Proportion of UK peat cover (%)
Blanket peatland	15736	87
Upland Raised Bog	862	5
Lowland Raised Bog	60	<1
Fen (all types)	1400	8

2.1.2 Geotechnical Properties of Peat

The geotechnical properties of peat relate to those which influence its engineering suitability and are strongly influenced by peat type i.e. whether it is fibrous (typically less decomposed) or amorphous-granular (typically highly decomposed) (Berry and Poskitt, 1972, Landva and Pheeney, 1980). Peat type can be influenced by the vegetation present at the time of formation and the degree of decomposition (Rezanezhad et al., 2016). Commonly referenced geotechnical properties include moisture content, bulk density, shear strength, permeability (hydraulic conductivity), void ratio and compressibility (Hobbs, 1986, Kazemian et al., 2011). Saturated peat is characterised by high moisture contents by volume, typically 90-98 %. Even in the unsaturated zone above the water table, peat moisture content can be 90-95 % by volume (Holden, 2006).

The bulk density of peat is low, although it does typically increase with depth and degree of decomposition. Boelter (1969) found that fibrous (less decomposed) and sapric (highly decomposed) peats had bulk densities of < 0.075 g cm^{-3} and > 0.195 g cm^{-3} respectively. Between 10 and 40 cm depth Lewis et al. (2012) found bulk density to range between 0.055-0.11 g cm^{-3} in an Irish blanket peatland, whilst Holden and Burt (2002b) recorded bulk densities of 0.15 g cm^{-3} at the surface and 0.27 g cm^{-3} at 50 cm under *Eriophorum* spp. in a North Pennine blanket peatland. Bulk density of peat has also been found to vary temporally with change in peat surface elevation (Price and Schlotzhauer, 1999).

In addition, the peat type can influence the shear and tensile strength of the peat and the way it responds to compressive forces. Fibrous peat has a higher initial shear strength up to a maximum pore pressure than more amorphous peat (Mesri and Ajlouni, 2007, Hendry et al., 2014), due to its maximum friction angle being 40-60°. By comparison, silt and soft clays have a maximum friction angle of < 35° (Mesri and Ajlouni, 2007). The fibres are seen to provide reinforcement to the peat due to their tensile strength (Hobbs, 1986). The compressibility of peat is influenced by the structure and pore arrangement which in turn is influenced by the degree of decomposition. Undecomposed peat found at the surface has more elastic and plastic properties as it is able to expand and contract upon wetting and drying (Rezanezhad et al., 2016). The large pore size and high initial permeability mean more fibrous peats experience high rates of primary compression compared with more decomposed peats which have smaller pore sizes and lower permeability (Barden, 1968). With respect to engineering, peat permeability and hydraulic conductivity are key properties as they control consolidation through the rate of water loss from pore space. The faster the movement of water through the peat, the faster the rate of primary compression (Hobbs, 1986). The impact of construction on peat will be considered further in section 2.3.2.

2.1.3. Hydraulic Conductivity of Peat

The hydraulic conductivity of peat is a function of pore size and alignment, which are influenced by vegetation type during formation (Gnatowski et al., 2010), effective stress and the degree of decomposition, and the hydraulic gradient (Holden and Burt, 2003a). Hydraulic conductivity influences the depth of the water table and zones of active decay and accumulation (Rycroft et al., 1975), ground water flow patterns (Fraser et al., 2001) and dominant runoff pathways (e.g. Holden and Burt, 2003a).

Numerous studies have measured hydraulic conductivity in different peatland types (Table 2.3). With respect to the acrotelm-catotelm model (section 2.1.1.3), peat is split into zones of high (acrotelm) and low (catotelm) hydraulic conductivity (Lindsay et al., 1988). Kettridge et al. (2012) observed that just below the water table (0.3–0.7 m) trapped gas was the primary control on hydraulic conductivity variation, whilst at a greater depth (0.7–1.3 m) change in the relative volume of the peat was the main control. Whilst numerous studies have shown a depth gradient in hydraulic conductivity (Boelter, 1965, Hoag and Price, 1995, Clymo, 2004), there are others that have identified layers of higher hydraulic conductivity at depth due to differences in peat composition (Chason and Siegel, 1986, Beckwith et al., 2003b). This consequently negates the simple acrotelm-catotelm split in hydraulic conductivity.

Table 2.3 Summary of a selection of existing studies measuring hydraulic conductivity. Within the measurement method column, MCM refers to Modified Cube Method.

Reference	Peatland Type	Sampling Depth (m)	Measurement Method	K (cm s^{-1})
Boelter (1965)	Raised	0 – 0.6	Piezometer	7.5*10-4 - 3.8*10-2
Chason & Siegel (1986)	Raised	0.5 – 3.0	Piezometer & MCM	10^{-3} (Field) 10^{-5} -10^{-2} (Lab)
Baird (1997)	Valley Fen	Surface	Tension Disk Infiltrometer	4.1*10^{-4}
Schlotzhauer & Price (1999)	Cut Over	0.1 – 0.8	Piezometer	2.9*10^{-6}
Baird & Gaffney (2000)	Drained Fen	0 - 1.3	Piezometer	3.7*10^{-4}
Fraser et al. (2001)	Raised	0 – 0.45	Piezometer	10^{-8}– 10^{-3}
Beckwith et al. (2003a)	Raised	0 - 1.5	MCM	5.0*10^{-4} - 7.0*10^{-3}
Holden & Burt (2003a)	Blanket	0.1 – 0.8	Piezometer	10^{-7} - 10^{-5}
Baird et al. (2004)	Fen	0.45	Piezometer	1.4*10^{-3} - 3.0*10^{-2}
Clymo (2004)	Raised	0.1 – 7.0	Piezometer	7.0*10^{-7} - 5.0*10^{-6}
Surridge et al. (2005)	Fen	0 – 1.0	Piezometer & MCM	1.6*10^{-3} – 1.0*10^{-4}
Hogan et al. (2006)	Fen	0 – 2.0	Piezometer	10^{-6} – 10^{-3}
Baird et al. (2008)	Raised	0 – 4.0	Piezometer	9.6*10^{-5} - 1.4*10^{-2}
Price et al. (2008)	Raised	0 – 0.05	Tension Disk Infiltrometer	2.4*10^{-2} – 1.8*10^{-1}
Rosa and Larocque (2008)	Fen	0.5 – 2.5	Piezometer & MCM	1.2*10^{-5} – 6.9*10^{-3}
Lewis et al. (2012)	Blanket	0.1 – 0.4	MCM	10^{-4} – 10^{-2}
Cunliffe et al. (2013)	Blanket	0.04 – 0.5	MCM	3.0*10^{-6} – 1.4
Branham & Strack (2014)	Maritime Bog & Fen	0.03 – 0.08 & 0.20	MCM	9.2*10^{-2} – 1.2
Morris et al. (2015)	Raised	0 – 0.5	MCM	7.2*10^{-6} – 2.7*10^{-2}

Furthermore, studies have also identified spatial variation in hydraulic conductivity within a peatland in relation to vegetation type and thus pore structure (Holden et al., 2001), peat microforms, e.g. hummocks versus hollows (Waddington and Roulet, 1997, Branham and Strack, 2014, Baird et al., 2016), and location within raised bogs and blanket peatlands, i.e. centre versus margin (Lapen et al., 2005, Baird et al., 2008, Lewis et al., 2012). When based on a limited number of sampling points, there is the potential for generalised conclusions of catchment scale hydraulic conductivity to be drawn, a result of not capturing the spatial variability in this property (Holden and Burt, 2003a). Spatial variation of hydraulic conductivity also has implications for how a peatland may respond to disturbance (see section 2.2.2).

Peat is anisotropic, meaning that properties such as hydraulic conductivity are not uniform in all directions (Beckwith et al., 2003b). This can have implications for the direction and volume of flow through peat (Baird et al., 1997, Holden, 2009b, Kazemian et al., 2011). A number of studies have observed positive anisotropy in peat where horizontal flow was several orders of magnitude faster than vertical flow (Boelter, 1965, Chason and Siegel, 1986, Hobbs, 1986, Beckwith et al., 2003b, Rosa and Larocque, 2008, Lewis et al., 2012, Cunliffe et al., 2013). A natural laminar structure has been observed in peat (M. Waddington, *pers. comm.*), especially fibrous peats, thought to be caused by the effective pressure from newer peat accumulating over older peat (Hendry et al., 2014). Branham and Strack (2014) observed a depth effect with a shift from negative (vertical flow faster than horizontal flow) anisotropy at the surface to positive anisotropy at depth. A climatic effect was also identified with positive anisotropy more prevalent in wetter maritime climates and negative anisotropy linked with drier continental climates.

The method used to measure hydraulic conductivity can influence the accuracy of the results. Both field and laboratory methods have been utilised and examples are illustrated in Table 2.3. In the field, piezometers and tension disk infiltrometers are traditional methods, however, these cannot always capture the anisotropy. In addition, the Hvorslev calculation of hydraulic conductivity is based on incompressible, isotopic, homogenous soils, characteristics which peat does not have (Rosa and Larocque, 2008). As a result, within blanket peat, the use of piezometers in measuring hydraulic conductivity have yielded values which are too high (Holden and Burt, 2003a). Furthermore, during installation the clogging of pores around a piezometer and piezometer intakes can affect flow (Baird et al., 2004), as can the volume of the slug inserted or removed from the piezometer (Rosa and Larocque, 2008).

Laboratory methods such as the modified cube method (MCM), developed by Beckwith et al. (2003a), can address the issue of anisotropy in peat by allowing measurements in the horizontal and vertical (Kruse et al., 2008, Lewis et al., 2012). However laboratory methods can be criticised for not taking into account the natural heterogeneity of peat systems. Caution is recommended in the use of the MCM and slug tests in surface peat with a high porosity (Rosa and Larocque, 2008).

2.1.3.1 Hydraulic Conductivity in Blanket Peatlands

Despite many studies examining the hydraulic conductivity of peatland environments, those specific to blanket peatlands are still limited (e.g. Holden and Burt, 2003a, Lewis et al., 2012, Cunliffe et al., 2013). The zone of high hydraulic conductivity in blanket peat is restricted to near the surface. Hoag and Price (1995) recorded values of 1.6 cm s^{-1} within the acrotelm, whilst at a depth of 0.5 m, the hydraulic conductivity had reduced to 1.0×10^{-7} cm s^{-1}. In a North Pennine blanket peatland, the zone of high hydraulic conductivity was restricted to the top 0–10 cm of the peat profile (Holden and Burt, 2003c), predominantly the top 5cm (Holden et al., 2001). Below

10 cm depth, hydraulic conductivity showed little vertical variation; however spatial variation was observed (Holden and Burt, 2003a).

Lewis et al. (2012) observed spatial variation in an Irish blanket peatland with lower hydraulic conductivity at the peatland margin in the riparian zone compared with centre of the peatland. A similar observation was made by Lapen et al. (2005) in a Newfoundland blanket peatland. At the small scale, Cunliffe et al. (2013) recorded large variation in hydraulic conductivity around a single peat pipe (section 2.1.5.3), with clear evidence of anisotropy that differed with the orientation of measurement relative to the pipe. The findings from this study further suggest that 'hot-spot' zones within a peatland exist, therefore assumptions of homogenous properties and processes in the catotelm are not applicable.

2.1.4 Hillslope Hydrology

Water can move through multiple pathways within a typical hillslope. As overland flow, water travels over the surface, a result of (i) infiltration-excess overland flow, where water input rate > infiltration rate, or (ii) saturation-excess overland flow, where the water table resides at or near the soil surface meaning water is unable to percolate down and instead flows over or re-emerges at the surface (Burt, 2001, Holden, 2009c). The chemistry of the water can be indicative of the relative proportions of overland flow by the different pathways. Infiltration-excess overland flow will have had little interaction with the soil matrix and therefore the chemistry of it will be similar to the rainwater. In contrast to this, saturation-excess overland flow (return flow) will include water re-emerging from the soil matrix where solutes may have been leached (Burt, 1986).

The movement of water through a hillslope as throughflow can occur in three ways: (i) matrix flow, (ii) macropore flow, and (iii) pipe flow. These different flow pathways within any given soil will allow water to travel at different speeds. Matrix flow is usually the slowest flow pathway as water moves through the smallest pores before reaching the stream. It has been found, however, that macropore flow, which may be the result of burrowing animals, root growth , cracking of soils or chemical/physical erosion of soil material, can transport water very quickly through the soil profile and into the stream (Holden, 2005c). Macropores are pores within the soil greater than 0.1 mm in diameter (equating to negative soil water tension of 3 cm) whilst soil pipes, which have been found in most environments, can range up to several metres in diameter (Holden, 2005c, Holden, 2009c).

2.1.5 Hydrological Properties of Blanket Peatlands

The hydrology of a peatland is central to its formation and functioning (Holden, 2005b). Although some characteristics are similar between peatlands, such as shallow water tables for most of the year (Holden, 2005b), which maintain the anaerobic conditions required for peat accumulation, differences exist in the inflows and outflows which influence the hydrological regimes of a peatland (Rydin and Jeglum, 2006). Furthermore, as has been outlined in section 2.1.3 the hydraulic conductivity of peat varies between peatland types.

Whilst ombrotrophic peatlands only receive their inputs from precipitation, minerotrophic peatlands receive inputs from groundwater and surface flow, in addition to precipitation (Charman, 2002). In the case of minerotrophic peatlands, the water moves through the peatlands from inlet to outlet, by contrast ombrotrophic peats tend to be water shedding (Damman, 1986). Peatlands are large stores of water, however, baseflow from them throughout the year tends to be minimal (Holden, 2006). There are exceptions, where the peatland is connected through groundwater sources to the wider hydrological system (Roulet, 1990).

This section will primarily focus on the hydrological properties of blanket peat. There are many similarities between ombrotrophic bogs in general and blanket peatlands, such as flashy hydrological regimes (Holden, 2006) and dominant water loss through surface runoff (Price, 1992). Following water-table drawdown during dry periods, however, groundwater flow patterns in other ombrotrophic peatlands have been found to alter, so that water from deeper in the peat profile, or from deeper groundwater sources, 'recharge' the peat nearer the surface (Branfireun and Roulet, 1998, Fraser et al., 2001). Waddington and Roulet (1997) suggested that in some ombrotrophic peatlands viewing overland flow as the dominant outflow is unsuitable and groundwater flux should also be taken into consideration. Furthermore, peatlands which contain permafrost show different runoff pathways depending on the depth of thaw and generate large quantities of surface runoff during the spring snow-melt period and late-summer rain events (Quinton and Hayashi, 2005, Quinton et al., 2009).

2.1.5.1 Hydrological Regime and Water Table

Blanket peatlands are hydrologically detached from the surrounding catchment; with almost all water inputs from precipitation. A common misconception is that blanket peatlands act as a reservoir storing water and can sustain stream flow during drier periods in the year (Holden, 2006). The response of blanket peatlands to rainfall is rapid and a blanket peatland stream hydrograph is characterised by a steep rising and recession limb and minimal baseflow (Price, 1992, Evans et al., 1999). The hydrological regime of blanket peatlands has consequently been termed 'flashy', with high peak flows and discontinuous flow in the summer (Price, 1992, Evans et al., 1999, Holden and Burt, 2003c).

Shallow water tables are a common feature of blanket peatlands. Records from a North Pennine blanket peatland showed the water table to be within 5 cm of the surface for 83 % of the time during a three year study (Evans et al., 1999). Furthermore, on a blanket peatland in Upper Wharfedale the water table was within 10 cm of the peat surface for 75 % of the time between January and June 2004, with a maximum depth of 25 cm recorded over the whole study period (December 2002-2004) (Holden, 2006). Subsequent studies at the same peatland recorded the water table at the peat surface for 18 % of the study period (January 2005 – June 2006) (Holden et al., 2011).

Water-table depth exhibits temporal variation, both diurnally and seasonally. Diurnal variation is clearly observed when the water table is below 5 cm in the peat profile and water-table depth is primarily controlled by evapotranspiration (Evans et al., 1999). Blanket peatlands tend to be fully saturated during winter months (Holden, 2005b, Holden et al., 2011), related to the typically higher levels of rainfall experienced during these months which maintain the water table at the surface, and lower evapotranspiration. During warmer (drier) summer months (May, June, July) the water table can drop to depths > 20 cm, as has been observed in Upper Wharfedale (Holden et al., 2011). In a North Pennine peatland the maximum depth was 42 cm below the surface (Evans et al., 1999). Following rainfall, water table recovery to near the surface is rapid, even during the summer months (Evans et al., 1999, Holden et al., 2011). Water table in a blanket peatland also exhibits spatial variation; this is in part related to topography, which will be discussed further in section 2.1.6.

Clear links exist between water-table depth and the hydrological regime of blanket peat covered catchments (Evans et al., 1999). The ‘flashy’ regime can be attributed to the shallow water tables which limit the infiltration of water into the peat and therefore promote saturation-excess overland flow (section 2.1.5.2) (Evans et al., 1999, Holden and Burt, 2003c). Furthermore, shallow water tables reside in the zone of high hydraulic conductivity (section 2.1.3.1) allowing rapid sub-surface runoff to peatland streams (Price, 1992, Holden and Burt, 2003c). Evans et al. (1999) observed the greatest variation in runoff production when the water table was within 5 cm of the surface and attributed it to variability in the rainfall characteristics, as opposed to the water storage potential of the peat. It is apparent therefore that disturbances to a peatland which alter the water-table depth can have implications for the wider functioning of the system (section 2.2.3).

2.1.5.2 Runoff Pathways

Price (1992) showed runoff to be the dominant pathway for water loss from a Newfoundland blanket peatland when compared with evaporation. Saturation-excess overland flow and near-surface flow rapidly develop in peatlands following rainfall due to the frequently shallow water tables (< 10 cm) (Evans et al., 1999, Holden and Burt, 2003b, Holden et al., 2011), and the lower hydraulic conductivity of peat below 10 cm (Holden and Burt, 2003c). Surface flow accounted for 81 % of runoff from a North Pennine blanket peatland, whilst a further 17 % of flow came from the top 1 – 5 cm of the peat (Holden and Burt, 2003b). In addition, Wallage and Holden (2011) found 74 % of near-surface flow occurred through macropores (> 1mm in diameter). Overland flow has been found to occur following low intensity rainfall (Holden and Burt, 2002b) and Evans et al. (1999) observed no occurrences of high stream discharge with low water tables in their three year study. Both these situations are therefore indicative of saturation-excess overland flow production rather than infiltration-excess overland flow production in blanket peatlands.

Highly variable vertical and horizontal hydraulic conductivities, large supplies of available water, and the development of desiccation cracks are found in peatlands and can result in the formation of macropore and pipe networks (Holden and Burt, 2003c). Despite little runoff being produced below 10 cm, networks of macropores can create preferential flow routes, transporting water from hillslope to stream rapidly (Jones, 1997, Holden et al., 2001) and are important runoff pathways. Results from shallow peat, found pipes contributed 50 % of streamflow (Holden, 2009c) and in a blanket peatland, macropores were found to account for 35 % of the runoff whilst 10 % of flow was through pipes in the deep peat (Holden and Burt, 2002c).

According to Price (1992) and Evans et al. (1999) baseflow in blanket peatlands is minimal. However, more recent work has suggested pipes could maintain flow for longer than other runoff pathways, contributing to baseflow (Holden and Burt, 2002c) and potentially limiting the ‘flashiness’ of the river regime (Smart et al., 2013). Within blanket peatlands, pipe networks are complex (Billett et al., 2012), sometimes including inactive or discontinuous pipes (Holden, 2004) and showing differences in pipe connectivity depending on the height of the water table and volume of discharge (Dinsmore et al., 2011). Over a 33 month study period Holden et al. (2012b) found that 85 % of studied pipe outlets changed their morphology through an increase or decrease in diameter. By comparison, pipe networks in permafrost peatlands are more linear features, ordered in a downstream direction (Carey and Woo, 2000).

The presence of macropore and pipe networks in peatlands further supports the argument that the current acrotelm-catotelm model is unsuitable for explaining peat hydrology (section 2.1.2). Not only do they provide connectivity between shallower and deeper layers of peat (Smart et al., 2013), they may also be conduits of much higher hydraulic conductivity in zones typically considered to have low conductivity (Holden and Burt, 2003b). Increased connectivity has the potential to alter the role of deep peat as a carbon store, with evidence suggesting a change in hydrological conditions could release CO_2 from deep peat (Billett et al., 2012, Holden et al., 2012c). Whilst early studies of macropore and pipe networks highlighted the significance of their role for runoff from blanket peat, recent studies have potentially made a larger contribution to understanding peat hydrology, especially in blanket peatlands. Changes to pipe outlet morphology have shown that these systems are dynamic. Changes to internal morphology could have implications for their role in peat hydrology and therefore the overall functioning of peatland systems.

2.1.6 The Influence of Topography in Blanket Peatlands

Blanket peatlands exist independently from topographic controls due to the unique climatic conditions which permit their formation (section 2.1.1.5). In contrast with other peatland types, blanket peatlands cover both flat areas and steeper slopes (< 15°). Peat depth varies with topographic position (Parry et al., 2012), shallower peats have been measured on slopes and deeper peats in flatter locations within a blanket peatland (Hobbs, 1986). Variation in peat properties and functioning is probable with topographic variation in peat formation.

Few studies have given detailed consideration to properties such as bulk density and hydraulic conductivity at specific topographic positions (e.g. top-slope, mid-slope, bottom-slope) within a blanket peatland. Holden (2005a) observed greater heterogeneity in hydraulic conductivity and bulk density with depth at top- and bottom- slope locations compared with the mid-slope. In addition, the formation of peat pipes was more likely in top-slope locations due to the greater variation in hydraulic conductivity. From this study, Holden (2005a) proposed that the underlying topography influenced the type of peat which accumulated over time, with more variation in top- and bottom-slope locations due to greater microtopographic variation including hummocks and hollows. Whilst Lewis et al. (2012) observed an increase in bulk density and a decrease in hydraulic conductivity from the centre of a blanket peatland to the peatland margin, it was not clear from this study at what distance the topographic locations could be labelled, top- mid- and bottom-slope. In this instance the measurements were only taken from 10-20 cm and 30-40 cm depths in the peat profile.

Topography influences water-table depth, with shallowest water tables typically found in bottom-slope locations and deepest water tables in mid-slope locations (Holden, 2009b). This will, in part, be influenced by the structure of the peat at the specific topographic locations. Section 2.1.4 outlined the principles of hillslope hydrology. Similar spatial variation in the dominant hydrological pathways has been observed in blanket peatlands (Holden and Burt, 2003c). This is linked to the level of saturation of the peat (water-table depth) and therefore whether saturation-excess overland flow or sub-surface flow occurs. Bottom-slope locations produce saturation-excess overland flow for a longer duration than top-slope or mid-slope locations as the water draining from these topographic locations converge in the bottom-slope. Near-surface flow preferentially occurs in mid-slope locations and can be linked to the deeper water table at this location (Holden and Burt, 2003c). In addition, temporal variation has been observed in the contributing areas to runoff production on a hillslope with time since a rainfall event (Holden and Burt, 2003b).

Given the topographic variation in processes and properties within an undisturbed blanket peatland the magnitude of response of a peatland to disturbance is likely to be influenced by the topographic position. This is an important consideration for this thesis.

2.1.7 The Role of Vegetation in Peatlands

The distribution of vegetation between and within peatlands is influenced by their hydrological and chemical properties including pH, nutrient availability, C/N ratio, water-table depth and variation, peat depth and slope (Malmer, 1986, Cooper et al., 1997, Bubier et al., 2006, Breeuwer et al., 2009, Sottocornola et al., 2008, Andersen et al., 2011). Consequently, the vegetation composition of fen peatlands can differ greatly from blanket peatlands. In addition, some peatlands are naturally forested, whilst others are characterised by low shrub like vegetation.

The present day vegetation cover on the peatland surface has an influence on the carbon dioxide (CO_2) uptake of the peat (Laine et al., 2007) and some vegetation types can also influence the release of methane (CH_4) (Bubier, 1995). Therefore, vegetation cover impacts on the wider scale role of the peatland in the global carbon cycle (section 2.1.8). Spatial variation exists in the surface vegetation composition of a peatland and this therefore leads to spatial variation in the gas flux concentrations. Vegetation composition has also been found to influence the chemistry of runoff water from peatlands, for example, the concentration of dissolved organic carbon in the water (DOC) (Armstrong et al., 2012, Parry et al., 2015).

Numerous feedbacks exist between peatlands and their vegetation. During the initial formation of peat the vegetation present influences the structure of the peat that forms, which in turn influences the hydrological processes which lead to the further development of the peatland (Charman, 2002). As a peatland develops and the flow pathways alter within it, this can lead to changes in water sources and therefore nutrient inputs. Changes in vegetation composition of a peatland have been especially evidenced in the minerotrophic fen to ombrotrophic bog transition (Charman, 2002). Over time, the vegetation composition of peatlands can also shift as a result of climate change (Ellis and Tallis, 2000). As has been noted in sections 2.1.1, 2.1.2 and 2.1.3, the structure of the peat is important for its continued development. Vegetation therefore plays a key role in the way in which a peatland grows.

Direct and indirect feedbacks exist between peatland vegetation and hydrology. Directly, the type of vegetation cover influences the magnitude of evapotranspiration from a peatland, which in turn influences the depth of the water table (Waddington et al., 2015). The depth of the water table however, can influence the vegetation composition at the surface as some species prefer wetter or drier conditions (e.g. Laine et al., 2007). The presence of vegetation on the peat surface and its composition can also regulate whether overland flow occurs, influencing the volume of runoff (Grayson et al., 2010) and the velocity of runoff (Holden et al., 2008). Within a blanket peatland, water-table depth is the main control on species distribution (Cooper et al., 1997, Sottocornola et al., 2008). Microtopography can result in spatial variation in peat hydrology due to the differences in vegetation found on the differing microtopographic features (Waddington et al., 2010).

Indirectly, the vegetation composition influences the structure of the peat during growth. This in turn has an influence on pore size and orientation (section 2.1.3) and therefore rate of water flow through the peat. Within a blanket peatland setting, difference in the dominant vegetation type at the surface has been found to influence dominant flow pathways at depth. For example, where *Eriophorum vaginatum* was present on the peat surface, flow was rapid through the top 5cm of the peat profile, but below this depth there was reduced lateral water movement. In addition, under *Eriophorum*-covered peat the volume of runoff from the surface and 1-5 cm depth was the same (Holden and Burt, 2003b). Peat under *Sphagnum* had a higher proportion of macropore flow (Holden et al., 2001). *Sphagnum* and bare peat have been found to have different hydraulic properties compared with *Eriophorum* and *Calluna* peats (Boelter, 1965, Holden, 2009a). When considering the functioning of peatlands, it is therefore important to consider feedbacks that exist with vegetation.

2.1.8 Peatlands and the Carbon Cycle

Peatlands are seen as regulators of the global climate (Joosten and Clarke, 2002), although there is uncertainty in their role. Peatlands influence the global climate by sequestering atmospheric CO_2 in the living vegetation and dead biomass (Baird et al., 2013), and current estimates suggest that it is the biggest terrestrial store of carbon (Yu, 2012). Peatlands also release carbon as CO_2 through the aerobic decay of organic matter and CH_4 through anaerobic decay processes. Peatlands are the largest natural terrestrial source of atmospheric CH_4 (Baird et al., 2013). Carbon can also be lost from peat as dissolved organic carbon (DOC), another product of the decomposition of organic matter (Limpens et al., 2008) and particulate organic matter (POC), a result of the erosion of peat (Grayson et al., 2012). Currently, peatlands are sinks for CO_2 and sources of CH_4 (Baird et al., 2013), however, this may alter with a changing climate and land-use change in peatlands (section 2.2).

The main controls that influence the peat carbon cycle include vegetation composition, temperature, water-table depth and peat chemistry (Holden, 2005b). Variation in the size of carbon flux exists between peatland type: emissions of CH_4 from fens is higher than other peatlands as the zones for anaerobic respiration are often close to the surface in most peatlands

(Holden, 2005b). Within peatlands spatial variation exists in carbon fluxes. Spatial variation of water-table depth has been found to influence the flux of CH_4 (e.g. Moore and Roulet, 1993), and DOC release (e.g. Boothroyd et al., 2015). Some studies have shown evidence of a relationship between water-table depth and CO_2 flux (e.g. Juszczak et al. 2013), whilst others have not (e.g. Lafleur et al., 2005). Linked with variation in water-table depth, Strack et al. (2006) observed variation with microtopography, with hollows and lawns acting as CO_2 sinks and hummocks swapping between sources and sinks of CO_2 in a fen peatland. In addition, spatial variation in vegetation composition has yielded differences in fluxes (section 2.1.7). The size of flux has also been found to vary temporally, with diurnal and seasonal fluctuations (e.g. Waddington and Roulet, 1997, Lafleur et al., 2005, Strack et al., 2006, Koehler et al., 2009)

Whilst peatlands are currently seen as a store of carbon, perturbations through a changing climate have the potential to disturb the size of current flux (Belyea and Malmer, 2004, Bridgham et al., 2008, Limpens et al., 2008).

2.2 Disturbances to Peatlands

2.2.1 What are the disturbances?

Peatlands around the world have been subject to a range of anthropogenically driven disturbances to their functioning, which may result in impacts to the structure of the peat (section 2.2.2), hydrological properties (section 2.2.3) or vegetation composition (section 2.2.4). All peatlands will be considered, although the primary focus will be on disturbances to blanket peatlands.

Often peatlands are not subjected to a single disturbance. For example, drainage has been used in many peatlands as a method of land preparation for activities which could further disturb the peat system. These include peat cutting and harvesting (Cooper and McCann, 1995, Price, 1997, Van Seters and Price, 2001), afforestation (Minkkinen and Laine, 1998, Anderson et al., 2000, Wellock et al., 2011), agriculture (McLay et al., 1992), and construction on peat (Lindsay and Bragg, 2005, Grieve and Gilvear, 2008). In addition, peatlands have also been subjected to prescribed burning (Holden et al., 2007), grazing (Pellerin et al., 2006, Oom et al., 2008) and disruption through the laying of pipelines and powerlines (Lee and Boutin, 2006, Williams et al., 2013, Braverman and Quinton, 2016). Variation exists in the areal coverage of disturbances. Whilst some occur in patches (of varying size), e.g. peat extraction, afforestation, burning and grazing, others can be viewed as more linear disturbances, e.g. drainage channels and the installation of powerlines.

Disturbances to peatland functioning can also be naturally driven, such as a changing climate. Predicted changes in temperature and rainfall (IPCC, 2014), have potential implications for the ecology and hydrology of peatlands, with particular respect to rates of production and decomposition (Ise et al., 2008) and the hydrological regime (Whittington and Price, 2006). Furthermore, changes to the ecohydrological functioning of peatlands have the potential to alter their role within the global carbon cycle (section 2.1.8). The current global distribution of peatlands is also influenced by climate (section 2.1.1) and therefore changes to the climate may not only impact the functioning of individual peatlands but also their distribution (Gallego-Sala et al., 2010). Peatlands which have already been disturbed through other uses will already be more sensitive, further disturbance by a changing climate has the potential to exacerbate these impacts.

2.2.2 Disturbances to Peat Structure and Geotechnical Properties

The structure and geotechnical properties of undisturbed peat are outlined in section 2.1.2. Changes to peat structure are typically associated with compression triggered by an increase in vertical stress in the peat. Triggers can include mechanical loading (i.e. additional weight at the peat surface) or an increase in the effective pressure exerted by the peat itself. The compression of peat is related to the way in which water is held in the peat and how it is expelled. Water is held in peat in three forms; (i) intracellular (held at pressure < -10 kPa), (ii) interparticle (held at pressures > -10 kPa) and (iii) adsorbed (held at pressures > -20 kPa) (Hobbs, 1986). Intracellular water will drain freely under gravity, and forms intracellular and interparticle water will be expelled when pressure is placed on the peat. Most water in peat is held in intracellular and interparticle forms (Hobbs, 1986).

Changes to peat structure can be exhibited as changes in pore orientation, reductions in void space, increases in bulk density, and reductions in hydraulic conductivity (Hobbs, 1986). Three stages of compression and volume change in peat have been identified: normal compression, where volume change is equal to the volume of water lost from pores, residual shrinkage, where air enters the soil, and normal shrinkage, which is related to the contraction of the matrix resulting from water tension in the soil (McLay et al., 1992, Price and Schlotzhauer, 1999).

Mechanical loading can occur through construction of embankments, vehicle movements over the peat surface or human and animal trampling. This results in an increase in vertical stress and expulsion of intracellular and interparticle water leading to compression (Lefebvre et al., 1984). The effect of mechanical loading will be considered in more detail in section 2.3.2, with respect to the construction of embankments and tracks on peat. Trampling by livestock has been addressed in grazing and burning studies and will be considered further on in this section.

2.2.2.1 Drainage

Peatland drainage can result in the water table becoming deeper (section 2.2.3.1). This can result in a loss of water from the pore spaces (intracellular water) and entry of air, in the surface peat especially. This has a two-fold effect: (i) water in the pore space provides support to the peat structure, therefore support is lost on the loss of water leading to potential collapse of the structure upon air entry (Lefebvre et al., 1984, Schlotzhauer and Price, 1999); (ii) the entry of air into the pore space can result in the occurrence of aerobic decomposition and the further structural collapse (Price and Schlotzhauer, 1999). In both cases this leads to an increase in the vertical stress on the peat and compression.

Within drained peatlands, lower surface elevations have been observed associated with afforestation (Anderson et al., 2000). In addition, increases in bulk density, especially in the surface peat have been observed. The response of a peatland to disturbance may vary between peatland types. Following eight years of drainage of a fen peatland bulk density was higher between 0 and 60 cm in the drained peat relative to the undrained peat, 0.144 g cm^{-3} and 0.083 g cm^{-3} respectively (Whittington and Price, 2006). By comparison, no significant difference was observed in the average bulk density (0 – 40 cm) between drained (40+ years) and undisturbed blanket peat, although the drained peat was more homogenous and at 5 cm depth a restored peatland had significantly lower bulk density than the drained peatland (Holden et al., 2011, Wallage and Holden, 2011). This suggests there may have been some compaction of the peat following drainage, and evidence of recovery after restoration.

Drainage and afforestation of boreal peatlands in Canada resulted in mean bulk densities 45-50 % higher than those in comparable undrained peatlands, although mean bulk density did show temporal variation (Rothwell et al., 1996). It does not always follow that drainage will lead to an increase in bulk density, however. In three different forested and drained peatlands in Ireland (raised bog, high and low level blanket peatland) bulk density values were within a range of non-forested peatlands (Wellock et al., 2011). Variation was observed with depth, however, with higher bulk density in the surface 20 cm compared with deeper in the peat profile, in line with other studies.

Increases in bulk density following drainage are often accompanied with decreases in hydraulic conductivity (Rothwell et al., 1996, Silins and Rothwell, 1998), resulting from a reduction in large pore spaces, and often an increase in smaller pore space (Silins and Rothwell, 1998). This occurrence is not always the case, however. A significant difference was not observed between mean near-surface hydraulic conductivity for undisturbed and drained blanket peatlands in the UK (Wallage and Holden, 2011). A significant difference with depth is possible, although was not considered in the Wallage and Holden (2011) study. A significant difference was observed between blanket peat with blocked and unblocked drains. An increased occurrence of macropores and pipes in blanket peat has also been observed following drainage (Holden et al., 2006), highlighting further change in peat structure. Further consideration will be given to the role of macropores in section 2.2.3.2

Structural changes following disturbance can also be exhibited through pore orientation. In some peats, especially those which are more fibrous, mechanical compression has been found to enhance the laminar structure of peat, with fibres and pores becoming predominantly orientated in the horizontal (Landva and Pheeney, 1980, Mesri and Ajlouni, 2007, O'Kelly and Pichan, 2013, Rezanezhad et al., 2016). There appear to be few studies which have considered how this alteration in peat structure and increase in anisotropy following mechanical compression of peat could alter the hydraulic conductivity and therefore the implications for the hydrological regime of disturbed peatlands.

2.2.2.2 Landslides

Landslides in blanket peatlands have been attributed to their inherent instability (a result of their topography and hydrology) combined with intense rainfall (Dykes and Warburton, 2008, Dykes et al., 2008). Although evidence is not conclusive, drainage, peat cutting (harvesting) and road construction have potentially exacerbated the instability leading to failure (Dykes and Jennings, 2011, Long et al., 2011). Instability is often the result of a reduction in peat shear and tensile strength, which can be related to changes in pore water pressure and hydrological flow pathways moving water through the peat (Dykes and Warburton, 2008). As has been discussed above, these changes can result from alterations to the structure of the peat.

2.2.2.3 Burning and Grazing

Prescribed burning also has the potential to alter the structure of peat. Changes in vegetation cover following burning (section 2.2.4) could affect peat structure in two main ways: (i) in the short term through changes in root networks as new vegetation grows (Clay et al., 2009) and (ii) in the long term through new peat formation (section 2.1.7). On a North Pennine blanket peatland, Worrall and Adamson (2008) suggested a change in soil water chemical composition could be indicative of a change in soil structure following burning and grazing, however, the results were not conclusive. In more recent work Holden et al. (2014) found that even following burning, macropore flow remained an important flow pathway in near-surface blanket peat. The proportion of flow through macropores was lower in more recently burnt sites compared with older burn (15+ years) and undisturbed sites, however. In addition, the near surface hydraulic conductivity was significantly lower in the more recently burnt plots compared with the older and undisturbed plots. Collapse of pores in the more recently burned plots and recovery with time since burn have been suggested as reasons for this difference.

2.2.2.4 Climate Change

The effects of a changing climate are often simulated in peatland studies through the initiation of drought conditions. Following simulated drought conditions Holden and Burt (2002a) found original peat moisture content was not regained 21 days after rewetting, suggesting a physical change in the peat structure. Following drought conditions, infiltration rates were found to have increased with increased runoff in the deeper peat. Whilst after three weeks infiltration occurred at a steadier rate, it was still 19 % higher than pre-drought infiltration. Experimental water-table drawdown on a fen peatland resulted in a lowering of the peat surface elevation, which was not consistent between topographic features (ridge, mat and lawn) (Whittington and Price, 2006).

Water–table drawdown through drainage has been used as a proxy for climate change although caution should be advised as other changes occurring in line with a changing climate could result in feedbacks which buffer some of the effects. Whittington and Price (2006) observed that the sites which had been drained for the longest exhibited the greatest amount of compression and therefore lowest hydraulic conductivity. Similar to Wallage and Holden (2006), Whittington and Price (2006) observed that the peat became more homogenous following drainage. In addition, drained peat was found to be more rigid and less able to exhibit volumetric change with varying water-table depth. This suggests a loss of the elastic properties of peat. Whittington and Price (2006) attribute this to the decrease in pore pressure following drainage resulting in irreversible change.

Few studies appear to solely focus on structural changes to peat following disturbance. In most cases structural changes are illustrated through observed changes in bulk density, hydraulic conductivity, soil moisture content and macropore flow. In addition, studies of physical changes to blanket peatlands also appear to be limited.

2.2.3 Impacts to Peat Hydrological Properties

Observed changes in hydrological properties are closely related to changes in peat structure following disturbance.

2.2.3.1 Changes in Water-Table Depth

Drainage of peatlands results in deeper water tables (e.g. Burke, 1975, Stewart and Lance, 1991, Price, 1997, Whittington and Price, 2006, Armstrong et al., 2010, Wilson et al., 2010, Holden et al., 2011). Greater fluctuation in water-table depth has been recorded in drained peatlands compared with undrained (Whittington and Price, 2006, Wilson et al., 2010, Holden et al., 2011). In addition, afforestation on drained peatlands has been found to result in even deeper water tables, resulting from evapotranspiration by the trees (Anderson et al., 2000, Lewis et al., 2013). Following the removal of trees, water tables have been found to become shallower (Holden, 2009c). Furthermore, the blocking of drainage ditches in peatlands has also been found to result in shallower water tables relative to drained conditions (Armstrong et al., 2010, Wilson et al., 2010, Holden et al., 2011). The recovery of peatland hydrology following drain blocking has been found to be variable and site specific, emphasising the importance of the spatial scale of investigations (Wilson et al., 2011a).

Water-table drawdown following drainage exhibits spatial variation with distance from the drain. The efficacy of drainage and therefore the distance effect has been attributed to the degree of decomposition of the peat (Rothwell et al., 1996). Indeed, Boelter (1972) reasoned that the changes in water-table height following drainage was dependent on the hydraulic conductivity of the peat, which in turn was dependent upon the level of decomposition of the peat. Within blanket peatlands, the greatest impact has been observed close to the drains (Holden et al., 2006, Armstrong et al., 2010), this could be related to the lower hydraulic conductivity below 5 cm (section 2.1.3.1) and low hydraulic gradient reducing the effect of the drains at a greater distance.

Early work suggested that water-table drawdown around drains would be equal on both sides (Burke, 1975), more recent studies have not observed this, although peatland type and location of the drain are probable influences. An asymmetrical deepening of water table has been observed in blanket peatlands with the deepest water tables occurring downslope of the drain (Stewart and Lance, 1991, Holden et al., 2006, Armstrong et al., 2010, Wilson et al., 2010). This has been attributed to the topography of blanket peatlands (section 2.1.6). When cut parallel to the contours, drains shorten the slope length and therefore reduce the size of the upslope contributing area (Holden et al., 2011), in addition they redirect flow from reaching further downslope (Stewart and Lance, 1991). Figure 2.1 provides a schematic of this effect. Drains are not exclusively cut across slopes, however, and have been found at a range of angles to the slope, including straight downslope in some cases. The influence of drain orientation is considered further in section 2.2.3.3.

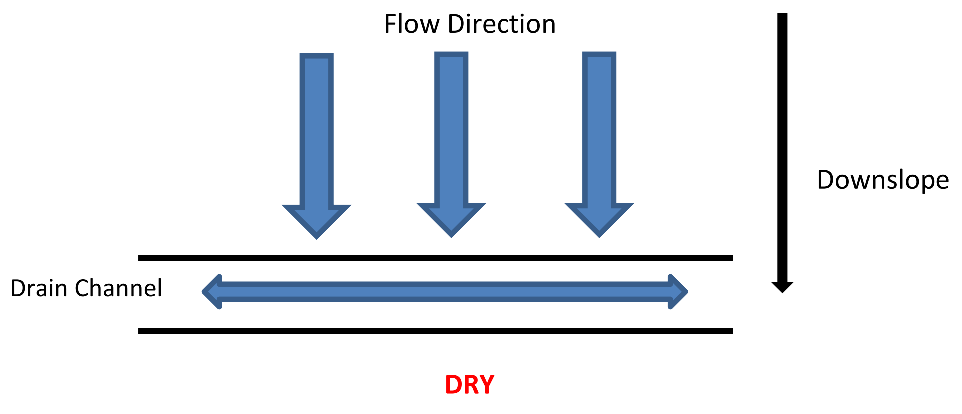

Figure 2.1 Schematic of the redirection of flow by a drainage channel from upslope to downslope in a blanket peatland when installed parallel to the contours.

There is limited evidence of the direct impacts of grazing (and by association compaction) on water-table depth. In blanket peatlands, the impacts are often considered in conjunction with the effects of burning (Worrall et al., 2007a, Clay et al., 2009). Clay et al. (2009) expanding on the work by Worrall et al. (2007a) identified shallower water tables in burned and grazed plots compared with undisturbed plots. The greatest differences in water-table depth between disturbed and undisturbed plots were observed in the summer months. It should be noted that potential limitations of these studies, relating to hydrological independence of the study plots, have been critiqued by Holden et al. (2012a). With respect to burning impacts on blanket peat, contrasting results were observed by Holden et al. (2015), where the depth to water table increased following burning, with the deepest water tables in the most recently burned plots. There was little difference between the oldest burn plots (15 + years) and undisturbed plots.

Worrall et al. (2007a) and Clay et al. (2009) attribute shallow water tables to the removal of vegetation following burning and grazing which reduce water losses through evapotranspiration. In addition, they suggest that trampling and compaction of the peat through grazing could lead to a potential reduction in water-table depth. In contrast, Holden et al. (2015) suggest the loss of vegetation following burning could result in heating of the peat to a greater depth during warm, sunny days, leading to increased evaporation and an increased depth to water table.

Within drained and harvested (Schlotzhauer and Price, 1999) or drained and afforested peatlands (Silins and Rothwell, 1998), changes in peat structure have been linked to increases in water retention at a range of tensions, with the exception of saturation. This has been attributed to an increase in the depth to the water table, increase in effective stress and increase in the number of smaller pores. Water which is held at higher tensions becomes less available to vegetation; therefore change in water-table depth can have longer term implications for vegetation composition in a peatland (McLay et al., 1992, Silins and Rothwell, 1998).

It is predicted that at northern latitudes, climate change will result in higher temperatures and lower summer rainfall. Consequently, the effect of climate change in peatlands is often simulated through water-table drawdown experiments (e.g. Whittington and Price, 2006, Strack and Waddington, 2007, Clark et al., 2009). In addition, the effect of drought conditions on water-table depth have been considered as proxies for a changing climate (e.g. Evans et al., 1999). Due to their dependence on niche climatic conditions to maintain shallow water tables, blanket peatlands are therefore very sensitive to climate change (Ellis and Tallis, 2000).

2.2.3.2 Changes in Runoff Pathways

Runoff pathways are influenced by water-table depth, soil moisture content and peat structure (hydraulic conductivity). The occurrence of macropores in drained peatlands was addressed in section 2.2.2. Meyles et al. (2006) observed a change in the soil moisture threshold that led to the generation of surface runoff following sheep grazing. A difference in the threshold was noted between wet and dry conditions, however.

In blanket peatlands, drainage has been associated with a reduction in the occurrence of overland flow generation, especially downslope of the drain (Holden et al., 2006), supporting the link between water-table depth and overland flow occurrence in blanket peatlands (section 2.1.5). In addition, increases in flow at depths greater than 10 cm have also been observed. In a drained and afforested catchment in Caithness there was a 7 % reduction in runoff generation during spring and summer, however this was not reflected as a decrease in peak discharge (Anderson et al., 2000).

Evidence suggests that drainage and drought conditions in blanket peat result in an increase in functional macroporosity (Holden and Burt, 2002a) and a greater density of peat pipes (Holden, 2005a). Older drained peats were found to have a higher density of pipes compared with more recently drained peat (Holden, 2005a). Within actively eroding areas of a blanket peatland in the South Pennines, UK, Daniels et al. (2008) observed flow was predominantly through pipes and macropores and not as overland flow. The development of macropores and pipes has been linked to a lowering of the water table and drying of the peat associated with drainage and erosion. However, Wallage and Holden (2011) observed that whilst macroporosity in near-surface blanket peat remained high (> 60 %), functional macroporosity was significantly lower in drained peat compared with undrained peat. Alterations in the dominant flow pathways have implications for the hydrological regimes of peat covered catchments (section 2.2.3.3).

Contrasting evidence exists for the effect of burning on runoff production in blanket peatlands. Whilst Clay et al. (2009) found the highest occurrence of overland flow from the most recently burned plots (10 year burn) at their study site, Holden et al. (2015) found that the most recently burned plots had the lowest occurrence of overland flow. The most recently burned plots in Holden et al. (2015) were much younger (< 2, 4 and 7 years) than the Clay et al. (2009) plots, in addition the oldest plots were 10+ years. This may therefore partially explain the difference in findings. The differing results in overland flow occurrence between the two studies are supported by the differences in recorded water table depth (section 2.2.3.1). The generation of hydrophobic compounds following burning have also been observed (DeBano, 2000), which has the potential to influence runoff pathways and therefore the mixing of water. Clay et al. (2010) suggest this as a possible reason for the observed difference in soil water-rainwater composition following burning.

2.2.3.3 Changes in Hydrological Regime

Section 2.1.5 highlighted the connections between water-table depth and runoff pathways on the hydrological regime of a peat covered catchment. Consequently changes in water-table depth and runoff pathways following disturbance are often reflected in changes to the hydrological regime.

Two ways in which peatland drainage can potentially alter the hydrological regime of a catchment include: (i) reducing the size of stream flow peaks due to increased storage space for water following water-table drawdown and (ii) increasing the size of stream flow peaks resulting from faster flow through drains (Holden et al., 2006, Ballard et al., 2012).

Evidence from field studies is mixed; early work by Conway and Millar (1960) showed a faster response in peak flow to rainfall in catchments that were drained and burned. Further investigation at the same site by Holden et al. (2006) 50 years later still recorded higher flow peaks in drained and gullied catchments compared with undisturbed ones. However, a change in lag time between peak rainfall and peak flow was observed in drained catchments in Holden et al. (2006), which could be attributed to changes in the condition of the drains in the 50 years in between studies as well as change in the dominant flow pathways following drainage (section 2.2.3.2). The difference between these two studies emphasises the need for long term monitoring of disturbances in peatlands.

Contrasting these studies, Burke (1975) found that runoff remained quicker from undisturbed plots relative to drained peatlands. The areal coverage of three studies varied greatly, however; whilst Burke (1975) measured the effects on experimental plots of 0.35 ha, Conway and Millar (1960) and Holden et al (2006) investigated the effects in catchments that were much larger (4.8 and 3.8 ha respectively). In addition the orientation of the drains to the slope had greater variation for Conway and Millar (1960) compared with Burke (1975).

Recent modelling work has suggested that the density, condition and layout of drains on a hillslope can influence the hydrological response through their effect on flow velocity and the travel time of runoff through the drains to the stream channel (Ballard et al., 2012, Lane and Milledge, 2013). Depending on the orientation of the drain to the slope, redirection of flow through the drain may lengthen or shorten the flow pathway relative to the undisturbed hillslope hydrological processes (Lane and Milledge, 2013). The effect of drains on timing of runoff from a hillslope is particularly important. Even if lower flow peaks do occur following drainage, a development of synchronisation between the hillslope and the flood peak in the main catchment river channel may lead to bigger flood peaks further downstream and potentially cause greater damage (Holden, 2005b).

Modelling of afforested drained peatlands has shown difference in the volume of streamflow from the catchment due to deeper water tables and less effective rainfall (Lewis et al., 2013). Within this study, however, the density of the drainage network was important leading to increased streamflow, particularly in wetter conditions.

As has been briefly mentioned in relation to drainage channels, hydraulic roughness influences the speed of runoff and therefore the rate at which it reaches stream channels (Holden et al., 2008). Feedbacks exist between vegetation and peatland hydrology (section 2.1.7), and changes have been observed in vegetation cover following disturbance (section 2.2.4). A loss of vegetation cover through grazing (Meyles et al., 2006) or a change in species composition through drainage has the potential to alter the hydraulic roughness of the peat surface and the response of the hydrological regime. In blanket peat covered catchments, periods of low vegetation cover were associated with increases in peak discharge. Following a period of vegetation restoration lower peak discharges were recorded (Grayson et al., 2010).

Linear disturbances, such as power line rights of way, seismic lines and winter roads, found in Canadian boreal peatlands, have the potential to dramatically alter the hydrologic regime of discontinuous permafrost peatlands through alteration in peat thermal properties (Quinton et al., 2009). The removal of trees reduces the insulation to the peat, resulting in increases in the thaw depth of permafrost peats along these linear pathways earlier in the season than would be expected in undisturbed peatlands. In addition, subsidence of the peat surface has been observed, creating depressions along the linear disturbances. Shallow water tables and depressions combined with periods of high flow (e.g. snow melt season) create seasonally active conduits between peatlands (Williams et al., 2013). In addition, the creation of a permanently unfrozen layer has been observed in some instances, through which water is able to flow throughout the year (Braverman and Quinton, 2016). Consequently, peatlands which stored water when the peat was frozen to shallow depths (flat bogs) drain through the previously frozen peat plateau into fen peatlands (Braverman and Quinton, 2016). This therefore has implications for the timing and delivery of water during the year and impacts on flow peaks further downstream. It has been noted that discontinuous permafrost peatlands respond differently to linear disturbances compared with continuous permafrost peatlands (Williams et al., 2013).

2.2.4 Impacts to Peatland Vegetation

Disturbances to peatlands can affect vegetation in several ways. The magnitude of impact is not homogenous within a peatland, due to the heterogeneity of species cover (Milne and Hartley, 2001). Directly, disturbances such as grazing and burning can result in the total removal of the vegetation (Evans, 1997, Meyles et al., 2006, Pellerin et al., 2006) and exposure of the peat surface. Furthermore, there is evidence of changes in species composition following disturbance.

In the case of grazing, more palatable species may be preferentially removed (Groome and Shaw, 2015), due to this, Pellerin et al. (2006) observed greater impacts of grazing to vegetation composition on minerotrophic fens compared with blanket peatlands. Smith et al. (2003) observed spatial variation in the impact of grazing on vegetation on an ombrotrophic peatland, with greatest effects of the cessation of grazing found at the periphery of the peatland compared with the centre.

Burning is actively used as a method to alter species composition, in favour of the growth of *Calluna vulgaris* (Rawes and Hobbs, 1979). Some studies have measured the effects of burning and grazing. On the same plots where Worrall et al. (2007a), Worrall and Adamson (2008) and Clay et al. (2009) investigated the impacts to peat structure and hydrology, Ward et al. (2007) observed a 51% reduction in the shrub and bryophyte biomass under burning and grazing compared with undisturbed plots. Grazing did not affect gramminoid cover; however, burning resulted in an 88% reduction in cover relative to undisturbed plots.

Indirectly, disturbances leading to compression of peat can alter pore water availability to plants, which in turn would lead to changes in species composition (McLay et al., 1992). Evidence from studies on the effect of drainage is unclear, with observed shifts to species preferring drier conditions on the downslope side of the drains in some cases (e.g. Stewart and Lance, 1991, Wilson et al., 2011b). Patterns observed were not always significant, however, (e.g. Gatis et al., 2015), and may be influenced by the peatland and vegetation type present.

Feedbacks exist between climate change and vegetation, with the potential for alterations in vegetation with a wetter climate and change in temperature. This then has the pontential to influence the structure and hydrology of the peat and its ability to sequester carbon (Belyea and Malmer, 2004).

2.3 Tracks and Peatlands

For the purpose of this synthesis the term 'track' will be used in reference to constructed roads and unsurfaced routes, created by vehicle use, human and livestock trampling. Section 2.3.1 focuses on impacts of roads and tracks in general considering properties typically measured and methodological approaches used. Section 2.3.2 focuses on current understanding on the impact of tracks in peatland environments.

2.3.1 Impacts of Roads and Tracks

Tracks are linear disturbances and therefore do not have a large areal footprint. Road widths can vary between 2 m and 22 m depending on their purpose. However, they can extend for many kilometres and are seen as disjunctions in the landscape (Lindsay, 2007). Consequently, they have the potential to be a large disruption to the functioning of an environment. It has been suggested that the impacts of a track can extend beyond its immediate footprint (Forman and Alexander, 1998, Dale et al., 2005).

Evidence from these studies has shown that constructed and unsurfaced tracks alter the natural environment, through impacts to a range of physical, hydrological, ecological and chemical properties. Previous studies have investigated the impacts of tracks to these properties in a variety of environmental settings, including those related to forestry operations, agricultural uses, military manoeuvres and tourism. Table 2.4 provides examples of specific properties typically measured in relation to the impact of tracks from a selection of previous studies. Tracks have been linked with altering soil bulk density, soil structure, and pore orientation, leading to changes in permeability and infiltration rate. Furthermore, they have the potential to alter the hydrological regime of catchments. Impacts to ecology have been reported including animal mortality and habitat fragmentation (Trombulak and Frissell, 2000) and changes in vegetation composition, including loss of vegetation cover.

Table 2.4 Examples of typical properties measured and experimental design from a selection of existing studies investigating the impact of tracks (unsurfaced and constructed) in a range of environmental settings. (✓) indicates that the property was modelled/simulated but not actually measured. Continued on page 36.

Reference	Location	Experimental Design	Properties Measured										
			Physical				Physical/Hydrological		Hydrological		Ecological	Chemical	
			Soil Pore Size & Orientation	Bulk Density	Surface Profile Shape	Soil Strength/ Resistance	Permeability/ Infiltration Rate	Soil Moisture	Flow Regime	Runoff	Vegetation Composition	Soil Chemistry	Water Chemistry
Unsurfaced													
Dale and Weaver (1974)	Montana (USA)	Control/Treatment									✓		
Weaver and Dale (1978)	Montana (USA)	Disturbed/Undisturbed		✓	✓		✓	✓			✓		
Payne et al (1983)	Montana (USA)	Control/Treatment		✓		✓					✓		
Braunack et al (1986a)	Australia (Queensland)	Before/After		✓	✓	✓	✓						
Thurow et al. (1995)	Texas (USA)	Control/Treatment		✓			✓	✓			✓	✓	
Alakukku (1996)	Finland	Control/Treatment	✓					✓					
Ziegler and Giambelluca (1997)	Thailand	Field/Modelling		✓			✓						
Hutchings et al. (2002)	UK (Northumberland)	Disturbed/Undisturbed		✓		✓		✓					
Hirst et al. (2003)	UK (Salisbury Plain)	Before/After & Control/Treatment				✓					✓	✓	
Eliasson (2005)	Sweden	Before/After		✓	✓	✓		✓					
Eliasson and Wästerlund (2007)	Sweden	Before/After		✓	✓	✓		✓					
Kelleway (2006)	Australia (New South Wales)	Control/Treatment		✓		✓		✓			✓		
Pickering et al (2011)	Australia (New South Wales)	Control/Treatment		✓							✓		

Table 2.4 (continued) Examples of typical properties measured and experimental design from a selection of existing studies investigating the impact of tracks (unsurfaced and constructed) in a range of environmental settings. (✓) indicates that the property was modelled/simulated but not actually measured.

			Properties Measured										
			Physical				Physical/Hydrological		Hydrological		Ecological	Chemical	
Reference	**Location**	**Experiment Design**	**Soil Pore Size & Orientation**	**Bulk Density**	**Surface Profile Shape**	**Soil Strength/ Resistance**	**Permeability/ Infiltration Rate**	**Soil Moisture**	**Flow Regime**	**Runoff**	**Vegetation Composition**	**Soil Chemistry**	**Water Chemistry**
Unsurfaced (continued)													
Lindsey and Selim (2012)	Louisiana (USA)	Before/After & Control/Treatment incl. Time since impact		✓		✓		✓					
Nortjé et al. (2012)	South Africa	Disturbed/Undisturbed				✓		✓					
Bottinelli et al. (2014)	France	Control/Treatment incl. Time since impact	✓			✓							
Constructed													
Harr et al (1975)	Oregon (USA)	Control/Treatment							✓				
King and Tennyson (1984)	Idaho (USA)	Before/After							✓				
Keppeler and Ziemer (1990)	California (USA)	Before/After							✓				
Wemple et al. (1996)	Oregon (USA)	Control/Treatment (Paired Catchment)							✓	✓			
Bowling et al. (2000)	Washington (USA)	Control/Treatment (Paired Catchment)							✓	(✓)			
La Marche and Lettenmaier (2001)	Washington (USA)	Field/Modelling							(✓)	✓			
Forsyth et al. (2006)	Australia (Queensland)	Field/Modelling								✓			✓

Table 2.4 highlights a disparity in the properties measured in relation to unsurfaced tracks (predominantly physical properties) and those in relation to constructed tracks (predominantly hydrological properties). In addition, there is a difference in the approaches utilised in the experiment design, with before-after comparison more common for unsurfaced tracks compared with constructed tracks. The use of control-treatment set-up has been popular in many studies (e.g. Iverson et al., 1981, Braunack, 1986b, Thurow et al., 1995, Pickering et al., 2011). A sub-group of this set-up is the disturbed-undisturbed arrangement, where tracks are already in existence prior to the start of the study. In these instances samples are typically collected from ‘disturbed’ wheel-rut locations and ‘undisturbed’ locations either in the middle of the track or off the track edge (e.g. Weaver and Dale, 1978, Hutchings et al., 2002), often using a transect approach (e.g. Arnesen, 1999). The number of tracks included in the experiment set-up also varies between studies; in most cases multiple lengths of track are established, each representing a different combination of influential conditions, e.g. vehicle type *x* frequency of use (e.g. Abele et al., 1984, Ahlstrand and Racine, 1993, Hirst et al., 2003), however some studies measure the impact to a single track at different stages of use (Calais and Kirkpatrick, 1986).

With respect to studies of unsurfaced tracks in particular, a number of common influential factors are included in the experiment design. Some examples are provided in Table 2.5. Numerous studies have recorded increases in compaction, rut depth and bulk density following increased vehicle use and trampling along track routes (e.g. Braunack, 1986a, Whinam and Chilcott, 2003). Variations in impacts with slope position have also been observed, particularly with respect to unsurfaced tracks. In some studies position on slope is defined by slope angle (e.g. Jamshidi et al., 2008, Jourgholami et al., 2014), whilst in others it is differentiated by soil wetness (Thurow et al., 1995, Alakukku, 1996a, Nortje et al., 2012). Topography is known to influence soil moisture content (Burt and Butcher, 1985). Track type has also been given consideration in some studies, with a focus on alleviating the magnitude of impacts. For example, the use of brash mats to protect the underlying soil in forest operations has been compared with driving directly on the soil surface (Hutchings et al., 2002, Eliasson and Wästerlund, 2007).

Within the literature considered here, there are no studies which have compared the magnitude of impact between constructed or unsurfaced roads. Given the differences in their purposes of use this is potentially not surprising. In addition, despite tracks potentially having an impact over an area larger than their immediate footprint, this has also not been addressed in the literature.

Table 2.5 Influential factors considered in a selection of track studies included in this synthesis, thought to affect the magnitude of track impact.

Influential Factor	**Reference**
Vehicle Type	Jansson and Johansson (1998) Eliasson (2005) Bottinelli et al. (2014)
Slope Angle	Weaver and Dale (1978) Jamashidi et al (2008) Jourgholami et al. (2014)
Orientation to Slope	Ziegler et al. (2001) Lindsay and Bragg (2005)
Frequency of Use	Iverson et al. (1981) Payne et al. (1983) Braunack et al. (1986a) Kevan et al. (1995) Wood et al. (2003) Hirst et al. (2003) Pickering et al. (2011)
Moisture Content	Thurow et al. (1995) Alakukku (1996) Nortje et al. (2012) Lindsey and Selim (2012)

2.3.2 Impacts of Tracks in Peatlands

In peatlands more specifically, tracks have been used to facilitate access in these environments for millennia. For example, there is evidence of Neolithic trackways created from logs uncovered in the Somerset levels (UK) (Greary and Fyfe, 2016). Currently, the presence of tracks in peatlands is increasing to provide access for a range of purposes including forestry, agriculture, access roads to wind farms and oil sands, and recreation, e.g. games sports (Dargie, 2004, Turetsky and St. Louis, 2006, SNH, 2013). Despite their extensive use, understanding of the impacts of tracks in peatland environments is severely limited. Furthermore, experimental designs are such that drawing comparisons between studies is challenging.

A review of the existing literature relating to tracks and peatlands has been undertaken by Natural England (Grace et al., 2013), the synthesis presented here complements the review, whilst expanding on it through the addition of new material. Existing studies, where the impacts of tracks have been directly measured, are presented in Table 2.6. Here the properties typically measured in relation to peatland tracks, the locations of these studies and the methodologies adopted are outlined. Further discussion, including current assumptions regarding the impact of tracks to peat physical and hydrological properties and vegetation characteristics, is provided in sections 2.3.2.1-2.3.2.2.

Table 2.6 Summary of existing peatland tracks studies outlining location, climate, peat type, track type, properties measured and methodological approaches used. Continued on pages 40-41

Reference	Location	Climate	Peatland Type	Track Type	Properties Measured: Vegetation	Properties Measured: Hydrological Properties	Properties Measured: Physical Properties	Number of Tracks Included in Study	Methodology
Gersper and Challinor (1975)	Alaska (USA)	Arctic	Tundra (Shallow Peat)	Unsurfaced (Vehicle)	Vegetation Loss (Erosion)	-	Bulk Density Soil Morphology Thaw Depth	Single Track	**Control and Treatment** Measurements six years after final disturbance Three moisture regimes On-track and off-track sampling
Sparrow et al. (1978)	Alaska (USA)	Arctic	Tundra (Shallow Peat)	Unsurfaced (Vehicle)	Species Composition	-	Bulk Density	Six tracks – multiple sites within each (differing terrain, vegetation and intensities of use)	**On-track (Disturbed) vs Off-track (Undisturbed)** Recorded species composition, signs of plant injury, collected soil samples
Chapin and Shraver (1981)	Alaska (USA)	Arctic	Tundra (Shallow Peat)	Unsurfaced (Vehicle)	Species Composition	-	Bulk Density Thaw Depth	Six tracks across four sites – different ages since creation/abandonment	**Control and Treatment** Differing moisture regimes Quadrats Sample collection
Umeda et al. (1985)	Japan	Maritime	Low lying peatland	Constructed	-	Water-table depth	-	Single Track	**Spatial Impact** Two transects across track – measured for different time periods (extended up to 250 m from track edge)
Bradof (1992)	Minnesota (USA)	Subarctic	Pattern peatland (disturbed)	Constructed (Highway 71)	-	Water-table depth – no clear effect >10m from road	-	Single Track (Highway) (with ditches)	**Spatial Impact**– transects extending from edge of road
Ahlstrand and Racine (1993)	Alaska (USA)	Maritime and Arctic	Shallow Peat (Permafrost)	Unsurfaced (Vehicle)	Species Composition	-	Surface Profile Shape	200 'lanes' – each lane a combination of vehicle type, frequency of use, season of use	**Control and Treatment** – 3 replicates of each treatment **Before and After**

Table 2.6 Summary of existing peatland tracks studies outlining location, climate, peat type, track type, properties measured and methodological approaches used.

Reference	Location	Climate	Peatland Type	Track Type	Properties Measured			Number of Tracks Included in Study	Methodology
					Vegetation	Hydrological Properties	Physical Properties		
Charman and Pollard (1995)	UK (SW England)	Maritime	Blanket Peat	Unsurfaced (Vehicle)	Species Composition	-	-	Three Tracks– different ages since abandonment	**On-track (Disturbed) vs Off-track (Undisturbed)** Quadrats
Angold (1997)	UK (S England)	Maritime	Heathland	Constructed (A31 between Bournemouth and Southampton)	Species Composition and Growth Rate	-	-	Single Road	**Spatial Impact** Vegetation composition measured along survey lines – 25 m long parallel to the road at distances (10, 25, 45, 80, 150,200 m from road edge)
Rusekas (1998)	Russia	Arctic	Boreal	Constructed	-	-	Bulk Density Hydraulic Conductivity	Single Track (with ditches)	**On-track (Disturbed) vs Off-Track (Undisturbed)**
Arnesen (1999)	Norway	Arctic	Rich Fen	Unsurfaced (Human Trampled)	Change in Composition	-	Surface Profile Shape	Single trampled track – different sampling locations along track	**On-track (Disturbed) vs Off-track (Undisturbed)** Majority of measurements made post-sampling: 1982, 1990, 1995 Permanent transect installed
Nugent et al. (2003)	Ireland	Maritime	Raised Peatland (Forested)	Unsurfaced (Vehicle)	-	Soil Moisture Content	Cone penetration resistance Surface Profile Shape	Four extraction tracks – two intensities of use	**Before and After** – sampling locations in wheel ruts, multiple points along each track
Wood (2003)	UK (NE England, SW Scotland)	Subarctic Oceanic	Forested Deep Peat	Slash Roads	-	-	Bulk Density Soil Penetration Resistance Hydraulic Conductivity	Three tracks - four sampling plots per track	**On-track (Disturbed) vs Off-track (Undisturbed)** Data collected 1 week after disturbance

Table 2.6 Summary of existing peatland tracks studies outlining location, climate, peat type, track type, properties measured and methodological approaches used.

Reference	Location	Climate	Peatland Type	Track Type	Properties Measured			Number of Tracks Included in Study	Methodology
					Vegetation	Hydrological Properties	Physical Properties		
Robroek et al. (2010)	UK (NW England)	Subarctic Oceanic	Blanket Peat	Unsurfaced (Human Trampled)	Species Composition	Overland Flow Occurrence Water Chemsitry	Bulk Density	Two tracks – different ages since abandonment	**Control and Treatment** – vegetation survey events, fortnightly monitoring water chemistry and runoff water
Bocking (2015) MSc. Thesis	Canada	Subarctic	Fen	Constructed (Range Road 90A)	Species Composition Tree mortality & density	Water-table depth Overland Flow Occurrence	-	Single Track	**Spatial Impact** - sample collection (peat and tree rings), regular monitoring water-table depth (May-August, 2012, 2013), transects – tree density, quadrats – vegetation cover
Pilon (2015) MSc. Thesis	Canada	Subarctic	Fen	Constructed	-	Water-table depth Runoff pathways	Hydraulic Conductivity Peat subsidence	Single Track	**Transects/ Off-track vs under-track,** Quadrats – vegetation cover.

As is evidenced in Table 2.6, both constructed and unsurfaced tracks exist within peatland environments. Variation is found within each group, however, dependent upon the purpose of use or the way in which the tracks were created (Figure 2.2). Constructed roads are typically used in conjunction with heavier vehicles, whilst unsurfaced tracks have been created by heavier military vehicles (e.g. Charman and Pollard, 1995), forest harvesting machinery (e.g. Wood et al., 2003, Saunders and Ireland, 2005) and off-road vehicles (which vary in weight) (Gersper and Challinor, 1975). For descriptions of the difference between 'cut and fill' and floating roads please see Chapter 1. Figure 2.3 illustrates the difference between a 'cut and fill' and floating road. Floating roads are more typically found on deeper peat and gentle slopes, compared with cut and fill roads which on steeper slopes can be cut into the hillslope and across natural flow pathways (Dargie, 2004).

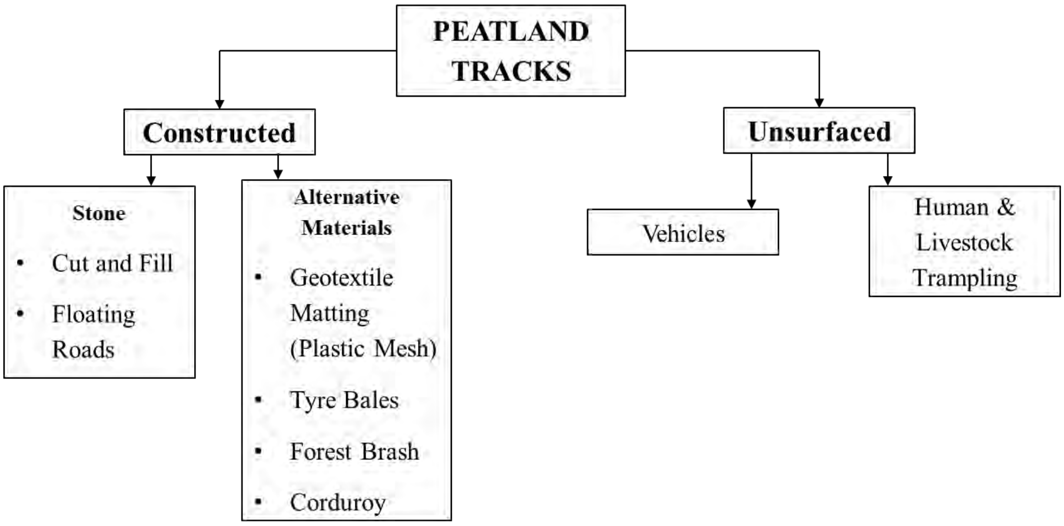

Figure 2.2 Different track types found within peatland environments based on existing literature.

Figure 2.3 a-b a) Example of a 'cut and fill' road where the peat has been excavated and aggregate placed along the base of the trench to form the travelling surface. Photo Courtesy of North Pennines AONB. b) Example of floating road on blanket peat where the aggregate is placed on top of the peat surface.

2.3.2.1 Impacts to Physical Properties

The high compressibility of peat (section 2.1.2) means that loading at the surface leads to a consolidation of the peat due to an increase in the effective pressure and loss of water (section 2.2.2). Extensive research has been undertaken relating to the geotechnical properties of peat with respect to engineering, and frequently investigates the challenges of constructing embankments (for roads and railways) on peat (Lefebvre et al., 1984, Weech and Lister, 2009, Hendry et al., 2014). The compression of peat upon loading occurs in two stages: stage one is primary consolidation where the unsaturated zone is compressed and water is lost from larger pore spaces (Barden, 1968, Berry and Poskitt, 1972). In peat comprised of large pores, e.g. more fibrous peat, primary consolidation can be extensive. Stage two is secondary compression, where interparticle water is lost (section 2.2.2). Secondary compression has been found to assume a linear decline with logged time (Barden, 1968). It has been suggested in some cases that secondary compression can occur indefinitely and is evidenced as creep in the peat (Berry, 1983). It should be noted the embankments referred to in these studies are often with the purpose of supporting heavy loads, e.g. tankers and lorries, and highways.

Several approaches have been used to speed up the consolidation process, including installing drainage ditches to lower the water table leading to peat consolidation (Munro, 2004) (also see section 2.2.2) or through preload surcharging, where a load larger than the final required load is added to the peat surface to speed up the consolidation process (Berry, 1983, Crowl and Lovell, 1987). When the additional load is removed, the peat has consolidated to an acceptable level. This method requires the elastic properties of peat to be lost through irreversible change in pore structure and water pressure (Kazemian et al., 2011, Hendry et al., 2014) so that rebound cannot occur (see section 2.1.2 for peat geotechnical properties).

Following embankment construction on more fibrous peats an enhancement in the laminar structure has been found to occur relative to more amorphous peats (Landva and Pheeney, 1980, Lefebvre et al., 1984, Mesri and Ajlouni, 2007, Hendry et al., 2014). This has implications for the hydraulic conductivity of the peat and therefore flow pathways. Such matters do not appear to have been considered with respect to track construction on blanket peat, however.

Consolidation of peat is often seen as a necessity in track construction to ensure the integrity of the road and its functionality (Weech and Lister, 2009). However, it is acknowledged that compression can impact on peatland hydrology (considered further in section 2.3.2.2). Reducing the extent of compression has been considered in several studies. These include the use of geogrids to spread the load under the aggregate used for the embankment (Barry et al., 1992, Barry et al., 1995, Giroud, 2009) or the addition of piles into the forested swamp peat to provide additional support, although this method has not always proved effective (Barry et al., 1995). The long-term efficacy of these methods does not appear to be addressed in the literature.

As was discussed in section 2.2.2, compression of peat can be exhibited through reductions in pore size, increases in bulk density and decreases in hydraulic conductivity. With respect to constructed tracks, measurement of these properties is limited, as access to the peat under the track is difficult, and consequently results are mixed. Compared with undisturbed peat, Ruseckas (1998) found higher bulk density and lower hydraulic conductivity under roads in drained ombrotrophic and fen peatlands in Russia. Hydraulic conductivity under the road was higher in the drained fen than the drained bog between 2 and 80 cm depth, yet bulk density was higher in the drained fen compared with the drained bog between 2 and 50 cm depth which is surprising. Landva and Pheeney (1980) observed a reduction in moisture content under a road embankment on a raised peat bog, potentially indicating some compression, and a small decrease in porosity was found (96 % to 91%) following construction. Van Seters and Price (2001) also recorded lower moisture content under roads across a cutover peatland, relative to the rest of the peatland.

Measurements of changes in physical properties directly under the track are more prevalent in studies of unsurfaced tracks (see Table 2.6). Tracks in arctic tundra environments created by military or off-road vehicles (e.g. All-Terrain Vehicles) are characterised by increased surface peat bulk density (Gersper and Challinor, 1975, Sparrow et al., 1978, Chapin and Shaver, 1981, Racine and Ahlstrand, 1991, Ahlstrand and Racine, 1993), and changes in the surface profile morphology through rut formation (Abele et al., 1984). The moisture content of the soils has been found to influence the level of compaction (Gersper and Challinor, 1975). Increases in bulk density, in addition to vegetation removal (section 2.3.2.3), have often been found to result in increases in the thaw depth on track relative to off-track in these environments. Variation in thaw depth has been observed between number of passes over the track (Abele et al., 1984) and vehicle type (Chapin and Shaver, 1981). It is difficult to draw comparisons between the studies, however, due to differences in experiment set-up and the types of vehicles used.

In forestry operations where heavy harvesting machinery has been used directly on the peat brash matting, straw and wood chips have been trialled to spread the load of the vehicle and protect the peat surface of a raised bog (Saunders and Ireland, 2005). However, studies of the efficacy of these methods in peatland environments are limited. Nugent et al. (2003) observed that brash mats were successful on a raised bog in increasing the stress threshold before peat failure occurred when driven over. In addition, Wood et al. (2003) found few significant impacts to bulk density or hydraulic conductivity following harvesters driving over brash protected peat.

Unsurfaced tracks created by human trampling on a blanket peatland in the North Pennines, UK, did not show significantly higher bulk density values compared with undisturbed peat (Robroek et al., 2010). Unpublished data from Zhao and Holden (Holden et al., 2007, Zhao, 2008), showed an increase in bulk density along sheep trampled tracks, in addition to a decrease in saturated surface hydraulic conductivity compared with areas that had not been grazed. Trampling by humans can also lead to a lowering of the peat surface elevation relative to surrounding undisturbed peat (Arnesen, 1999). In this study the magnitude of impact was found to vary with track position in the fen peatland. The impact was less where vegetation was denser and the peat was drier.

Despite the geotechnical (physical) properties of peat being important for construction on peatlands, there appear to be few studies which have actively measured changes in these key properties. Hydraulic conductivity is important for water flow patterns in peatlands, and compression can potentially have a considerable effect on it, yet measurement of change following track use is nearly non-existent. Much of the work related to unsurfaced tracks appears to have been focused in arctic tundra environments, and the effects of driving on other peatlands such as blanket peatlands is very limited (only one study identified in Table 2.6).

2.3.2.2 Impacts on Hydrological Properties

Tracks on peatlands have the potential to impact hydrological properties in a number of different ways. The level of current knowledge differs between constructed peatland tracks (Figure 2.4) and unsurfaced peatland tracks (Figure. 2.5), although it is not extensive in either instance, as shown in Table 2.6. This is surprising given that numerous best practice documents for track construction state that impacts to hydrology should be avoided where possible (Munro, 2004, SNH, 2013).

A number of studies have shown the impact that the presence of a track on a peatlands can have. In these cases the presence of the track is not the main focus of the study, rather it is the disturbance which has led to longer-term changes in the landscape. Direct measurement of changes in water-table depth around a track are limited. An embankment supporting a railway across the Cacouna Bog in Canada created a zone of highly compressed peat and acted as a barrier to water flow, completely separating the peatland with respect to hydrology (Van Seters and Price, 2002). A similar affect was observed at the field site used in Moore et al. (2015), where an embankment constructed in the 1950s led to changes hydrophysical properties in the surrounding poor fen peatland following long-term water-table manipulation. In Lieffers and Rothwell (1987) tree death was used to demonstrate a change in hydrological conditions around a constructed track (20 years since construction).

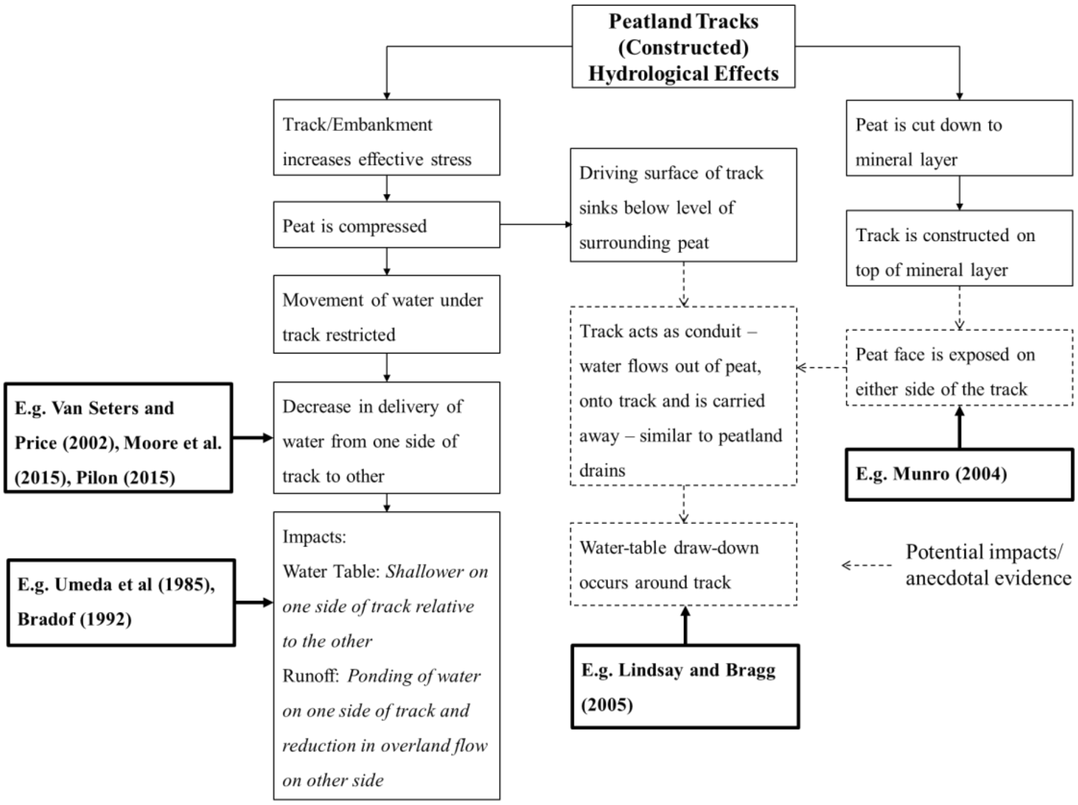

Figure 2.4 Conceptual diagram of impacts of constructed peatland tracks on hydrological properties based on existing literature and personal communication.

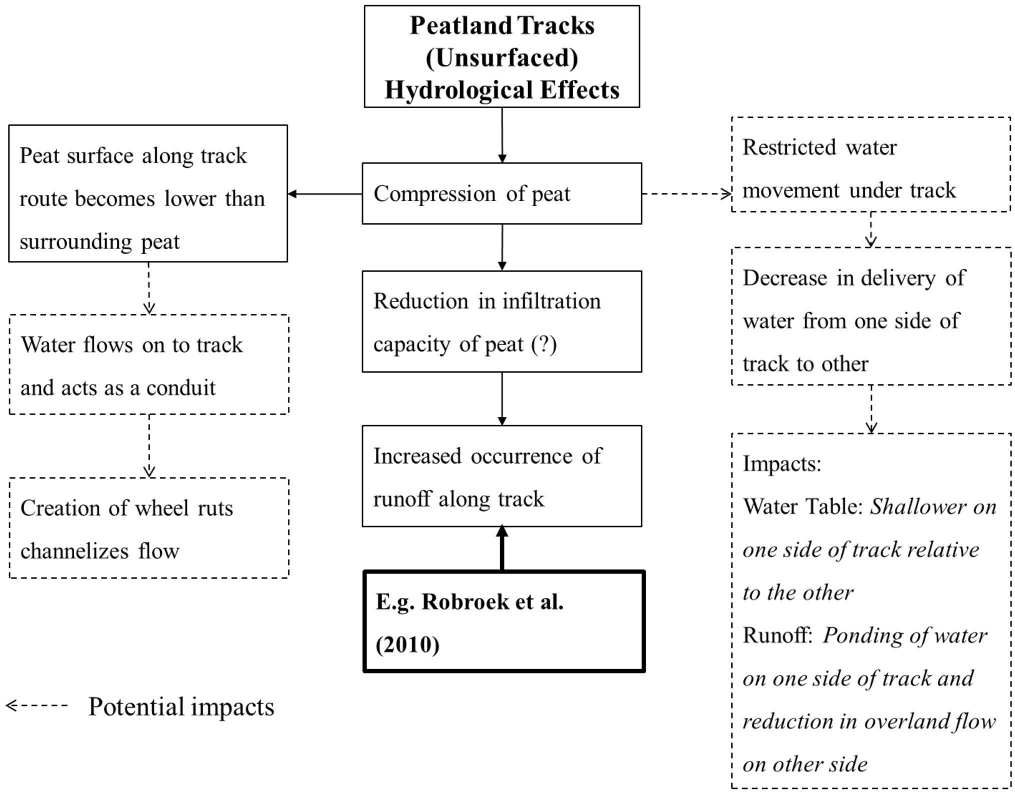

Figure 2.5 Conceptual diagram of impacts of unsurfaced peatland tracks on hydrological properties based on existing literature and anecdotal evidence.

A similar approach was used in Bocking (2015) where poor cross-track drainage (culvert size not adequate for volume of water), for a 40-year old track on a poor fen limited hydrological connectivity and resulted in ponding water on one side and a drying of conditions on the other. In contrast to the ponding observed in Bocking (2015), where flow through culverts does occur, areas of erosion have been observed at the outflow as the previously dispersed water flow becomes more concentrated (Tague and Band, 2001).

Direct measurements of water-table depth around constructed tracks are sparse in the existing literature (four studies identified in Table 2.6). Based on two different transects, each monitored at a different time in the year, (Umeda et al., 1985) observed shallower water-table depths on the 'upslope' side of a track relative to the 'downslope' side. The peatland was patterned comprising of a bog to fen transition. The gradient of change in water-table depth across transects was steeper for one transect compared with the other and was attributed to the difference in delivery of water from one side of the track to the other. Whilst at one location water flow was impeded by the track embankment, at the other location constant seepage meant there was a continued water supply. These findings should be treated with caution, however, given the difference in location of the transects within the peatland. The time of year of measurement may also account for the differences observed due to a difference in antecedent conditions which could influence the response.

Highway 72 runs through patterned Red Lake peatlands in Minnesota. The road was constructed by excavating peat and drainage ditches were installed on either side of it (Bradof, 1992). Monitoring of track impacts in a disturbed area of the peatland showed water-table drawdown on either side of the track which was attributed to the drainage ditches. An effect on water-table depth was not observed beyond 10 m from the drainage ditches on the 'upslope' side of the track (Bradof, 1992). Following track and ditch installation a change in direction of the flow gradient was observed. In addition, greater fluctuation in water-table depth was found on the west side of the track relative to east, suggesting the water balance of the west side of the track was more influenced by precipitation and evapotranspiration following track construction.

Currently the effects of unsurfaced tracks, created by vehicles or human trampling, on water-table depth or runoff have not been addressed in detail in the literature, as evidenced in Table 2.6. Given their prominence in peatlands, especially blanket peatlands in the UK, this is surprising. On tracks created through human trampling on blanket peat, a higher occurrence of overland flow was observed along the abandoned tracks compared with the control track (Robroek et al., 2010). Arp and Simmons (2012) suggested that tracks created by off-road vehicles on fen peat and silt soils led to the creation of hydrologically active pathways, following the channelization of flow, which altered drainage networks. Beyond this, however, any other effects to hydrology have not been addressed.

Evidence from the literature suggests tracks can impact hydrology beyond their immediate footprint, however, this evidence base is limited and few studies are based on the same peatland type. Distance effects cited in the literature, though largely unsubstantiated, have varied between 2.5 and 250 m away from blanket peatland tracks (Lindsay, 2007). Parallels can be drawn between peatland drainage and the presence of tracks in the landscape. The effect of peatland drains varied between peat types (Boelter, 1972), it therefore follows that the effect of tracks, which disturb the landscape in a similar way to drains, could also show variation in impacts between peatland types. Furthermore, evidence has shown that drainage can affect the hydrological regime of a catchment (section 2.2.3.2). It could therefore be assumed that tracks could have a similar effect, especially where they act as hydrological conduits.

2.3.2.3 Impacts on Vegetation

Impacts to vegetation have been addressed more frequently in the existing literature, with nine studies identified in Table 2.6 which have measured this property. The construction of tracks on peat typically requires the removal of vegetation. In addition, changes in vegetation composition have been observed around tracks, and it has been suggested this is related to changes in the hydrological regime. Lieffers and Rothwell (1987) and Bocking (2015) observed that with a shallower water table and surface flooding due to impounded water by a track embankment crossing a poor fen (section 2.3.2.2), conditions were too wet on one side of the track relative to the other and tree die-back occurred. In contrast, a drying on the other side of the track resulted in change in species to those preferring drier conditions. A disturbance to vegetation composition either side of a trunk road running through heathland (UK) has also been observed (Angold, 1997), with an increase in the abundance of *Molinia Cerula* and decrease in *Lichen* spp. abundance. A distance effect was also found with a decrease in the abundance of *Calluna vulgaris* with proximity to the road. In this case the shift in vegetation composition has been attributed to a change in soil chemistry due to the presence of the road.

With respect to unsurfaced tracks, most of the impacts to vegetation cover are considered directly along the track route. Creation of unsurfaced tracks by vehicles is typically associated with loss of vegetation cover and an increase in the occurrence of bare peat on peatlands ranging from blanket peat to fens (Chapin and Shaver, 1981, Charman and Pollard, 1995, Arnesen, 1999, Robroek et al., 2010). Tracks in arctic tundra environments can change the thermal profile of the peat, leading to changes in the vegetation composition. Such changes can be attributed to the presence of the track as they were not observed off-track (Challinor and Gersper, 1975, Chapin and Shaver, 1981). Some species are more resistant to the effects of driving than others; (Sparrow et al., 1978) observed sedges preferentially remained following disturbance by off-road vehicles. Following the creation of tracks by military vehicles on a blanket peatland in the UK, (Charman and Pollard, 1995) identified a shift from blanket bog communities to grassland heath communities. Tracks on blanket peat which had been abandoned for 24 years showed poor recovery of vegetation to undisturbed conditions.

Trampling over peat also results in loss of vegetation cover and change in species composition (Calais and Kirkpatrick, 1986, Arnesen, 1999, Robroek et al., 2010). The anastomosing of tracks, through both vehicle use and human trampling, can extend the area of influence of a track and is often first evidenced through an increasing loss in vegetation cover. Calais and Kirkpatrick (1986) measured impacts of tracks on shallow peat soils and valley peats as disturbance was ongoing. They observed greatest effects of trampling within the first few months, after which point the level of disturbance plateaued. This study also considered the effect of number of passes over the track and the slope angle in addition to peat depth, altitude and aspect and initial vegetation cover. Although not significant, slope angle was found to influence the magnitude of effect. By comparison, the tracks included in Robroek et al. (2010) were at a single topographic location on blanket peat.

Most studies adopt a before and after set up or disturbed/undisturbed set up. In the case of Robroek et al (2010) ‘disturbed’ tracks with different times since abandonment were compared with a control track (a nearby undisturbed area of peatland). Robroek et al (2010) observed that bare peat occurrence was lower in the oldest abandoned tracks compared with the more recently abandoned track. Whilst *Sphagum* recovery was rapid in this study, it was not matched by the recovery of *Calluna vulgaris* or *Eriophroum angustofolium*. Arnesen (1999) investigated recovery of vegetation cover after trampling on a fen peatland. Recovery was seen to be slow after 15 years since trampling and vascular plants had been impacted more than bryophytes. The dominant vegetation type also differed between trampled and undisturbed areas.

It is apparent from the literature that the vegetation present before disturbance can influence the level of impact observed. In addition, the mode by which the track has been formed appears to have an influence. It is difficult to draw direct comparisons between studies, however, as the peatlands on which they take place differ and will be subject to different hydrological regimes, as well as the initial peat properties which have the potential to influence the magnitude of response to disturbance.

2.4 Chapter Summary

Disturbances to peatlands such as drainage, harvesting, burning, afforestation, and the installation of power lines and pipe lines disrupt the natural functioning of these systems. Effects are exhibited through changes to numerous properties central to peatland processes, including bulk density, porosity, moisture content, hydraulic conductivity, and water-table depth. In turn, changes in these properties are manifested as alterations in dominant flow pathways and catchment hydrological regimes, which all have implications for peatlands acting as stores of carbon. The response of peatlands to disturbance varies between peatland (peat) type (e.g. fibrous versus amorphous peat), location within the peatland (e.g. topographic position), the intensity of disturbance (e.g. density of drainage ditches) and time since disturbance (e.g. age of burning). Whilst some disturbances affect a wide area because of their spatial coverage (e.g. burning, harvesting and afforestation), others may have a smaller immediate footprint, but their impacts can be observed at the wider spatial scale (e.g. drainage, pipelines and powerlines).

Linear disturbances in peatlands are an increasingly common feature (Turetsky and St. Louis, 2006). Whilst drainage, seismic lines, pipelines and powerlines have been given due consideration in the literature, the impact of tracks in peatland environments is limited. As with other linear disturbances, tracks have the potential to impact peatland functioning not only within their immediate footprint but at a wider spatial scale. Such effects have been observed in non-peatland environments (section 2.3.1). Tracks in peatland environments are split into two main groups: constructed and unsurfaced. Constructed roads are typically those which involve the construction of an embankment on the peat surface or cutting into the peat. Newer types of tracks are being used in peatland environments which sit between constructed and unsurfaced tracks (Grace et al., 2013), although presently the impacts of these have not been considered.

Much of the literature within this subject area is formed from technical reports and grey literature. The evidence base from peer-reviewed work is limited. Within peatland environments a large proportion of work is focused on peat compression under embankment construction and the engineering challenges associated with building on peat. Monitoring of impacts is predominantly restricted to bulk density and degree of compression, and properties such as hydraulic conductivity are not as frequently addressed. The same is true for unsurfaced tracks as well, whether they have been created by vehicles or human/livestock trampling. Impacts to vegetation from track use have also been considered in the literature, although this is predominantly in relation to unsurfaced tracks. Despite the importance of hydrology in peatlands, understanding of the impact of tracks on peatland hydrology is severely limited. Whilst a limited number of studies addressed the effect of constructed (embankment) tracks, the effect of unsurfaced tracks is virtually unknown. In addition, it is difficult to draw comparisons between existing studies due to the wide variety in peatlands, track types, vehicles, frequencies of use, properties monitored and experiment set-ups considered. As was outlined in section 2.3.1 these are all influential factors which can affect the magnitude of impact. Based on evidence from other disturbances to peatlands, Figure 2.6 provides a schematic of the expected impacts to peatland properties following track construction or establishment.

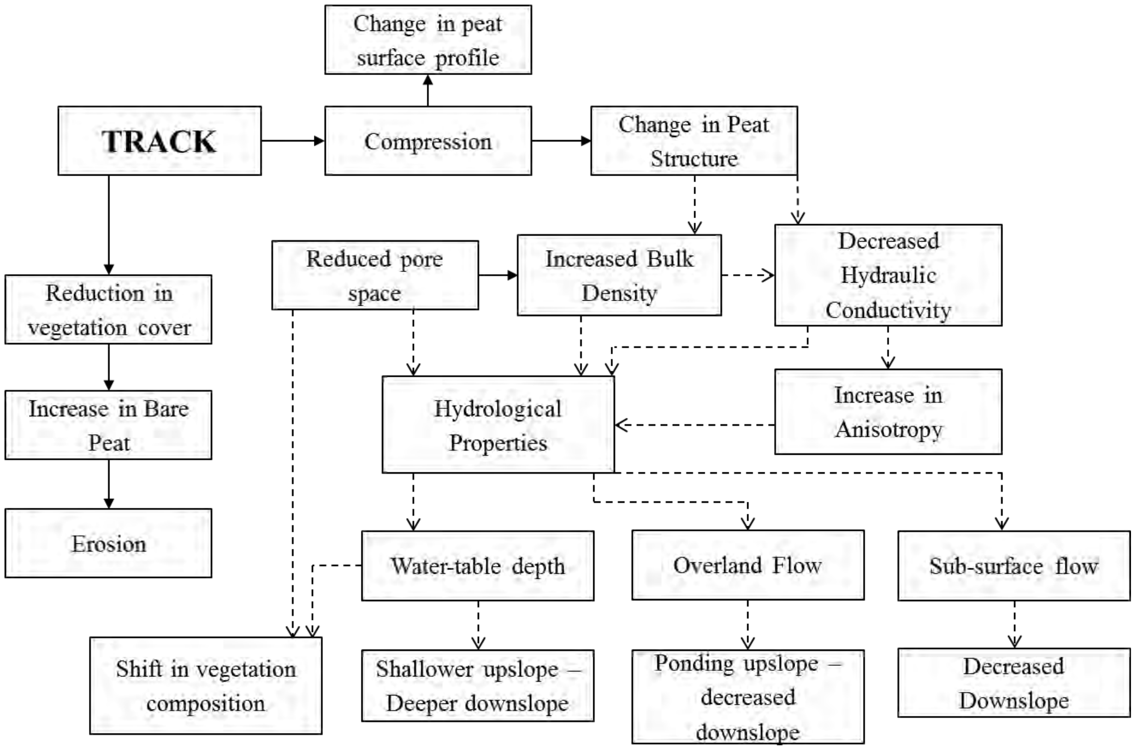

Figure 2.6 Conceptual diagram of links between different peatland properties and impacts following track construction and use. Solid links show current evidence exists, dotted links are suggested impacts or those based on anecdotal evidence.

With respect to the impact of tracks in peatlands, there are clearly large research gaps still to be addressed. More specifically, it has become apparent through the review of previous studies, that the impact of tracks on blanket peat is under-represented in the scientific literature, as highlighted by Table 2.6. A small number of studies have investigated impacts to vegetation following the creation of unsurfaced tracks by vehicles or human trampling. However, there does not appear to be any published evidence of the impact of vehicle tracks (constructed or unmade) on physical properties and hydrological processes in blanket peatlands. Blanket peatlands differ considerably from other peatland types in that they are independent from topography for their formation and consequently can occur on relatively steep slopes. Consequently, there is potential for tracks to have greater impacts on blanket peatlands due to topographic influences. Given the widespread use of vehicles in blanket peatlands this is clearly an important area for research.

2.5 Research Gaps

This synthesis of the existing literature has highlighted a number of research gaps relating to the impact of tracks on key aspects of peatland functioning, namely: physical properties, hydrological properties, and vegetation composition, as evidenced through the studies included in Table 2.6. In the context of a blanket peatland, the specific research gaps which will be addressed within the following thesis are outlined in Figure 2.7.

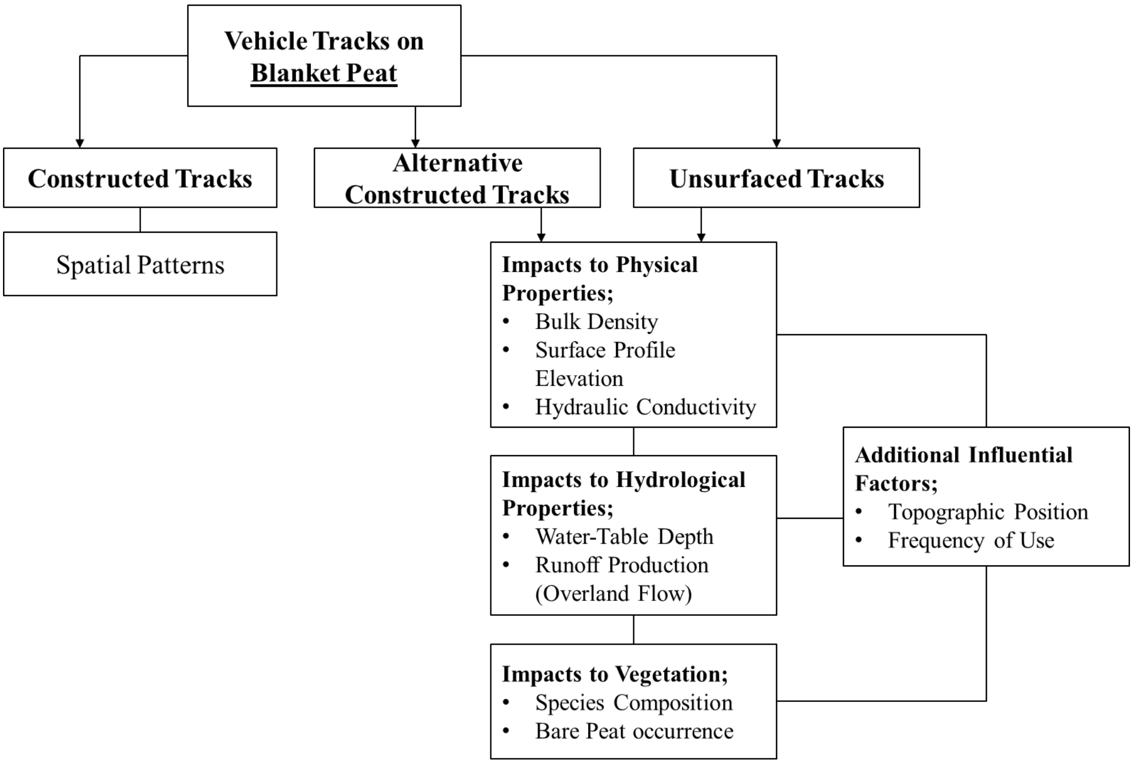

Figure 2.7 Research being undertaken in this thesis to address current research gaps, with specific reference to impact of vehicle tracks in blanket peatland environments.

CHAPTER 3: SITE SELECTION AND DESCRIPTION

This project was designed in two parts: (i) a regional survey across the North of England to investigate general patterns of track impacts and (ii) an intensive study on Moor House NNR to examine impact of tracks on peatland properties in more detail. The experimental design was developed with advice from a stakeholder advisory group who provided guidance on typical track use on a moorland. The resultant design provided a balance between an ideal experimental set up and practical application to ensure the project outcome was a meaningful representation in terms of track use in a blanket peatland environment.

3.1 Regional survey

Locations in the north of England (North Pennines and Cheviots) were identified for a regional study of tracks on working estates. Stakeholder engagement was undertaken to find suitable locations, with requests being sent out for sites which offered a range of different track types, including stone, plastic, unsurfaced and other alternatives such as corduroy roads (Section 2.3.2), as well as tracks of different ages and with different topographic settings. All tracks were required to cover blanket peat, although the land surrounding the tracks may have been subjected to a range of management conditions such as burning, grazing and drainage. Blanket peat cover was verified using data from the North Pennines AONB. Six working estates were identified for inclusion in the study, located in the North Pennines (n = 4) and the Cheviots (n = 2). Selected tracks on Moor House NNR (see section 3.2) were also included in the study. Multiple track sections from now on referred to as 'reaches' were identified for measurement at each site. The total number of track reaches surveyed was 29.

Typical vegetation of northern blanket peatlands was found at each site with coverage dominated by *Calluna vulgaris, Eriophorum vaginatum, Eriophorum angustifolium* and *Sphagnum* spp. In some locations *Polytrichum commune* and *Phragmites australis* were also found to be present, but with a lower percent cover. Table 3.1 provides background information for the estates used. Full details of the methodology used for data collection is provided in Chapter 4 with detailed descriptions of each track reach included in the study.

Table 3.1 Descriptions of regional study sites, more detailed descriptions are provided in Chapter 4.

Site Name	Location	Land Management	Location	Altitude Range (m)	Track Types	Number of Reaches
Birkdale	North Pennines	Burned, Drained & Grazed	54°38'N 2°19'W	533 - 580	Stone	3
Garrigill	North Pennines	Burned & Drained	54°43'N 2°25'W	578 - 651	Stone & Plastic	6
Lilburn	Cheviots	Burned	55°27'N 2°06'W	388	Stone	1
Linhope	Cheviots	Burned	55°29'N 2°02'W	478	Plastic	1
Moor House	North Pennines	Grazing	54°41'N 2°22'W	540 – 559	Stone, Plastic, Unsurfaced & Wooden	6
Wemmergill	North Pennines	Burned & Drained	54°34'N 2°13'W	405 – 572	Stone	9
Whelhope	North Pennines	Burned	54°48'N 2°19'W	556 – 558	Plastic	3

3.2 Intensive Study on Moor House NNR

3.2.1 Site Description

The largest component of this project was an intensive study that was mainly focused on the impact of plastic mesh track use with low-ground-pressure vehicles. A plastic mesh track was installed specifically for the purpose of this project. It was required that the track should be installed on an accessible but relatively undisturbed peatland, in order to avoid confounding variables such as the effects of burning, drainage, and erosion. Given these requirements a suitable location was found on Moor House National Nature Reserve. Using Moor House provided the added benefit of access to existing background data on the ecology and geology of the site in addition to long-term rainfall and temperature records.

Moor House is located in the North Pennines, UK (54° 41' N, 2°22' W), a designated Area of Outstanding Natural Beauty (Figure 3.1) and covers an altitude of 450 to 893 m (Billett et al., 2010). The climate is classified as subarctic oceanic with mean annual temperatures of 5.8° and mean annual rainfall around 2012 mm, although a warming trend has been observed in the temperature and rainfall records with increases in winter temperatures and smaller diurnal variation since 1931 (Holden and Rose, 2011).

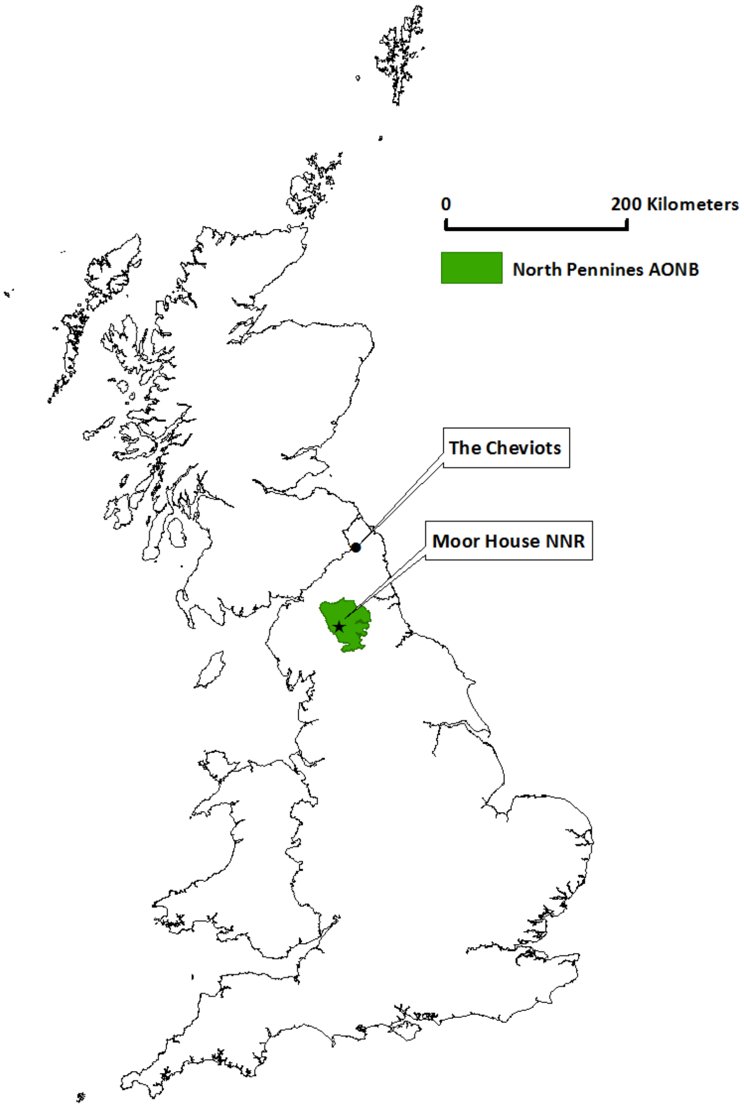

Figure 3.1 Location of Moor House NNR in relation to Great Britain. North Pennines AONB and the Cheviots (locations of sites in the regional survey) are also shown © Ordnance Survey, 2016.

Valley peats, flush peats and blanket peatlands have formed on the site, with peat formation initiating in the late Boreal around 8,000 BP (Johnson and Dunham, 1963). The underlying geology of the area is a mix of carboniferous limestone, sandstone and shale, overlain by impermeable glacial boulder clay (Johnson and Dunham, 1963). Blanket peat depths range between 0.5 m on some of the steeper slopes to > 4 m in some flatter areas. Moor House presents one of the most extensive and least damaged areas of M19 classified peatland in England, according to the National Vegetation Classification (NVC) code. It is dominated by *Calluna vulgaris-Eriophorum vaginatum* species, with an understory of *Sphagnum* spp. (Averis et al., 2004). Pools and hollows which are synonymous with wetter peatlands are not typically found in *Calluna vulgaris-Eriophorum vaginatum* dominated environments, although wetter channels may contain *Eriophorum angustofolium* (Averis et al., 2004). There has been limited disturbance (burning and drainage) to Moor House in the last 60 years and with limited grazing (ave. 0.5 sheep per ha) it renders it a suitable location to study a (relatively) ‘pristine’ blanket peatland environment.

The area of Moor House identified for experimental track installation fulfilled a number of requirements including easy access for installation, frequent driving, and regular monitoring. It also offered a large expanse of relatively undisturbed blanket peat where different treatments could be established, and a range of topographic locations were covered in line with the key research questions outlined in the introduction (Section 1.3). The location of the study site within Moor House is outlined in Figure 3.2. The elevation of the area ranged from approximately 540-560 m a.s.l, with an average slope angle of 5°.

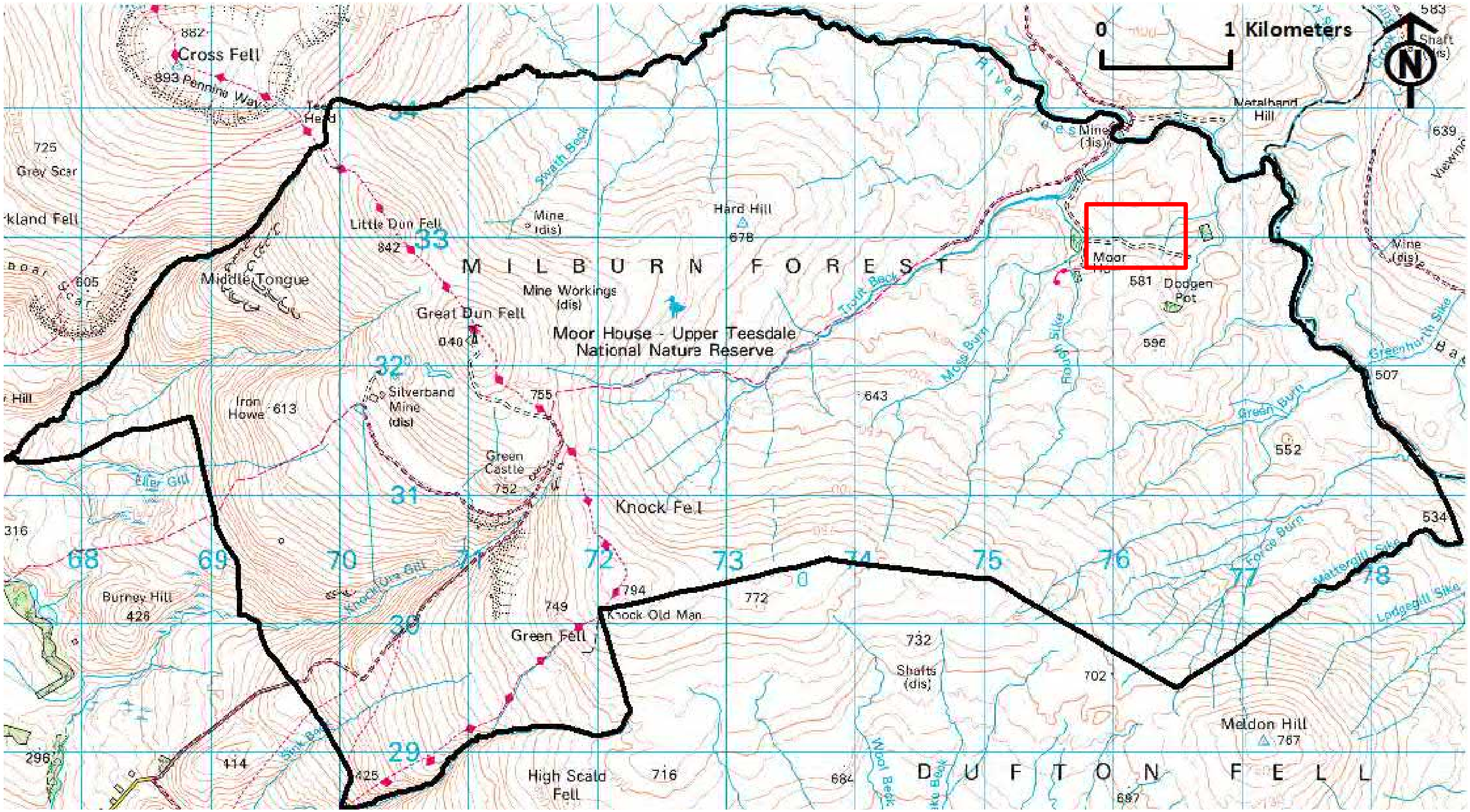

Figure 3.2 Area covered by Moor House NNR (black line) and location of intensive study site within Moor House (red box). © Ordnance Survey, 2016. Moor House NNR outline available from: https://data.lter-europe.net/deims/site/bf78c96f-0763-4b31-b1a6-6eccef19edd1

3.2.2 Track Route Design

Installation of a track specifically for the purpose of the project ensured the environmental variables which may influence hydrological responses (e.g. climate and peat type) were accounted for. In addition, the influential factors of track type, topographic location and frequency of use could be effectively controlled, whilst ensuring the track route represented reality as much as possible. Finally, the track installation process could also be closely monitored.

The track route design for the intensive study included three track types. Two previously untested tracks were made available to the project: a plastic mesh track suitable for low-ground-pressure vehicles, and an articulated wooden track suitable for 4x4 vehicles. Further details of the plastic mesh and articulated wooden track are provided in Table 3.2. The third track type was an 'unsurfaced' track, where driving by the low-ground pressure-vehicle would occur directly over the vegetation. This was included following discussion with the stakeholder advisory group.

Table 3.2 Characteristics of the plastic mesh and articulated wooden tracks installed at the Moor House experiment site

Characteristics	Plastic Mesh Track	Articulated Wooden Track
Total Length	~1.5 km	~ 0.3 km
Manufacturer	Terram	John Carrick
Material	UV Stabilised HDPE	Oak Planks (n = 94), Steel Links (n = 186), HDPE Underlay
Dimensions	2.5 m x 15 m (section size) 0.0145 m (thickness)	3.2 x 0.15 x 0.1 m (Single Plank) 0.45 x 0.28 x 0.1 m/ thickness – 0.05 m (Single Steel Link)
Weight	2 kg m^{-2}	184 kg m^{-2}

Typically, previous studies have investigated three of four frequencies of use in order to comprehensively investigate track impacts (e.g. Racine and Ahlstrand, 1991, Alakukku, 1996a, Pickering et al., 2011, Nortje et al., 2012). Discussions between myself and the stakeholder advisory group led to recommendations being made for the different frequencies of use to be adopted in this project. The primary focus of the intensive study was the impact of the plastic mesh track; consequently this was divided into multiple treatments (frequencies of use). The articulated wooden and unsurfaced tracks were subject to one treatment each. The different treatments had to be representative of typical track use in upland environments throughout the year.

Plastic mesh tracks, if applied more widely to upland peatlands in the UK in the future, are expected to have the most intensive use between late summer and autumn (August to October) in line with grouse shooting operations. It was important therefore to include a treatment for the plastic mesh track with increased usage in the autumn. Vehicles used for grouse shooting in the autumn months would also be heavier due to the transportation of people on shooting parties. To incorporate this into the treatment design, a duplicate of the treatment with increased shooting season use was implemented but with additional weight added. An idealised representation of track use during the grouse shooting season was therefore established by inclusion of two treatments with additional passes in the autumn, one driving unloaded during this period and one driving loaded with weights to represent passengers.

On the advice of the manufacturers of the plastic mesh track, a treatment was included where the track was left to settle for an additional ten months prior to commencement of driving. The plastic mesh track theoretically allows vegetation to grow through the spaces within the mesh thereby allowing improvements in track aesthetics in the wider landscape and also offering the potential to limit the impact of the track by allowing natural growth and regeneration. The growth of vegetation through the track is also thought to 'knit' the track to the surface and prevent buckling and lifting which would limit the protective use of the track.

Ultimately, five treatments were determined for the plastic mesh track (**PWEEK.AL, PWEEK.AH, PWEEK, PMONTH, PDELAYED**) a comparable treatment for the unsurfaced track (**U**) and a treatment representative of expected use for the articulated wooden track (**W**). It was important for the treatments to be a suitable representation of real world usage, covering a rage of possible intensities of use. In conjunction with this practical limitations were placed on the amount of plastic mesh tracking that was available to the project, in part due to cost of the material. Consequently the experiment at the Moor House site was focused on including a number of frequencies and did not replicate only one or two treatments. Table 3.3 provides full descriptions of the different treatments.

The track route design therefore had to include the five treatments for the plastic mesh track, a section for the unsurfaced route and an area for the articulated wooden track. As these tracks were traversing blanket peat which can cover steeper slopes, the influence of topographic location was a key research area for this study (Section 1.2.3). Consequently, with the exception of the articulated wooden track, all treatments needed to cover the same range of topographic locations so that this could be addressed. In order to ensure a treatment covered a range of topographic locations, a hillslope profile was roughly divided into three sections; a top-slope, a steeper middle-slope and a shallower bottom-slope, from hereon in referred to as S1, S2, and S3 respectively..

Table 3.3 Description of the characteristics of each driving treatment. Characteristics of the control treatment are also included.

Treatment	Weekly Usage (passes over track per week)	Total No. Passes	Topographic Positions	Track Type	Vehicle Type	Additional Information
PWEEK.AL	2 (April – End July, October - April) 10 (End July – October)	412	S1, S2, S3	Plastic Mesh	Argocat	
PWEEK.AH	2 (April – End July, October – April 10 (End July – October)	412	S1, S2, S3	Plastic Mesh	Argocat	Vehicle Weighted (End July to October)
PWEEK	2	156	S1, S2, S3	Plastic Mesh	Argocat	
PMONTH	0.5	38	S1, S2, S3	Plastic Mesh	Argocat	
PDELAYED	2 (from February 2015)	76	S1, S2, S3	Plastic Mesh	Argocat	
U	0.5 (stopped April 2015)	24	S1, S2, S3	Unsurfaced	Argocat	Driving over vegetation, no track surface
W	10	780	S3	Wooden Beams	4x4 vehicle	30 m length of track
C	0	0	S1, S2, S3	Unsurfaced	None	No driving or track, undisturbed hillslope control

A combined approach of using GIS and on-site ground truthing was utilised to determine a suitable layout for the experimental track route. Potentially suitable routes were tested through the creation of topographic index (TI) maps, similar to the approach used by Dixon et al. (2004)

The equation used to determine the topographic index (TI) is as follows;

$$TI = \ln (\alpha/\tan\beta)$$

where α is the upslope contributing area per unit contour length, and β is the local topographic gradient (Beven and Kirkby, 1979). A 5 m resolution filled DEM (sinks removed) was used to generate the slope, flow direction (using a multiple flow direction model) and flow accumulation layers required to create the topographic index.

A TI map was created for the site of the experiment track route on Moor House. Model I represented the TI map before the inclusion of a track (Figure 3.3). Potential track routes placed upon Model I were then explored within GIS to ensure that: (i) the track route covered a range of topographic locations (each treatment needed to cover a range of wetness index values indicative of different slope positions), (ii) all treatments were hydrologically independent of each other, and (iii) the treatments were sufficient in length to provide a representative view of hydrological response to track installation. The three topographic locations were differentiated by the combination of wetness index values and slope angles, as well as the position on a hillslope profile when in the field. Table 3.4 outlines the characteristics used to determine and define each topographic location to be included in each treatment along the track route.

Table 3.4 Characteristics used to define the three topographic locations (S1, S2 and S3) to be included in each treatment (except treatment **W**)

Topographic Location	Position on 'idealised' Slope Profile	Defining Characteristics	Topographic Index Value	Slope Angle
S1		- Shallower Slope Angle - Low wetness index values (indicative of drier water shedding conditions)	~ 4.8-6.0	~ 0-4°
S2		- Steeper Slope Angles - Lower wetness index values	~ 5.6-7.0	~ 4-8°
S3		- Shallower Slope Angles - Higher wetness index values (indicative of wetter, water collecting locations)	~ 7.0-9.0	~ 0-4°

The DEM was carved out to a depth of 1 m along potential track routes, creating a TI map 'including' a track (Model II) (Figure 3.4). Impact to a depth of 1 m was an overestimation for the track types included in this intensive study, however, it was a suitable nominal value to ensure a careful approach to defining the track route and avoid interaction effects between sections of tracks. Model III shows the areas of maximum potential track impact (Figure 3.5). This was created by subtracting Model II from Model I.

Determination of the best route in the model was ground truthed in the field using GPS. Influential variables in the track route design included treatment, topographic location and track type. Therefore, further complicating factors such as gullies or areas of markedly different vegetation had to be avoided. Ground truthing identified unsuitable sections of the proposed route, e.g. traversing areas dominated by *Juncus effuses*, as opposed to the more typical *Calluna vulgaris–Eriophorum vaginatum* cover. Improvements to the proposed track route were made following ground truthing. A new model was created for the improved route following the same original process to ensure that all criteria were met (range of topographic locations, hydrologically independent, suitable treatment length). Figure 3.6 outlines the final track route, including the locations of the different treatments and topographic locations.

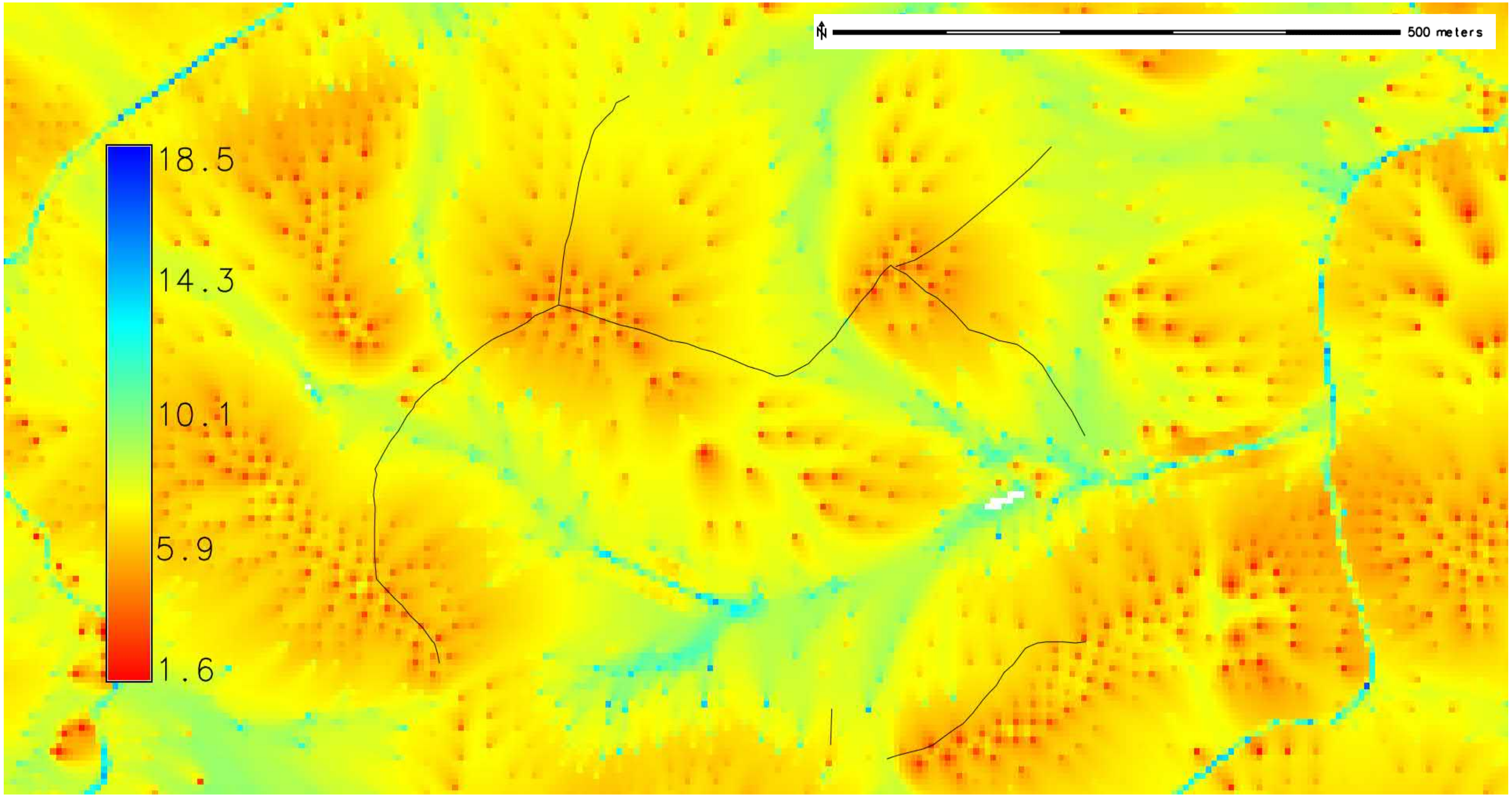

Figure 3.3 TI map for the selected track site on Moor House before the inclusion of a track route in the model (Model I). The driest locations are shown in red and the wettest locations in dark blue.

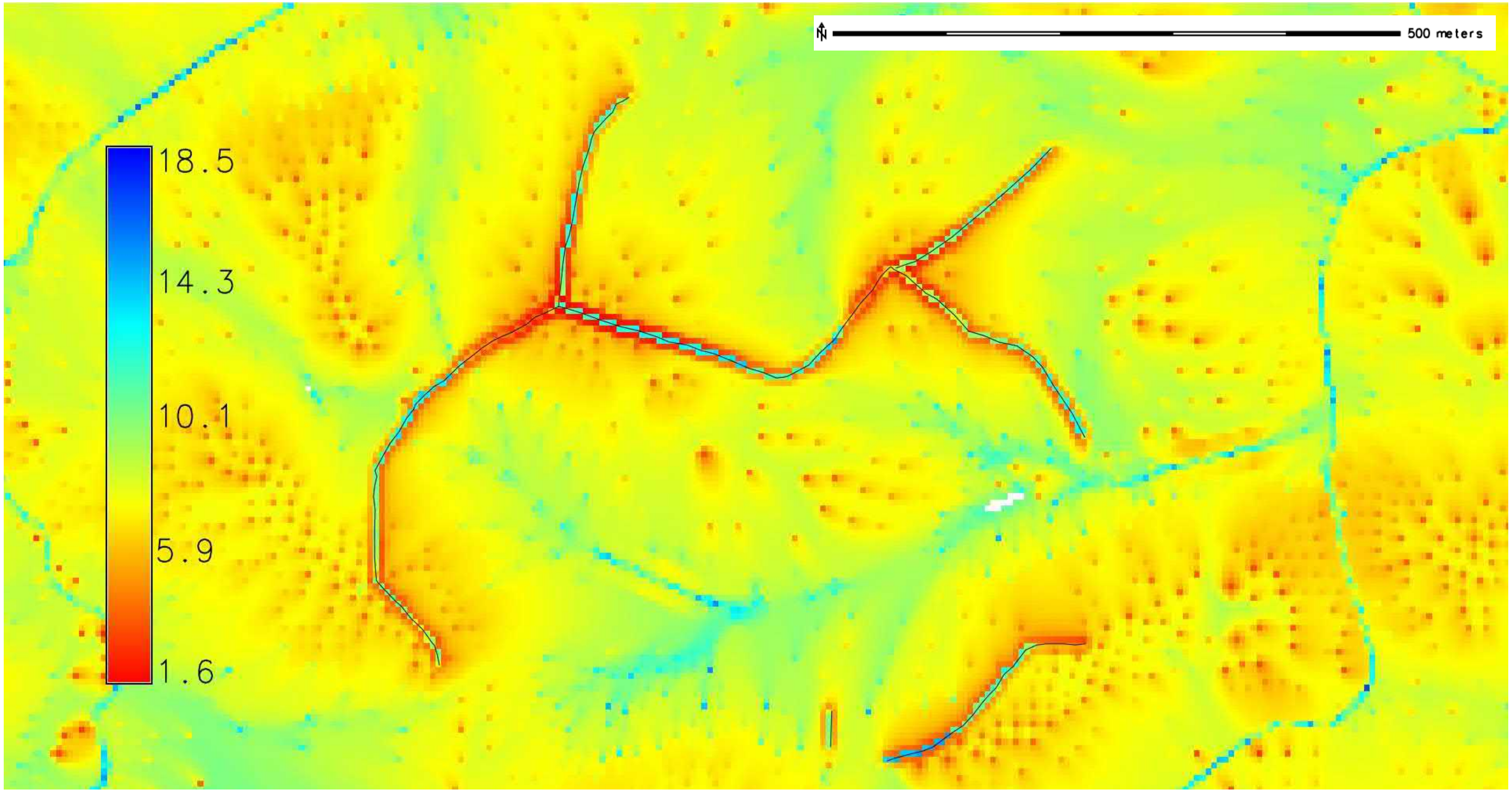

Figure 3.4 TI map of the selected site for the track on Moor House 'including' the track route in the model (Model II). The driest locations are shown in red and the wettest locations are shown in blue.

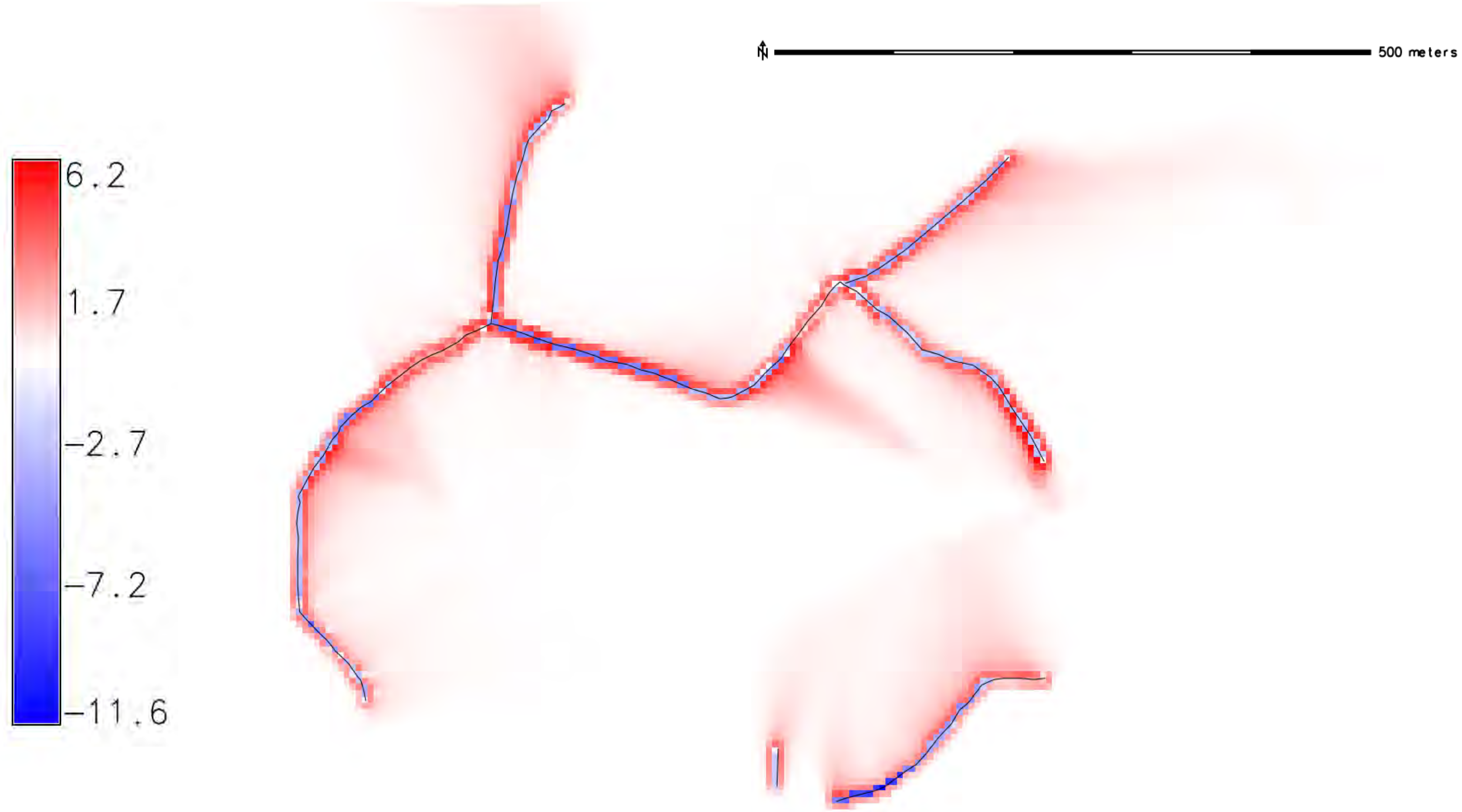

Figure 3.5 Difference map showing the maximum potential change in wetness following the inclusion of the track route in the model (Model III = Model I minus Model II). Areas of drying are shown in red and areas of increased wetness are in blue.

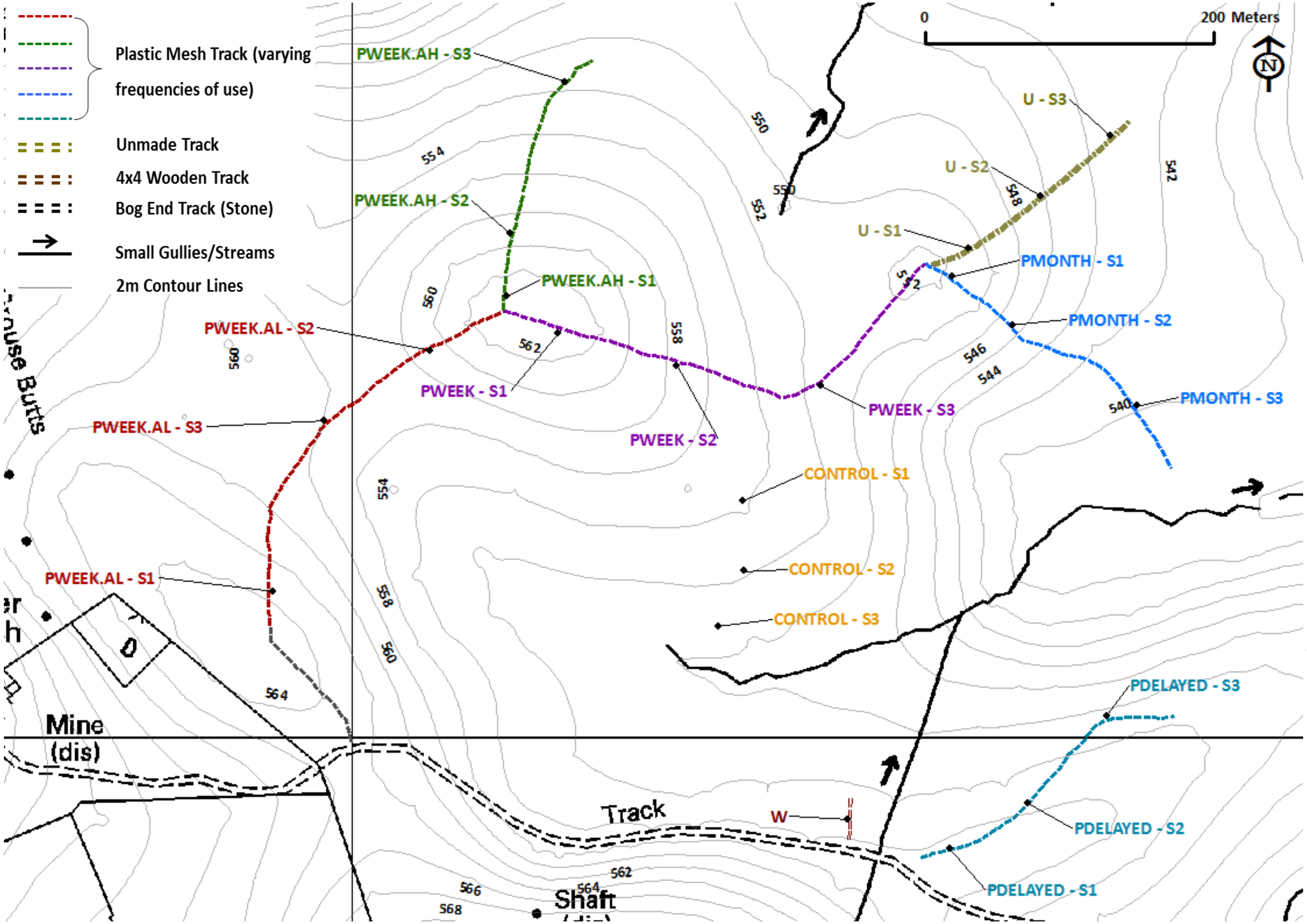

Figure 3.6 Track route installation on Moor House NNR. The three track types are shown; plastic mesh (5 treatments), unmade track (1 treatment), and articulated wooden track (1 treatment). Breakdown of topographic locations are shown for each treatment. Control treatment area is highlighted in yellow.

The orientation of the plastic mesh track to the slope contours and therefore the flow direction pathways varied by topographic location. This arrangement was supported by observations made during visits to working estates where plastic mesh tracks were already installed prior to the Moor House experiment, and further verified during the regional survey. A schematic diagram of the orientation of the plastic mesh, articulated wooden (S3 only) and unsurfaced tracks to the contours and therefore typical flow directions at each topographic position is presented in Figure 3.7. At topographic location S1 the track was typically on the flat, at topographic location S2 it was perpendicular to the contours (i.e. straight up and down the hill) and at topographic location S3 it was parallel or diagonal to the contours, cutting across flow direction pathways.

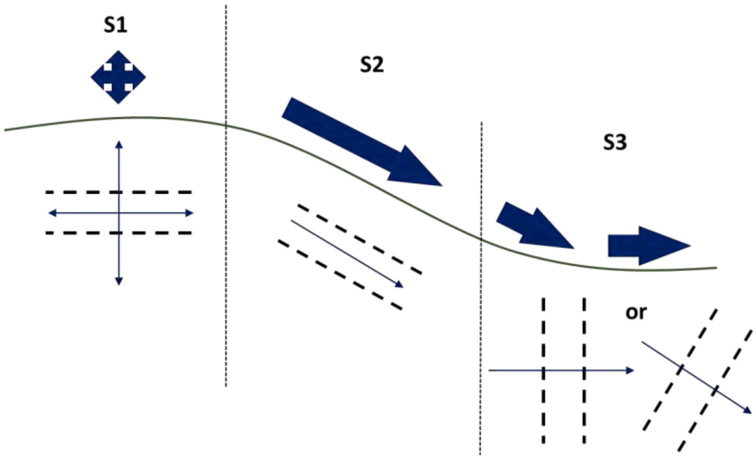

Figure 3.7 Schematic of breakdown of the hillslope profile within each treatment (excepting treatment **W**). Expected direction of water flow on undisturbed hillslope is presented (thick blue arrows) and the orientation of the track (dotted black lines) to the contours and flow direction (thin blue lines) at each topographic is also shown.

3.2.3 Track Installation

A SOFTRAK low-ground-pressure vehicle was used to install the plastic mesh track in July 2013 (Figure 3.8a). Using a forager attachment, excess cut vegetation was removed from the track route, and blown to the sides (Figure 3.8b). The cut vegetation was removed to promote new vegetation growth. Placing the matting directly on top of the cut vegetation may have hampered vegetation regrowth, resulting in a layer of dead vegetation under the track. The plastic mesh was rolled out by hand (Figure 3.8c) and pinned into place using 0.3 m length metal staples (Figure 3.8d). The plastic mesh was pinned down to keep it in place until sufficient vegetation was able to knit through the gaps in the mesh and prevent track movement.

The articulated wooden track was installed in September 2013. A tractor with mower attachments was used in the installation of this track type. Vegetation was cut along the predetermined route and removed. A thinner plastic mesh was then laid over the top of the cut area and the wooden beams (oak) forming the track were put into place by hand, connected together with metal links (Figure 3.9). This track works on tension to prevent it from sinking into the peat. Piles were therefore installed at either end of the track length and the inter-linking beams were stretched between.

Figure 3.8 a-d a) Cutting of track route using a SOFTRAK with mower attachments, b) Removal of excess cut vegetation along track route using the SOFTRAK with forager attachment, c) Positioning of plastic mesh along route, and d) pinning of track route into place. Photos a) and b) courtesy of Alistair Lockett (North Pennines AONB Partnership).

Figure 3.9 a-b Installation of wooden 4x4 track on Moor House NNR. a) Cut track route with thin plastic mesh and b) Oak beams laid along track route, connected with metal links. Photos courtesy of Andy Lloyd.

3.2.4 Equipment Set-up and Monitoring Regime

Two main approaches were used for the data collected for the intensive study on Moor House: (i) before/after, and (ii) continuous. The properties measured for this project, the frequency of data collection and the relevant chapter are presented in Table 3.5. Full details of equipment installation, sample collection and analysis relevant to each peatland property measured are provided in the respective chapters. Hourly rainfall and temperature data used in Chapters 5, 6 and 7 was provided by the Environmental Change Network (ECN) and from their weather station located at Moor House.

As indicated in Figure 3.6 and Table 3.2, an area of the study site was designated as a control treatment where there was no disturbance to the peat. Sample collection and equipment set-up within this treatment (**C**) was carried out in exactly the same way as in the track treatments. The control treatment provided background data collected from the same time period as the disturbed treatments.

Table 3.5 Data collection approach and sampling frequency for each variable measured in the intensive study and relevant chapter in thesis.

Peatland Properties	Data Collection Frequency	Field Installation of Equipment	Laboratory Analysis	Relevant Chapter
Bulk Density	Before/After	-	Yes	5
Hydraulic Conductivity	Before/After	-	Yes	5
Surface Profile Elevation	Before/After	-	-	5
Water-Table Depth	Continuous	554 Dipwells	-	6
Overland Flow	Continuous	120 Crest-Stage Tubes	-	6
Vegetation Composition	Before/After & Monthly (Treatment U only)	-	-	7

3.2.5 Driving Regime

Driving over the plastic mesh, articulated wooden track and unsurfaced track commenced on 4th April 2014, when the plastic mesh track had been installed for eight full months and the articulated wooden track for six full months. A schedule of driving was designed and driving was undertaken every fortnight until the 4th November 2015. Table 3.2 provides the driving information for the different treatments, including the topographic locations covered, the number of passes each week and the total number of passes in each treatment over the study period. Whilst the number of passes in each treatment could be seen as a conservative estimate of typical use, in a ‘real world’ situation there would be times in the year when the track was not used at all, and other times when it would be used more frequently. This approach of using a controlled set-up allowed for the capture of ‘real world’ variability. Poor weather conditions and site inaccessibility suspended driving briefly in January and February 2015.

Driving on the plastic mesh and unsurfaced treatments was undertaken using an Argocat capable of transporting six people (or four people plus kit). From mid-June to the end of October each year the Argocat was weighted for driving over treatment **PWEEK.AH**. The additional weight added to the vehicle during these months was ~375 kg, calculations were based on an average male weighing 83.6 kg (ONS, 2010) and average kit weighing 10 kg per person (Moorland Association, *pers. comm.*). Driving over the articulated wooden track was undertaken using a 4x4 road vehicle.

Natural England granted permission for the inclusion of the unsurfaced track in the study. A condition of the use of this track type was that track use would be suspended when damage was visually observed to the vegetation and peat (as determined by Natural England Reserve Staff). Consequently, driving over the unsurfaced track was suspended at the end of April 2015, when damage had been observed.

3.3 Chapter Summary

In this chapter a general overview of the selection of study sites for the regional survey and intensive study undertaken between June 2013 and November 2015 has been provided. In addition, the methodologies for track route development and installation of the plastic mesh and articulated wooden tracks forming part of the intensive study on Moor House have been described. The regional survey will address the more general patterns of track impact, focusing on the response of a single measurement (volumetric soil moisture content) around different track types, tracks of different ages and in different topographic settings (Chapter 4). The intensive study on Moor House will allow for a more focused study of the impact to key peatland properties through the use of previously untested tracks. These properties include bulk density, hydraulic conductivity and surface elevation (Chapter 5), water-table depth and overland flow occurrence (Chapter 6), and vegetation composition (Chapter 7). All four key research areas: the influence of track type, the influence of frequency of use, the influence of topographic location, and the spatial extent of impacts, will be addressed in the intensive study.

CHAPTER 4: THE IMPACT OF TRACKS ON BLANKET PEAT – A REGIONAL SURVEY OF THE NORTH PENNINES AND CHEVIOTS

4.1 Introduction

The use and development of peatlands around the world has served multiple purposes including peat harvesting for fuel, access to oil sands, forestry enterprises (including palm oil plantations), renewable energy, agriculture and recreation activities. Associated with development is the need for vehicular access. Consequently roads and tracks, both constructed and unsurfaced, have increasingly become a feature of peatland environments (Turetsky and St. Louis, 2006, Brown, 2013). Globally, peatlands are important stores of carbon, provide freshwater, and support a range of unique habitats and biodiversity (Gorham, 1991, Littlewood et al., 2010). The development of peatlands has the potential to disrupt the natural functioning of these systems.

Although tracks are an increasingly common feature of peatland environments, the understanding of the impact of roads and tracks on peatlands is still limited. Peat is highly compressible (Hobbs, 1986) and a number of studies have considered the geotechnical challenges of constructing roads on peat (Lake, 1961, Hobbs, 1986, Barry et al., 1992, Blackwood and Vulova, 2006, Kazemian et al., 2011). Studies of the impacts beyond the magnitude of primary compression and secondary consolidation to the underlying peat (Barden, 1968, Berry, 1983, Barry et al., 1992) are minimal, however. This is surprising given best practice for road construction on peatlands advises that roads are sited and constructed to minimise their impact on natural hydrological flow pathways (Barry et al., 1995, Munro and MacCulloch, 2006, SNH and FCE, 2010). The hydrology of peatlands is central to their functioning (Holden, 2005b) and disturbance has been found to affect the ability of peatlands to store carbon (Limpens et al., 2008).

Linear disturbances in Canadian peatlands, which include seismic lines, power-line rights of way, and roads, have been found to alter flow pathways resulting from changes in the thaw depths and increase in active zones for water transport (Quinton et al., 2009, Braverman and Quinton, 2016). Differences in water-table depth either side of roads and tracks have been observed in some studies (Umeda et al., 1985, Bradof, 1992, Pilon, 2015). In addition, changes to physical properties (Ruseckas, 1998) and vegetation composition (Lieffers and Rothwell, 1987, Bocking, 2015), have been linked to changes in the hydrological conditions, resulting from the presence of a track.

Previous research has mainly focused on a single road or track in a single location. There are, however, many differences between tracks which could impact on the results which are being observed. In the UK for example, the type of track constructed on a peatland varies dependent upon peat depth and the type of vehicles using the track.

'Cut and fill' roads require the removal of the peat along the proposed route down to the mineral layer, with the void then being back filled with aggregate. Floating roads by comparison sit on top of the peat surface. Engineers consider these the preferred option for road construction on deep peat (> 50 cm) (Munro, 2004). A base of geotextile matting is laid on the peat surface before aggregate is placed on top. Typically the aggregate is graded by size so that the largest stones are placed on the bottom and become finer at the track surface. In some situations aggregate of the same size will be laid for the whole track profile and then crushed once *in-situ*. An adaptation of the 'borrow-pit' method (SNH and FCE, 2010) has also been used in UK peatlands. In a line running parallel to the proposed track route the peat is removed down to the mineral layer. Mineral soil is then extracted and placed on the peat surface forming the track route. Aggregate is placed on top of this mineral soil. The peat initially removed to access the mineral soil is put back into the newly created ditch parallel to the track. It has been suggested that with respect to 'cut and fill' roads if a more porous material is used to fill the void this could limit the potential reduction in throughflow under the track (Pilon, 2015, Chimner et al., 2016).

Recently, for use with lighter-weight low-ground-pressure vehicles, plastic tracks have been installed, which sit on top of the peat surface and require minimal ground preparation prior to installation (Natural England, Moorland Association, *pers. comm.*). It is therefore possible that a difference in the magnitude of impact on peatland hydrological properties would be evident between the different construction methods and track types.

Current best-practice guidelines for road construction on peat provides advice on suitable locations within a landscape for track construction, particularly with respect to landscape aesthetics and effects on biodiversity (SNH, 2013). However, the influence of construction location does not appear to have been given due consideration in most published studies of track impacts on peatlands. Spatial variation exists within the physical and hydrological properties of a peatland (Holden and Burt, 2003a, Holden and Burt, 2003c, Holden, 2005a, Lewis et al., 2012, Branham and Strack, 2014). It therefore follows that the impact of a track could differ depending on its location within a peatland. There is potential for the impact of a track to extend beyond its immediate footprint. Parallels have been drawn between the effects of tracks and drainage ditches on blanket peatlands, where impacts have been observed at distance from the drainage ditch (Holden et al., 2006), in some cases up to 30 m (Wilson et al., 2010). The greater the distance of impact from the track edge, the greater the impact to the peatland system as a whole. Most existing studies of tracks are located in low gradient peatlands. Blanket peatlands, however, can form on steeper slopes (up to ~ 15°). Consequently, tracks on blanket peat may have a more pronounced spatial effect than that observed in low gradient peatland systems, especially where they traverse steeper slopes. Such an effect has been observed around drainage ditches in blanket peatlands (Holden et al., 2006).

In addition to the location of the track within the peatland, magnitude of impact has been found to increase with an increasing number of passes. These observations have typically been made in relation to unsurfaced tracks on peat and non-peat soils (e.g. Eliasson, 2005). There is the potential therefore that with time since installation of a constructed track there would be greater evidence of an impact on peat properties.

Currently it is difficult to compare between tracks in previous studies due to differences in experimental design and the physical properties considered. Taking the same measurement around multiple tracks of different types and ages would allow for better comparison. The moisture content of soil influences a number of ecological, hydrological and geotechnical processes (Weiss et al., 1998, Romano, 2014). Within peatlands links exist between the soil moisture content and the depth to the water table (Price, 1997, Thompson and Waddington, 2008, Strack et al., 2009) and consequently measurement of soil moisture content provides a rapid assessment of the hydrological condition of the peat at a given point in time (Meyles et al., 2003). It is expected that wetter (ponding upslope) and drier areas (potentially deprived of water immediately downslope) are created by tracks as the tracks interrupt flow pathways. Using moisture content as a surrogate is therefore an effective way to establish whether such patterns exist.

The aim of this study was to sample several tracks across a large region to investigate whether constructed tracks impact blanket peat moisture content. The following hypotheses were tested: (i) volumetric moisture content will be higher on the upslope side of the track relative to the downslope side of the track, (ii) there will be more pronounced differences between upslope and downslope volumetric moisture content in mid-slope locations compared with flatter top- and bottom-slope locations, (iii) there will be more pronounced differences between upslope and downslope volumetric moisture content around older tracks, and (iv) a relationship will exist between volumetric moisture content and distance from the track edge, with lower moisture content closer to the track and a higher moisture content further away from the track edge. The findings of this study, covering a large spatial scale, provide context for the more intensive time-series monitoring undertaken on Moor House NNR which is dealt with in Chapters 5-7.

4.2 Methodology

4.2.1 Site and Track Characteristics

The regional survey was undertaken at six working estates, and on Moor House NNR. Five sites were located in the North Pennines and two in the Cheviots (Figure 4.1). Further information on the selection of estates included in the survey is provided in Chapter 3.

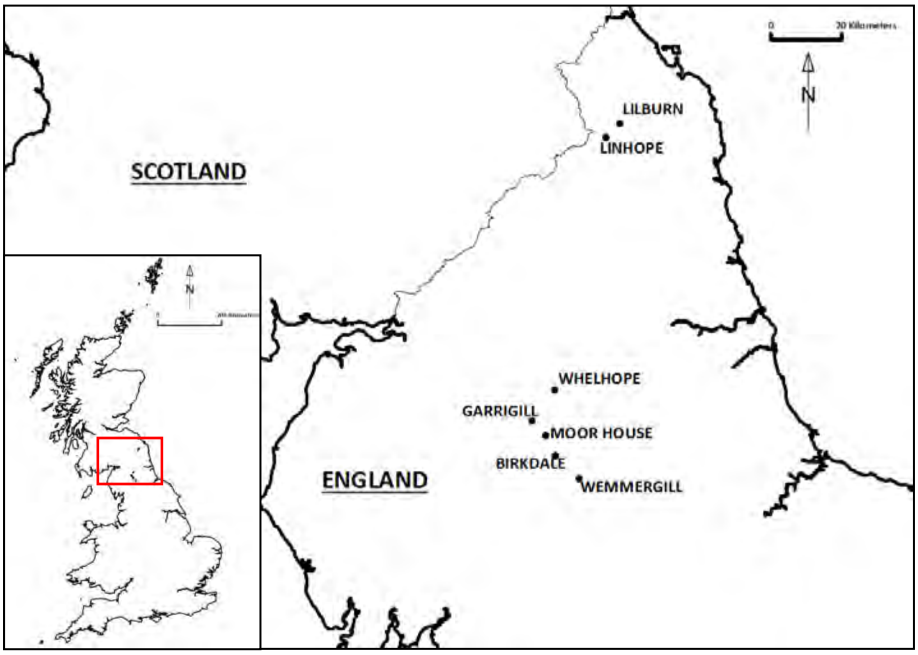

Figure 4.1 Location and names of estates used in the regional survey

The regional survey was designed to cover several track types which are representative of those typically found in blanket peatlands. Tracks included in the study were predominantly constructed from plastic or stone. Plastic tracks were either plastic mesh, similar to the type used in the intensive study on Moor House, or plastic boards (Figure 4.2). Stone tracks varied in material used (sandstone or limestone) and construction method (floating road or borrow pit) (Figure 4.3). Some stone tracks were constructed with drains on the upslope side whilst others cut across existing drainage channels and included culverts.

Figure 4.2 Types of plastic track included in the regional survey. Top image of plastic boards used in three study reaches. Middle image 2 m wide plastic mesh and bottom image 2.5 m wide plastic mesh, both constructed from UPVC.

Figure 4.3 Types of stone track included in the upland survey. Top image of a floating sandstone track. Middle image of a limestone floating track. Bottom image example of a borrow pit track, with excavation adjacent to the track (left of photo) indicated by the white arrows.

Twenty-nine track reaches, covering seventeen stone tracks and ten plastic tracks, an unsurfaced track and an articulated wooden track were surveyed. Altitudes of the reaches ranged from 388 m a.s.l to 651 m a.s.l. A track reach was determined as a 20 m length of track. For inclusion in the study, reaches were considered suitable where there was minimal disturbance (e.g. no erosion, gullies, or hagged peat) to an expanse of blanket peat 10 m either side of the track. A set of data on track context was collected at each site (Table 4.1). Table 4.2 outlines the characteristics for each track reach included in the survey.

Table 4.1 Overview of characteristics recorded for each track reach included in the upland survey

Characteristic	Description
Site Code and Reach Number	
Date	Sampling Date
Vegetation Composition	Surveying of vegetation composition to Taxonomic group level in 1 m^2 quadrats
Track Age	Time since installation, information provided by gamekeepers
Construction Method	Plastic tracks – vegetation cut or not cut prior to installation. Stone tracks – floating road, cut & fill or borrow bit method
Orientation to Slope	Direction of the track in relation to the slope; Perpendicular, Diagonal or Parallel
Topographic Location	Location of the track in the hillslope determined through visual observation. Top-, Mid- or Bottom-slope
Side	Indicating whether measurements were taken from the upslope or downslope side of the track
Distance	Estimation of distance of each measurement point from track edge using guides on markers for surveying area
Land Management Conditions	Evidence of burning, grazing, drainage or blocked drains. Information provided from visual observations and discussions with gamekeepers
Slope Angle	Determined in ArcGIS using OS 5 m DTM and GPS points recorded in field
Aspect	Determined in ArcGIS using OS 5 m DTM and GPS points recorded in field
Altitude	Determined in ArcGIS using OS 5 m DTM and GPS points recorded in field

Table 4.2 Characteristics of individual track reaches included in the regional survey (continued on pages 79-80)

Site	Reach Code	Track Type	Track Age (Years)	Topographic Location	Altitude (m a.s.l)	Orientation to Slope Contour	Slope Angle (degrees)	Aspect of Track	Land Management Conditions	Dominant Vegetation	Sampling Date (2015)
WHELHOPE	WH1	Plastic	1-5	Middle	557	Perpendicular	8-10	East	Burn	*Sphagnum* spp.	17-Mar
54°48'N 2°19'W	WH2	Plastic	1-5	Middle	558	Diagonal	4-6	North East	Burn	*Sphagnum* spp.	16-Apr
	WH3	Plastic	1-5	Middle	556	Diagonal	4-6	North East	Burn	*Sphagnum* spp. & *Calluna vulgaris*	16-Apr
GARRIGILL	GG1	Plastic	<1	Top	578	Parallel	2-4	West	Blocked Drain	*Eriophorum* spp.	18-Mar
54°43'N 2°25'W	GG2	Stone	1-5	Top	651	Parallel	0-2	East-South East	Burn	*Eriophorum* spp.	19-Mar
	GG3	Plastic	1-5	Middle	594	Parallel	4-6	East-South East	Burn and Drain	*Eriophorum* spp.	19-Mar
	GG4	Plastic	1-5	Middle	630	Perpendicular	4-6	East	Burn and Drain	*Eriophorum* spp.	2-Jul
	GG5	Plastic	1-5	Middle	640	Perpendicular	2-4	South East	Burn and Drain	*Eriophorum* spp.	2-Jul
	GG6	Stone	15+	Middle	605	Parallel	4-6	West	Drain	*Sphagnum* spp.	2-Jul
LILBURN 55°27'N 2°06'W	LB1	Stone	15+	Top	388	Parallel	0-2	Flat-North East	Burn	*Eriophoru m* spp.	21-May

Table 4.2 continued Characteristics of individual track reaches included in the regional survey

Site	Reach Code	Track Type	Track Age (Years)	Topographic Location	Altitude (m a.s.l)	Orientation to Slope Contour	Slope Angle (degrees)	Aspect4-6 of Track	Land Management Conditions	Dominant Vegetation	Sampling Date (2015)
LINHOPE 55°29'N 2°02'W	LH1	Plastic	1-5	Top	478	Parallel	0	Flat-South	Burn	*Calluna vulgaris*	21-May
MOOR HOUSE	MH1	Stone	15+	Bottom	554	Parallel	4-6	North East	Grazed	*Sphagnum* spp.	23-Jun
54°41'N 2°22'W	MH2	Stone	15+	Middle	559	Diagonal	8-10	North East	Grazed	*Sphagnum* spp.	24-Jun
	MH3	Plastic	1-5	Bottom	552	Diagonal	2-4	North East	Grazed	*Eriophoru m* spp.	24-Sept
	MH4	Plastic	1-5	Bottom	540	Parallel	0-2	Flat-South	Grazed	*Calluna vulgaris*	24-Sept
	MH5	Unsurfac ed	1-5	Bottom	543	Diagonal	0-2	Flat-North East	Grazed	*Calluna vulgaris*	24-Sept
	MH6	Wooden	1-5	Bottom	553	Perpendicular	0-2	Flat-North East	Grazed	*Calluna vulgaris*	16-Sept
WEMMERGILL	WG1	Stone	5-10	Middle	544	Parallel	6-8	South East	Burn and Blocked Drain	*Eriophoru m* spp. & *Calluna vulgaris*	21-Jul
54°34'N 2°13'W	WG2	Stone	5-10	Top	536	Parallel	2-4	South-South East	Burn and Blocked Drain	*Eriophoru m* spp.	21-Jul
	WG3	Stone	5-10	Middle	472	Parallel	4-6	East-South East	Burn and Blocked Drain	*Eriophoru m* spp.	24-Jul

Table 4.2 continued Characteristics of individual track reaches included in the regional survey

Site	Reach Code	Track Type	Track Age (Years)	Topographic Location	Altitude (m a.s.l)	Orientation to Slope Contour	Slope Angle (degrees)	Aspect of Track	Land Management Conditions	Dominant Vegetation	Sampling Date (2015)
WEMMERGILL 54°34'N 2°13'W	WG4	Stone	5-10	Middle	470	Parallel	4-6	South East	Burn and Blocked Drain	*Calluna vulgaris*	24-Jul
	WG5	Stone	5-10	Bottom	446	Parallel	4-6	South East	Burn and Blocked Drain	*Calluna vulgaris*	24-Jul
	WG6	Stone	5-10	Middle	549	Parallel	2-4	South	Grazed and Drained	*Eriophoru m* spp.	6-Aug
	WG7	Stone	5-10	Middle	572	Parallel	2-4	Flat-South	Grazed and Drained	*Callulna vulgaris*	6-Aug
	WG8	Stone	5-10	Middle	442	Parallel	6-8	South East	Grazed and Drained	*Polytrichu m* spp. & *Phragmites*	3-Sept
	WG9	Stone	5-10	Bottom	405	Parallel	0	Flat-South	Cut, Grazed and Drained	*Sphagnum* spp. & *Calluna vulgaris*	3-Sept
BIRKDALE 54°38'N 2°19'W	BD1	Stone	15+	Top	580	Parallel	4-6	South East	Grazed	*Eriophoru m* spp.	5-Aug
	BD2	Stone	15+	Top	564	Parallel	0-2	East-South East	Hagged, Burned, Drained, Grazed	Bare Peat	5-Aug
	BD3	Stone	15+	Top	533	Parallel	2-4	South East	Burning and Grazed	-	5-Aug

Plastic mesh tracks were typically found to be installed on flatter areas or where there was minimal slope (categorised as parallel to the contours); when found on steeper slopes, they were typically installed perpendicular to the contours (i.e. the direction of travel was straight up and down slope). Consequently, there are few examples of clearly defined upslope-downslope arrangements around plastic mesh tracks. By comparison, stone tacks were typically installed parallel or diagonal to the contours (i.e they cut across flow pathways), and upslope-downslope sides could be more easily identified for these tracks. At the sites included in the regional survey, plastic and stone tracks were found at all topographic locations (top-, mid, bottom-slope), although plastic tracks were predominantly located at top- and mid-slope locations. It should be noted that the majority of track reaches were installed on slopes between 0 and 6° (according to a 5m DEM), therefore extreme slopes (up to 15°) which can be found in blanket peatlands were not common in the reaches included in the regional survey.

4.2.2 Field Data Collection

Track reaches were surveyed between 17th March and 3rd September 2015. Measurements were not taken when rainfall was forecast. However, there was bias in the sampling as the majority of the stone track reaches were surveyed in June, July and August, while the plastic mesh reaches were surveyed in March, April, May and September. This was a result of site accessibility.

In place of measurement of gravimetric moisture content using samples collected in the field, dielectric permittivity was instead recorded, in line with other studies (Meyles et al., 2003, Comas et al., 2005, Parry et al., 2014) and allowed for a much greater sample number in a given time period. Dielectric permittivity was measured non-destructively in the top 6 cm of the peat profile using a DECAGON GS3 Soil Moisture Sensor, which has an accuracy of ±0.03 cm^3 cm^{-3} in peat soils. Peat is a wet medium with a high water content by volume (Hobbs, 1986). Dielectric permittivity is considered a more sensitive measure; able to capture the smaller variation in volumetric moisture content often found in peat. Section 4.2.2 describes the conversion of dielectric permittivity to volumetric moisture content.

Dielectric permittivity readings were taken in an area 10 m x 20 m on either side of the track in each selected reach. Approximately 20 readings were taken randomly within the survey area up to 10 m away from the track edge (Figure 4.4). Readings were, however, preferentially (approx. 75 %) taken within 5 m of the track edge as this was where the greatest impact was expected.

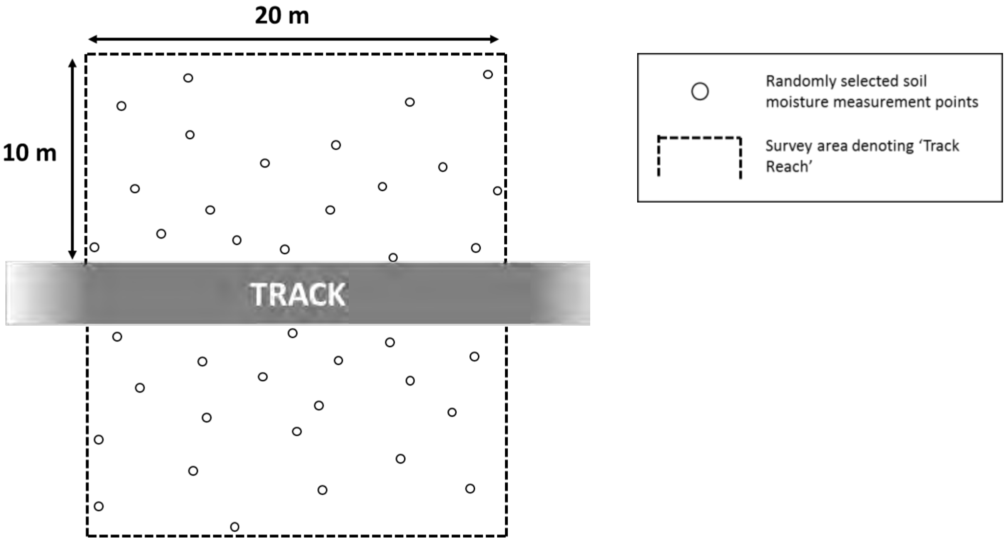

Figure 4.4 Schematic of volumetric moisture content measurements in around track reaches included in the upland survey

Vegetation was surveyed to taxonomic level in three 1 m^2 quadrats on either side of the track within the marked area (Figure 4.4). Surveying locations were selected by throwing the quadrat to randomly fall within the marked area. Vegetation cover was recorded under six main categories, identified as key species on blanket bogs in the North Pennines (Averis et al., 2004), % *Calluna Vulgaris,* % *Eriophorum* spp., % *Sphagnum* spp., % *Molinia* spp., % bare peat, and % Other. % Other included *Polytrichum* spp., *Phragmites* and *Juncus* spp.

4.2.3 Calculation of Volumetric Water Content

Dielectric permittivity was converted to volumetric moisture content using an existing calibration model. This was due to the large spatial scale of the study and the associated variation in vegetation and degree of peat humification, which prevented the creation of a calibration model using samples collected in the field (Comas et al., 2005). Degree of peat humification is a key influence on dielectric permittivity (Kellner and Lundin, 2001) as higher humification is associated with reduced porosity which can influence the water content of the soil.

The four phase empirical mixing model developed by Yu et al. (1999) was used to calculate volumetric moisture content as it allows the adjustment of parameters included in the model based on peat physical properties (Kellner and Lundin, 2001). It allowed the inclusion of fraction of bound water and structural orientation of peat particles into the model which could influence dielectric permittivity in peat. The equation below was used:

$$\theta = \frac{K_a^{\alpha} - (1-n)K_{sol}^{\alpha} - nK_{air}^{\alpha} + \theta_{bw}\,(K_w^{\alpha} - K_{bw}^{\alpha})}{K_w^{\alpha} - K_{air}^{\alpha}}$$

where, K_a is the measured dielectric permittivity, K_{sol} is the dielectric permittivity of dry peat, K_{air} is the dielectric permittivity of air, K_w is the dielectric permittivity of water, K_{bw} the dielectric permittivity of bound water, θ_{bw} is the fraction of bound water, n is porosity, and α is the soil geometry parameter. In this study the values used for the model parameters (Table 4.3) were derived from other data collected in this study (n and K_w) or were commonly used in other studies applying mixing models to peat (K_{sol}, K_{air}, K_{bw}, θ_{bw}, and α) (Kellner and Lundin, 2001, Parsekian et al., 2010, Strack and Mierau, 2010, Parry et al., 2014). As data were not calibrated with site specific samples the results reported here should be considered relative values of volumetric moisture content and not absolute.

Table 4.3 Parameter values used with four phase mixing model in this study to determine volumetric moisture content from dielectric permittivity

Model Parameter	Parameter Values	Source
K_a	Measured	Fieldwork
K_{sol}	2	Parry et al. 2014
K_{air}	1	Parry et al. 2014
K_w	83.6	Own Data
n	0.8	Own Data
α	0.35	Strack and Mireau (2010)
K_{bw}	3.2	Parry et al. 2014
Θ_{bw}	0.0061	Kellner and Lundin (2001)

4.2.4 Statistical Analysis

For analysis, the data was categorised according to the orientation of each track reach to the contours as this determined whether the two sides of the track could be defined as upslope-downslope (where it ran parallel to the contours and cut across flow pathways) or Sides A-B (where the track ran perpendicular to the contours). Using this categorisation of the data led to an unbalanced design, with data from only one track reach often forming a sub-set for testing the influence of topographic position or track age. Data were therefore only tested statistically where appropriate, and when data from more than one reach made up a sub-set. Data from plastic and stone tracks were also treated separately. Two sample t-tests were used for the following data sets, perpendicular plastic tracks (Side A vs Side B), parallel stone tracks *x* track age (Upslope vs Downslope). Two-way ANOVAs were used to test the difference between upslope and downslope sides for the following data sets, parallel and diagonal plastic mesh tracks, parallel and diagonal stone tracks, parallel stone tracks *x* topographic position. Where appropriate *post-hoc* testing was undertaken using the Tukey method. Further statistical testing could not be undertaken for the plastic mesh tracks. Backward stepwise regression analysis was used to determine the influence of vegetation cover at taxonomic level on average volumetric moisture content by track reach. In all statistical tests p was deemed significant at values ≤ 0.05.

4.3 Results

4.3.1 General Descriptive Statistics

Volumetric moisture content ranged between 0.339 cm^3 cm^{-3} and 0.989 cm^3 cm^{-3}, with mean and median values of 0.894 cm^3 cm^{-3} and 0.907 cm^3 cm^{-3} respectively. 79.5 % of the data ranged between 0.870 cm^3 cm^{-3} and 0.970 cm^3 cm^{-3}. Volumetric moisture content measured around the tracks varied depending on track type. A breakdown of the track reaches included in the regional survey by track type, orientation of the track to the contour, topographic position, track age and orientation of the track by topographic position is provided in Table 4.4. The unsurfaced and articulated wooden tracks are not included in Table 4.4 as only one reach was surveyed for each of these track types. Overall descriptive statistics for all four track types (plastic mesh, stone, unsurfaced and articulated wooden), are shown in Table 4.5.

Table 4.4 A breakdown of the number of track reaches included in the study according to influential factors including, track type, track orientation to the contours, topographic position, track age and orientation of the track *x* topographic position.

Factors		**Plastic**			**Stone**		
Track Type			10			17	
Track Orientation to Contour							
	Perpendicular		3			-	
	Parallel		4			16	
	Diagonal		3			1	
Topographic Position							
	Top		2			6	
	Middle		6			9	
	Bottom		2			2	
Track Age							
	<1		1			-	
	1-5		9			1	
	5-10		-			9	
	15+		-			7	
Track Orientation *x* Topographic Position		**Top**	**Middle**	**Bottom**	**Top**	**Middle**	**Bottom**
	Perpendicular	-	3	-	-	-	-
	Parallel	2	1	1	6	7	3
	Diagonal	-	2	1	-	1	-

Table 4.5 Descriptive statistics for moisture content around plastic and stone tracks. Values are given in cm^3 cm^{-3}. Where Q_1 is the 25th percentile value and Q_3 is the 75th percentile value.

	n	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
Plastic	526	0.920	0.046	0.387	0.905	0.927	0.946	0.981	0.041
Stone	694	0.875	0.077	0.381	0.865	0.892	0.912	0.981	0.046
Unsurfaced	40	0.895	0.101	0.533	0.573	0.937	0.954	0.975	0.081
Wooden	40	0.878	0.144	0.339	0.903	0.931	0.941	0.989	0.038

Volumetric moisture content was highest around the plastic tracks and lowest around the stone tracks. The stone tracks were predominantly surveyed in the warmer summer months (June, July, August), while the plastic tracks were predominantly surveyed in March, April and September (two reaches were surveyed in July) which may have influenced the results. Further analysis investigates the spatial patterns of volumetric moisture content around the two main different types of tracks (plastic mesh and stone).

4.3.2 Differences Between Track Sides

Plastic mesh tracks were found installed perpendicular ($n = 3$), parallel ($n = 4$) and diagonal ($n = 3$) to the contours. A significant difference was not found between Side A and Side B of the perpendicular plastic mesh tracks ($p = 0.121$). For the parallel and diagonal plastic mesh tracks, which both cut across natural flow pathways creating upslope-downslope sides to the surveyed reaches, analysis using a two-way ANOVA showed there to be a significant difference between the moisture content between the two track orientation categorisations ($p = 0.009$). There was no significant difference however, between the upslope and downslope sides of these plastic tracks ($p = 0.695$). The interaction between track orientation and side of track was not significant either ($p = 0.177$), indicating that the influence of the side of the track is not influenced by the orientation of the track to the contours. Descriptive statistics are outlined in Table 4.6.

Table 4.6 Descriptive statistics for the difference between the two sides of plastic mesh tracks, categorised by their orientation to the contours. Values are given in cm^3 cm^{-3}. *N* is the number of individual volumetric moisture measurements taken.

	N	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
Perpendicular									
Side A	73	0.882	0.052	0.538	0.871	0.894	0.906	0.943	0.035
Side B	73	0.897	0.065	0.387	0.889	0.902	0.919	0.964	0.030
Parallel									
Upslope	106	0.938	0.030	0.796	0.922	0.947	0.957	0.981	0.035
Downslope	102	0.935	0.026	0.836	0.924	0.939	0.951	0.981	0.027
Diagonal									
Upslope	86	0.925	0.044	0.623	0.915	0.929	0.949	0.981	0.033
Downslope	86	0.930	0.029	0.697	0.920	0.935	0.945	0.961	0.024

Stone tracks included in this study were installed parallel (*n* = 16) or diagonal (*n* = 1) to the contours, cutting across flow pathways and thereby creating upslope-downslope sides to the reaches. A two-way ANOVA showed there to be no significant difference between the moisture content around the two track orientations (p = 0.132). There was a significant difference between the two sides of the tracks (p = 0.005) (Figure 4.5). The interaction between track orientation and side of track was marginally not significant (p = 0.057). Caution should be taken in interpreting the breakdown of the data as only one stone track was categorised as diagonal to the contours. The removal of the diagonal track data from the analysis yielded a marginally not significant difference between the upslope and downslope sides of the tracks (p = 0.060). Descriptive statistics are provided in Table 4.7.

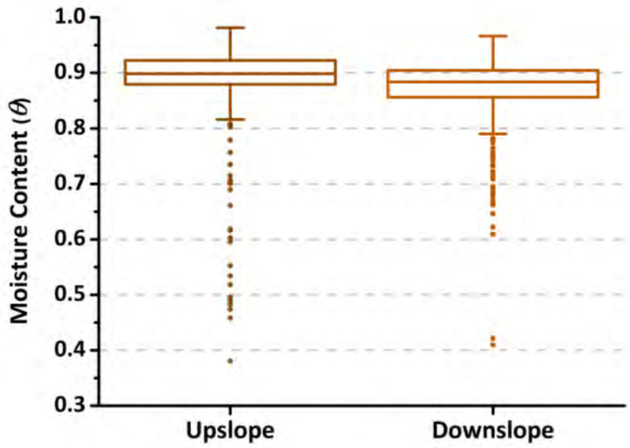

Figure 4.5 Boxplot of moisture content around parallel and diagonal stone tracks combined on the upslope (N = 347) and downslope sides (N = 347), showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

Table 4.7 Descriptive statistics for the difference between the upslope and downslope sides of the stone tracks categorised by their orientation to the contours. Values are given in cm^3 cm^{-3}. N is the number of individual volumetric moisture measurements taken.

	N	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
Parallel									
Upslope	327	0.882	0.086	0.381	0.880	0.899	0.922	0.981	0.043
Downslope	327	0.871	0.068	0.410	0.861	0.885	0.905	0.967	0.044
Diagonal									
Upslope	20	0.887	0.058	0.715	0.868	0.896	0.928	0.968	0.060
Downslope	20	0.828	0.054	0.743	0.783	0.825	0.873	0.909	0.090

4.3.3 Influence of Track Topographic Location

Perpendicular plastic mesh tracks (*n* = 3) were only found at a mid-slope topographic position. Parallel plastic mesh tracks (*n* = 4) were surveyed at all three topographic locations, however, only one reach was surveyed at mid- and bottom-slope locations. Diagonal plastic mesh tracks (n = 3) were surveyed at mid- (n = 2) and bottom-slope (n = 1) locations. Due to the smaller number of reaches included in each sub-group further statistical analysis was not undertaken. Descriptive statistics (Table 4.8) exhibit similar average moisture content values on either side of the track at each topographic location. There is also no clear evidence of an upslope-downslope effect around the parallel and diagonal plastic tracks at each topographic position, although caution should be taken as several topographic locations only contained one track reach at each orientation to the contours.

Table 4.8 Descriptive statistics for moisture content around plastic mesh tracks, by topographic location and track orientation to the contours. Values are given in $cm^3\ cm^{-3}$. N is the number of individual volumetric moisture measurements taken.

	N	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
TOP									
Parallel									
Upslope	53	0.928	0.029	0.831	0.913	0.925	0.951	0.974	0.038
Downslope	53	0.926	0.023	0.836	0.915	0.929	0.940	0.960	0.026
MIDDLE									
Perpendicular									
Side A	73	0.882	0.052	0.538	0.871	0.894	0.906	0.943	0.035
Side B	73	0.897	0.065	0.387	0.889	0.902	0.919	0.964	0.030
Parallel									
Upslope	22	0.950	0.015	0.919	0.944	0.952	0.960	0.974	0.016
Downslope	29	0.944	0.013	0.909	0.936	0.944	0.956	0.968	0.019
Diagonal									
Upslope	66	0.917	0.047	0.623	0.910	0.925	0.941	0.958	0.031
Downslope	66	0.926	0.032	0.697	0.918	0.931	0.941	0.953	0.022
BOTTOM									
Parallel									
Upslope	20	0.945	0.041	0.796	0.940	0.954	0.964	0.981	0.024
Downslope	20	0.945	0.037	0.850	0.941	0.953	0.969	0.981	0.028
Diagonal									
Upslope	20	0.950	0.022	0.911	0.928	0.949	0.970	0.981	0.042
Downslope	20	0.944	0.013	0.914	0.936	0.949	0.952	0.981	0.016

Stone tracks parallel to the contours (n = 16) were found at all three topographic locations (top-, mid- and bottom-slope), while the diagonal stone track (n = 1) was found at a mid-slope topographic location. Statistical analysis was only undertaken on the parallel stone track data to determine the influence of topographic location. Using a two-way ANOVA, a significant difference was found between topographic locations (p < 0.001), but not between the two sides of the track (p = 0.674). There was a significant interaction (p <0.001). *Post-hoc* testing yielded a significantly higher moisture content on the upslope side of the track compared with the downslope side at the top- and mid-slope topographic locations ($p < 0.001$ and $p = 0.020$ respectively). No significant difference was found at the bottom-slope location ($p = 0.096$). Descriptive statistics are presented in Table 4.9.

Table 4.9 Descriptive statistics for moisture content around stone tracks, by topographic location and track orientation to the contours. Values are given in $cm^3\ cm^{-3}$. *N* is the number of individual volumetric moisture measurements taken.

	N	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
TOP									
Parallel									
Upslope	127	0.900	0.048	0.596	0.887	0.903	0.921	0.968	0.034
Downslope	127	0.871	0.068	0.421	0.862	0.889	0.905	0.946	0.043
MIDDLE									
Parallel									
Upslope	140	0.893	0.065	0.496	0.877	0.899	0.930	0.981	0.054
Downslope	140	0.876	0.053	0.646	0.861	0.881	0.906	0.966	0.045
Diagonal									
Upslope	20	0.887	0.058	0.715	0.868	0.896	0.928	0.968	0.060
Downslope	20	0.828	0.054	0.743	0.783	0.825	0.873	0.909	0.090
BOTTOM									
Parallel									
Upslope	60	0.821	0.146	0.381	0.817	0.889	0.906	0.938	0.089
Downslope	60	0.858	0.092	0.410	0.847	0.888	0.905	0.946	0.058

4.3.4 Influence of Track Age

Moisture content decreased with track age (time since installation) around both plastic and stone tracks. Plastic tracks covered two age categories: < 1 year ($n = 1$) and 1-5 years ($n = 8$) and stone tracks covered three age groups: 1-5 years ($n = 1$), 5-10 years ($n = 9$) and 15+ years ($n = 7$). The tracks included in the intensive study also fall into the 1-5 year age category. The highest average moisture content was found around the plastic mesh track < 1 year old (0.931 $cm^3\ cm^{-3}$) and the lowest average moisture content around stone tracks 15+ years old (0.843 $cm^3\ cm^{-3}$).

Moisture content was found to be higher around the < 1 year old plastic mesh track compared with the 1-5 year old plastic mesh track (Figure 4.6). However, statistical analysis was not appropriate due to the unbalanced number of tracks in each group. Plastic mesh tracks parallel to the contours were in the age categories < 1 year old ($n = 1$) and 1-5 years ($n = 3$). Plastic mesh tracks perpendicular and diagonal to the contours were only in the 1-5 year age category ($n = 3$ for each orientation). Descriptive statistics for the breakdown of the data are provided in Table

4.10. Again there is no clear influence of track age on an upslope-downslope effect around the parallel and diagonal plastic tracks.

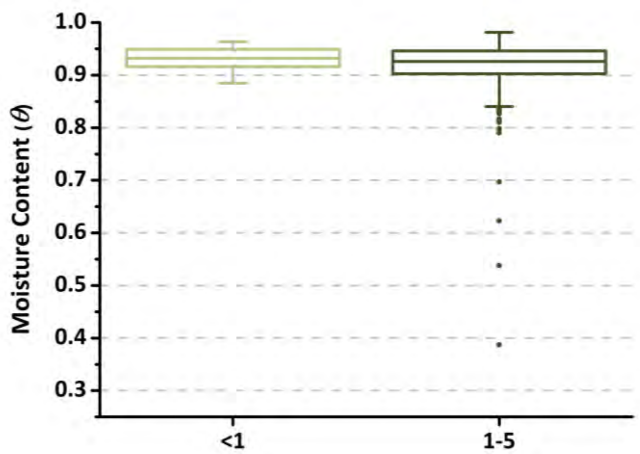

Figure 4.6 Boxplot of moisture content around plastic tracks of different ages (data from both sides of track combined, <1 year, N = 66, 1-5 years, N = 460) showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

Table 4.10 Descriptive statistics for moisture content around plastic mesh tracks, by track age and track orientation to the contours. Values are given in $cm^3\ cm^{-3}$. N is the number of individual volumetric moisture measurements taken.

	N	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
<1									
Parallel									
Upslope	33	0.935	0.020	0.893	0.916	0.941	0.953	0.963	0.037
Downslope	33	0.926	0.019	0.885	0.915	0.929	0.939	0.960	0.024
1-5									
Perpendicular									
Side A	73	0.882	0.052	0.538	0.871	0.894	0.906	0.943	0.035
Side B	73	0.897	0.065	0.387	0.889	0.902	0.919	0.963	0.030
Parallel									
Upslope	73	0.939	0.033	0.796	0.924	0.948	0.959	0.981	0.036
Downslope	69	0.939	0.028	0.836	0.932	0.944	0.954	0.981	0.022
Diagonal									
Upslope	86	0.925	0.044	0.623	0.915	0.935	0.939	0.981	0.033
Downslope	86	0.930	0.029	0.697	0.920	0.929	0.945	0.981	0.024

Moisture content was found to be higher around the stone track 1-5 years old than the stone tracks 5-10 years and 15+ years (Figure 4.7). Peat moisture content was found to be significantly higher around the 5-10 year old stone tracks than the 15+ years stone tracks (p <0.001). Stone tracks parallel to the contours were in all three age categories; 1-5 years (n = 1), 5-10 years (n = 9), 15+ years (n = 6). The single stone track diagonal to the contours was in the 15+ years age category.

Descriptive statistics are presented in Table 4.11. In all the track orientation *x* age categories moisture content was higher on the upslope side of the track relative to the downslope. Statistical testing (two-sample t-test) of the differences for the 5-10 year and 15+ years stone tracks did not yield significant differences between the upslope and downslope sides however (p = 0.245 and 0.292 respectively). Statistical testing for the 1-5 year parallel stone track and 15+ years diagonal stone track was not undertaken.

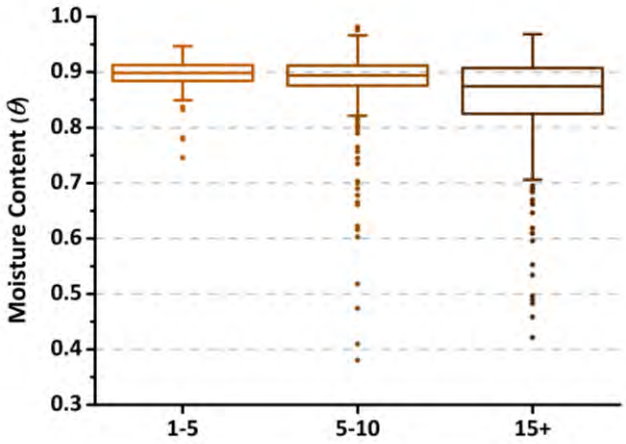

Figure 4.7 Boxplot of moisture content around stone tracks of different ages (data from both sides of track combined, 1-5 years, N = 58, 5-10 years, N = 460, 15+ years, N = 176). Showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

Table 4.11 Descriptive statistics for moisture content around stone tracks, by track age and track orientation to the contours. Values are given in cm^3 cm^{-3}. N is the number of individual volumetric moisture measurements taken.

	N	Mean	St Dev	Min	Q_1	Median	Q_3	Max	IQR
1-5									
Parallel									
Upslope	29	0.905	0.020	0.866	0.894	0.901	0.919	0.947	0.025
Downslope	29	0.879	0.048	0.746	0.852	0.896	0.909	0.946	0.057
5-10									
Parallel									
Upslope	230	0.889	0.070	0.381	0.880	0.897	0.920	0.981	0.040
Downslope	230	0.882	0.054	0.410	0.868	0.891	0.908	0.966	0.039
15+									
Parallel									
Upslope	68	0.850	0.133	0.458	0.836	0.900	0.932	0.968	0.096
Downslope	68	0.829	0.094	0.421	0.817	0.864	0.888	0.937	0.070
Diagonal									
Upslope	20	0.887	0.058	0.715	0.868	0.896	0.928	0.968	0.060
Downslope	20	0.828	0.054	0.743	0.783	0.825	0.873	0.909	0.090

4.3.5 Distance Effect

Variation was found in moisture content with distance from the track edge around plastic and stone track types. Further statistical analysis was not undertaken on the plastic mesh or stone tracks moisture content data when categorised by track orientation to the contour or topographic location. Graphical analysis of the stone tracks, categorised by topographic position showed lower moisture content on the downslope side relative to the upslope side at the top- (n = 6) and mid-slope locations (n = 8) (Figure 4.8a,b), but not at the bottom-slope (n = 3) location (Figure 4.8c). The large error bars indicate that there is large spatial variability in the moisture content.

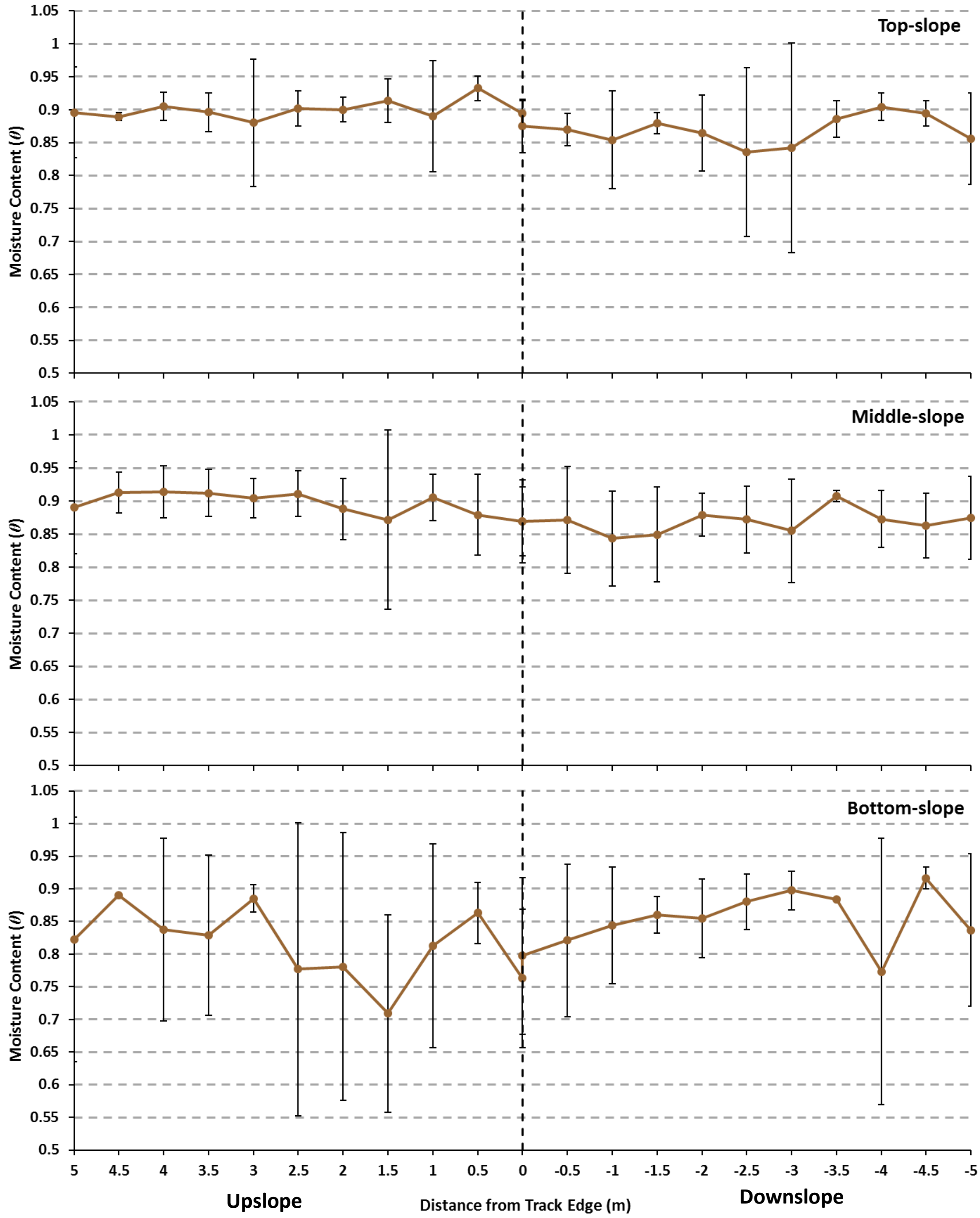

Figure 4.8 Average moisture content within 5 m of stone track edge by topographic location. Top-slope (n = 6 parallel), Middle-slope (n = 7 parallel and 1 diagonal), Bottom-slope (n =3 parallel). Error bars show ± standard deviation.

4.3.6 Land Management Conditions

Different combinations of land management conditions were found around the track reaches surveyed. A count of the track reaches in each land management condition by track orientation to the contour is presented in Table 4.12. Where one management method was dominant around a track reach, a single classification was given e.g. burned, drained, blocked drain or grazed. Where it was not possible to determine between management conditions these were placed into the 'Mixed' class. This classification included; burned & blocked drain, burned & drained, burned & grazed, cut & grazed & drained, grazed & drained, and hagged & drained & burned & grazed. Descriptive statistics are presented in Table 4.13. For the plastic tracks the lowest average moisture content was yielded around the track in the burned land management condition (0.910 $cm^3\ cm^{-3}$) and the highest in grazed (0.946 $cm^3\ cm^3$). The lowest moisture content around stone tracks was associated with drainage (0.816 $cm^3\ cm^{-3}$), while the highest was with mixed conditions (0.885 $cm^3\ cm^{-3}$). No further analysis was undertaken on this breakdown of the data.

Table 4.12 Categorisation of the plastic and stone track reaches by orientation to slope and land surrounding land management condition.

Factors		**Plastic**			**Stone**	
Land Management		**Perpendicular**	**Parallel**	**Diagonal**	**Parallel**	**Diagonal**
	Burned	1	1	2	2	-
	Drained	-	-	-	1	-
	Grazed	-	1	1	2	1
	Blocked Drain	-	1	-	-	-
	Mixed	2	1	-	11	-

Table 4.13 Descriptive statistics for moisture content around plastic and stone track, further classified by land management. Values are given in $cm^3\ cm^{-3}$. *N* is the number of individual volumetric moisture measurements taken.

	N	**Mean**	**St Dev**	**Min**	Q_1	**Median**	Q_3	**Max**	**IQR**
Plastic									
Burned	238	0.910	0.058	0.387	0.900	0.922	0.938	0.974	0.039
Blocked Drain	66	0.931	0.020	0.885	0.916	0.932	0.949	0.963	0.033
Grazed	80	0.946	0.030	0.796	0.936	0.951	0.961	0.981	0.025
Mixed	142	0.919	0.031	0.790	0.897	0.918	0.948	0.974	0.051
Stone									
Burned	114	0.879	0.081	0.421	0.878	0.900	0.920	0.968	0.042
Drained	40	0.816	0.101	0.496	0.761	0.854	0.884	0.948	0.123
Grazed	120	0.858	0.090	0.458	0.845	0.881	0.906	0.968	0.060
Mixed	420	0.885	0.065	0.381	0.876	0.894	0.981	0.981	0.037

Around stone tracks, at some sites, drainage channels were found to run parallel to the track on the upslope side (Figure 4.9), whilst others ran from the upslope to the downslope through culverts under the track. Stone tracks with drains on the upslope side had an average moisture content of

0.870 cm^3 cm^{-3}, whilst stone tracks without drains had a moisture content of 0.865 cm^3 cm^{-3}. No significant difference was found between these data sets.

Figure 4.9 Stone tracks with drainage channels running parallel to the track on the upslope side.

4.3.7 Dominant Vegetation Cover and Volumetric Moisture Content

Dominant vegetation cover in the 10 m area either side of the track varied between the track reaches (data not included for MH3, MH4, MH5 and MH6). Backwards elimination stepwise regression analysis showed average percent cover of *Calluna vulgaris, Sphagnum* spp.*, Molinia* spp. and bare peat to be significant in predicting average volumetric moisture content (by track reach) (p = 0.004, 0.007, 0.026 and 0.035 respectively, R^2 = 24.9 %). Average percent cover of *Eriophorum* spp. was eliminated with p = 0.767, and average percent cover 'Other' was eliminated with p = 0.463. 'Other' included species which had in general low percentage cover, such as non-*Sphagnum* mosses, *Juncus* spp. and *Polytrichum* spp.

4.4 Discussion

This regional survey is the first to be undertaken to investigate the impacts of tracks on blanket peat hydrology. Previous research has assumed that the presence of a track on peat would impact on natural flow pathways (e.g. Barry et al., 1992, Lindsay, 2007) , potentially creating a difference in the wetness of the peat either side of the track (see also Figure 6.1). Volumetric moisture content relates to water-table depth (Price, 1997, Strack and Waddington, 2007), and was considered a useful measurement given that moisture data could be more quickly captured across a wider spatial area to test for patterns generated by the presence of the tracks on blanket peat.

Comparison of volumetric moisture content showed that the effect differed between the types of track surveyed. The range in the moisture content was comparable between the track types and attributable to the spatial heterogeneity of soil moisture content (Meyles et al., 2003, Petrone et al., 2004). Several probable reasons for this difference exist, including: (i) an effect of the track on the surrounding peat; (ii) difference in the typical locations where the tracks are installed as plastic tracks are traditionally for use in areas of deep, wet peat which cannot easily be traversed by heavier vehicles and the construction of stone tracks is not appropriate; and (iii) bias in the sampling of the tracks. Despite care being taken to select sampling days where no rain was forecast, the nature of this study meant that antecedent conditions were not comparable. Such an issue was also encountered by Armstrong et al. (2010) who conducted peatland spatial water quality surveys. Due to site access restrictions there was a bias in the sampling, with plastic tracks typically surveyed in March, April, May and September and stone tracks surveyed in June, July and August. Therefore subsequent spatial patterns were considered relative to a specific track type.

4.4.1 Upslope-Downslope Differences

Of particular interest was the relative impact to moisture content on the upslope and downslope sides of tracks (hypothesis i), especially seeing as blanket peat can form on steep gradients which may exacerbate impacts. It was expected that the greatest differences in volumetric moisture content would be observed where tracks were parallel to the contours as this would cut across natural flow pathways; a similar effect to those observed around drainage ditches (Stewart and Lance, 1991, Holden et al., 2006, Holden et al., 2011). It became apparent during the regional survey, however, that true upslope-downslope differences were typically only found in relation to the stone tracks. Plastic tracks were rarely found to be installed parallel to the contours on steep slopes (Figure 4.10), due to practical implications for the vehicles using them. There is a greater chance of sliding off the track when it is installed parallel to the contours. Instead, when installed on steep slopes plastic tracks are more commonly found to run perpendicular to the contours of steeper slopes, i.e. the direction of travel is straight up and downslope. Consequently plastic tracks rarely have a distinct upslope-downslope gradient. In addition, the slope angles where the track reaches were located predominantly ranged between 0 and 6°, a couple of track reaches were on slopes as steep as 8-10°. Therefore, even where tracks did cut across flow pathways and ran parallel or diagonal to the contours, the gradient of the slope was often quite shallow.

Figure 4.10 Plastic tracks installed perpendicular to the contours (i.e. straight up- and downslope) on working estates

The orientation of a track to the slope therefore defines whether there are upslope and downslope sides to a track. The installation of some plastic tracks perpendicular to the contours (*n* = 3) resulted in no upslope-downslope arrangement, while those installed parallel (*n* = 4) and diagonal (*n* = 3) to the contours were typically on shallow slope angles, leading to an indistinct upslope-downslope arrangement. Unsurprisingly no significant difference was observed between the two sides of the perpendicular plastic tracks. Furthermore no significant difference was observed in the volumetric moisture content upslope and downslope of the parallel and diagonal plastic mesh tracks.

While the orientation of the track to the contours and the slope angle are key influences, the lack of significant difference between the upslope and downslope sides of the plastic tracks (where applicable) can probably be attributed to the nature of the track as well. Plastic tracks, unlike stone tracks, do not appear to create a barrier to flow, permitting water to flow both under and over the track. The way in which plastic tracks are installed may also influence the lack of difference between the upslope and downslope sides. The installation of plastic tracks is associated with minimal disturbance to the peat and on many working estates they are laid directly on the vegetation without any ground preparation (Moorland Association, *pers. comm.*). Consequently there are a number of explanations as to why no upslope-downslope difference was observed around the plastic tracks included in the regional survey.

In contrast, stone tracks were all installed either parallel (*n* = 16) or diagonal (*n* = 1) to the slope contours, resulting in an upslope-downslope arrangement which respect to hydrological flow pathways. It should be noted however that even the stone tracks included in this survey were installed on relatively shallow slopes which could lead to indistinct upslope-downslope arrangements in some cases. For the parallel and diagonal stone tracks data combined a significantly higher moisture content was found on the upslope side of the track relative to the downslope side (Figure 4.5). However the removal of the data for the diagonal track, resulted in a marginally non-significant difference between the upslope and downslope sides of the parallel stone tracks. Descriptive statistics still show upslope moisture content to be higher than downslope moisture content however (Table 4.7). Despite not being significant, the difference in moisture content for the upslope and downslope sides of the track in this study could be indicative of a loss of connectivity of water flow pathways between the two sides of the track. Road construction was either of a floating road or borrow pit design which are more destructive to the surrounding peat. Visual observations also showed ponding on the upslope side of tracks in some locations, which were not evident on the downslope sides. On a larger scale this has been observed around roads on Canadian boreal peatlands (Lieffers and Rothwell, 1987, Bocking, 2015), leading to tree die back as conditions became too wet.

The lack of significant difference in moisture content between the two sides of the plastic tracks and the parallel stone tracks mean that hypothesis (i) is rejected. However, with respect to the stone tracks there is a suggestion that an upslope-downslope difference is occurring.

4.4.2 Influence of Topographic Location

Holden et al. (2006) recognised the importance of topographic location (i.e. flat or sloping ground) in relation to the extent of impact of drains on blanket peatlands. Drains running parallel to the contours of steeper slopes exhibited a greater drying effect on the downslope side relative to the upslope, with less equal water-table drawdown, when compared with drains installed on flatter areas of blanket peat. Soil moisture around the plastic tracks did not exhibit a clear difference between the two sides of the track (Side A vs Side B, Upslope vs Downslope) for any orientation to the contours at any of the three topographic locations (Table 4.8).

Around the stone tracks, the upslope-downslope effect did vary by topographic location. For the parallel stone tracks only (*n* =16), at top- and mid- slope locations, moisture content was found to be significantly higher on the upslope side of the track relative to the downslope side of the track (Table 4.9). In the bottom-slope location, however, there was no significant difference in moisture content between sides of the track. This therefore suggests that the topographic positioning of a stone track does have an influence on the magnitude of effect, especially where the track cuts across the slope. What has not been determined here is whether the difference is the result of a backing up of water on one side of the track relative to the other or a redirection of flow along the track and this requires further investigation. From these results hypothesis (ii) can be accepted for parallel stone tracks but not plastic tracks.

4.4.3 Influence of Track Age

Studies of the impact of tracks under different intensities of use are common for unsurfaced tracks (e.g. Braunack, 1986a, Kevan et al., 1995, Wood et al., 2003, Nortje et al., 2012). However, the age of constructed tracks has not been given much consideration in the literature. The longer a disturbance is present the greater impact it is likely to have. Moore et al. (2015) showed how a change in flow patterns, following construction of an embankment on a Canadian peatland 50 years previously, had led to the creation of drier and wetter areas and subsequent changes in the peat physical properties (hydraulic conductivity) as a result. It was therefore expected that around older tracks the upslope-downslope difference would be more pronounced.

For both the plastic and stone tracks there was evidence of an age effect, with the highest average volumetric moisture content recorded around the ‘youngest’ tracks in both cases (< 1 year for plastic and 1-5 years for stone) (Figures 4.6 and 4.7). Caution should be exercised in the interpretation of the results as only one plastic track reach was in the < 1 year category and one stone track reach in the 1-5 year category. It was not possible to test the influence of track age on the plastic tracks data including the sub-grouping of track orientation. Statistical testing of parallel stone tracks in the 5-10 year and 15+ years age categories did not yield significant differences between the upslope and downslope sides of the track. However for all the stone track orientations in the three age categories, average moisture content appeared to be higher upslope relative to the downslope (Table 4.11). As topographic location does appear to have an effect with respect to the stone tracks (section 4.4.2), it would be useful to determine whether the age effect is enhanced at different topographic locations. It was not possible to break the age categories down further by topographic location due to small sample sizes.

Hypothesis (iii) was rejected for both plastic and stone tracks, although some of the stone track data hints at an age effect. These results therefore suggest it would be prudent for longer-term monitoring to be undertaken to determine how track impacts may change over time.

4.4.4 Distance from Track Edge and Volumetric Moisture Content

It has been suggested that the impact of a track can extend beyond its immediate footprint (Lindsay, 2007), although exact distances have rarely been measured. Given the small sample size it was not possible to investigate a relationship between distance from the track edge and volumetric moisture content for the plastic tracks included in this study. Graphical analysis of volumetric moisture content upslope and downslope of the stone tracks at different topographic locations (Figure 4.8a-c) showed no clear patterns and large standard deviations. Consequently hypothesis (iii) was rejected

Within 1.5 m of the track edge downslope of the stone tracks, average volumetric moisture content was slightly lower compared with the upslope side at top-slope locations which could indicate an effect of the track (Figure 4.8a). Although the large error bars should be taken into consideration. During surveying it was observed that the physical ‘influence’ of a stone track often extended beyond its immediate footprint with respect to the material used for construction. For some reaches the texture of the peat was much grittier, potentially related to methods used to repair stone roads, which often involves the addition of more aggregate and regrading of the track surface (Natural England, *pers comm*). It has been noted that through track construction on blanket peat the introduction of mineral soils or rock which are not base poor, such as granite, can lead to a shift to more minerotrophic vegetation species (Stunnell and Jones, 2010).

4.4.5 Additional Observations

Tracks are often constructed with drainage channels on their upslope edge to redirect water. There was no significant difference in the volumetric moisture content around stone tracks that had been constructed with a drain on the upslope side and those which had not. Hence stone tracks appear to have an impact on the peat independent of whether there is a drain installed and this could have implications for the procedure of track installation on blanket peatlands in the future.

Variation in volumetric moisture content has been attributed to vegetation composition (Oleszczuk et al., 2008). Average percent cover of *Calluna vulgaris, Sphagnum* spp. *Molinia* spp. and bare peat were found to be significantly associated with volumetric moisture content, however the model was not particularly strong. Due to the feedbacks which exist between vegetation and moisture content, it was not clear whether the moisture content influenced the vegetation composition, i.e. the plants were growing in wet and dry locations so as best to fit their preferences, or whether the vegetation was influencing the moisture content on the days of sampling. The vegetation cover at the sites included in this study was similar between sites and it is possible that tracks installed on peatlands with very different vegetation types may exhibit different impacts to those shown here. It is therefore important that vegetation effect is taken into consideration in future studies.

4.4.6 Undertaking a Regional Survey

As this was the first extensive survey undertaken to investigate the impact of tracks in blanket peatland environments, it provided the opportunity to gain an insight into the impact of track on blanket peat hydrology, which is central to its functioning. Undertaking a regional survey has both advantages and disadvantages, however, which should be given due consideration. With respect to the advantages of a regional survey, it provided the opportunity to measure a range of existing tracks over a wider spatial area than that covered in the study undertaken at Moor House (intensive study). Through the regional survey tracks installed within a range of land management conditions could be included, as well as tracks which had been subjected to 'real world' use. In addition, it meant that the same methodological approach could be used to gain information around a range of tracks, and therefore created a dataset that was more comparable than a number of existing studies.

There are however disadvantages associated with regional surveys, which can limit their usefulness and means that caution is required in the interpretation of results. Within regional surveys, it is not possible to fully control for antecedent conditions, which can influence the data depending on when it was collected. Often within regional surveys, the sites which are used are those which are accessible, consequently the sampling may be unavoidably biased or unbalanced due to issues with access permissions. This in turn can have implications for the type of analysis which can be undertaken on the data collected. Visiting multiple sites in the 'natural environment' means that, combined with accessibility issues, it can often be challenging to find identical sites for comparison, for example tracks may be installed on slightly different slope angles or have a slightly different aspect. Within a regional survey it is not always possible to control all the potentially influential variables. For example, although topographic locations were categorised into top-, mid- and bottom-slope there was variation in the slope angle within these locations, especially in the mid-slope locations. Regional surveys are therefore beneficial, but when interpreting the findings their limitations should be recognised.

4.5 Chapter Summary

- Natural spatial variation in moisture content was observed around all track reaches measured, although in general the moisture content was high at all sites (0.8 to 0.9 cm^3 cm^{-3}).
- The spatial patterns of volumetric moisture content around the tracks depended on track type, topographic location and by association the orientation of the track to the contours. Not all of the reaches included in the study exhibited an upslope-downslope arrangement around the track.

- Where an upslope-downslope arrangement existed, moisture content was found to be higher on the upslope side relative to the downslope side for the stone tracks but not the plastic tracks (parallel and diagonal orientations to the contours).
- These observed differences could also be attributed to track construction method and track material.
- Topographic location appears to influence the difference between upslope and downslope depending on track type and orientation to the contours. No such effect was observed in relation to plastic tracks. Moisture content was found to be significantly higher upslope of parallel stone tracks relative to the downslope at top- and mid-slope locations.
- Although there was a suggestion of an age effect, with lower moisture content observed around older stone tracks, there was no clear evidence of an effect on the upslope-downslope difference.
- Results suggest stone tracks have a greater impact than plastic tracks. However antecedent conditions during sampling may have influenced this result. To further investigate whether this is a true effect, moisture content should be measured around stone and plastic tracks at different times of the year.
- Moisture content around the plastic and stone tracks was found to vary with land management condition and vegetation type. The effect of drains on the upslope side of stone tracks did not appear to have an influence, however.
- The use of plastic tracks on blanket peat is relatively recent (within the last 5 years). To fully understand the effects of plastic tracks longer-term monitoring would be beneficial.

CHAPTER 5: SENSITIVITY OF BLANKET PEAT PHYSICAL PROPERTIES TO LOW-GROUND-PRESSURE AND 4x4 VEHICLE USE

5.1 Introduction

In pristine peatland systems the structure and physical properties of peat are influenced by past vegetation composition and degree of decomposition (Boelter, 1969). In turn the structure of peat is important for its functioning. The permeability of peat, combined with the hydraulic gradient, determines the movement of water through the peat matrix both laterally and vertically (Holden and Burt, 2003a). Patterns in the hydraulic conductivity (*K*) of peat are often considered to be dominated by zones of fast flow in the near-surface peat and zones of slow flow with depth. In zones of slow flow waterlogged conditions can be maintained and peat is able to accumulate (Belyea and Clymo, 2001). Dominant flow pathways are influenced by *K*, while *K* may also influence water-table depth. Furthermore, *K* can influence carbon cycling within the peat due to the close relationships between carbon cycling and hydrological function (Holden, 2005b).

The structure of peat is related to the water storage capacity and specific yield. The specific yield is the volume of water that is drained under gravity per unit area of the peat (Boelter, 1965). A change in structure has the potential to alter the tension at which water is held in the pore spaces leading to water stress and reduced availability of water to plants (McLay et al., 1992, Price and Schlotzhauer, 1999). The structure of peat varies depending on the formation of the peat and the vegetation present at the time of formation. Consequently there is wide ranging spatial variation in peat structure (see section 2.1.2 and 2.1.3). Common properties used to characterise peat structure include bulk density and *K*.

Bulk density typically shows an increase with depth in the peat profile and is related to degree of decomposition, with more decomposed peats exhibiting a higher bulk density compared with newer peat (Boelter, 1969). It has also been suggested that *K* can decrease with depth. This is not true for all locations and zones of higher *K* have been observed at greater depths (Beckwith et al., 2003a), related to the composition of the peat in these locations. Peat is known to be anisotropic, often with a difference of several orders of magnitude between rates of flow in the horizontal and vertical direction (Hobbs, 1986). In-field measurements do not always fully capture anisotropy within peat (Surridge et al., 2005), as *K* in one direction can be preferentially captured over the other, depending on the measurement method used. Therefore, to capture the horizontal and vertical variation laboratory methods could be used, such as the modified cube method (MCM) (Beckwith et al., 2003a), which allows both the horizontal and vertical *K* to be determined on the same sample. The MCM uses cubes of peat extracted from defined depths within the peat profile for the determination of *K*. Testing has shown results yielded from this method to be relatively precise and differences in horizontal and vertical *K* to be representative of natural phenomena as opposed to artefacts of the method used (Beckwith et al., 2003a).

With respect to blanket peatlands in particular, understanding of *K* is limited and data has been collected using many different measurement methods including piezometers (Holden and Burt, 2003a), tension infiltrometers (Holden et al., 2001), mini-disk infiltrometers (Wallage and Holden, 2011) and the modified cube method (Cunliffe et al., 2013). Spatial variability in *K* has been observed (Lewis et al., 2012), and Holden (2005a) noted an influence of topography, with greater variability in *K* observed at top- and bottom-slope locations compared with the mid-slope. A similar pattern in variation was observed for bulk density as well (Holden, 2005a).

Loading of non-peat soils through road construction and vehicle use has been found to result in changes in soil structure through compression and compaction (Eliasson, 2005). Such changes in soil structure are often exhibited as decreases in soil porosity and *K* (e.g. Bottinelli et al., 2014) and increases in bulk density (e.g. Alakukku, 1996a). Peat soils are known to be highly compressible due to their high water content by volume (Hobbs, 1986). It would therefore be expected that vehicle movements over peat could lead to compaction and a change in peat structure. These could be exhibited as increases in bulk density, decreases in *K* and changes in the surface profile.

There are few studies of constructed roads and embankments on peat that measure impacts to these properties. Gunn et al. (2002) observed evidence of compaction under access roads for windfarms on blanket peat, with resultant decreases in *K*. *K* in Gunn et al. (2002) was measured using constant head permeameter apparatus. Most studies of impacts of constructed tracks focus on how bulk density and *K* influence the suitability of the peat for construction and the degree of compaction, rather than impacts to the properties themselves. For example, compaction is expected to be greater in more fibrous peats compared with amorphous peats (Crowl and Lovell, 1987). Some studies have suggested that compression could lead to enhanced horizontal flow and reduced vertical flow (Landva and Pheeney, 1980, Lefebvre et al., 1984, Hendry et al., 2014). Actual measurement of such an occurrence does not appear to have occurred, however. It is important to understand whether both vertical and horizontal *K* are affected and the magnitude of impact in each direction. Given that tracks have the potential to interrupt lateral flows across peat, leading to a footprint of impact greater than the track area, it is important to establish how horizontal *K* and lateral flow is affected.

Changes in surface profile elevation along track routes, and the formation and change in depth of wheel ruts have commonly been recorded in studies of unsurfaced tracks on non-peat and shallow peat soils (e.g. Eliasson, 2005). Ares of increased lowering of the surface have been associated with areas of greatest pressure (i.e. the directly under the vehicle wheels) leading to the formation of wheel ruts. Studies in Arctic tundra regions have recorded rut formation and increases in thaw depth following vehicle use along unsurfaced routes (e.g. Gersper and Challinor, 1975, Chapin and Shaver, 1981). In addition a small number of studies based in forested peatlands have considered mitigation methods to reduce the formation of wheel ruts created by forest harvesting machinery (e.g. Hutchings et al., 2002, Wood et al., 2003).

Within blanket peatland environments, evidence of the effect of unsurfaced vehicle tracks on peat physical properties is severely limited. Small scale work considering the impact of human and animal trampling on blanket peat has been undertaken (Clay et al., 2009, Robroek et al., 2010). However Robroek et al. (2010) observed no significant difference in bulk density between trampled and untrampled routes. To the authors knowledge, within blanket peatlands there is currently no published evidence of the impact of unsurfaced vehicle tracks on bulk density and *K*. In addition, visual observations of vehicle wheel tracks over moorlands in the UK, suggest a compression of the vegetation. It is unclear, however, whether this visual compression of vegetation is also manifested as changes to the structure of the peat or the surface elevation. At present there have been no attempts to quantify such impacts in these environments.

Given the increasing occurrence of constructed and unconstructed tracks in peatlands around the world (Turetsky and St. Louis, 2006), it is important to understand the impact that this may be having on peat physical properties and structure. In UK peatlands, the use of lighter weight geotextile matting (plastic mesh tracks) has been trialled as an alternative to driving directly on the peat surface. The use of a track has the potential to spread the weight of a vehicle more and therefore reduce the concentrated pressure which can occur under the vehicle wheels. Here the impacts of a low-ground-pressure vehicle (14.5 kN m^{-2}), commonly used in the UK uplands, in conjunction with two different track types (plastic mesh and unsurfaced) (Figure 5.1a and b) are presented. In addition, the impact of an articulated wooden track, suitable for 4x4 vehicles is also investigated (Figure 5.1c).

Figure 5.1 a-c Track types which have been included in this study. a) Plastic mesh, b) unsurfaced and c) articulated wooden.

The aim of this study was to investigate the impact of three different track types used in conjunction with low-ground-pressure or 4x4 vehicle use on three different indicators of peat structure: (i) bulk density, (ii) *K*, and (iii) peat surface profile elevation. The following hypotheses were tested, each assuming that the vehicles will impart physical changes to the peat through loading: (i) there will be evidence of higher bulk density after driving compared with before, (ii) *K* will be lower after driving compared with before driving, and (iii) the peat surface profile will become lower with an increasing number of passes. Four factors which could be influential to the magnitude of impact were outlined in Chapter 1. Table 5.1 outlines which influential factors will be considered with each hypothesis.

Table 5.1 Hypotheses tested within the chapter and influential factors considered within each hypotheses.

Hypothesis No.	Influence of Track Type	Spatial Extent of Impact	Influence of Topography	Influence of Frequency of Use
(i)	✓	✓		✓
(ii)			✓	✓
(iii)	✓	✓	✓	✓

5.2 Methodology

5.2.1 Field Sampling

5.2.1.1 Bulk Density and Hydraulic Conductivity

All samples were collected from Moor House NNR (see Chapter 3 for full site description). Field samples were collected for laboratory determination of bulk density (gravimetric method) and *K* using the modified cube method (MCM). Baseline samples were collected prior to track installation in July 2013 (before samples). Repeat samples were collected in June 2015 (bulk density) and August 2015 (*K*) 16 months after driving commenced and 24 months after track installation (after samples).

Samples for bulk density were collected from all eight treatments of the experimental site. In each treatment, samples were stratified in a grid formation (Figure 5.2) at different locations across the track to allow for on- and off-track comparison. Cores were collected from the mid-slope topographic location in each treatment. The mid-slope location was selected as blanket peat has been found to be more homogenous on slopes (Holden, 2005a), therefore this would reduce the influence of natural spatial variability in interpreting the results.

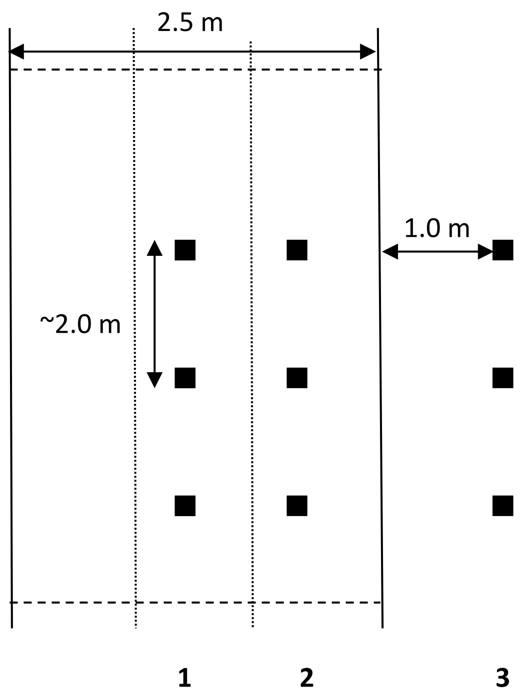

Figure 5.2 Stratified grid arrangement used for the collection of cores for bulk density analysis. Off-track cores were always collected from the left-side of the track (heading downslope) for consistency. Sampling location 1 = Mid-track, sampling location 2 = 'Wheel Rut', sampling location 3 = 1m Off-track.

Cores for bulk density analysis were extracted to a maximum depth of 1 m using a 'box-corer' (inner dimensions 5.6 cm x 5.3 cm) comprised of three fixed sides and a removable fourth side. Surface vegetation was carefully removed to expose the peat surface prior to core extraction. For sample extraction after track installation, a hole was cut in the plastic mesh to allow access to the peat surface. The three fixed sides of the corer were inserted into the peat, to the full 1 m depth or until the corer met with resistance (basal clay). The open fourth side meant the peat being cut was still supported by the surrounding peat, similar to a Wardenaar corer (De Vleeschouwer et al., 2010), and reduced compression of the peat. The fourth removable side was then inserted into the peat before the core was extracted (Figure 5.3).

Any compression which did occur on insertion of the corer into the peat was recorded, along with the dominant vegetation type around the sampling locations. The cores were wrapped in PVC film, transported in guttering to protect them and stored at 4°C until analysis. The regular shape of the extracted core allowed for more precise sub-sampling in the laboratory.

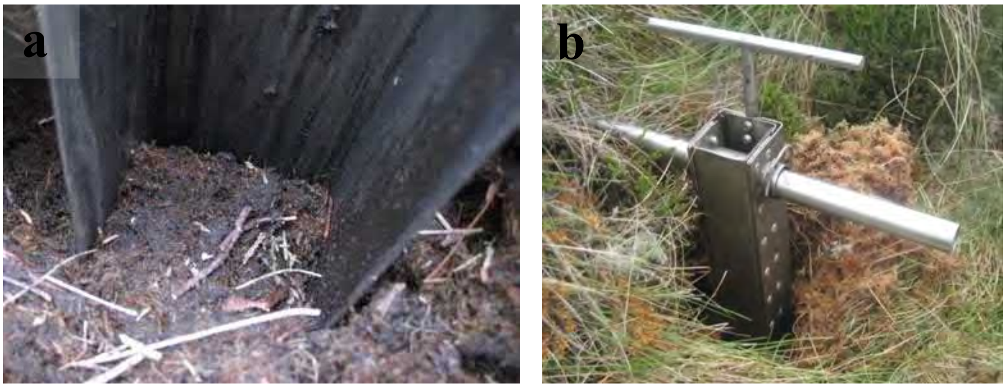

Figure 5.3 a) Insertion of corer with three fixed sides into peat, surface was cleared of vegetation and compression was minimal. b) Corer with fourth side in place prior to core extraction.

For surface *K* analysis (0-10 cm) using the MCM (Beckwith et al., 2003a), cubic peat samples were collected in the field. Sample size used for the MCM was variable within the existing literature. Cubes of 10 cm length (volume 1000 cm^3) were collected using open-ended metal boxes. This size of peat cube was also used by Cunliffe et al. (2013) and Lewis et al. (2012) as it was seen to capture some preferential flow pathways that smaller peat samples may exclude.

K samples were collected from treatments **PWEEK.AL** and **PMONTH** (heaviest and lightest driving use respectively) and the control (**C**) (n = 15 per treatment). Within each treatment samples were collected from each topographic location (S1, S2, S3) (n = 5 per topographic location). For samples collected prior to track installation, the vegetation was cleared away to the peat surface. All *after driving* samples were collected from under the track. The track was cut to expose a sampling area and vegetation was cleared where necessary (Figure 5.4). Care was taken not to disturb the sample on extraction. Where resistance was encountered on the insertion of the sampling box into the peat, scissors were used to cut the vegetation to reduce the occurrence of compression of the sample.

Figure 5.4 a-d Collection of after samples for Laboratory *K* analysis using the modified cube method; a) track cut away to expose vegetation, b) clearing of vegetation to reveal peat surface, c) locating of metal box and start of sample extraction, d) sample after extraction.

5.2.1.2 Surface Profile Elevation

Change in peat surface elevation was captured through topographic surveys. A baseline survey was carried out in March/April 2014, after track installation, but prior to the start of driving. Repeat surveys were carried out after six and eighteen months of driving. All topographic surveys were undertaken using a Spectra Precision Geodimeter Total Station 608S, which is accurate to millimetre level.

Peat surface elevation was measured along track cross-section transects. Typically transects extended out to 5 m either side of the tracks (2 m for treatment **U**). Off-track the surveying frequency was every 50 cm, on-track the survey frequency was every 10 cm. The start and end points of transects were marked with flags and left *in-situ* for the duration of the field experiment. On-track survey points were marked with dye so that the same points could be returned to accurately on each visit. Due to weather conditions and time constraints it was not possible to survey all transects on each visit In treatments **PWEEK.AL**, **PWEEK.AH**, **PWEEK**, and **PMONTH** one transect was established per topographic location (S1, S2, S3) and measurements were taken on every visit. In treatment **U** a transect was established at topographic location S3, with measurements taken on every visit. In **PDELAYED**, one transect was established per topographic location, measurements were taken on the second and third survey visits. In treatment **W** a single transect was established and measured on the second and third visits. Duplicate measurements of selected transects were undertaken during the final survey to determine the influence of human error. In all measurements surface profile elevation was measured to the peat surface, not to the track surface. Surface profile elevation was not measured in the control treatment, without this information it was therefore not possible to assess the error in method.

5.2.2 Laboratory Methodology

5.2.2.1 Bulk Density

To provide consistency across the site, the top 50 cm of each core was used. For each peat core, samples were divided into 2 cm sections between 0 and 30 cm depth and 5 cm sections between 30 and 50 cm. The dimensions of each individual sub-sample were recorded, and care was taken when some parts of the sample were missing to ensure accurate estimates of sample volume. Samples were dried for at least 36 hours at 105 °C until they had reached a constant weight (Parry and Charman, 2013). Bulk density was calculated by dividing the dry weight by the field moist sample volume.

5.2.2.2 Hydraulic Conductivity

The MCM was used here as it allowed measurement of K in the vertical and horizontal. The method outlined in Cunliffe et al. (2013) was followed, with some slight adaptations given differences in the samples being tested in the two studies. Cunliffe et al. (2013) predominantly examined K in samples from deeper in the peat profile, whereas the samples in this thesis were from the peat surface. In order to remove any smeared peat which may have occurred through sample collection, ~0.5 cm of peat was shaved off every face of each sample. Other studies have used non-serrated blades to achieve this (e.g. Beckwith et al., 2003a, Cunliffe et al., 2013) but due to the large sample size (1000 cm^3), the open structure of surface peat and the presence of *Calluna vulgaris* stems in many of the samples, an electric slicer (Lakeland Ltd. Manual Electric Slicer Model 13665) was found to be the best device to limit further disturbance to the sample.

Samples were coated in paraffin wax (Rosa and Larocque, 2008, Lewis et al., 2012, Cunliffe et al., 2013), which limits preferential flow down the sides of the sample, and two opposing faces were exposed. Samples were left to become saturated through upward wetting for at least 2 hours. Upward wetting reduced the occurrence of trapped gas bubbles in the sample which could alter *K* (Beckwith et al., 2003a). In some cases it was necessary to leave samples soaking overnight to ensure they were fully saturated. Water chemistry has the potential to affect the *K* due to soil-water interactions (Ours et al., 1997). Consequently the water used for the tests was collected from a stream close to the sampling locations.

The samples were set-up as shown in Figure 5.5. Water was ponded in a reservoir at the top of the sample and infiltrated through the sample. The reservoir was kept full to maintain a constant head. The volume of water displaced from the container was collected and recorded over time. This value was used in the calculation of *K*.

Figure 5.5 Experiment set-up of surface peat samples to measure *K* using the modified cube method.

Three consecutive measurement runs were undertaken per sample to determine whether there was any temporal variability. Ambient temperature affects water viscosity and was therefore recorded. All results were standardised to 20 °C. Following three runs, each sample was left to drain under gravity for two hours, before being re-sealed, rotated by 90°and two new faces exposed. The hydraulic head was kept constant throughout the sample run and the determination of *K* assumed Darcy's flow law.

The equation below was used in the calculation of *K*:

$$K = \frac{Q}{A} \times \frac{\Delta L}{\Delta H}$$

where, Q is discharge (mL s^{-1}), using the average of the three consecutive runs, A is the area of the smallest exposed face, ΔL is the length of the sample and ΔH is the head difference across the length of the sample (Cunliffe et al., 2013).

For each sample, K was measured in one vertical and one horizontal direction (selected randomly). K_v was generally measured before K_h. However, for some selected samples K_h was run before K_v to determine whether sampling order induced any bias. The selected bias test samples (n = 14) were from different treatment x topographic location combinations. Anisotropy was reported as $\log_{10}(K_h/K_v)$, as this allows easy graphical comparison of the data (Chason and Siegel, 1986, Beckwith et al., 2003a, Cunliffe et al., 2013). Where the value of anisotropy was 0, $K_h = K_v$, a positive value of anisotropy meant that $K_h > K_v$, and a negative value meant that $K_v > K_h$ (Beckwith et al., 2003a).

5.2.3 Statistical Analysis

Data were analysed using Minitab version 17.1.0. Bulk density (BD) and K data were tested for differences in before and after driving data, in addition to interaction effects with treatment, topographic location, sampling location and depth where applicable. BD data fulfilled the assumption of ANOVA. A general linear model (GLM) was run with the raw data (where residuals showed an acceptable distribution around normal) and further tests of difference were performed using one-way ANOVA and two-sample T-tests. K data was found to be skewed to the right. A $\log_{10}$ transformation gave the data a more normal distribution, but with unequal variance and small sample size the data did not fulfil the assumptions of ANOVA. A GLM was run using the log transformed data (where residuals showed an acceptable distribution around normal) and further tests of difference were performed using Kruskall-Wallis and Mann-Whitney on the raw data. The small sample size (n = 5) in the slope-treatment breakdown of K data meant that only non-parametric tests would be appropriate. Statistical analysis was only performed for on-track change in surface profile elevation data. The on-track data offered greater precision. Elevation data was mainly found to be normal and showed equal variance. Paired t-tests were used to determine the difference in mean elevation in each transect for different surveying dates. Differences in elevation between sampling dates were also calculated and tested for normality. This data did not share equal variance and therefore Kruskall-Wallis tests were used. In all analyses, effects were considered significant if $p \leq 0.05$.

5.3 Results

5.3.1 Bulk Density

5.3.1.1 Antecedent Conditions

Total rainfall (mm) and average temperature (°C) have been calculated for the 30 day periods preceding the bulk density sample collection events in 2013 and 2015 to provide an indication of antecedent conditions. Rainfall totals were either similar between 2013 and 2015 or higher in 2013 compared with 2015. However, in general temperatures were typically higher in 2013 compared with 2015, with the largest difference of ~7°C. Therefore evapotranspiration rates were likely to be higher in 2013 compared with 2015, leading to drier peat being sampled in 2013 compared with 2015. In addition, although rainfall totals were sometimes lower in 2015, there were slightly more days with rain in the 30 day period.

Table 5.2 Total rainfall and average temperature for 30 day period preceding sampling days for bulk density sample collection.

Sampling Date	Total Rainfall (mm)	No. of Rain Days	Average Temperature (°C)
2013			
2-3 July	96.5	15	10.0
16 & 18 July	56	11	12.4
8 August	172.5	12	14.6
14 August	203	17	13.6
2015			
22-23 June	105.5	19	7.7
16 September	112	19	10.0

5.3.1.2 Bulk Density Analysis

Between 0 and 50 cm depth, bulk density (BD) ranged from 0.020 to 0.535 g cm^{-3}, with a mean of 0.093 g cm^{-3} and a median of 0.092 g cm^{-3}. The range was smaller for Before BD compared with After BD (0.254 and 0.501 g cm^{-3} respectively). BD showed variation with depth (Figure 5.6) and this variation was found to occur by treatment and sampling location. Extreme BD values within the 0 to 50 cm depth could be attributed to the shallow peat depth in treatments **PMONTH, PDELAYED** and **C**. In both Before and After BD the greatest variation with depth was observed between 0 and 30 cm (Figure 5.6).

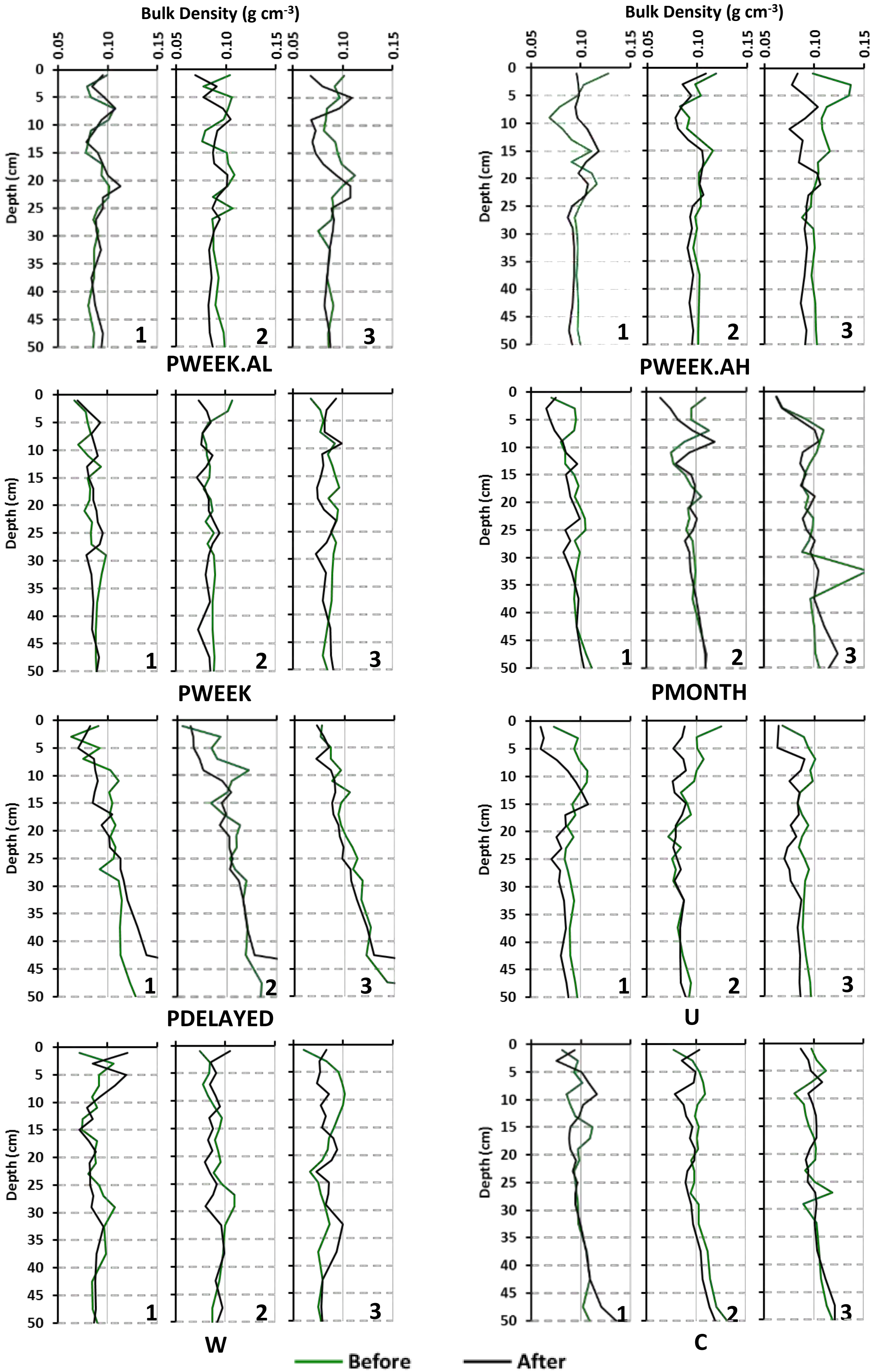

Figure 5.6 Depth profiles to 50 cm for Bulk Density, representing each treatment and location across track. 1 = mid-track location, 2 = Wheel Rut Location, 3 = 1m Off Track

Between 0 and 30 cm, BD ranged from 0.020 to 0.173 g cm^{-3}, with a mean of 0.091 g cm^{-3} and a median of 0.091 g cm^{-3}. BD showed variation between treatments (Figure 5.7). **PWEEK.AH** yielded the highest mean and median BD and **PWEEK** the lowest. Overall, mean and median BD was significantly greater for the before samples compared with the after samples (Table 5.3). The range in BD was more comparable for before and after data (0.152 and 0.122 g cm^{-3} respectively) between 0 and 30 cm compared with 0 and 50 cm. Further statistical analysis was therefore based on 0 to 30 cm data.

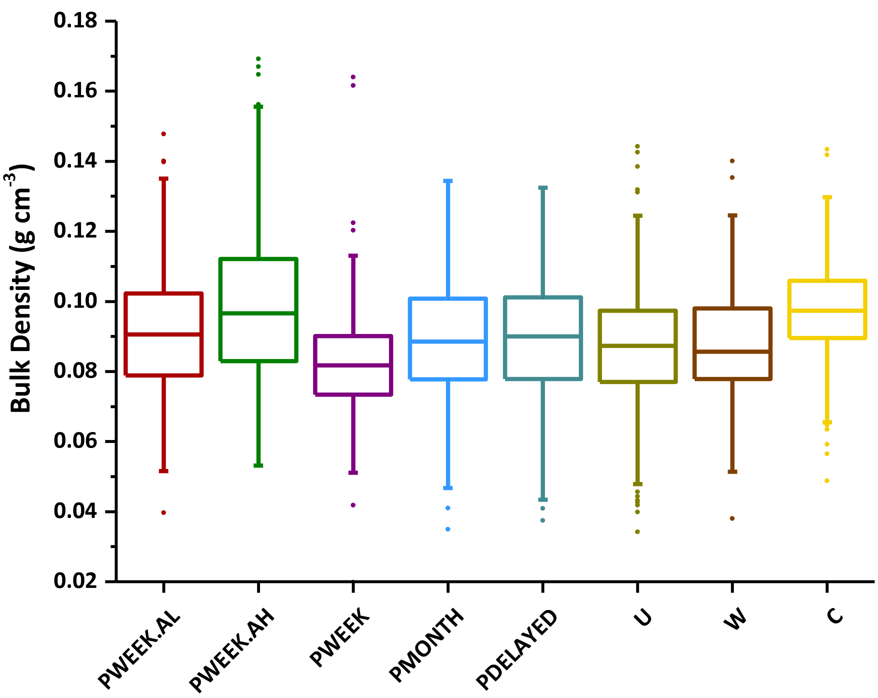

Figure 5.7 Boxplot of bulk density (0-30 cm) by treatment, showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

Table 5.3 Descriptive statistics for before and after bulk density between 0 and 30 cm depth.

	n	Mean (g cm^{-3})	Minimum (g cm^{-3})	Median (g cm^{-3})	Maximum (g cm^{-3})	IQR
Before	1080	0.093	0.020	0.092	0.172	0.021
After	1080	0.089	0.034	0.089	0.156	0.021

The GLM output highlighted the factors which explained variation in BD between 0 and 30 cm, in addition to significant interactions between factors (Table 5.4). Time (Before/After), treatment and depth were all found to strongly influence variation (p <0.001 for all), whilst sampling location across the track was not (p = 0.130). The interaction of time *x* treatment *x* location *x* depth was found to be marginally non-significant (p = 0.058).

Table 5.4 Significant influential factors and interactions on variability in bulk density, determined through a GLM. p was significant at ≤ 0.05.

Influential Factor	P value
Time (Before/After)	<0.001
Treatment	<0.001
Depth	<0.001
Time *x* Treatment	<0.001
Time *x* Location	0.006
Treatment *x* Depth	<0.001
Time *x* Treatment *x* Location	0.017
Time *x* Treatment *x* Depth	0.013

Time was significant as a main effect and also within a number of interactions, and is of importance to this study in determining whether track installation and use had an impact. Time was found to share significant interactions with treatment, location, and depth (when combined with treatment). To fully understand the effect of time on BD, the data was broken down further. Between and within treatment differences for Before and After BD were investigated. Between treatments, those which were not significantly different from each other for Before BD (0-30 cm) were also not significantly different for After BD (0-30 cm) (Figure 5.8). Within all treatments, Before BD (0-30 cm) was higher than After BD (0-30 cm) (Figure 5.8). This difference was only significant in **PWEEK.AH**, **PMONTH**, **PDELAYED** and **U** (p = 0.002, 0.017, 0.002 and < 0.001 respectively). It should be noted however, that Before and After BD varied as much in treatment **C** (see Figure 5.6 and 5.7), where there was no driving, as it did in the other treatments, where driving took place. Therefore some of the significant differences observed may be due to natural variation in peat BD between 0 and 30 cm.

Sampling location, on-track (1 and 2) and off-track (3), was not a significant main effect on BD variation, however two important interactions to investigate further were time *x* location and time *x* treatment *x* location**.** Between and within differences for Before and After BD were analysed. Before BD was higher at all three sampling locations compared with After BD. Before BD was not significantly different between the three sampling locations. For After BD sampling locations

1 (mid-track) and 3 (1 m off-track) were significantly different from each other, but neither was significantly different from sampling location 2 (wheel rut). Within a sampling location, Before BD was significantly higher than After BD at sampling locations 2 and 3 ($p < 0.001$ for both).

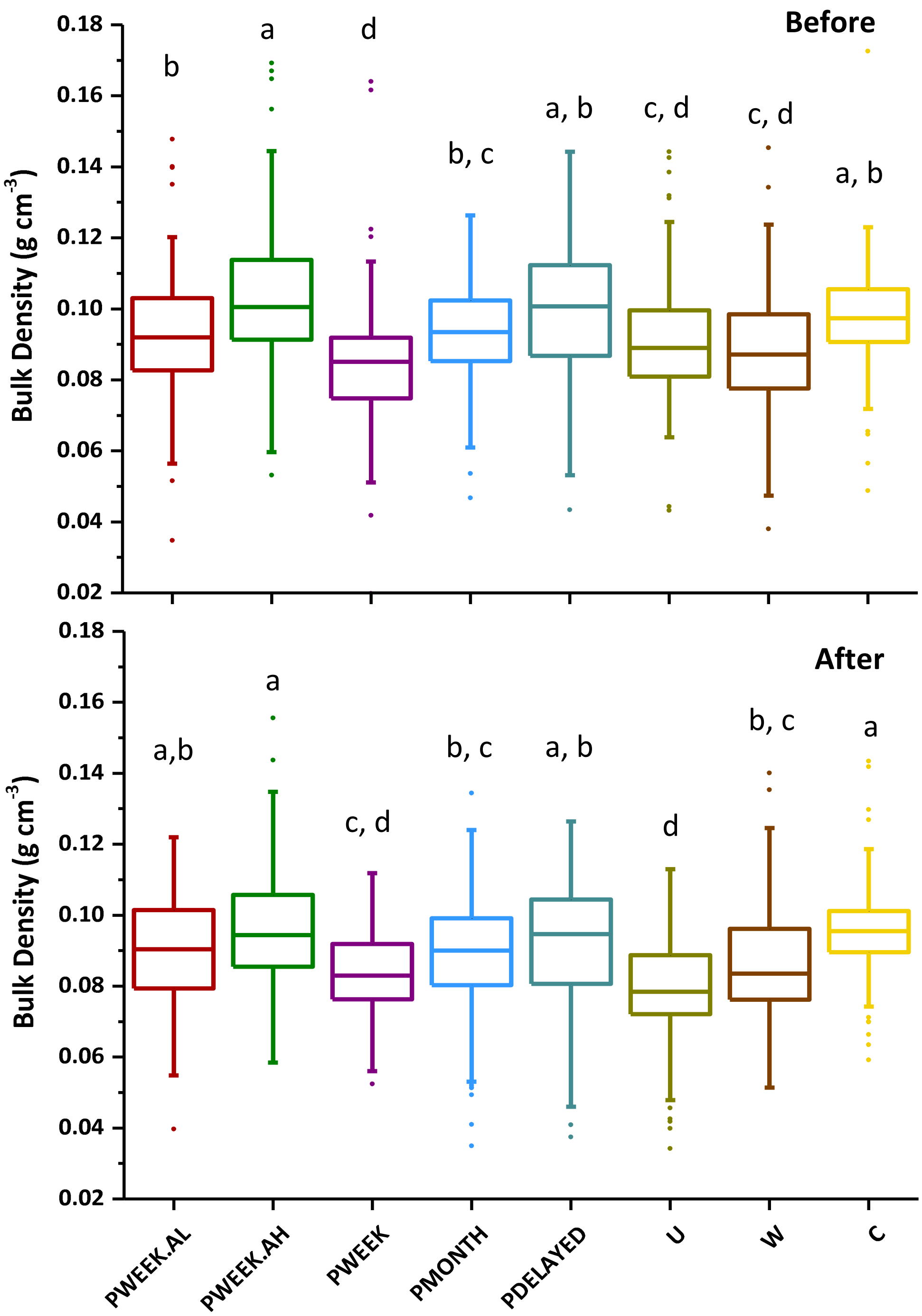

Figure 5.8 Boxplot of variation in Before and After bulk density between 0 and 30 cm depth by treatment. showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data. Treatments which share the same letter were not significantly different from each other in the before and after data when analysed separately.

Table 5.5 *p* values from *post-hoc* testing of differences in After BD between sampling locations across track

	Mid-Track (1) v Wheel-Rut (2)	Mid-Track (2) v 1m Off Track (3)	Wheel-Rut (2) v 1m Off Track (3)
PWEEK.AH	0.139	0.006	0.100
W	0.574	0.024	0.093

The pattern of variation in BD with sampling location was different between the treatments and by time (time *x* treatment *x* location) and did not always follow the general pattern. In all treatments, no significant difference was observed in average Before BD (0-30 cm) between sampling locations. In After BD, a difference was observed, with on-track BD higher than off-track BD in **PWEEK.AL**, **PWEEK.AH**, **U** and **W**. This spatial pattern was not observed in **PWEEK**, **PMONTH**, or **C**. The on-track versus off-track comparison only showed a significant difference in **PWEEK.AH** and **W** ($p = 0.020$ and 0.045 respectively). Results of *post-hoc* testing are shown in Table 5.5. In both treatments, mid-track BD was significantly different from BD 1 m off-track. However, mid-track and wheel rut, and wheel-rut and 1 m off track BD were not significantly different from each other.

The residuals of on-track After minus Before BD showed variation between treatments and by depth within a treatment (Figure 5.9). There was no consistency in the depth at which the greatest change was observed. In treatments **PWEEK.AL**, **PWEEK.AH**, and **PWEEK**, there appeared to be a shift from a negative change (decrease) in BD in the top 0 to ~5 cm to a positive change (increase) in BD between ~5 and 15 cm. In **PDEALYED** little change in BD was observed at the surface, however between 2 and 20 cm in general the difference was negative. In treatment **U** the difference between Before and After BD was mainly negative. In treatments **W** and **C** a positive change in BD was observed in the surface peat (0-2 cm), treatment **W** also showed a positive change between 6 and 10 cm depth. Treatment **C** showed the least variation around zero of all of the treatments for 'on-track' data. The different direction of change in surface BD in treatment **W** compared with treatments **PWEEK.AL**, **PWEEK.AH**, **PWEEK**, **PDELAYED** and **U** suggested an influence of track type. The difference in incremental depth and direction of change between 0 and 10 cm within each treatment is outlined in Table 5.6. The sample size was not large enough for meaningful statistical analysis.

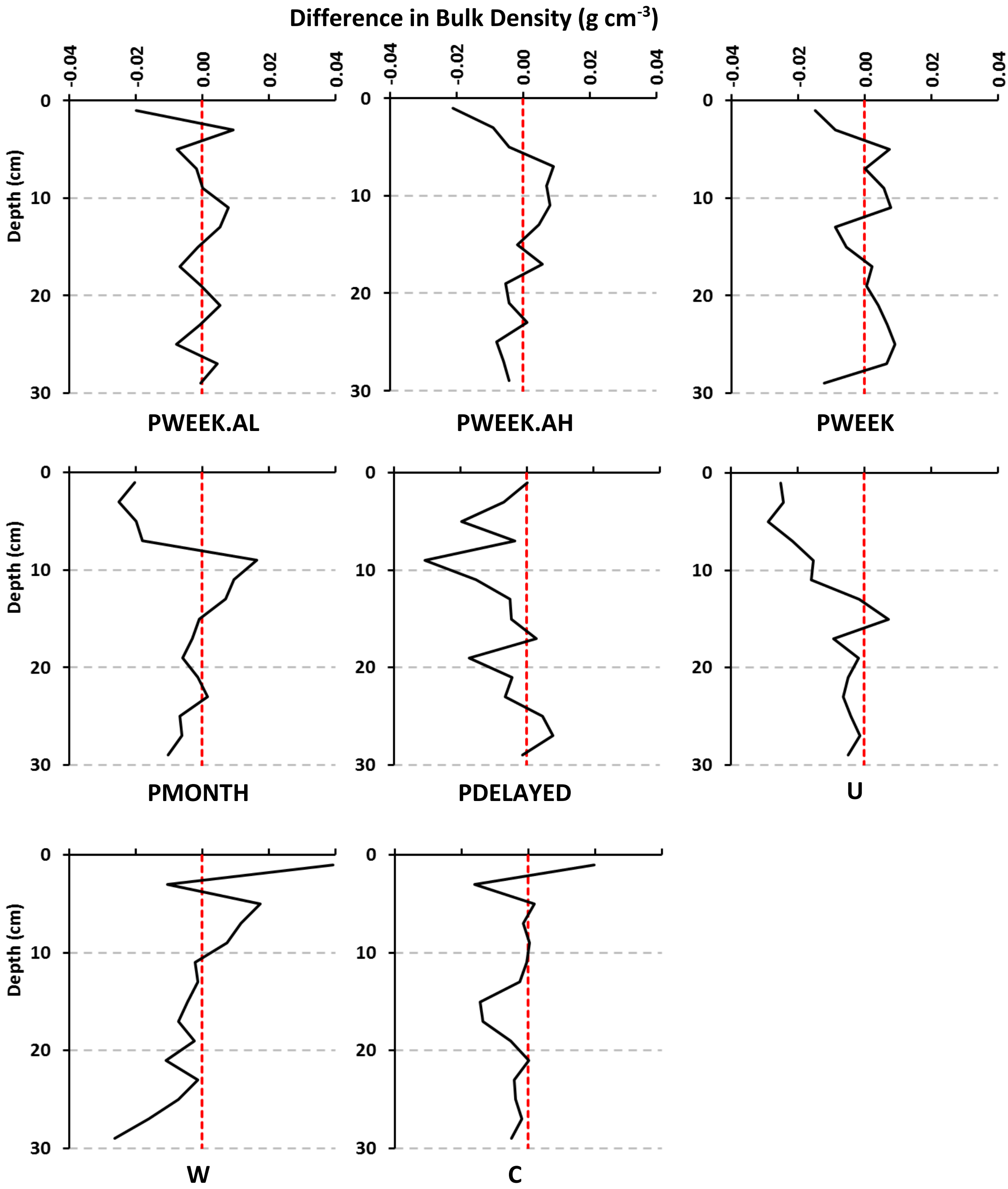

Figure 5.9 Difference (After minus Before) in on-track bulk density with depth between 0 and 30 cm. Negative values indicate a decrease in bulk density and positive values an increase in bulk density.

Table 5.6 Comparison of mean Before and After on-track BD and direction of change in 2 cm increments between 0 and 10 cm depth for each treatment. Where difference was ≤ 0.002 g cm^{-3} no direction of change is given.

Treatment	Depth	*n*	Before BD Mean (SE Mean)	After BD Mean (SE Mean)	Direction Change
	0-2	6	0.102 (0.009)	0.082 (0.009)	Decrease
	2-4	6	0.078 (0.006)	0.087 (0.006)	Decrease
PWEEK.AL	4-6	6	0.094 (0.007)	0.087 (0.005)	Decrease
	6-8	6	0.104 (0.008)	0.103 (0.006)	Decrease
	8-10	6	0.099 (0.004)	0.099 (0.006)	
	0-2	6	0.123 (0.011)	0.102 (0.007)	Decrease
	2-4	6	0.101 (0.004)	0.091 (0.006)	Decrease
PWEEK.AH	4-6	6	0.100 (0.012)	0.096 (0.009)	Decrease
	6-8	6	0.080 (0.007)	0.090 (0.007)	Increase
	8-10	6	0.080 (0.006)	0.087 (0.006)	Increase
	0-2	6	0.087 (0.017)	0.072 (0.005)	Decrease
	2-4	6	0.090 (0.015)	0.081 (0.006)	Decrease
PWEEK	4-6	6	0.082 (0.004)	0.089 (0.005)	Increase
	6-8	6	0.080 (0.004)	0.081 (0.005)	
	8-10	6	0.076 (0.014)	0.081 (0.004)	Increase
	0-2	6	0.089 (0.009)	0.069 (0.007)	Decrease
	2-4	6	0.094 (0.002)	0.069 (0.008)	Decrease
PMONTH	4-6	6	0.095 (0.007)	0.075 (0.010)	Decrease
	6-8	6	0.103 (0.006)	0.085 (0.008)	Decrease
	8-10	6	0.084 (0.008)	0.100 (0.009)	Increase
	0-2	6	0.073 (0.012)	0.073 (0.008)	
	2-4	6	0.078 (0.008)	0.071 (0.007)	Decrease
PDELAYED	4-6	6	0.088 (0.006)	0.069 (0.003)	Decrease
	6-8	6	0.083 (0.005)	0.090 (0.005)	Increase
	8-10	6	0.112 (0.007)	0.082 (0.006)	Decrease
	0-2	6	0.099 (0.016)	0.074 (0.010)	Decrease
	2-4	6	0.099 (0.009)	0.074 (0.012)	Decrease
U	4-6	6	0.097 (0.007)	0.068 (0.006)	Decrease
	6-8	6	0.103 (0.006)	0.081 (0.004)	Decrease
	8-10	6	0.104 (0.007)	0.088 (0.005)	Decrease
	0-2	6	0.073 (0.003)	0.112 (0.007)	Increase
	2-4	6	0.095 (0.008)	0.085 (0.003)	Decrease
W	4-6	6	0.088 (0.005)	0.105 (0.011)	Increase
	6-8	6	0.084 (0.008)	0.096 (0.011)	Increase
	8-10	6	0.084 (0.007)	0.091 (0.007)	Increase
	0-2	6	0.079 (0.008)	0.099 (0.010)	Increase
	2-4	6	0.097 (0.008)	0.081 (0.006)	Decrease
C	4-6	6	0.098 (0.007)	0.100 (0.006)	
	6-8	6	0.104 (0.006)	0.103 (0.005)	
	8-10	6	0.097 (0.006)	0.098 (0.011)	

5.3.2 Hydraulic Conductivity

K values covered a large range of five orders of magnitude from 1.17 x 10^{-1} to 5.08 x 10^{-6} cm s^{-1}, with a median of 2.23 x 10^{-4} cm s^{-1} and a geometric mean of 3.25 x 10^{-4} cm^{-1}. Horizontal *K* (K_h) was faster than vertical *K* (K_v) (Figure 5.10). K_h ranged from 1.17 x 10^{-1} to 1.61 x 10^{-5} cm s^{-1}, with a median of 1.19 x 10^{-3} cm s^{-1}. K_v ranged from 2.18 x 10^{-3} to 5.08 x 10^{-6} cm, with a median of 8.19 x 10^{-5} cm s^{-1}. Both K_h and K_v were skewed to the right.

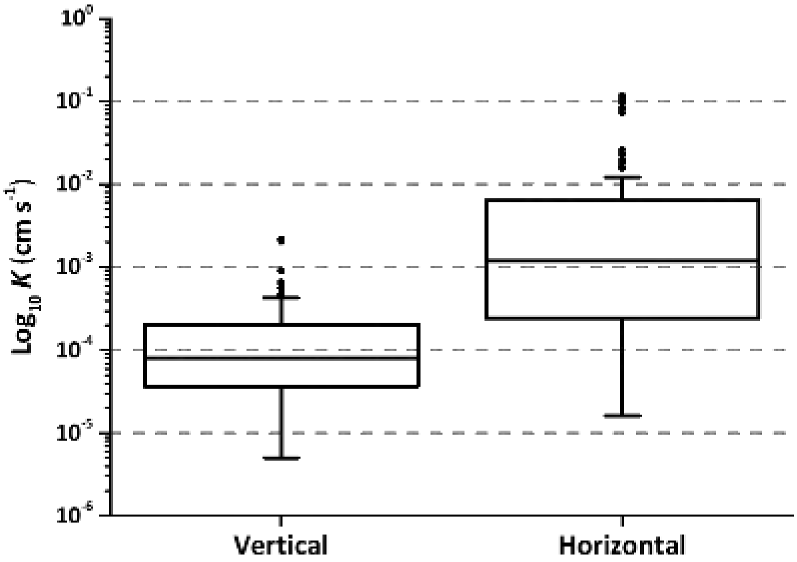

Figure 5.10 Boxplot showing K_v and K_h for all samples, showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

K_h was faster than K_v for before samples and after samples. For the 14 samples tested to ensure the pattern was inherent in the data and not a result of the laboratory procedure $K_h > K_v$ (K_h was measured before K_v). The samples were found to be highly anisotropic, with 90 % showing positive $log_{10}(K_h/K_v)$ values (Figure 5.11), suggesting a laminar structure in the surface peat. For both the before and after datasets K_v was significantly different from K_h at $p < 0.001$.

Anisotropy was significantly different between topographic locations ($p < 0.001$). *Post-hoc* testing showed no significant difference between topographic locations S1 and S2 ($p = 0.706$). Anisotropy was significantly higher at both of these locations compared with S3 (S1 v S3, $p = 0.003$; S2 v S3, $p = 0.001$).

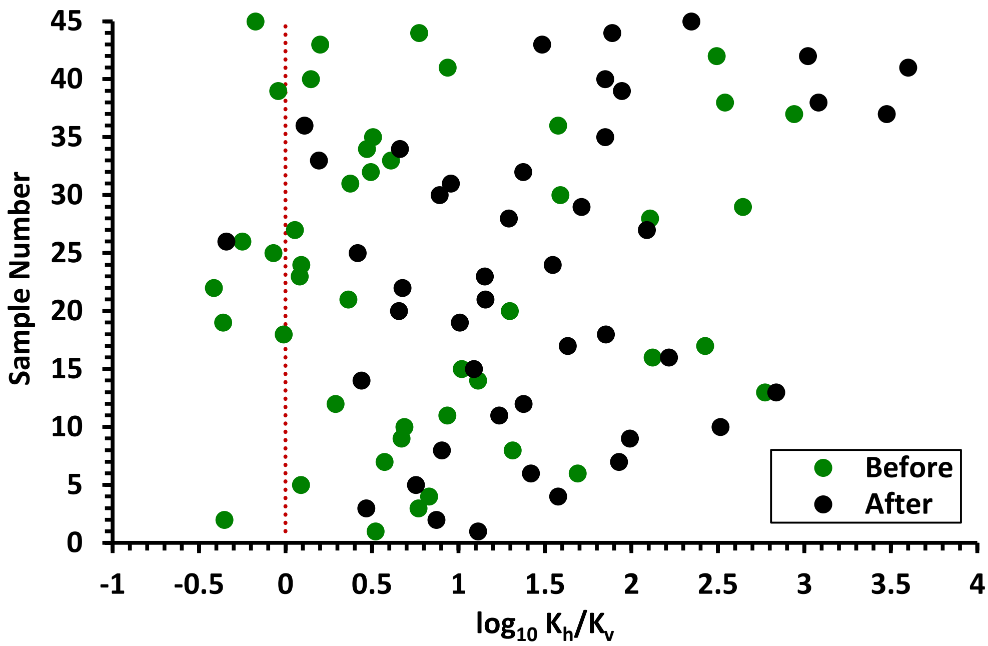

Figure 5.11 Distribution of $\log_{10}(K_h/K_v)$ values for Before and After *K*.

A GLM was used to determine the factors influential to *K* variability. Input factors were flow direction (Vertical/Horizontal), time, treatment and topographic location. Significant influential factors and interactions are shown in Table 5.7.

Table 5.7 Significant influential factors and interactions on variability in *K*, determined through a GLM.

Influential Factor	P Value
Flow Direction (Vertical/ Horizontal)	<0.001
Treatment	0.010
Flow Direction *x* Time	0.004
Flow Direction *x* Topographic Location	0.002
Time *x* Treatment	0.046
Time *x* Topographic Location	0.008
Time *x* Treatment *x* Topographic Location	0.018

Due to the significant difference between K_v and K_h, all subsequent analysis was performed on K_v and K_h data separately. Despite not being a significant factor on its own, Time was found to be a significant factor when combined with flow direction, treatment and topographic location, the latter two individually and combined (Table 5.7).

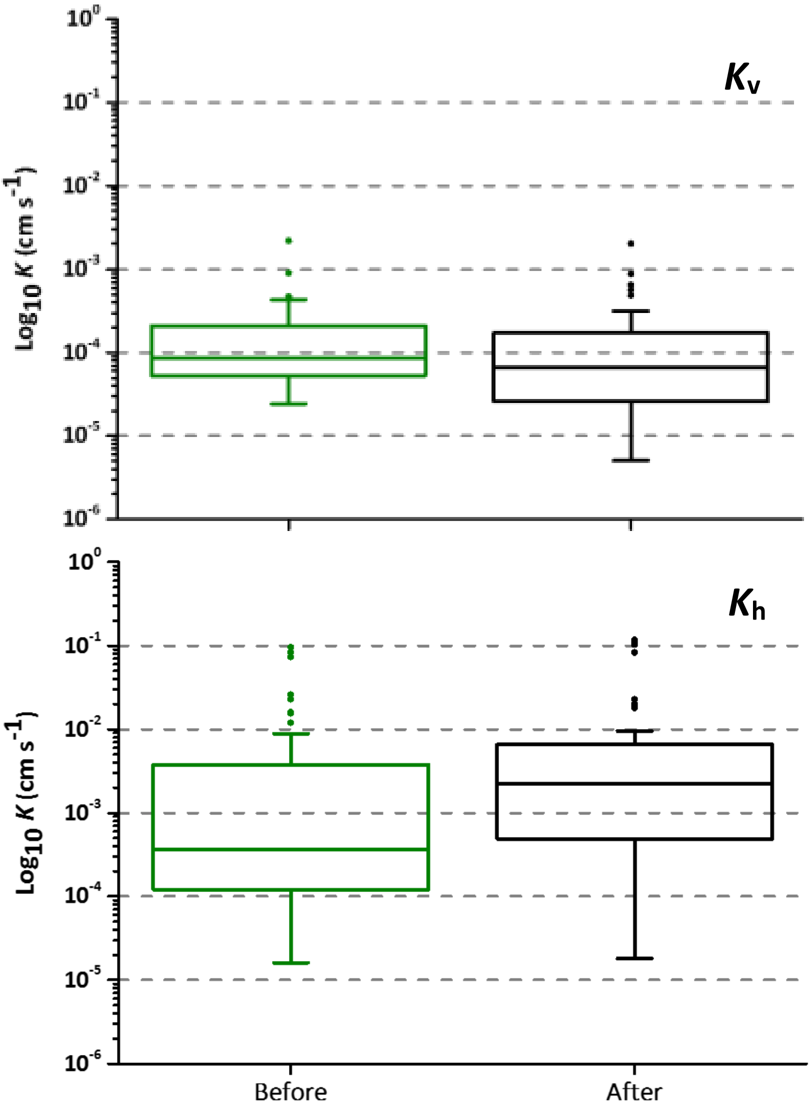

Figure 5.12 Boxplots comparing Before and After *K* for K_v and K_h separately, showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

Using the full dataset ($n = 45$ per group), K_v was found to be lower after driving compared with before, although not significantly ($p = 0.112$). K_h was significantly higher in the after samples (median 2.2 x 10^{-3} cm s^{-1}) compared with before (3.7 x 10^{-4} cm s^{-1}) ($p = 0.021$) (Figure 5.12). In order to determine whether treatment **C,** which had a differing direction of change compared to the rest of the K_v dataset and a larger magnitude of difference in the K_h dataset, was influencing the observed direction of change (i.e. increase or decrease in *K*), data from this treatment were removed from the analysis, leaving pooled data from treatments **PWEEK.AL** and **PMONTH** (*n* = 30 per group). K_v was significantly lower after driving compared with before ($p = 0.026$), whilst there was no significant difference for K_h (p = 0.243). Table 5.8 outlines the difference in results following the removal of treatment **C** data. Direction of change remained the same, however the significant differences changed on the removal of treatment **C**.

Table 5.8 Direction of change in K_v and K_h before driving compared with after driving, with and without data from treatment C. * denotes a significant difference.

Before to After	With treatment C	Without treatment C
K_v	⬇	⬇*
K_h	⬆*	⬆

When further investigated by treatment, direction of change in K_v was different in the driving treatments (**PWEEK.AL** and **PMONTH**) compared with treatment **C**. K_v decreased slightly from before to after in treatments **PWEEK.AL** and **PMONTH**, while it increased slightly in treatment **C**. None of the differences were significant. K_h increased slightly from before to after in all three treatments, yet only treatment **C** showed a significant increase ($p = 0.020$) (Figure 5.13). The range of After K_h for **C** was much larger than the other treatments. The magnitude of difference between before and after *K* does not appear to be influenced by treatment.

K by topographic location showed a smaller range in the After values compared with Before at location S1. *K* decreased from Before to After at all topographic locations, the difference was significant at locations S1 and S2 ($p = 0.011$ and $p = 0.038$ respectively). After K_v was marginally greater than Before K_v at topographic location S3. Median K_h was higher for after data compared with before at all topographic locations, and at location S3 showed a significant increase ($p = 0.001$) (Figure 5.14).

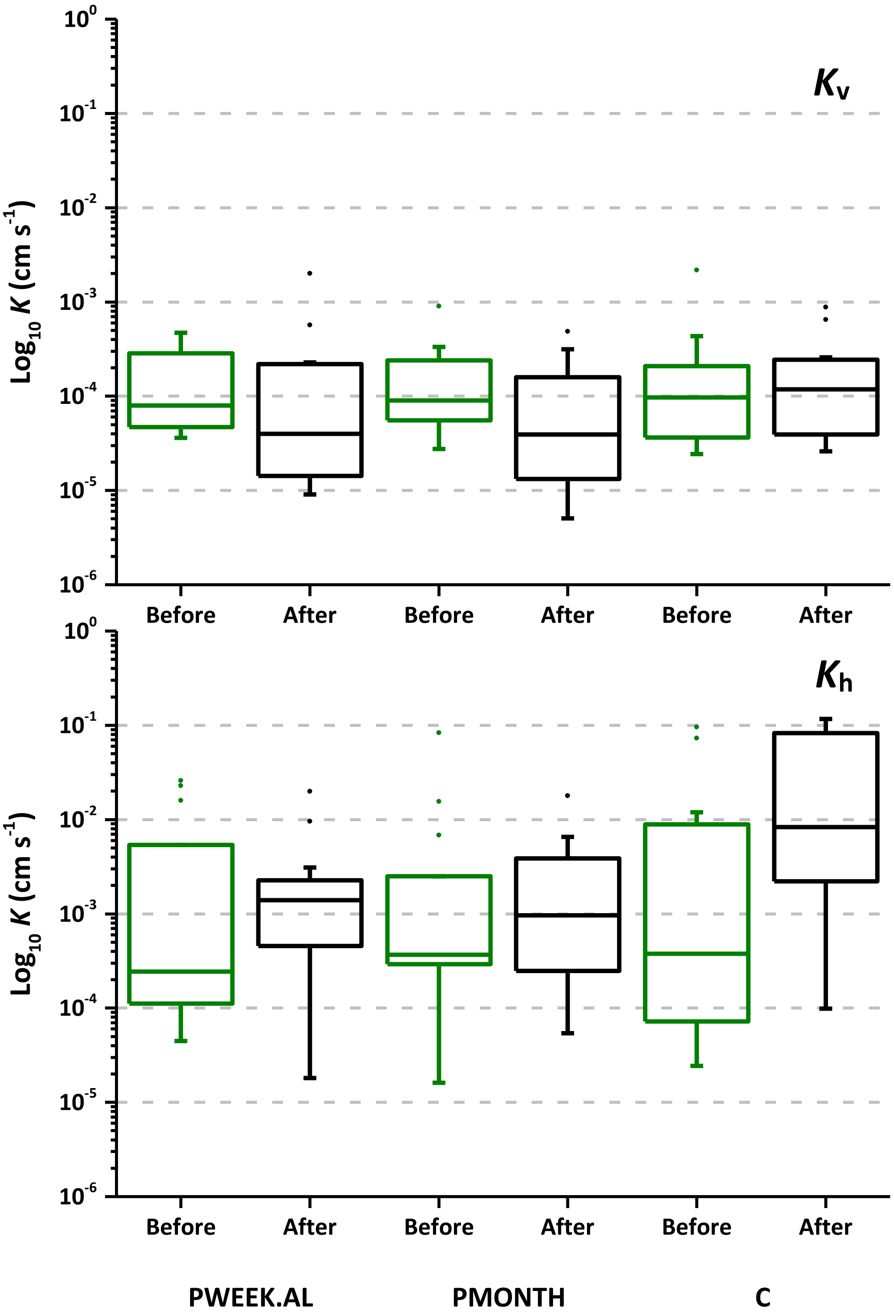

Figure 5.13 Boxplots comparing Before and After *K* by treatment. K_v and K_h are plotted separately, showing the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

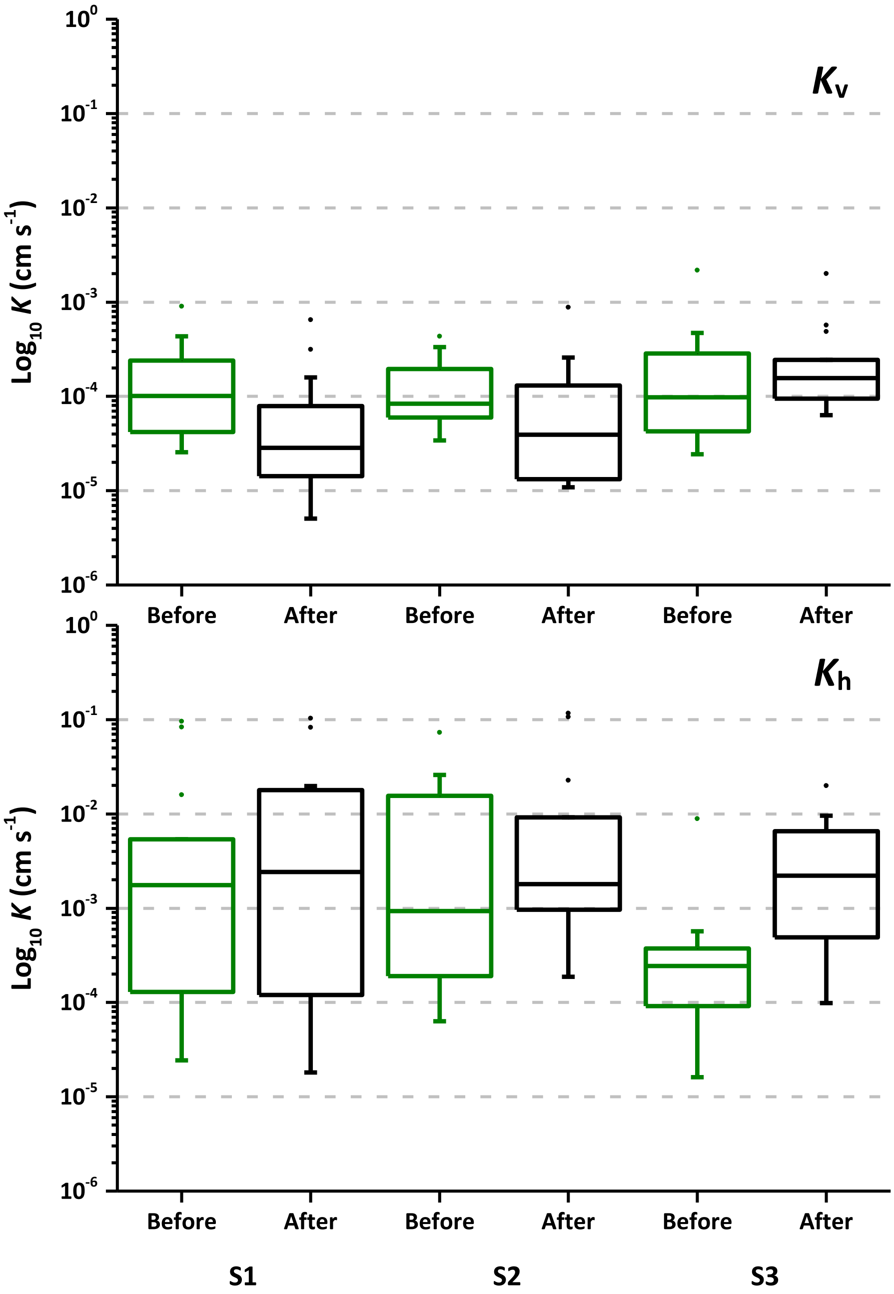

Figure 5.14 Boxplots comparing Before and After *K* by topographic location. K_v and K_h are plotted separately (**PWEEK.AL**, **PMONTH**, and **C** combined), S1 = Top-slope, S2 = Mid-slope, S3 = Bottom-slope. Boxplots show the median, first (Q1) and third (Q3) quartiles, and outliers. Outliers are calculated as values less than Q1 – 1.5 x (Q3 – Q1) and greater than Q3 + 1.5 x (Q3 – Q1), where 1.5 is a pre-defined coefficient to suitably capture the range in the data.

To fully understand the impact of the track on surface peat *K*, data were broken down by flow direction, treatment and topographic location (n = 5 per group). Differences between before and after for K_v and K_h were only significant in treatments **PWEEK.AL** and **PMONTH**. Out of the six driven treatment *x* topographic location combinations, five showed a decrease in K_v from before to after of which two were significant (**PWEEK.AL *x* S1** and **PMONTH *x* S3**). Five also showed an increase in K_h from before to after of which two were significant (**PWEEK.AL *x* S3** and **PMONTH *x* S3**). Test statistics for individual treatment *x* topographic location combinations for K_v and K_h are presented in Table 5.9.

Table 5.9 Descriptive and test statistics for Before and After K_v and K_h by treatment *x* topographic location. * = significant at $p \leq 0.05$.

Treatment	Topographic Location	Flow Direction	*n*	Before Median	After Median	P value	Direction of Change
PWEEK.AL	S1	Vertical	5	5.35×10^{-5}	1.42×10^{-5}	0.022 *	Decrease
		Horizontal	5	2.07×10^{-3}	4.65×10^{-4}	0.296	
	S2	Vertical	5	8.57×10^{-5}	3.24×10^{-5}	0.095	
		Horizontal	5	9.32×10^{-4}	1.39×10^{-3}	0.835	
	S3	Vertical	5	2.85×10^{-4}	2.18×10^{-4}	0.531	
		Horizontal	5	1.36×10^{-4}	3.10×10^{-3}	0.02 *	Increase
PMONTH	S1	Vertical	5	1.41×10^{-4}	2.59×10^{-5}	0.296	
		Horizontal	5	1.76×10^{-3}	2.74×10^{-3}	1.000	
	S2	Vertical	5	9.00×10^{-5}	1.32×10^{-5}	0.012 *	Decrease
		Horizontal	5	3.45×10^{-4}	9.66×10^{-4}	1.000	
	S3	Vertical	5	5.55×10^{-5}	1.44×10^{-4}	0.037 *	Increase
		Horizontal	5	1.21×10^{-4}	8.20×10^{-4}	0.037 *	Increase
C	S1	Vertical	5	2.09×10^{-4}	3.13×10^{-5}	0.676	
		Horizontal	5	1.24×10^{-3}	1.98×10^{-2}	0.144	
	S2	Vertical	5	7.56×10^{-5}	1.30×10^{-4}	0.144	
		Horizontal	5	3.68×10^{-3}	2.27×10^{-2}	0.210	
	S3	Vertical	5	1.07×10^{-4}	1.56×10^{-4}	0.676	
		Horizontal	5	3.42×10^{-4}	2.21×10^{-3}	0.403	

5.3.3 Surface Profile Elevation

On-track change in elevation ranged between 0.055 and -0.118 m, where positive values indicated an increase in peat surface elevation and negative values a decrease (lowering) in peat surface elevation. Off-track change in elevation ranged between 0.163 and -0.278 m. For both on-track and off-track, elevation change was greater between April 2014 and October 2014 compared with October 2014 and October 2015. Off-track elevation change covered a larger range than on-track elevation change for both survey periods (Table 5.10), and showed greater noise (Figure 5.15). Further analysis of change in surface profile elevation focused on on-track data, due to a greater level of confidence in the data (Table 5.10).

Table 5.10 Descriptive statistics for on- and off-track peat surface elevation change.

	n	Mean (SE Mean) (m)	Minimum (m)	Median (m)	Maximum (m)	Range (m)	IQR (m)
On-Track							
Apr 2014 – Oct 2014	328	-0.028 (0.001)	-0.104	-0.027	0.055	0.159	0.028
Oct 2014 – Oct 2015	447	-0.012 (0.001)	-0.118	-0.013	0.035	0.153	0.018
Off-Track							
Apr 2014 – Oct 2014	271	-0.036 (0.003)	-0.278	-0.033	0.133	0.411	0.062
Oct 2014 – Oct 2015	361	-0.014 (0.002)	-0.118	-0.014	0.163	0.281	0.031

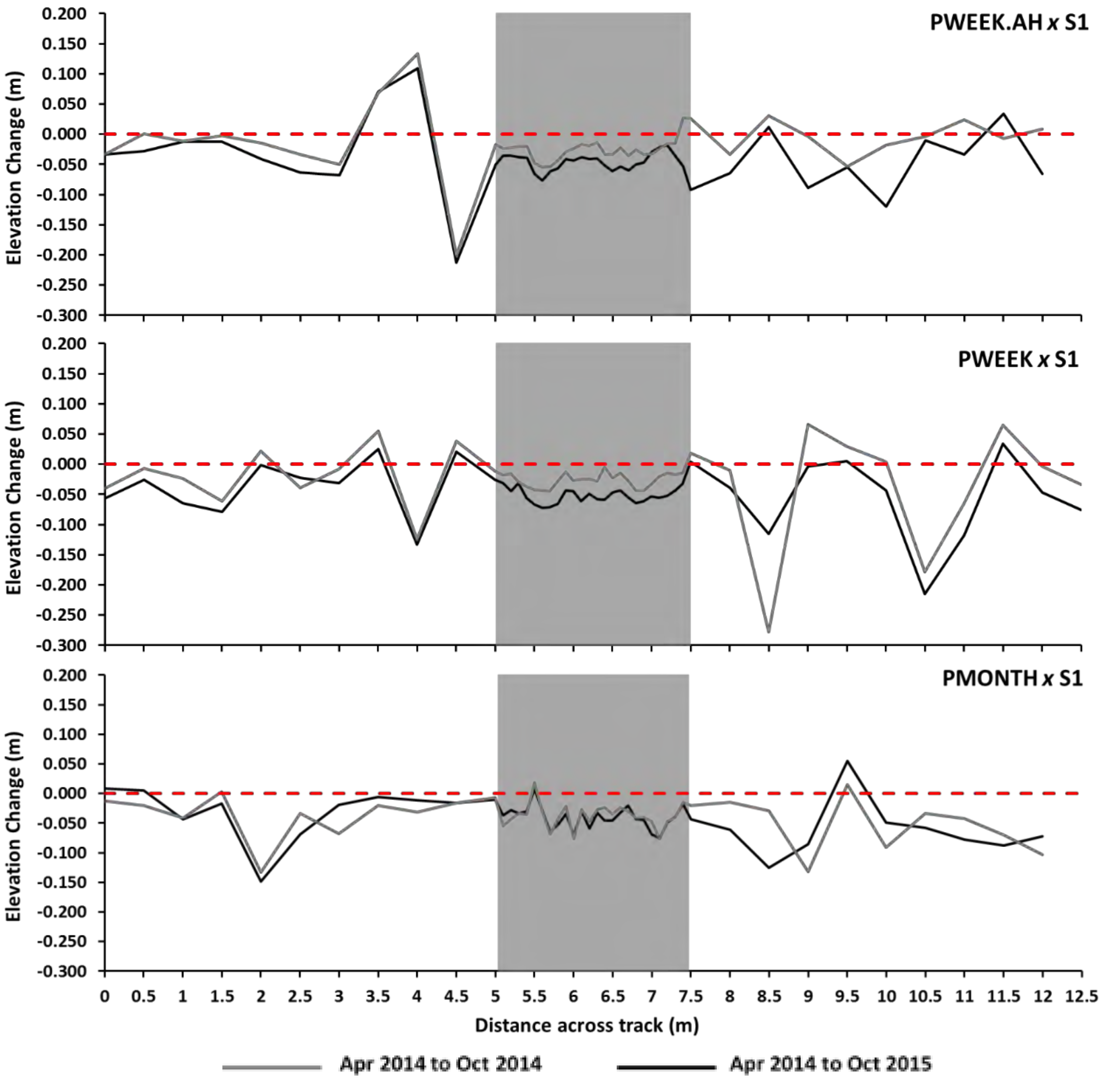

Figure 5.15 Example of difference in peat surface elevation change on-track (shaded area) and off-track. Elevation change is given relative to baseline elevation (April 2014).

Calibration transects were measured to determine the level of error in measurements between visits. Bivariate correlation and ANOVA were performed on data to check for the level of agreement between the repeated measures. Results are shown in Table 5.11. Strong agreement existed between the calibration transects, validating the elevation changes which are evident in the data.

Table 5.11 Calibration transect statistics showing the results for correlation and difference of means. * = p is significant at ≤ 0.05.

Treatment *x* Transect	Measure	Correlation		ANOVA	
		Correlation Coefficient	P-Value	F-Value	P-Value
	Northing	1.000	<0.001*	0.00	0.977
PWEEK.AL *x* S1	Easting	1.000	<0.001*	0.00	0.946
	Elevation	0.921	<0.001*	0.32	0.573
	Northing	1.000	<0.001*	0.00	0.987
PMONTH *x* S2	Easting	0.997	<0.001*	0.01	0.924
	Elevation	0.711	<0.001*	0.13	0.722
	Northing	1.000	<0.001*	0.00	0.997
PMONTH *x* S3	Easting	0.999	<0.001*	0.00	0.968
	Elevation	0.980	<0.001*	0.05	0.832

There was an overall lowering of the on-track peat surface elevation during the experimental driving period (Figure 5.16). In general, elevation change was greater between April 2014 and October 2014 (solid grey line) compared with October 2014 and October 2015 (dashed grey line). Measurements were only taken in the **PDELAYED** and **W** treatments in October 2014 and 2015. The change in elevation at a specific point along each transect was not always consistent between surveys. Some points showed a rise in elevation on one visit and a then a lowering in elevation on the next, especially between October 2014 and October 2015. Change in peat surface profile varied. The surface profile for treatment **W** was an exception however, which displayed a consistent lowering across the track cross-section.

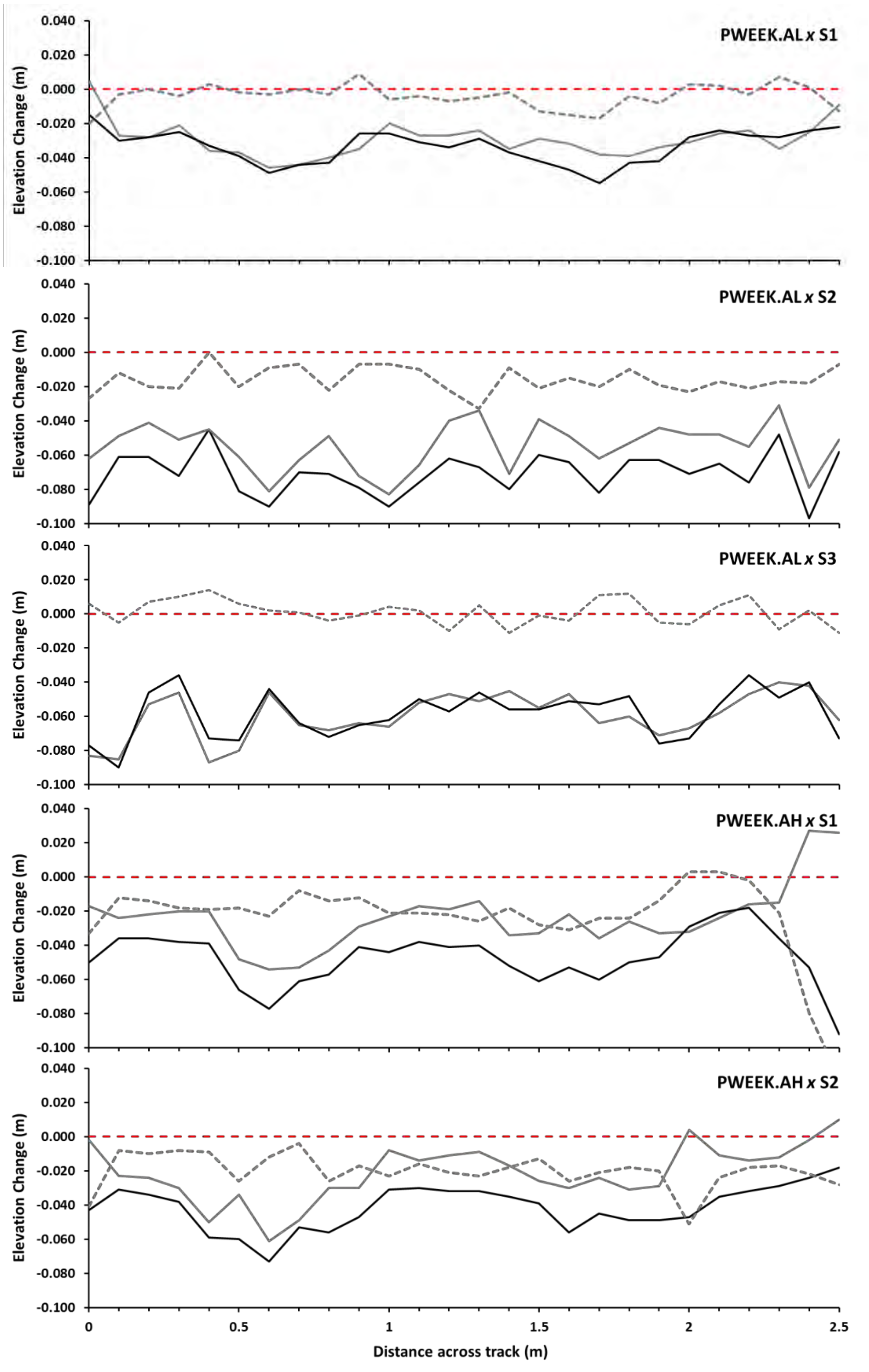

Figure 5.16 Profiles of on-track peat surface elevation for each treatment *x* topographic location surveyed. Elevation change is given relative to baseline elevation (April 2014) and between individual surveys (continued on pages 129-131).

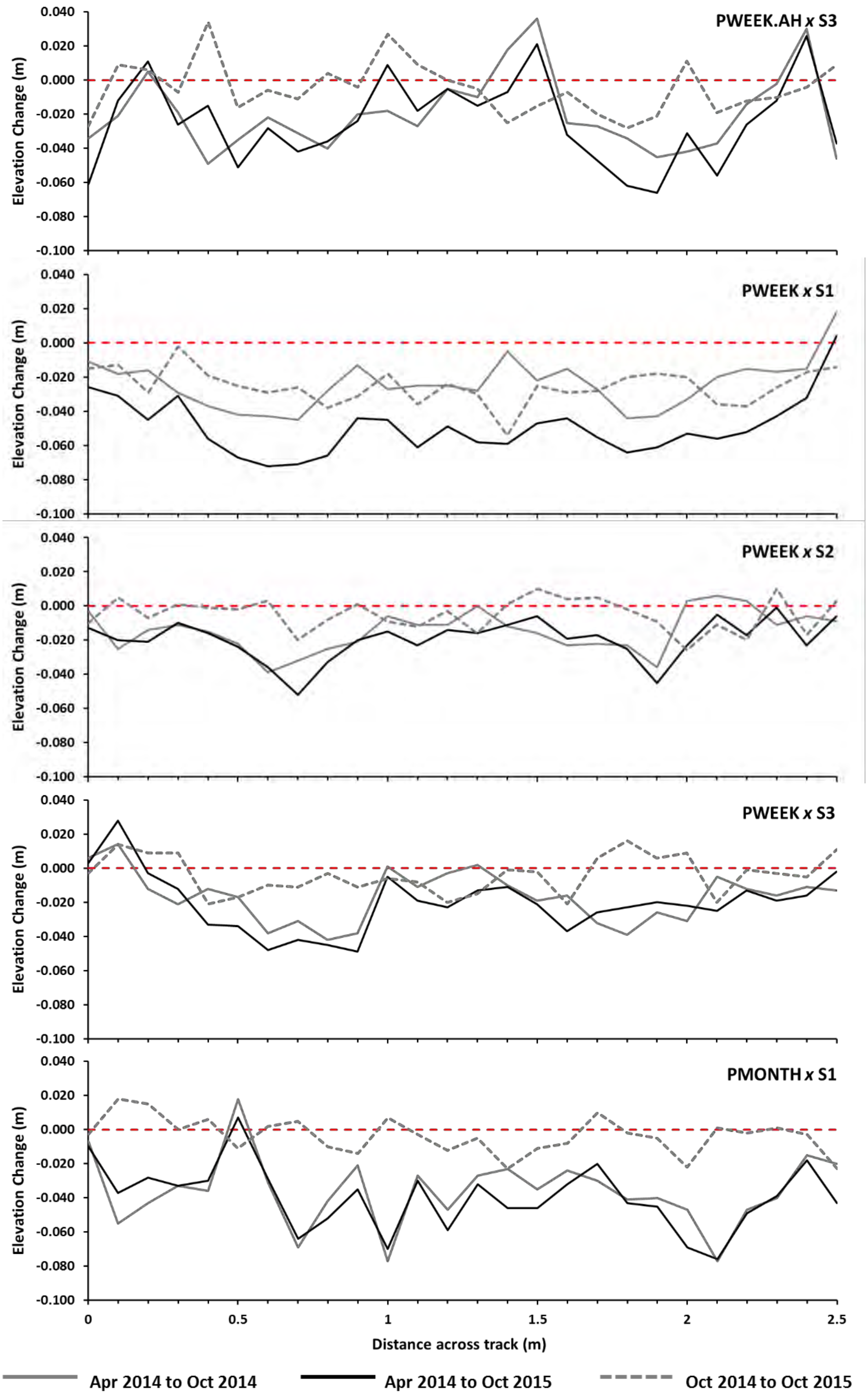

Figure 5.16 continued Profiles of on-track peat surface elevation for each treatment *x* topographic location surveyed. Elevation change is given relative to baseline elevation (April 2014) and between individual surveys.

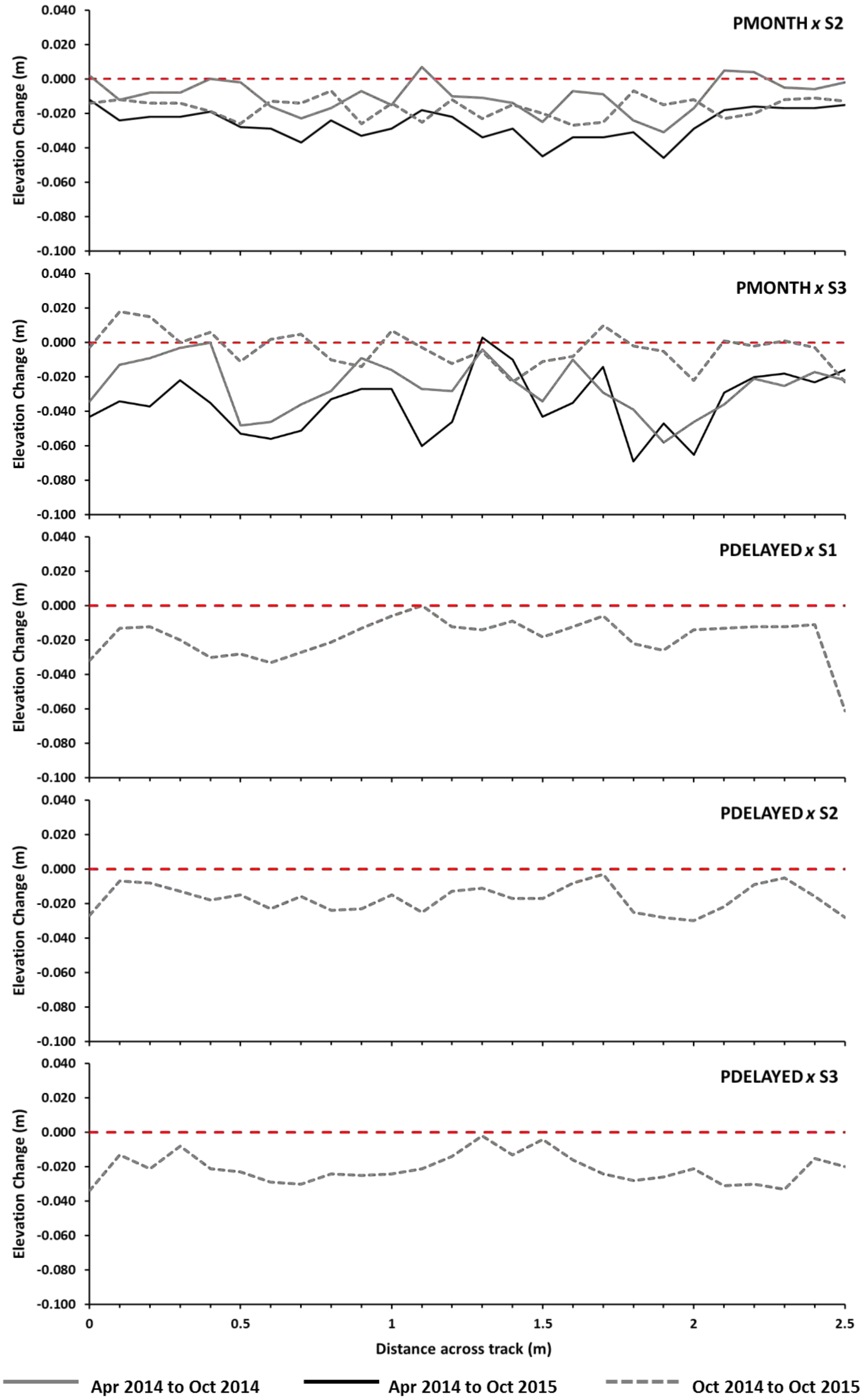

Figure 5.16 continued Profiles of on-track peat surface elevation for each treatment *x* topographic location surveyed. Elevation change is given relative to baseline elevation (April 2014) and between individual surveys.

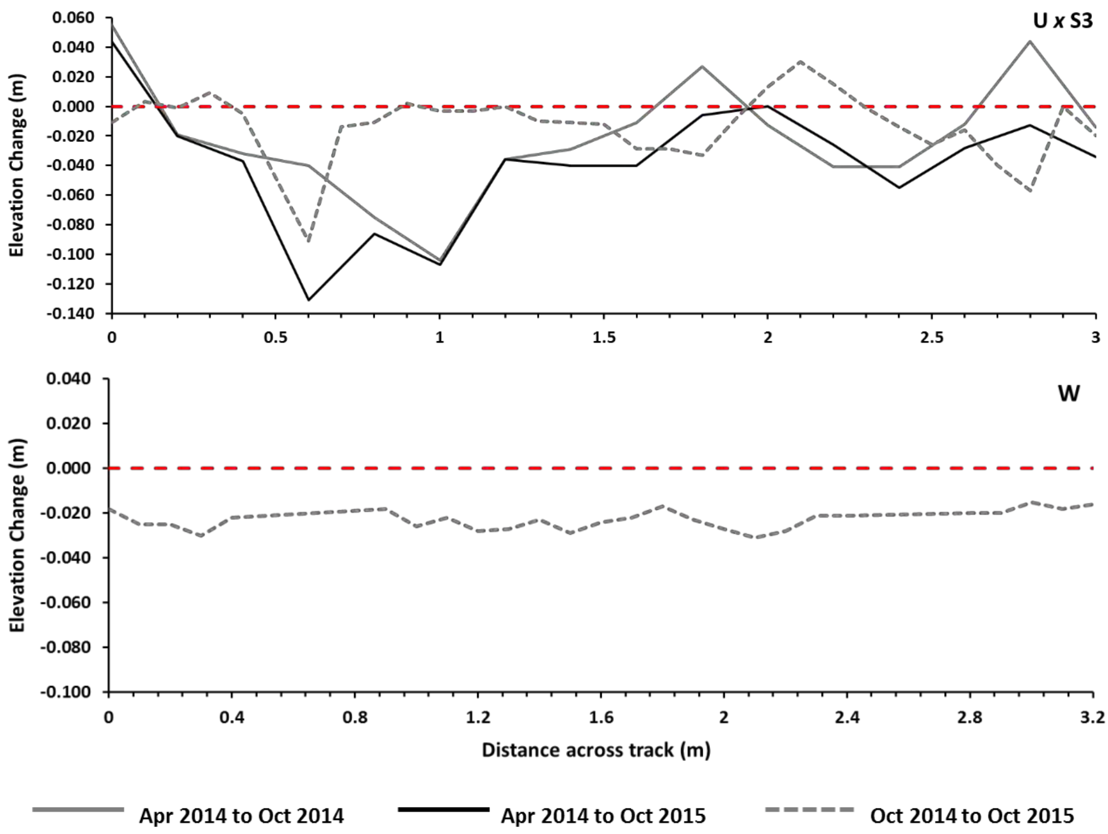

Figure 5.16 continued Profiles of on-track peat surface elevation for each treatment *x* topographic location surveyed. Note the difference y- and x-axis for **U *x* S3** and x-axis for **W**. Elevation change is given relative to baseline elevation (April 2014) and between individual surveys.

Some surface profiles (Figure 5.16) showed evidence of an enhanced lowering in the peat surface elevation between ~0.4 and 0.9 m and 1.6 and 2.1 m across the track. These were likely to relate to the location of the vehicle wheels and could indicate the beginning of wheel rut formation. The lowering of the peat surface in these locations was more pronounced in the more frequently used treatments (**PWEEK.AL**, **PWEEK.AH**, and **PWEEK**). There was also evidence of indenting of the surface profile under the tyres in treatment **U** (where no mesh track was present), between 0.7 and 1.5 m and 2 and 2.6 m.

Table 5.12 outlines results of paired t-tests for sampling dates and transects surveyed. Between April 2014 and October 2014 all treatment *x* topographic location combinations showed a significant decrease in overall peat surface elevation under the track. Between October 2014 and October 2015 there was more variation, and **PWEEK.AL *x* S3**, **PWEEK.AH *x* S3**, **PWEEK *x* S3**, and **PMONTH *x* S1** showed no significant difference in peat surface elevation.

Table 5.12 *P* values from paired t-tests for each combination of sampling dates for each transect surveyed. * = *p* is significant at ≤ 0.05.

Treatment	Topographic Location	April 2014 v October 2014	October 2014 v October 2015
	S1	<0.001*	0.006*
PWEEK.AL	S2	<0.001*	<0.001*
	S3	<0.001*	0.422
	S1	<0.001*	<0.001*
PWEEK.AH	S2	<0.001*	<0.001*
	S3	<0.001*	0.119
	S1	<0.001*	<0.001*
PWEEK	S2	<0.001*	0.014*
	S3	<0.001*	0.103
	S1	<0.001*	0.101
PMONTH	S2	<0.001*	<0.001*
	S3	<0.001*	0.003*
	S1	-	0.003*
PDELAYED	S2	-	<0.001*
	S3	-	<0.001*
U	S3	0.050*	0.003*
W	-	-	<0.001*

Mean on-track elevation change for each transect between April 2014 and October 2014, and October 2014 and October 2015 is shown in Figure 5.17. The mean elevation change between April 2014 and October 2014 was always negative, indicating an overall lowering of the peat surface elevation under the track. Between October 2014 and October 2015 there were two transects where the peat surface elevation appeared to have risen (**PWEEK.AL *x* S3** and **PMONTH *x* S3**). The greatest mean change in elevation, across the track, in either direction was found between April 2014 and October 2014 in **PWEEK.AL *x* S3** (-0.06 m), whilst the smallest was also found in this treatment *x* topographic location combination between October 2014 and October 2015 (0.001 m).

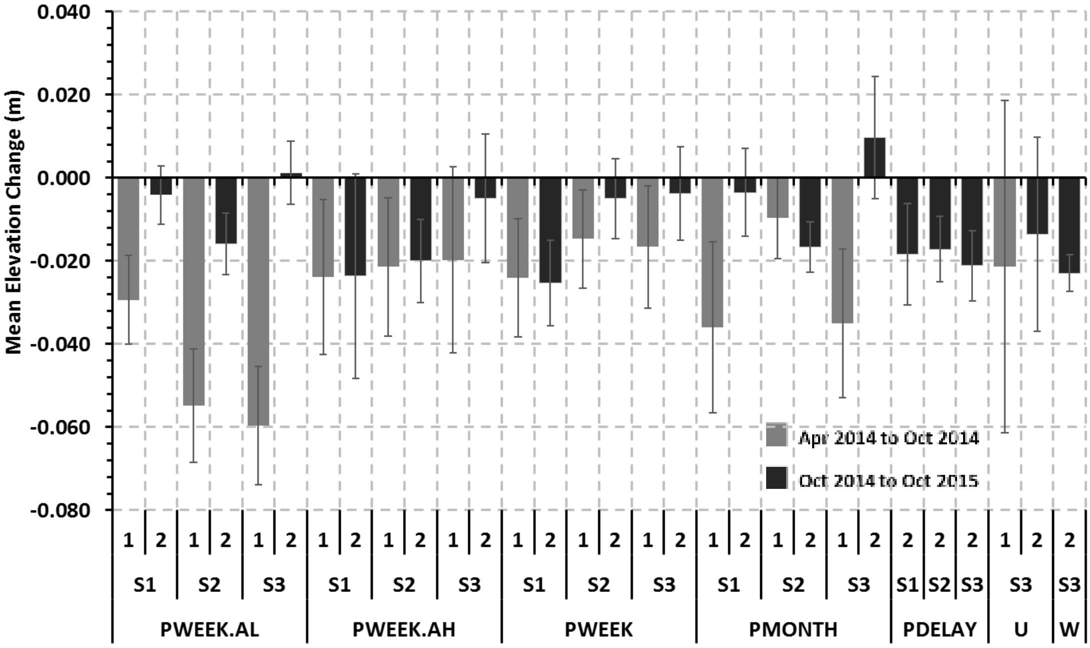

Figure 5.17 Mean elevation change for on-track data, between April 2014 and October 2014, October 2014 and October 2015 for each treatment *x* topographic location combination. Error bars show ± standard deviation.

Significant differences were found between treatments and between topographic locations for the change in elevation data, April 2014-October 2014 ($p < 0.001$) and October 2014-October 2015 ($p < 0.001$) in each case. There was no consistency in the way in which the change in elevation data varied by treatment or topographic location in the two datasets (April 2014-October 2014 and October 2014-October 2015). There was also no clear evidence of a dominant influence of treatment or topographic location on where the greatest changes in surface profile were observed.

5.4 Discussion

Change in three peat physical properties commonly associated with compression and compaction were investigated in this study: (i) bulk density (BD), (ii) *K*, and (iii) peat surface profile elevation, through a comparison of before and after disturbance data. These properties are related to peat structure and may influence the functioning of peat with respect to further development, movement of water (through the peat and over the surface), vegetation growth and carbon cycling. A difference between before and after measurements was observed in all of the properties measured, suggesting the installation of three different track types and driving over them by a low-ground-pressure or 4x4 vehicle had some impact. The direction of change was not always as expected or significant, however. Key observations for BD, *K*, and surface profile elevation with respect to the four influential factors are summarised in Table 5.13. This discussion briefly addresses the impacts to each property in turn before drawing them together to look at connections between the properties and which factors were most influential.

Table 5.13 Summary of key findings for each property with respect to the four key influential factors

	Bulk Density	**Hydraulic Conductivity**	**Surface Profile Elevation**
Track Type	Treatment **W** ↑ All other treatments ↓	n/a	Wheel rut formation – **plastic mesh** and treatment **U** Treatment **W** – consistent lowering across track width
Spatial Extent of Impact	On track often ↑ than off-track	n/a	n/a
Topographic Position	n/a	Degree of anisotropy differed between S1/S2 and S3	No clear effect
Frequency of Use	No clear effect	No clear effect	No clear effect

5.4.1 Bulk Density

It was hypothesised that BD would be significantly higher after track installation and driving compared with conditions before driving commencement. This hypothesis was not upheld for depth average BD (0-30 cm) however, as Before BD was significantly higher than After BD. Even within individual treatments, Before BD was higher than After BD between 0-30 cm, although the difference was not always significant.

Following disturbance, both Robroek et al. (2010) (human trampled track) and Wallage and Holden (2011) (drainage) observed no significant difference between control and treatment BD in blanket peatlands, and therefore the impacts observed here may not be totally unexpected. It should be noted that peat compression commonly reported is the result of peat drying, enhanced decomposition and collapse of structure (Price, 1997, Silins and Rothwell, 1998, Schlotzhauer and Price, 1999). In this study, however, the peat has been subjected to mechanical compression which may have an influence on the results being observed. Depending on the magnitude of the mechanical compression some of the elastic properties of the peat (Gunn et al., 2002, Rezanezhad et al., 2016) may have been retained. Therefore, after increased pressure had been removed there could have been some recovery in the surface peat. This will be discussed further in section 5.4.4. Robroek et al. (2010) also suggested that encouraged regrowth of vegetation on tracks could be a reason for the lack of significant difference in BD between control and treatment locations.

Vegetation regrowth was observed along the tracks in this study (for further detail see Chapter 7) and may therefore further explain some of the BD results.

In addition, antecedent conditions for this study based on rainfall and temperature data from the 30 days prior to the sampling events in 2013 and 2015 suggest that the peat may have contained more water in 2015 compared with 2013. Given the geotechnical properties of peat this may have resulted in an expansion of the surface peat in particularly and therefore resulted in lower bulk density. Furthermore, variation in Before and After BD observed in the control treatment (Figures 5.6 and 5.7) was as great as that observed in some of the driven treatments, especially for the surface peat. Therefore natural spatial variation in bulk density should also be taken into consideration.

There were some differences in After BD, at 0-30 cm depth, between on-track and off-track samples, with BD higher on-track relative to off-track in selected treatments (**PWEEK.AL**, **PWEEK.AH**, **U** and **W**). However, given the lack of significant differences in these on-track-off-track comparisons, this variation may be more attributed to spatial variation in BD than track impact.

While depth averaged BD (0-30 cm) did not show the expected increase from before driving to after, investigation of the impact with depth, for on-track BD, suggested that below ~5 cm there was evidence of an increase in BD in selected treatments (**PWEEK.AL PWEEK.AH**, **PWEEK** and **W**). It has been observed that compression is usually greater for deeper peats (Van Seters and Price, 2002) and could be related to the degree of decomposition and therefore the elastic potential of the peat (Crowl and Lovell, 1987). Given that the acrotelm in blanket peat is relatively shallow compared with other peat soils (~ 5-10 cm) (Holden and Burt, 2003b), this may explain the observed increase in BD below 6 cm. An alternative hypothesis to test would therefore be that the direction of change in BD following track installation and use varies depending on depth in the profile.

Treatment **W** showed the largest increase in BD between 0-2 cm. In addition, within the top 10 cm of the profile, a key depth which links with the sampling depth for *K* (section 5.4.2), an increase in BD was observed in a number of treatments between 6-10 cm (**PWEEK.AL, PWEEK.AH**, **PWEEK**, **PMONTH**). In contrast, treatment **C** showed evidence of an increase in the top 2 cm, but minimal change in BD up to 10 cm (Figure 5.9). This highlights that whilst there was natural variation in BD, as has been observed in other blanket peatlands (Lewis et al., 2012), the impacts can in part be attributed to the track.

5.4.2 Hydraulic Conductivity

Associated with the expected increase in BD, it was hypothesised that *K* after plastic mesh track installation and driving by a low-ground-pressure vehicle would be significantly lower than *K* before this activity. Similar to other studies of *K* in peat (e.g. Chason and Siegel, 1986, Beckwith et al., 2003a, Lewis et al., 2013, Branham and Strack, 2014), orders of magnitude differences were observed between vertical and horizontal *K*. The response of *K* to driving varied depending on the flow direction with evidence of reduced K_v but increased K_h. Furthermore, the difference was also influenced by topographic location and treatment (frequency of use) (discussed further in section 5.4.4.2).

Dominant vegetation type is understood to have a bearing on *K* in peat (Holden and Burt, 2003a, Gnatowski et al., 2010), in addition to vegetation age (Clay et al., 2009). Anisotropy showed variation with topographic location; where S1 and S2 were both significantly different from S3. *Calluna vulgaris* and *Eriophorum vaginatum* dominated S1 and S2 samples, while *Sphagnum* spp. were more common in S3 samples. *Calluna vulgaris* and *Eriophorum vaginatum* peats have a greater occurrence of horizontal roots and macropores in surface peat compared with *Sphagnum* peat, which has a more equal structure in the vertical and horizontal. This may therefore explain the different responses in *K* and is worthy of future investigation.

The orders of magnitude difference between vertical and horizontal *K* is important, yet previous work has not always considered it in much detail (e.g. Boelter, 1965, Holden and Burt, 2003a). Although a change in the strength of anisotropy in peat following mechanical compression has been suggested (Lefebvre et al., 1984, Hobbs, 1986, Hendry et al., 2014), within blanket peat it has not yet been measured. The decrease in K_v (significant at some locations in driven treatments) and increase in K_h would suggest a shift towards more positive anisotropy. This increase in K_h (significant at some locations in driven treatments) could be attributed to a change in pore alignment following compression, tending towards the horizontal (Landva and Pheeney, 1980, Hobbs, 1986, Hendry et al., 2014). The magnitude of this effect is dependent on the composition of the peat (i.e. more or less decomposed) and the fibre content. It would appear that the impact of the plastic mesh track and vehicle use is dependent upon the flow direction being measured, and therefore hypothesis (ii) cannot be fully accepted.

5.4.3 Surface Profile Elevation

The third hypothesis proposed that with an increasing number of passes over the three tracks there would be a lowering of the peat surface elevation. Based on data shown in section 5.3.3 this hypothesis can be partially accepted. The largest change in elevation appeared to occur after the first six months of driving compared with the following 12 months. Therefore while lowering did continue to occur with increasing use of the track, the rate of lowering appeared to decline. This has particular relevance for the plastic mesh tracks which are seen as temporary installations (Natural England, *pers. comm.*), as it suggests that the greatest impacts may occur shortly after initial installation and use. Consequently it could have implications for permitting regulations related to use of these tracks. The extent of surface lowering also did not appear to depend on the treatment, i.e. the greatest magnitude of lowering was not found in the most frequently used treatment as initially expected (further discussion section 5.4.4.2).

Antecedent conditions at the time of surveying should be taken into consideration, as a larger difference was also observed between April 2014 and October 2014 (first 6 months) compared with October 2014 and October 2015 (following 12 months) in the off-track data where there was no effect of driving. Prior to the April 2014 surveying days, rainfall had been heavier and the water table was more likely to be shallower. By comparison conditions had been much drier in the week preceding the October 2014 and 2015 surveying. Change in peat volume by variation in water-table depth has been observed in peatlands (Roulet, 1991, Schlotzhauer and Price, 1999, Price, 2003). While volume changes of the magnitudes reported in these studies are not expected in blanket peatlands, some of the large variation between April 2014 and October 2014 could in part be attributed to this. The noise in the off track data (Figure 5.15) meant it was difficult to determine the magnitude of lowering which could be attributed solely to track use and that to antecedent conditions. As conditions were similar for October 2014 and October 2015 it is likely that the differences observed between the surveying dates are the result of track effects rather than weather conditions.

Change in peat surface profile elevation was not consistent across the track width, with evidence of increases in elevation at some points and greater decreases at others (see Figure 5.16). Vegetation regrowth was observed along the tracks (for more information see Chapter 7), especially between October 2014 and October 2015, which may explain some of the increases in elevation. Within selected plastic mesh treatments and treatment **U,** enhanced lowering was observed, typically aligned with the location of the low-ground-pressure vehicle wheels. It is possible that formation of the wheel ruts, squashing of the peat in one location across the track width, could lead to the peat being pushed upwards in other locations, thereby also providing an explanation for the observed increase in peat surface elevation. The depressions observed in line with the wheel routes measured $\leq$ 0.02 m in depth. While previous work has observed rut formation, much of these published depths can be between 20 and 30 cm and often relate to heavier vehicles and unsurfaced tracks (e.g. Ahlstrand and Racine, 1993). In comparison, treatment **W** did not exhibit the formation of wheel rut depressions, however the driving surface of this track was raised above the peat which will have had an influence.

5.4.4 Connections and Influential Factors

5.4.4.1 Connections between Properties

Relationships between the three properties were expected with an increase in BD accompanied by a decrease in *K* and a lowering of the surface profile elevation. While the results do not necessarily follow this simple pattern, potential connections between the responses of the three properties have been identified. The breakdown of BD by depth showed that although there was a decrease in BD in the surface 0-6 cm, there was often an increase (or minimal change) below this depth (Figure 5.9). Hence, while new growth may have occurred at the surface and led to decreased BD, compaction occurred in the peat below the zone of typically higher flow in blanket peat (> 5 cm depth) (Holden and Burt, 2003b). The *K* samples covered 0-10 cm depth and therefore contained the depths which showed both a decrease and increase in BD. The significant decrease in K_v could be indicative of compaction below ~5 cm in the peat profile, whilst the increase in K_h could be due to new vegetation growth (link with BD section 5.4.1) or a change in pore alignment direction (see section 5.4.2). When the *K* samples were processed in the laboratory, preferential flow in one half of the sample was sometimes observed in the horizontal plane. The lowering of the surface elevation may therefore be evidence of the compaction which has occurred at depth > 5 cm as opposed to the surface which was more expected.

5.4.4.2 Role of Influential Factors

Track type (plastic mesh, unsurfaced or articulated wooden) appeared to be the most influential factor compared with topographic location and frequency of use on differences in impacts to BD, *K*, and surface profile elevation following track installation and use.

The three properties varied by topographic location and frequency of use (Table 5.6, 5.9 and Figure 5.16). Evidence suggested a response in the peat with an increasing number of passes e.g. continued lowering of peat surface profile from October 2014 to October 2015. In addition BD was found be higher on-track than off-track in **PWEEK.AL**, **PWEEK.AH**, **U** and **W**. However, there was lack of apparent trend in results for BD (limited to one topographic location), *K* (limited to two frequencies of use and one track type) and surface profile elevation which could be attributed to natural variation in the peat properties masking some of the influence of these factors.

In this study, for the plastic mesh track, BD was of the order **PWEEK.AH > PDELAYED > PWEEK.AL > PMONTH > PWEEK** for both before and after data, highlighting no clear effect of frequency of use. The order of the other treatments/ track types (**U, W,** and **C**) did vary slightly between before and after relative to the plastic mesh ones. Furthermore, it was not evident that *K* by frequency of use showed any clear trend with greater differences observed in the more frequently used treatment (**PWEEK.AL**) compared with the least frequently used treatment

(**PMONTH**). The same was true for mean elevation change in the surface profile, where a higher number of passes did not equate to greater surface lowering, or more pronounced wheel ruts. Investigating the impact of harvester use over brash tracks on forested deep peat Wood et al. (2003) also did not observe a relationship between dry bulk density and number of machine passes. Consequently, resulting from natural variation, the differences in the strength and elastic properties of the peat, often related to the degree of decomposition, may mean the response of peat to loading could vary. Price et al. (2005) consequently suggested BD was not necessarily the best indicator of compressibility.

Treatment **PDELAYED,** where the start of driving was delayed relative to the other driven treatments, showed some slight differences in response for BD (on-track) and surface profile elevation relative to the other plastic mesh treatments. For example, the formation of wheel ruts was less clearly defined in this treatment, possibly because vegetation had already started to grow back by the time the driving started and therefore provided greater protection to the peat underneath. The difference may, however, just be due to the shorter driving period over the track. Further investigation is needed to differentiate between the results.

Mean change in surface profile elevation (Figure 5.17) and *K* (Figure 5.13) both showed variation in change with topographic location. However, there was no clear trend that the greatest impacts were observed in one topographic location relative to another. Explanatory factors for this include the dominant vegetation types in these locations and therefore the peat composition (Boelter, 1969, Holden and Burt, 2003a) and the rate of regrowth (elevation).

Clear differences were observed in the response of BD and surface profile elevation in relation to track type. With respect to BD, treatment **W** (wooden articulated track) was the only driving treatment to exhibit an increase in BD in the surface 0-2 cm and at depth. The plastic mesh treatments of **PWEEK.AL**, **PWEEK.AH**, **PWEEK**, and **PMONTH** exhibited the increase in BD at depth but not in the surface 0-5 cm. In contrast treatment **U** (unsurfaced track) exhibited a decrease in BD up to 15 cm. The response of surface profile elevation showed all treatments exhibited a lowering of surface elevation over time. While the plastic mesh track and unsurfaced track showed variation in the extent of lowering across the track width, the lowering in treatment **W** was of a fairly consistent depth (~ 0.02 m).

Treatment **U** responded in the most surprising way. It was expected that driving over unsurfaced peat would have the greatest impact with respect to bulk density and change in surface profile. However, such an effect was not observed. Unlike the other treatments the vegetation was not cut along this route and there was minimal disturbance prior to driving commencing. Hence, the density of vegetation present on this track could have protected the surface peat. Vegetation analysis (Chapter 7) showed minimal evidence of bare peat occurring on this track route, suggesting that the route stayed protected through the experimental period. This treatment was also subjected to the lowest driving usage with only 24 passes over the track in total. In addition, driving was suspended in April 2015, therefore offering time for vegetation recovery. There may be a threshold of impact related to unsurfaced tracks. Prior to reaching this threshold unsurfaced tracks are potentially more robust than surfaced tracks as the vegetation provides protection to the peat (this is of course dependent on the density of the vegetation cover). When the threshold is reached, e.g. the surface cover of vegetation is broken and bare peat occurs, a tipping point occurs, after which impacts to the unsurfaced track become greater than those under surfaced tracks, such as the plastic mesh in this study. It is possible that this threshold was never reached on treatment **U** in this study.

The results from the plastic mesh track sit between those from treatment **W** and treatment **U**. The track routes for the plastic mesh and treatment **W** were both subjected to disturbance during the track installation. Whilst a low-ground-pressure SOFTRAK was used for the plastic mesh, a much heavier tractor was used for the articulated wooden track. This difference in installation approaches may partially explain some of the difference in BD response which has been observed. The surface BD (0-2 cm) in treatment **W** may have been compacted to an extent that couldn't recover, unlike that under the plastic mesh treatments. In addition, treatment **W** had the greatest constant weight applied to the peat, the heaviest vehicle and the most intensive usage.

The difference in the shape of surface profiles between the plastic mesh treatments, treatment **W** and treatment **U** can be attributed to the amount of contact the vehicle had with the peat surface. Although the plastic mesh track added some protection to the peat surface, and may have more evenly distributed the weight of the vehicle, more intense pressure points were in close contact with the peat surface, in the form of the vehicle wheels. The clear 'wheel-ruts' created in treatment **U** may partly be evidence of a flattening of the vegetation (as was also observed in Chapter 7). By contrast, the weight of the vehicle in treatment **W** was spread out over a wider span, and was also raised above the peat surface, due to the depth of the wooden beams. Therefore the pressure exerted may have been spread out over the width of the entire track, and hence was not exhibited through the creation of wheel ruts.

The results yielded in this study have not been quite as expected in the context of the findings from earlier studies on different soil types or other types of peat (e.g. Alakukku, 1996a, Ruseckas, 1998). It is recognised that the properties measured here (bulk density and *K*) differ in blanket peatlands compared with other peatlands, especially *K* (section 2.1.3). As most existing studies have not been undertaken on blanket peat this may explain why the findings from this study do not compare with those from previous work. However, as has been observed in this study, the type of track, and by association the vehicle used, is likely to be a key influential factor in the magnitude of impact. To date, most studies of tracks on peat are related to constructed tracks (aggregate based) or unsurfaced tracks created by larger off-road vehicles, often military vehicles.

Constructed tracks exert a constant pressure on the peat due to the weight of the aggregate (and other materials used) on the peat surface (Hobbs, 1986). The vehicles travelling over the track then add extra weight and increase the pressure exerted on the peat. Barry et al. (1992) observed that if vehicles needed to park up, additional areas would need to be created as the trunk roads were only constructed to support the constant load of the road and transient vehicle loads.

In contrast, all traffic over the tracks in this study was transient with the vehicles used (low-ground-pressure and 4x4) never being parked up on the tracks. The plastic mesh track also exerted less constant pressure and weight to the peat surface. In addition, while the articulated wooden track (treatment **W**) exerted slightly higher pressure it was not to the same extent as a constructed stone track. A low-ground-pressure-vehicle was used on the mesh track and the unsurfaced track (treatment **U**), weighing between 450 and 600 kg and exerting a pressure of 14.5 kN m^{-2}. Contrast this with the 1500 to 2000 kg 4x4 vehicle which travelled over treatment **W**, exerting a ground pressure of 205 kN m^{-2}. Furthermore, as the driving was undertaken on a fortnightly basis this allowed for recovery of the peat in between passes. As has previously been noted peat fibres have an elastic behaviour which allows them to recover from temporary loading (Gunn et al., 2002).

This study is the first to have considered the impact of these three track types on these three peat properties (BD, *K* and surface profile elevation). A lowering of the peat surface elevation was observed for all track types, however BD was not found to significantly increase. *K* decreased in vertical direction following driving but there was an increase in horizontal *K* within some locations. The intensity of driving (frequency of use) appeared to have a minimal role, however in relation to *K*, topography was found to be influential. The increase in *K* at certain locations suggested that flow was not impeded. The lowering of the peat surface elevation and rut formation may result in the channelization of flow (overland) down the track route. This was observed visually on certain occasions and would be an area for useful further study. To fully appreciate the impacts of these tracks on key physical properties, changes to peat structure should be considered in conjunction with impacts to water table under and around the track.

5.5 Chapter Summary

- Three properties indicative of peat structure; bulk density, *K* and surface profile elevation have shown evidence of change following track installation and use.
- The change in the properties following track installation was not always as expected. BD 0-30 cm) decreased from before to after the experiment under all three track types. Surface

profile elevation was lowered following track use for all three track types and the direction of change in *K* was dependent on the flow direction for the plastic mesh tracks.

- Variation in direction of change with depth was evident for on-track BD. A shift was observed from decreased BD to increased BD in a number of treatments (**PWEEK.AL**, **PWEEK.AH**, **PWEEK**, and **W**) below ~5 cm to ~ 15 cm.
- Strong positive anisotropy was found in the *K* data. In general, *K* exhibited a decrease in vertical flow and an increase in horizontal flow after driving over the plastic mesh tracks, however the magnitude and significance varied between treatment (frequency of use) *x* topographic location combinations.
- Lowering of track surface elevation was observed over time in all treatments (track type *x* frequency of use), with a suggestion of greater compression occurring after the first 6 months and in line with the location of wheels (for plastic mesh and unsurfaced treatments). Lowering was not consistent across the track surface suggesting recovery/regrowth in some places. Treatment **W** was an exception showing consistent lowering across the track width. This was likely to be associated with the track installation method and track design.
- Track type (plastic mesh, unsurfaced and articulated wooden), where applicable, appeared to have a greater influence of the magnitude of impact compared with frequency of use. The greatest impact was observed under the heaviest track (treatment **W**) with the most intensive use and the least vegetation recovery.
- Variation in magnitude of impact existed in relation to topographic location (S1, S2, and S3) but no clear patterns could be discerned and could therefore be attributed to natural spatial variation.
- Frequency of use (with particular reference to the plastic mesh track) did not exhibit any clear effect.
- Constant weight versus transient weight of the track is important for consideration and may determine the extent of impact.
- Vegetation recovery under the track may also dampen the potential effects of track use.

CHAPTER 6: RESPONSE OF BLANKET PEAT HYDROLOGICAL PROPERTIES TO LOW-GROUND-PRESSURE AND 4x4 VEHICLE USE

6.1 Introduction

Hydrological processes in blanket peatlands are closely linked to the functioning of these systems (Holden, 2005b). Undisturbed blanket peatlands are characterised by shallow water tables which reside within the top 10 cm of the peat profile for more than 75 % of the time (Evans et al., 1999, Holden and Burt, 2003c, Holden et al., 2011). Shallow water tables maintain anoxic conditions necessary for the preservation and accumulation of organic matter. Hydrological functioning is therefore fundamental to continuing peatland development (Holden, 2005b). Saturation-excess overland flow has been found to dominate flowpaths to streams in blanket peatlands, with 80 % of flow found to occur at the peat surface (Holden and Burt, 2003c). Flow regimes have consequently been termed 'flashy' due to the short lag time between rainfall events and peaks in stream discharge. These systems are also often characterised by minimal baseflow throughout the year (Evans et al., 1999). There are topographic and spatial controls on dominant runoff pathways in blanket peatlands with overland flow being more pronounced and occurring for a longer duration at bottom-slope locations when compared with top- and mid-slope locations (Holden and Burt, 2003c).

Hydrological processes exert an influence on the peatland carbon cycle (Belyea and Malmer, 2004, Holden, 2005b, Limpens et al., 2008). The position of the water table determines how much peat is accessible for oxidation, resulting in readily available carbon to be released as carbon dioxide (CO_2) back into the atmosphere by diffusion through the peat and plant mediated transport, or transported as dissolved organic carbon (DOC). Shallow water tables, however, can also result in the release of methane (CH_4), which is a more potent greenhouse gas than CO_2 (Baird et al., 2009). Flow pathways in blanket peatland control the export and movement of carbon in the form of DOC and particulate organic carbon (POC), in turn impacting on stream water quality (Martin-Ortega et al., 2014). The topographic variation in dominant flow pathways and water-table residence times is evidenced in DOC concentrations with higher concentrations found in mid-slope locations where water-table depth is deeper for longer and lower concentrations in bottom-slope locations where there is greater movement of water and flushing of the peat (Boothroyd et al., 2015).

Feedbacks exist between vegetation distribution and composition, and blanket peatland hydrology. Species present at the peat surface influence the rates of evapotranspiration and therefore the depth of the water table (Holden, 2006), whilst past species influence peat composition and structure and therefore rates of hydraulic conductivity (*K*) and the movement of water. In turn, dominant flow pathways and water-table depth influence dominant species distribution (Sottocornola et al., 2008). Furthermore, the density of vegetation cover can determine overland flow velocity and consequent stream flow peak times (Holden et al., 2008, Grayson et al., 2010). Changes in vegetation cover through disturbances to the peatland, such as tracks, therefore have the potential to affect the hydrological processes and existing feedbacks.

Disturbances to blanket peatlands, both human and climatically driven have been found to result in changes to the hydrological processes occurring. Future climate predictions suggest an increase in temperature, although direction of change in precipitation varies with location, as does the magnitude of change (Li et al., 2016). More drought periods have been suggested in a changing climate, with a predicted response in blanket peatlands of deeper water tables (Evans et al., 1999).

Drainage of blanket peatlands has resulted in the deepening of water tables in close proximity to the drains and a reduction in the occurrence of overland flow on drained hillslopes (Stewart and Lance, 1991, Armstrong et al., 2010, Holden et al., 2011). In addition to the influence of water-table depth, a dominant cause of the reduction in overland flow is the diversion of upslope flow in drains running across the slope. This shortens the length of the slope which supplies water to the next drain downslope. Stream flow regimes have also been found to change following drainage, with alteration in the timing of flood peaks in relation to rainfall events (Holden et al., 2004). The affect observed is often the result of a change in connectivity between the hillslope and the river channel; a function of the velocity of flow, the condition of the drains, their location on the hillslope and the orientation of the drain to the slope (Holden et al., 2006, Ballard et al., 2012, Lane and Milledge, 2013).

Currently, the impact of tracks, both constructed and unmade, on blanket peat hydrology is poorly understood. Constructed tracks have the potential to alter flow pathways, especially if constructed at an angle that is not directly downslope. Flow pathways could be altered due to: (i) the compaction of peat under the track, leading to lower hydraulic conductivities and reduced lateral flow (Van Seters and Price, 2001) (Figure 6.1); (ii) creation of a barrier for overland flow, potentially leading to a ponding upslope (Lindsay, 2007) (Figure 6.1); (iii) creation of a conduit, channelling water along the track so that water from the upslope side of the track does not reach the downslope side (Figure 6.2). Over the longer term there is also the potential for changes in vegetation composition following track construction or creation to affect flow pathways.

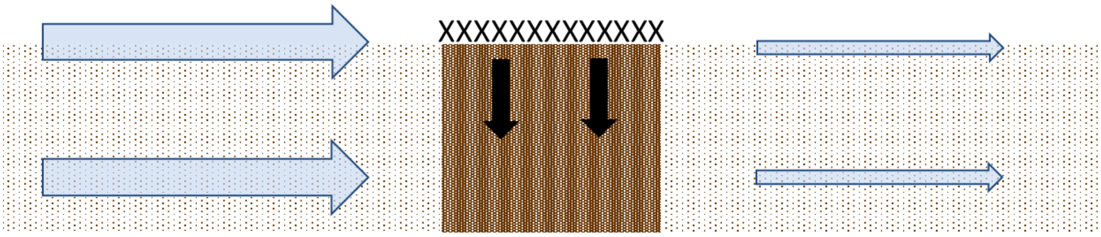

Figure 6.1 Schematic of how the presence of a track placed on the peat surface applies pressure to the peat surface, compacting the peat. The amount of flow able to reach the downslope side from the upslope side of the track is therefore reduced.

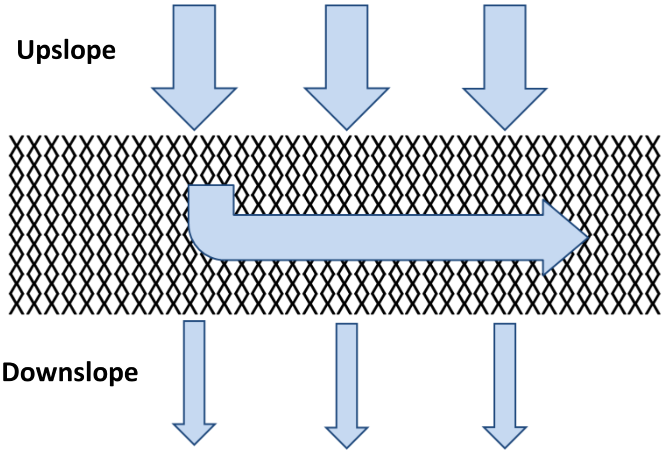

Figure 6.2 Schematic of diversion of flow along the track route from the upslope, preventing the same volume of water from reaching the downslope side of the track.

Impacts to flow pathways have been considered during access track construction for oil tankers on peat in East Sumatra (Barry et al., 1992, Barry et al., 1995), however the efficacy of mitigation measures applied during construction are rarely tested post construction. With respect to constructed tracks providing access to windfarms, anecdotal reports have suggested that impacts could be observed at distances up to 250 m from the track (Lindsay, 2007), but there is no hard evidence for such effects.

On a low lying peatland in Japan with flat topography, Umeda et al. (1985) observed deeper water tables downslope of constructed stone tracks relative to the upslope area, up to 30 m from the track edge. These findings were only based on two different transects, each monitored for a different short summer period and therefore caution is required in interpretation of the results. Bradof (1992) also observed an upslope-downslope difference in water-table depth up to 10 m distance around a section of Highway 72, running through the Red Lake peatlands in Minnesota. Following road construction a change in the direction of the hydraulic gradient was observed. Monitoring in this study took place over a slightly longer time period (~1.5 years). Considerable ponding of water upslope of linear disturbances has been found in Canadian fens, leading to changes in vegetation composition due to waterlogged conditions (Bocking, 2015). To the author's knowledge there is no published evidence of the impact of tracks, both constructed and unmade, on hydrological processes occurring within blanket peatlands, however. This is important because practitioners are seeking to install novel track types such as plastic mesh but without an evidence base.

The aim of this chapter was to understand the extent of impact of plastic mesh, unsurfaced and articulated wooden tracks on water-table depth and overland flow occurrence in a blanket peat environment. The effects of compression exhibited through measurement of bulk density and hydraulic conductivity are addressed in Chapter 5, whilst changes in vegetation cover are addressed in Chapter 7. The following hypotheses were tested: (i) there will be evidence of a change over-time in water-table depth; (ii) there will be evidence of the water table becoming shallower upslope of the track, and deeper downslope, as with peatland drainage; (iii) there will be an increase in the occurrence of overland flow resulting from the track; (iv) there will be evidence of a spatial impact of the track on blanket peat hydrology extending beyond its immediate footprint. Within these hypotheses the influence of track type, frequency of use and topographic location on impact magnitude were also considered.

6.2 Methodology

All water-table depth and overland flow measurements were taken at Moor House NNR (see Chapter 3 for full site description).

6.2.1 Equipment Installation

Variation was expected between the different treatments due to the heterogeneous nature of peatlands. To minimise this effect the instrumentation of each treatment was the same. In order to capture the spatial extent of track impacts on water-table depth and overland flow, dipwells (water-table depth) and crest-stage tubes (overland flow) were installed in transects across the track (Figure 6.3).

The manual dipwells were made using 2.5 mm diameter PVC piping, cut to a length of 1 m with 4 holes drilled in a ring around the pipe at 5 cm intervals down the length of the piping. The pipes were sealed at one end, and the peat was augured out using a gouge augur before the dipwells was installed. This limited the smearing effect during dipwell installation. The automated dipwells were made using 4 cm diameter PVC piping, with holes drilled in the same locations as the narrower diameter dipwells. After installation, all dipwells extended 5-10 cm above the peat surface and were covered with a cap to prevent rainwater entering. All dipwells were 'developed' by removing all water in the dipwells, and allowing dipwells to refill to unclog any water entry holes that may have become blocked by smearing during dipwell installation.

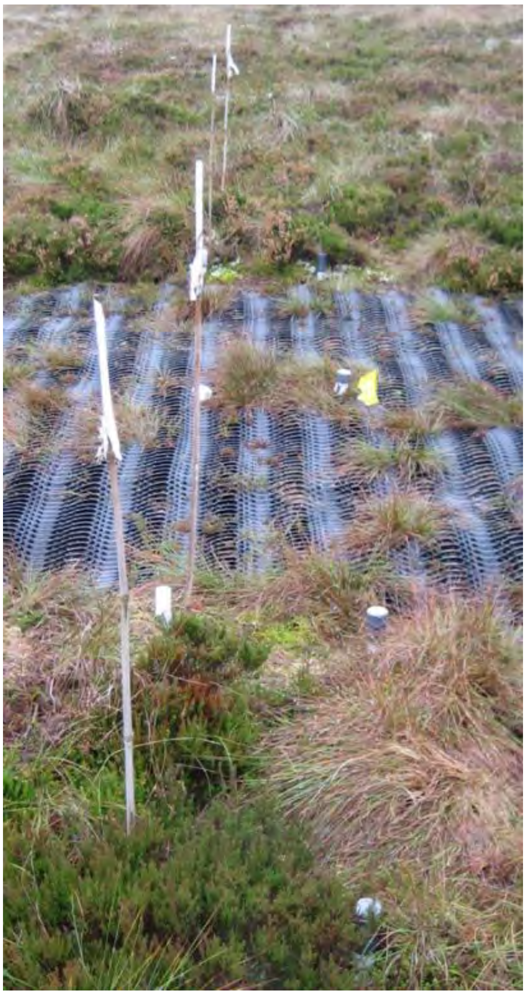

Figure 6.3 Dipwells and crest-stage tubes installed in the field along transects across the track (plastic mesh).

Crest-stage tubes were made from 4 cm diameter PVC piping, with 4 holes drilled in a ring around the piping. On installation these holes were lined up with the peat surface and the location of the holes was checked frequently to ensure they were still in line with the peat surface. All crest-stage tubes were covered with a cap to prevent contamination rainwater entering (as can be seen in Figure 6.3).

As illustrated in Figure 3.7 in Chapter 3, the orientation of the track to the slope varied between topographic locations, with the track at topographic locations S1 and S2 typically installed on the flat (principally S1) or perpendicular to the contours (principally S2). Consequently the track was installed in a water-shedding location where the flow direction was often parallel with the track. At topographic locations S1 and S2 in each treatment (see Chapter 3) three transects of five dipwells located mid-track and 0.2 and 1 m either side of the track were installed at right angles to the track (Figure 6.4). In total fifteen dipwells were installed at topographic locations S1 and S2. Along the middle transect five crest-stage tubes were also installed mid-track and at 0.2 and 1 m either side of the track. Within this chapter, with respect to water-table depth and overland flow occurrence around the tracks, the sides are defined as either right or left, with the same method of designation used in all treatments following the outward driving direction of the vehicle. The arrangement of the dipwells and crest-stage samplers in relation to the track and flow direction are illustrated in Figure 6.4a (S1) and 6.4b (S2).

As is shown in Figure 3.7, at topographic location S3 the track was typically installed so that it was parallel or diagonal to the contours, and therefore cut across the typical flow pathways. At topographic location S3, dipwell transects were installed in line with the direction of flow pathways, which were being intersected by the track. This approach to the installation was informed by the areas of maximum potential impact calculated from the topographic index maps (Figure 3.6). As the track runs parallel to the contours and cuts across flow pathways at this topographic location (Figure 6.4c), the two sides of the track have been defined as upslope and downslope. In treatments **PWEEK.AL**, **PWEEK**, **PDELAYED**, **U**, and **W**, three transects crossing the track were installed, each containing thirteen dipwells. Dipwells were installed mid-track and at 0.2, 0.5, 1, 2, 5, and 10 m upslope and downslope of the track. In treatments **PWEEK.AH** and **PMONTH** the middle transect was extended to include additional dipwells at 15, 20, 25, 30, 40 and 50 m (Figure 6.4c – grey markers). As with topographic locations S1 and S2, five crest-stage tubes were installed along the middle transect, mid-track and 0.2 and 1 m upslope and downslope of the track edge. In treatment **W**, additional crest-stage tubes were installed along the first and third transects, as this treatment only covered topographic location S3. Each treatment therefore contained fifteen crest-stage tubes

The control area with no track or driving (treatment **C**) had an identical instrumentation set-up to the treatments including tracks. In this treatment the middle transect in topographic location S3 was extended to include additional dipwells at 15, 20, 25, and 30 m distance from the nominal edge of the ‘track’. Lack of space prevented dipwells being installed at 40 and 50 m distance.

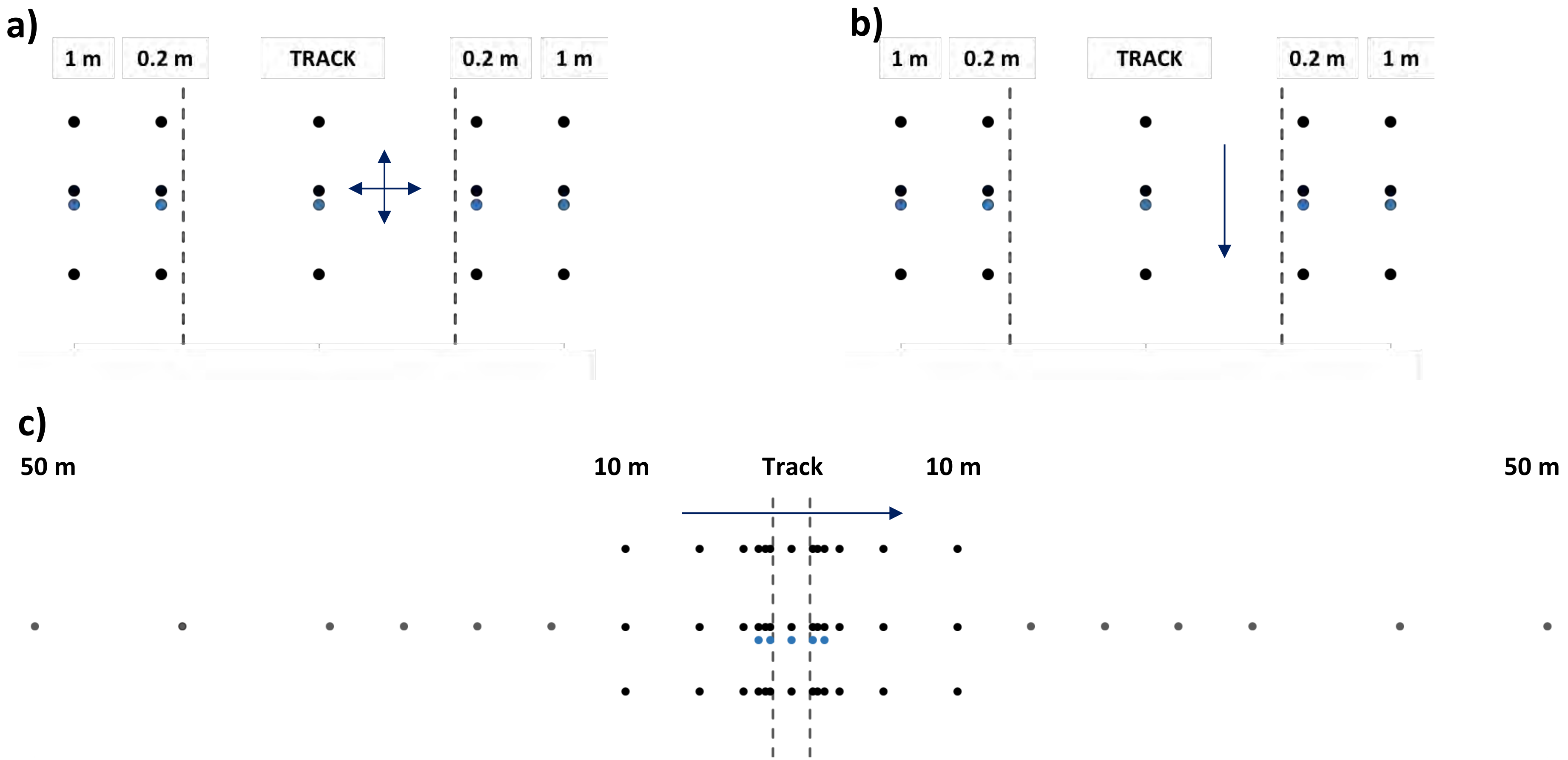

Figure 6.4 Schematic of the layout of dipwells and crest stage tube samplers relative to the track at each topographic location. a) Topographic location S1, b)Topographic location S2, c) Topographic location S3. Typical flow direction relative to the track is indicated by the blue arrow. An upslope-downslope direction only typically occurred at topographic location S3.

At topographic location S3 for treatments **PWEEK.AH, PMONTH,** and **C**, the dipwells located mid-track, and 0.2 and 1 m upslope and downslope, were fitted with automated loggers (In-situ Level 400 and In-situ Level 500). Therefore, at the site, thirteen dipwells recorded depth to water at 15-minute intervals for 18 months from April 2014 to November 2015. The mid-track dipwells in **PWEEK.AH** and **PMONTH** were automated in September 2014 and therefore recorded depth to water at 15-minute intervals for 13 months. The purpose of the automated dipwells was to provide a time-series of water-table depth (hypothesis i), whilst the manual dipwells were installed to capture any spatial variation in impact (hypotheses ii and iv).

The equipment set-up was replicated so that comparisons between treatments could be undertaken. Within treatment replication was performed to create a robust experimental design. In total 554 dipwells and 120 crest-stage tubes were installed across eight treatments (incorporating three different track types).

6.2.2 Sampling Regime

The plastic mesh track was installed in July 2013 and the wooden 4x4 track in September 2013. Driving commenced on all tracks in April 2014. Monitoring of water-table depth and overland flow was carried out for 18 months between 8th April 2014 and 5th November 2015. Water-table depth from the manual dipwells was monitored on a predominantly fortnightly basis using an In-Situ Rugged Water Level Tape (electronic dip meter). Depending on treatment and topographic location, manual dipwells were monitored every two to six weeks. Calibration readings were taken at the automated dipwells every six weeks to ensure the loggers were recording correctly. For both manual and automated dipwells, depth from the top of the dipwell to the peat surface was measured every six weeks from the same point on the dipwell to check for any movement.

The crest-stage tubes collected overland flow and were emptied every fortnight. From this the occurrence (presence or absence) of overland flow between monitoring visits was determined. Limited winter access to the site and buried equipment due to lying snow meant manual monitoring of water-table depth and overland flow was only undertaken once in December 2014 and no manual monitoring was undertaken during January and February 2015. Manual monitoring resumed on 11th March 2015.

6.2.3 Statistical Analysis

Statistical analysis was carried out in Minitab 17.1.0. Several approaches were used to analyse the water table and overland flow datasets. From the automated dipwells, mean daily water-table depth from thirteen of the fifteen installed dipwells was calculated. Two dipwells in treatment **C** recorded very deep water tables not comparable with the rest of the site and were therefore not included in the analysis. Mean daily water-table depth was used in all analysis relating to temporal effects. Change over time for driven treatments **(PWEEK.AH** and **PMONTH**) and the control treatment was determined. In addition, duration curves for mean daily water table were generated and compared between driven treatments and the control. Seasonal differences between each dipwell in the driven treatments and a control dipwell were calculated and a two-sample t-test was used to test for significant differences in the residuals for each season between years.

From the manual dipwells, individual measurements were used in generating descriptive statistics for comparisons between topographic locations, treatments, and distances from the track edges. In addition, distance-weighted water-table depth was used in a linear mixed effects model to test for differences between the two sides of the track at topographic locations S1, S2 and S3 separately. It was only possible to test hypothesis (ii) using data from topographic location S3. Statistical comparisons of water-table depth at individual distances (upslope and downslope) from the track edge were undertaken for topographic location S3 using a linear mixed effects model as well. Plots to investigate spatial patterns in water-table depth used seasonal average water-table depth for each distance from track edge *x* topographic location *x* treatment combination. For the overland flow data, percent occurrence was determined and plotted. Chi-squared tests of association were carried out to determine whether there was a difference in the occurrence in overland flow with sampling location across the track and also for the same sampling period between years. Results from statistical tests were considered significant at $p \leq 0.05$.

6.3 Results

6.3.1 Water Table

Data from the two dipwell types (automated and manual) was utilised in different ways in this analysis. Data from the automated dipwells was used to investigate temporal response of water-table depth and data from manual dipwells was used to investigate spatial effects of the tracks on water-table depth.

6.3.1.1 Descriptive Statistics

Overall 2015 had higher total rainfall compared to 2014; however month by month comparison for the monitoring period showed variation between years (Table 6.1). 2015 was more consistently wet than 2014. The long-term average rainfall at Moor House is 2012 mm (1953-1980, 1991-2006) (Holden and Rose, 2011), the annual total for 2014 was similar to this while the annual total for 2015 was slightly higher, although nearly a quarter of this total occurred in December 2015 when monitoring had finished. In addition, 2015 had a lower annual average temperature than 2014, and eight months had lower average temperatures compared with 2014.

This was reflected in less extreme variation in the water-table depth between monitoring visits to the manual dipwells during 2015.

Table 6.1 Monthly and annual total rainfall and average temperature for Moor House NNR. Months included in the monitoring period are shaded grey. Weather data courtesy of ECN

	2014		2015	
	Total Rain (mm)	Ave. Temperature (°C)	Total Rain (mm)	Ave. Temperature (°C)
January	291	1.7	176	0.5
February	335.5	1.7	80.5	0.3
March	153	3.1	149.5	1.7
April	150	5.9	86	4.6
May	167	7.9	222	5.6
June	51.5	11.2	71	9.3
July	89.5	13.0	169	10.8
August	204	10.1	151.5	11.3
September	26.5	10.4	62.5	8.5
October	218.5	7.8	115	7.0
November	150.5	4.9	397.5	5.3
December	231	1.7	536.5	4.7
ANNUAL	**2068**	**6.6**	**2217**	**5.8**

Between 8th April 2014 and 5th November 2015, the shallowest water table recorded across the whole site was -7.9 cm (i.e. ponding above the surface) whilst the deepest was 33.1 cm. Mean and median water-table depths across the whole site for this period were 7.5 and 7.3 cm respectively (n = 10575), the interquartile range was 6.7 cm. Seasonal variation was evident in water-table measurements, with the deepest water table recorded in July 2014 and June 2015, and shallowest depths recorded in spring and autumn of both years.

Unrelated to treatment, water-table depth showed variation with topographic location. Note that in locations S1 and S2 measurements were only taken up to 1 m from the track edge while location S3 included measurements up to 10 m distance from the track edge. For S3 measurements up to 1 m and 10 m distance are given. Topographic location S3 had the shallowest median water table at 6.6 cm (6.3 cm up to 10 m from track edge), whilst S1 had the deepest median water-table depth at 9.3 cm. S2 was between these with a median water-table depth of 8.8 cm (Figure 6.5).

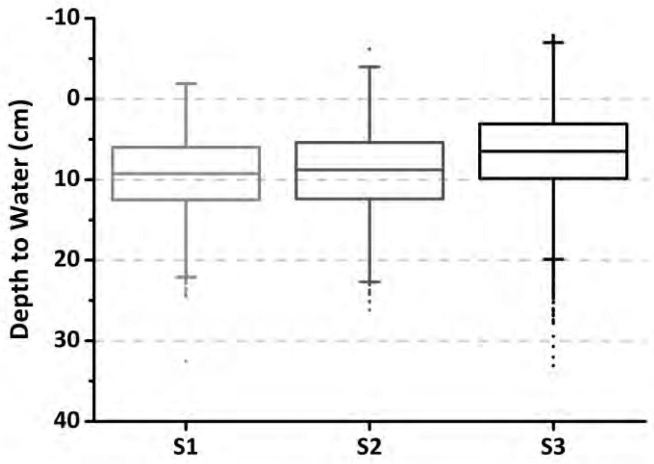

Figure 6.5 Boxplot of water-table depth by topographic location. S1= Top-slope, S2 = Mid-slope, S3 = Bottom-slope. Boxplot shows median, interquartile range, and outliers which are values below Q1 – 1.5 x (Q3-Q1) and above Q3+1.5 x (Q3-Q1).

Differences in median water-table depth between treatments were compared separately for each topographic location (Table 6.2). In topographic location S1, **PMONTH** had the shallowest median water table depth at 8.1 cm, whilst **PWEEK.AH** had the deepest at 10.7 cm. At topographic location S2, **PDELAYED** had the shallowest median water table at 5.5 cm, and the deepest median water table was in **PWEEK** (9.9 cm). Treatment **C** had the deepest water table at location S3 (8.1 cm). The shallowest median water table for location S3 (5.6 cm) was found in **PWEEK.AH** and **PMONTH**. These treatments had very different frequencies of use of the plastic mesh track. At the end of the experimental driving period **PWEEK.AH** had had 412 passes over it, whilst **PMONTH** had only 38. The data showed no clear evidence of a treatment effect (frequency of use or track type), as treatments with the deepest and shallowest water tables varied between topographic locations. Not all treatments followed the topographic pattern shown in Figure 6.5 either. For example, the shallowest median water table for **PDELAYED** was found at location S2 rather than S3.

Table 6.2 Median water-table depth and interquartile range (IQR) by treatment and topographic location. S1 and S2 include measurements up to 1 m from track edge, S3 includes measurements up to 1 m and up to 10 m from track edge. The shallowest median water-table depth for each topographic location is bold and the deepest median water-table depth is underlined.

Topographic Location	**S1**			**S2**			**S3**					
Inclusive distance from track edge	**1 m**			**1 m**			**1 m**			**10 m**		
	n	**Median**	**IQR**	***n***	**Median**	**IQR**	***n***	**Median**	**IQR**	***n***	**Median**	**IQR**
PWEEK.AL	225	8.8	6.4	225	8.8	7.4	525	<u>7.7</u>	6.7	975	7.7	7.1
PWEEK.AH	225	<u>10.7</u>	7.4	225	7.8	9.5	524	**5.8**	7.0	974	**5.6**	7.2
PWEEK	225	10.3	6.0	225	<u>9.9</u>	6.1	525	7.3	5.9	975	6.8	6.1
PMONTH	225	**8.1**	6.4	225	9.5	7.2	525	6.5	7.5	975	**5.6**	7.6
PDELAYED	225	8.8	7.5	225	**5.5**	6.5	525	5.9	6.4	975	5.9	6.3
U	222	8.9	4.8	223	9.1	4.9	525	6.0	6.2	975	6.4	6.3
W	n/a	n/a	n/a	n/a	n/a	n/a	504	6.5	7.6	936	6.1	7.6
C	165	10.3	6.5	180	9.2	6.7	375	7.2	6.0	750	<u>8.1</u>	5.5

6.3.1.2 Temporal Effect

Data from the thirteen automated dipwells was used to investigate temporal effects. The shallowest mean daily water table was recorded **1m upslope** of the track in **PMONTH** (-4.7 cm), the deepest value recorded was at **0.2 m upslope** of the track in **PWEEK.AH** (21.9 cm). In treatment **PWEEK.AH** mean daily water table was shallowest in the **mid-track** dipwell (**TRACK**), in **PMONTH** mean daily water table was shallowest **1m upslope** of the track (Table 6.3). Mean daily water table in the control was deeper than or equal to the water table in the driving treatments.

Table 6.3 Descriptive statistics from automated dipwells of mean daily water table by treatment and location along transect across track, including sample size. Distances are given from track edge. Descriptive statistics are for the period 12th September 2014 to 4th November 2015 when the mid-track dipwells (**TRACK**) were automated.

	n	Mean (cm)	Median (cm)	Min (cm)	Max (cm)	IQR (cm)	% Time above surface
PWEEK.AH							
1m Upslope	419	5.8	4.9	0.6	16.1	4.0	0
0.2m Upslope	419	6.8	4.7	-1.2	21.9	9.0	1.4
TRACK	419	1.9	0.0	-1.5	13.7	4.6	49.4
0.2m Downslope	419	6.5	5.3	0.0	19.6	5.4	0.2
1m Downslope	419	8.2	7.5	1.4	18.0	3.8	0
PMONTH							
1m Upslope	419	1.0	-0.4	-4.7	12.8	6.6	52.3
0.2m Upslope	419	3.2	1.2	-0.7	14.3	5.9	16.9
TRACK	419	4.1	2.9	-1.2	15.6	6.8	13.6
0.2m Downslope	419	4.7	4.0	-0.4	15.5	3.2	0.5
1m Downslope	419	5.9	5.1	0.7	15.3	3.2	0
CONTROL							
C-I	419	6.4	5.6	1.8	15.1	3.5	0
C-II	419	7.4	6.7	2.0	16.1	2.7	0
C-III	419	8.8	8.6	3.5	15.5	3.2	0

Depth duration curves showed the proportion of time the water table was at or below a certain depth below the peat surface for each automated dipwell during the monitoring period (Figures 6.6 to 6.11). Most automated dipwells showed the water table to be within 10 cm of the peat surface for more than 75 % of the monitoring period. The mean daily water table in the control dipwell (Control I) was within the top 10 cm of the peat surface for ~80 % of the monitoring period. However, the water table was never above the peat surface at this location during the monitoring period. Close agreement was found in the shape of the duration curves for the control dipwells (Figure 6.6). Furthermore, with the exception of the mid-track automated dipwells in **PWEEK.AH** and **PMONTH**, the shape of the duration curves is similar between the treatments and different locations in relation to the track, therefore suggesting that the water table was responding in a similar way, independent of treatment or location.

In treatment **PWEEK.AH**, the mean daily water table was above the peat surface for ~ 50 % of the time at the mid-track location. However, the mean daily water-table depth did not rise above the surface **1 m upslope** or **1 m downslope** of the track. In treatment **PMONTH**, there was a gradient of shallowest to deepest water-table across the track, with the highest proportion time the mean daily water table was above the surface at **1 m upslope** (52.3 %), and the lowest 0 % at **1m downslope** (Table 6.3).

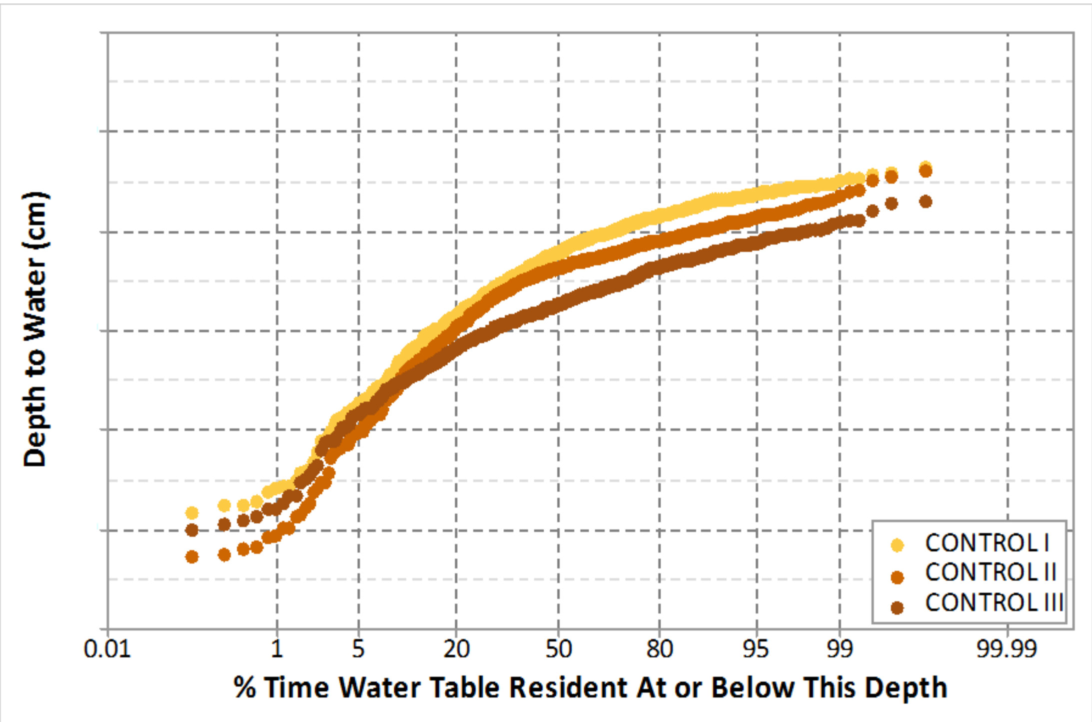

Figure 6.6 Depth duration curves for mean daily water table recorded in three automated dipwells in treatment **C**.

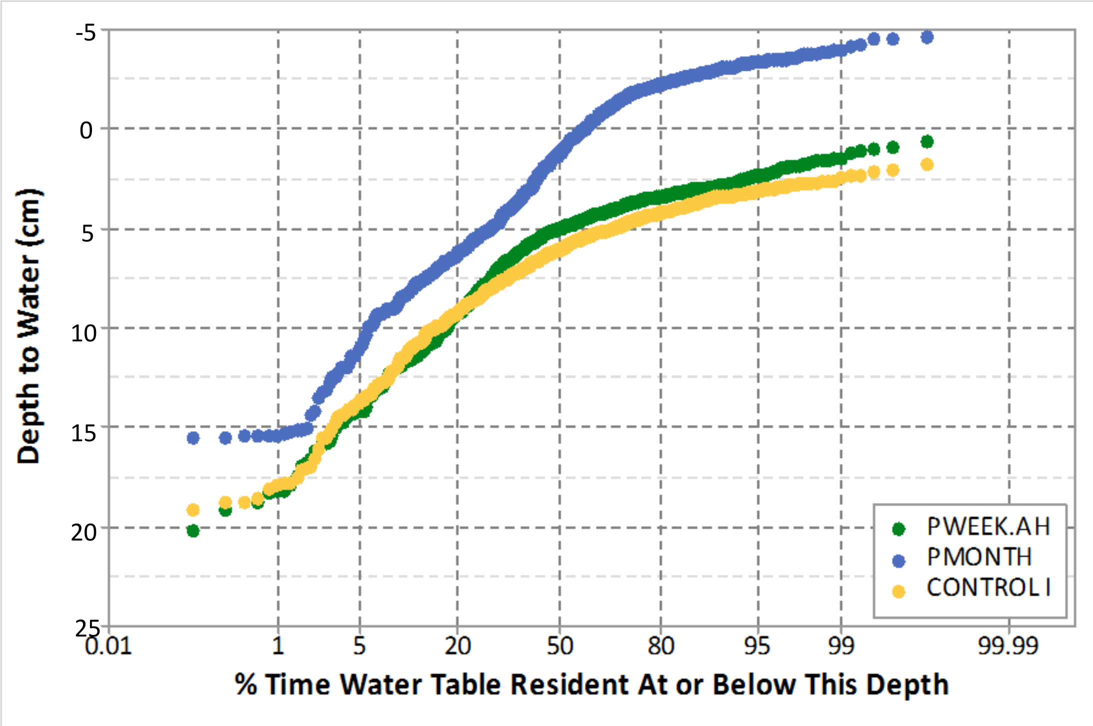

Figure 6.7 Depth duration curves for mean daily water table recorded **1 m upslope** of plastic mesh track in driving treatments, and at control dipwell C-I.

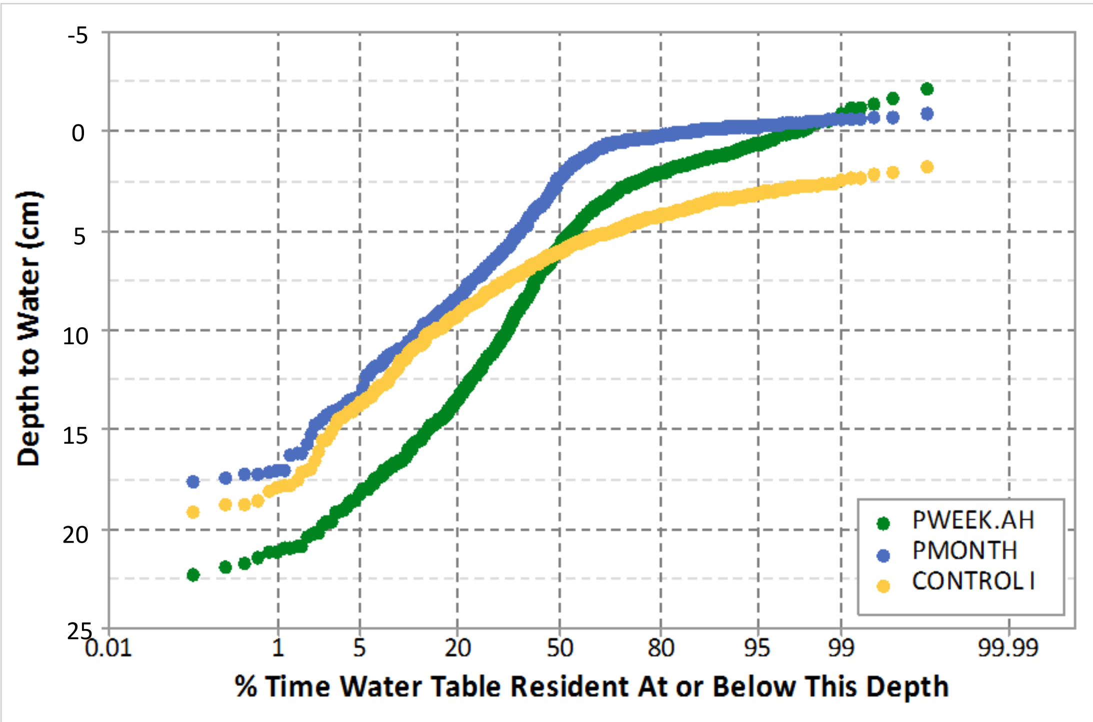

Figure 6.8 Depth duration curves for mean daily water table recorded **0.2 m upslope** of plastic mesh track in driving treatments, and at control dipwell C-I.

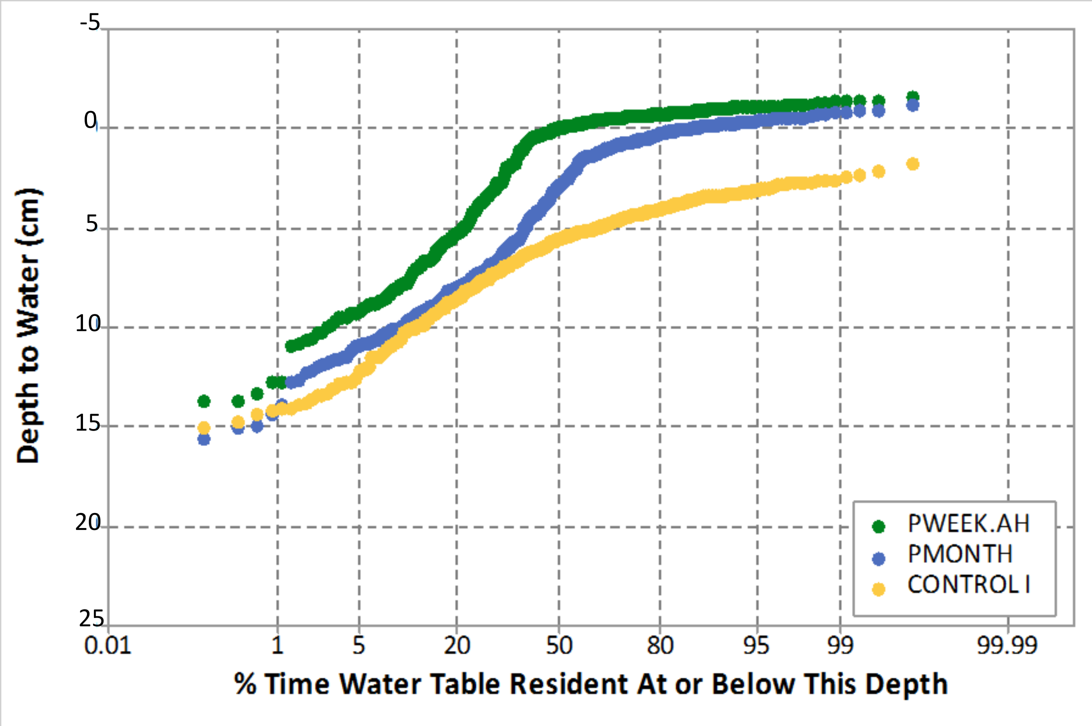

Figure 6.9 Depth duration curves for mean daily water table recorded at dipwells located in the middle of the plastic mesh track (**TRACK**), and at control dipwell C-I. Note that data are shown for September 2014 to November 2015 only.

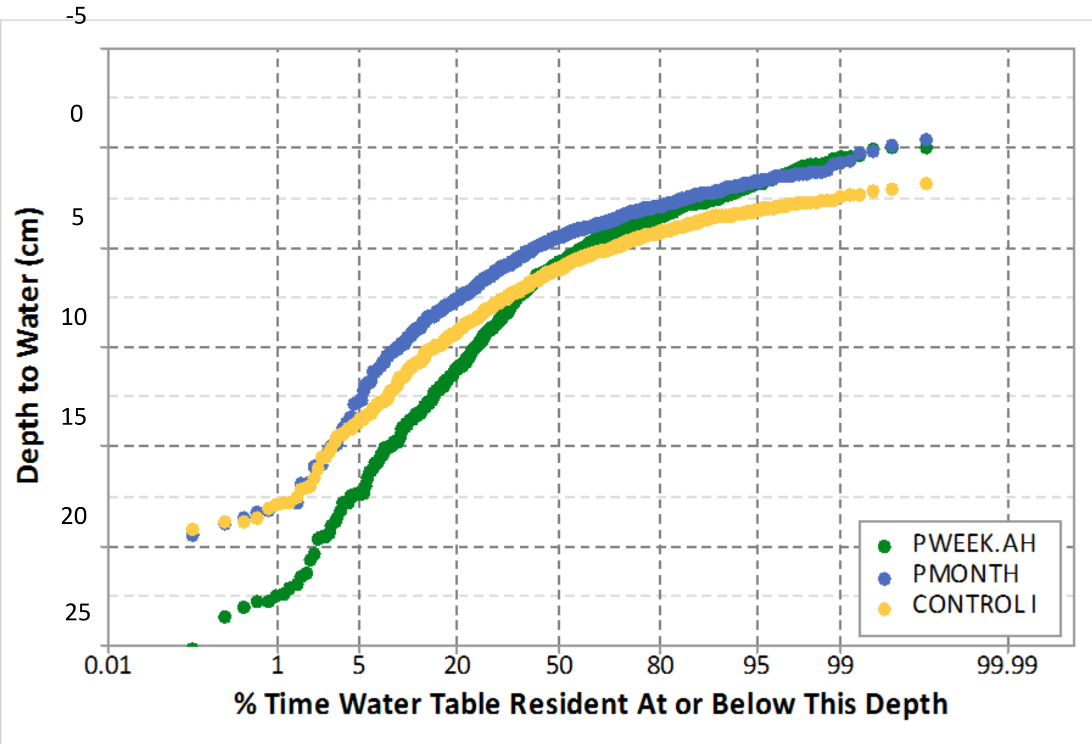

Figure 6.10 Depth duration curves for mean daily water table recorded at dipwells located **0.2 m downslope** of the plastic mesh track in the driving treatments, and at control dipwell C-I

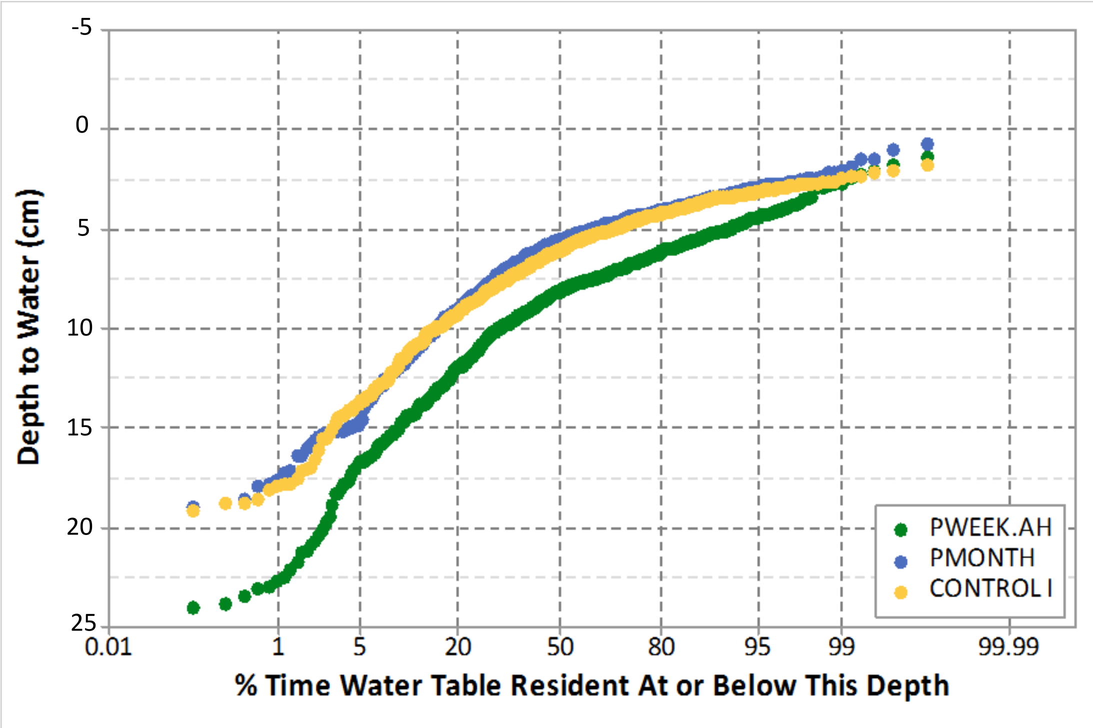

Figure 6.11 Depth duration curves for mean daily water table recorded at dipwells located **1 m downslope** of the plastic mesh track in the driving treatments, and at control dipwell C-I.

Comparisons of mean daily water table by treatment and distance from track are presented in Figures 6.12 to 6.16. Dipwell Control I was used as the control comparison in all of the plots. The response of the water table in all of the automated dipwells is comparable independent of treatment or distance from track. There was agreement between dipwells in times of shallower and deeper water tables during the monitoring period.

At **1 m upslope** of the track, mean daily water table in **PMONTH** was consistently shallower than **PWEEK.AH** and the control (Figure 6.12). Throughout the monitoring period there was close agreement in mean daily water table at **1 m upslope** between **PWEEK.AH** and the control. Mean daily water table in **PMONTH** continued to be shallower than **PWEEK.AH** and the control at **0.2 m upslope** of the track (Figure 6.13). At this location, **PWEEK.AH** showed the greatest variation in mean daily water table, shallow water table values were comparable with **PMONTH**. During periods of drawdown however, the mean daily water table in **PWEEK.AH** at **0.2 m upslope** was deeper than that in the control dipwell. There was evidence of the mean daily water table in the treatment dipwell being deeper than the control dipwell in **PWEEK.AH** at **0.2 m downslope** and **1 m downslope** as well. In the mid-track location (**TRACK**) mean daily water table was consistently shallower in **PWEEK.AH** compared with **PMONTH**, and both had a shallower water table than the control. In the second half of the monitoring period the gap between

TRACK mean daily water table for **PWEEK.AH** and **PMONTH** was appearing to widen, with the mean daily water table for **PWEEK.AH** becoming shallower (Figure 6.14).

Mean daily water table between treatments at **0.2 m downslope** and **1 m downslope** were more comparable between the three treatments. At **0.2 m downslope** the water-table depth in **PWEEK.AH** and **PMONTH** was marginally shallower than the control (Figure 6.15). At **1 m downslope,** however, mean daily water table was shallower in **PMONTH** and the control compared with **PWEEK.AH** (Figure 6.16). These data showed no one treatment to be associated with consistently shallower or deeper water tables than the other, variation existed depending on location in relation to the track.

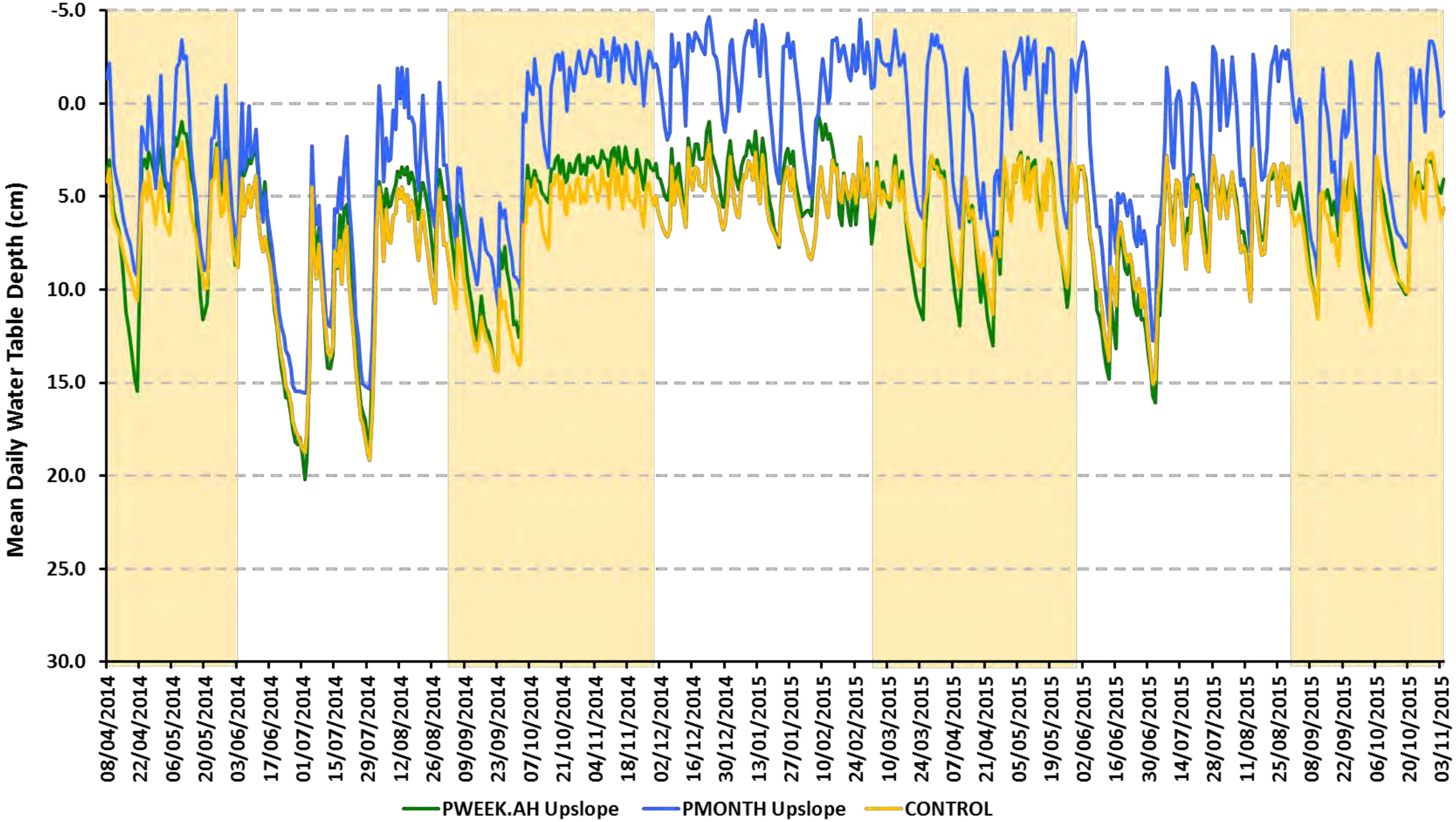

Figure 6.12 Mean daily water-table depth for automated dipwells **1 m upslope** of plastic mesh track in the driving treatments, and the control dipwell (C-I). Spring and autumn seasons are shaded yellow, summer and winter are shaded white.

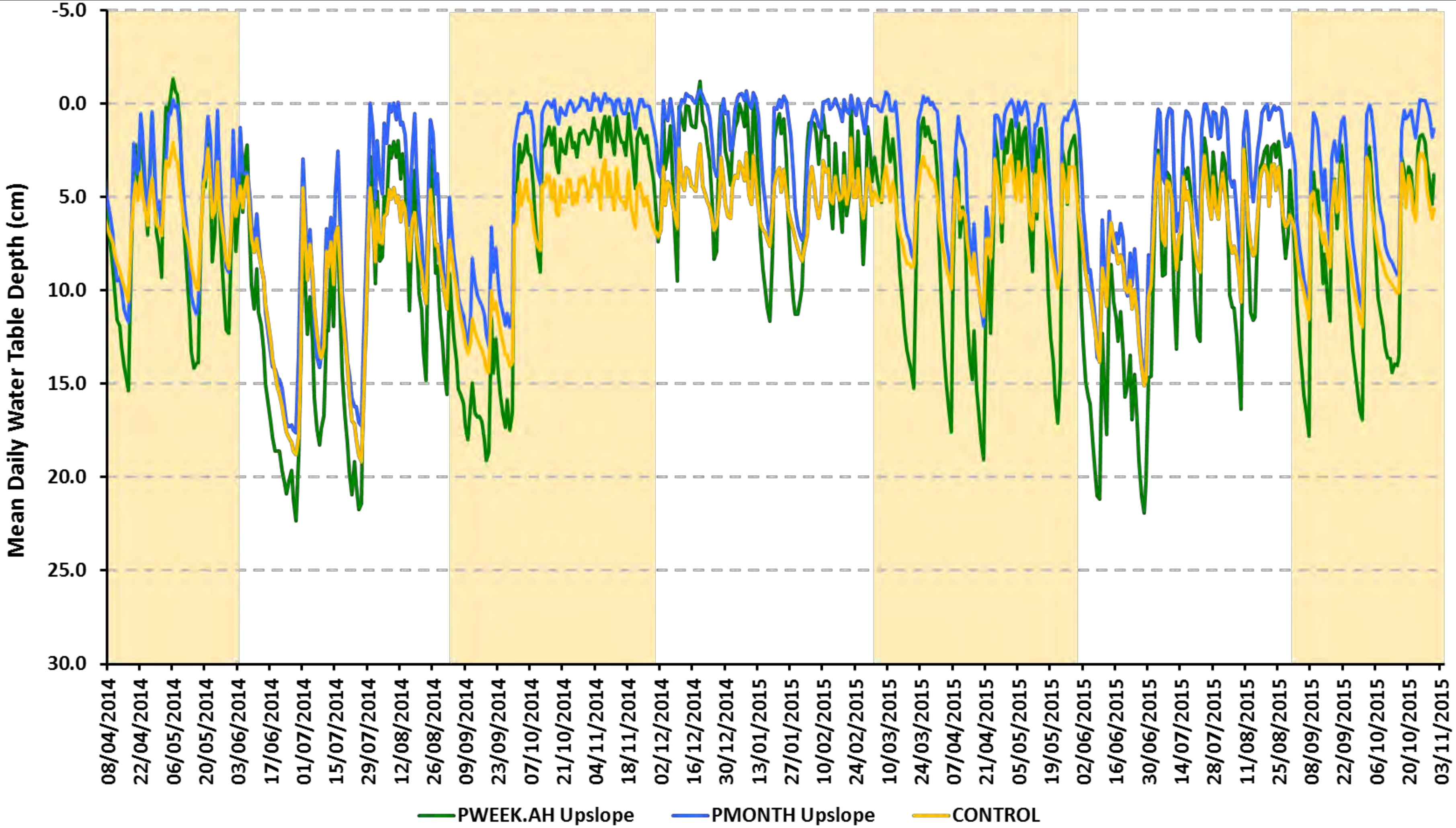

Figure 6.13 Mean daily water-table depth for automated dipwells **0.2 m upslope** of plastic mesh track in the driving treatments, and the control dipwell (C-I). Spring and autumn seasons are shaded yellow, summer and winter are shaded white.

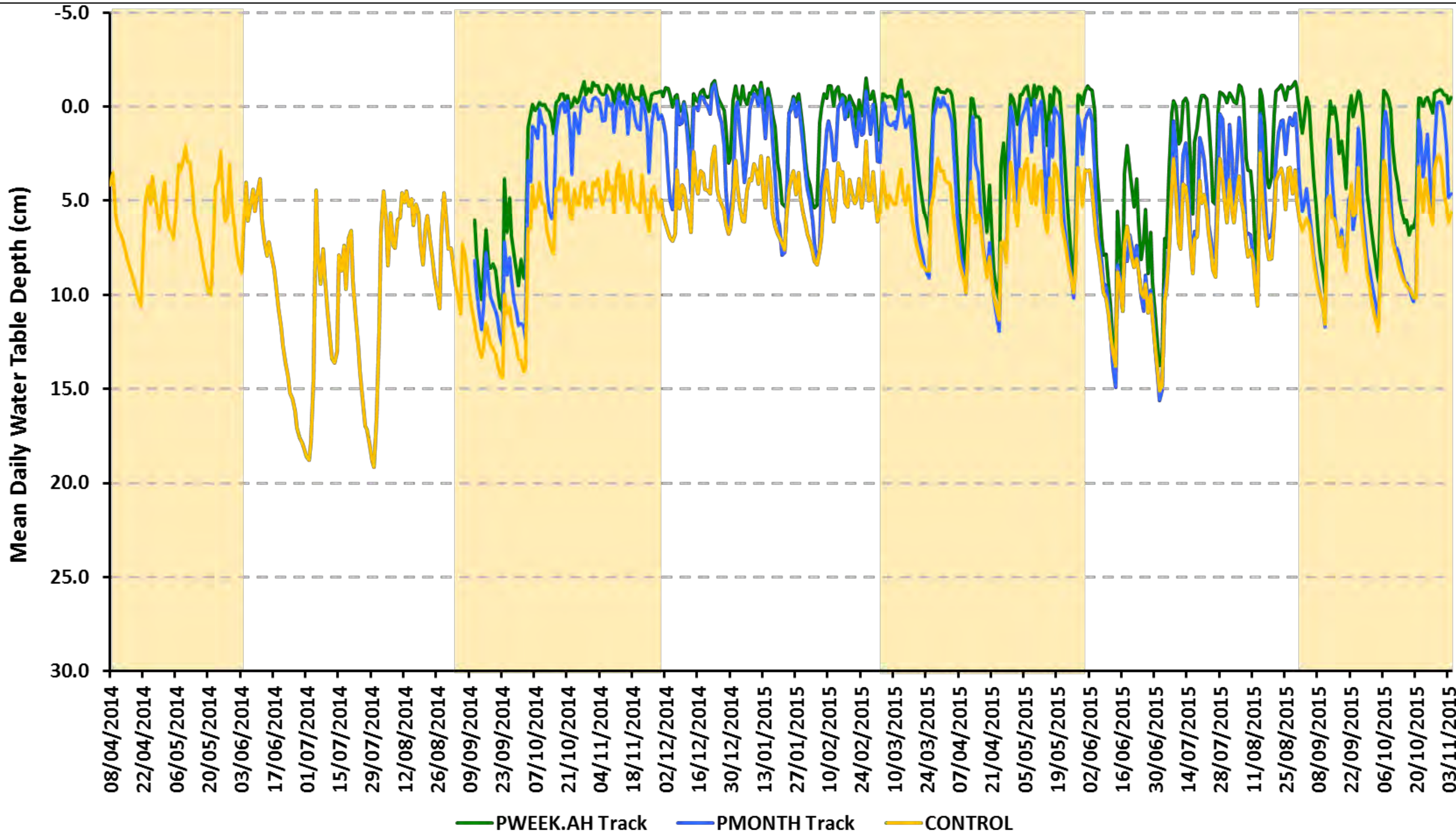

Figure 6.14 Mean daily water-table depth for automated dipwells in the middle of the plastic mesh track (**TRACK**) in the driving treatments, and the control dipwell (C-I). Spring and autumn seasons are shaded yellow, summer and winter are shaded white.

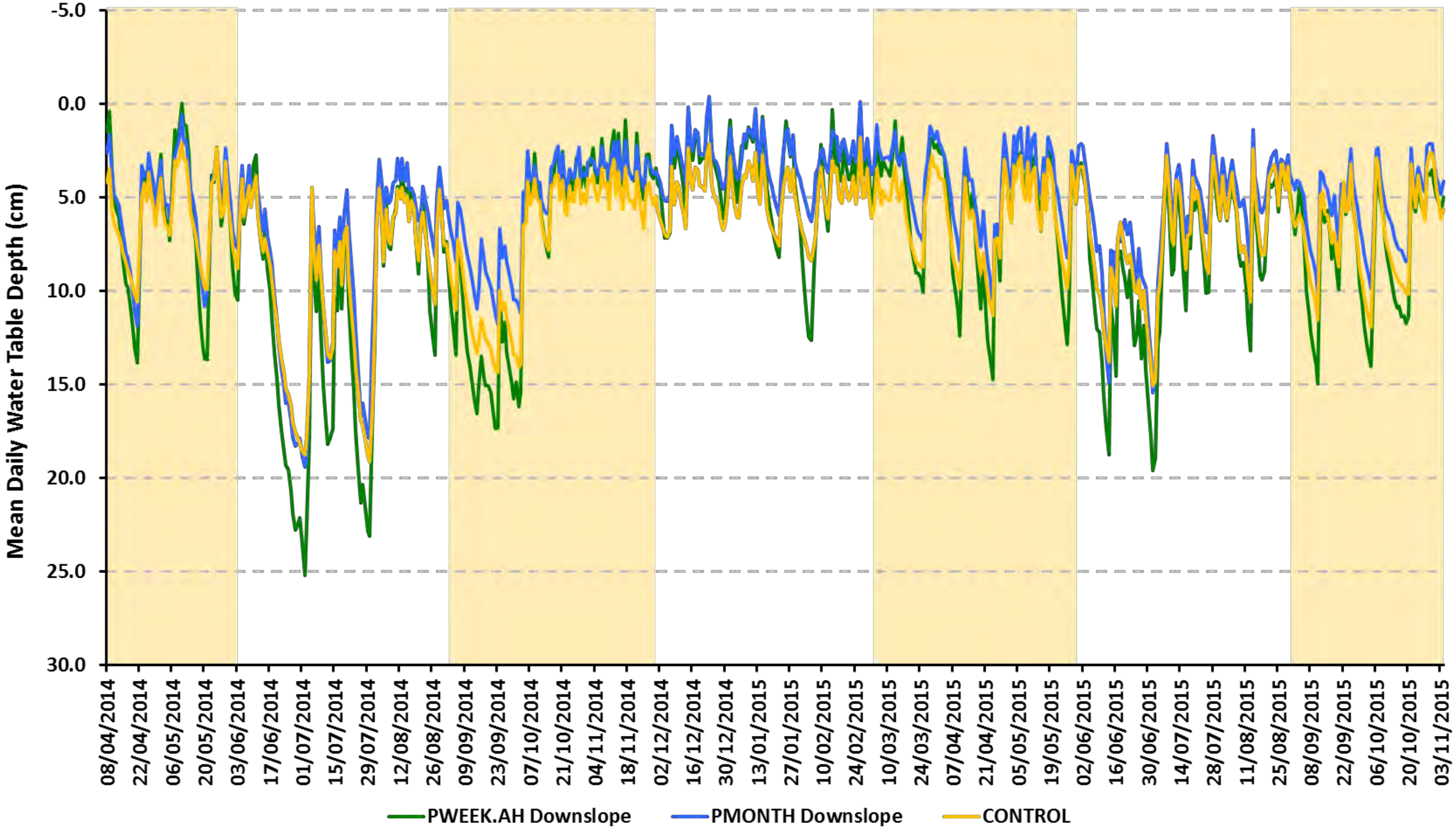

Figure 6.15 Mean daily water-table depth for automated dipwells **0.2 m downslope** of the plastic mesh track in the driving treatments, and the control dipwell (C-I). Spring and autumn seasons are shaded yellow, summer and winter are shaded white.

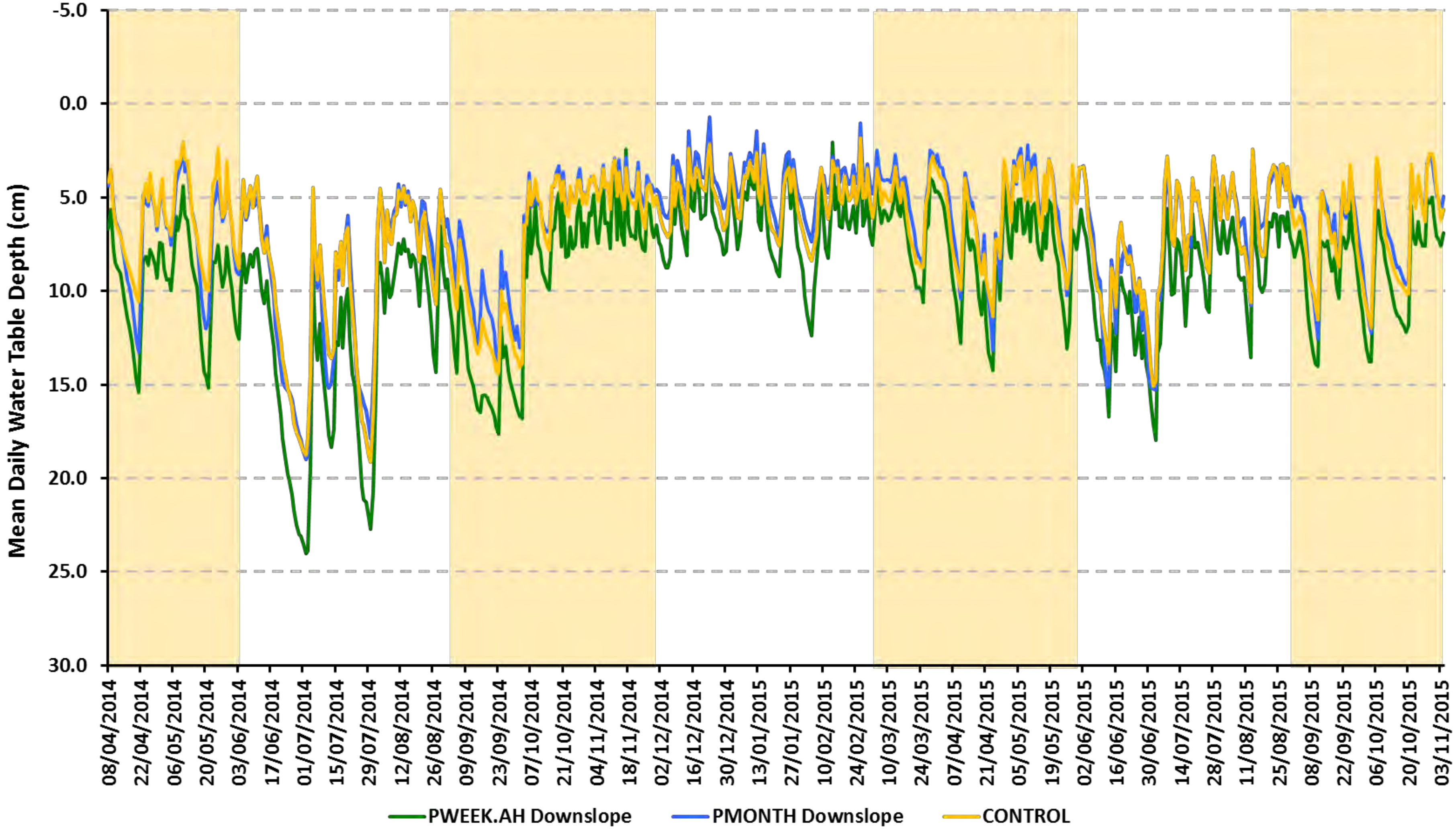

Figure 6.16 Mean daily water-table depth for automated dipwells **1 m downslope** of the plastic mesh track in the driving treatments, and the control dipwell (C-I). Spring and autumn seasons are shaded yellow, summer and winter are shaded white.

There was no clear evidence that the water table was becoming shallower or deeper over the monitoring period for the track sites. The residual between each treatment dipwell and Control I was calculated. Statistical analysis (t-test) yielded significant differences in the residuals between years and by season for most of the automated dipwells (Table 6.4).

Table 6.4 *P* values from t-tests comparing residuals for 2014 versus 2015 by season and dipwell location. Direction of change in water-table depth is recorded where difference was significant. * = significant at ≤ 0.05. ↑ = water table becoming shallower, ↓ = water table becoming deeper.

	PWEEK.AH		**PMONTH**	
SPRING				
1 m Upslope	0.005*	↓	<0.001*	↑
0.2 m Upslope	0.002*	↓	<0.001*	↑
TRACK	n/a	n/a	n/a	n/a
0.2 m Downslope	0.029*	↓	<0.001*	↑
1 m Downslope	<0.001*	↑	<0.001*	↑
SUMMER				
1m Upslope	<0.001*	↓	<0.001*	↑
0.2 m Upslope	0.144		0.002*	↑
TRACK	n/a	n/a	n/a	n/a
0.2 m Downslope	0.255		0.199	
1 m Downslope	< 0.001*	↑	0.473	
AUTUMN				
1m Upslope	<0.001*	↓	<0.001*	↓
0.2 m Upslope	0.193		0.228	↓
TRACK	0.008*	↓	<0.001*	↓
0.2 m Downslope	0.328		<0.001*	↓
1 m Downslope	<0.001*	↑	<0.001*	↓

However, the directions of change i.e. water table becoming shallower or deeper were not consistent within treatments or with distance from track. Between control dipwells Control I and Control II, a significant difference was found in residuals for spring (p = 0.026) but not for summer and autumn (p = 0.445 and 0.516 respectively). The presence of the track has had some impact although it is not clear in the time series data what this impact is with respect to the depth of the water table.

The interquartile range of the mean daily water table for the driven treatments (**PWEEK.AH** and **PMONTH**) was larger and more variable over the monitoring period compared with the mean daily water table recorded in the control treatment automated dipwells (Figures 6.17 to 6.19). Initial variation was observed in all of the automated dipwells between April and May 2014. Following this, the interquartile range for the control dipwells became more consistent over the monitoring period (Figure 6.19). However, in the driving treatments the large variation continued. **0.2 m upslope** in **PWEEK.AH** had the largest interquartile range. This was also the dipwell which showed the deepest drawdown in the times series plots. In all of the treatments the interquartile range was smaller during the winter months (October 2014 to March 2015), a time when the water-table depth was more consistently shallow.

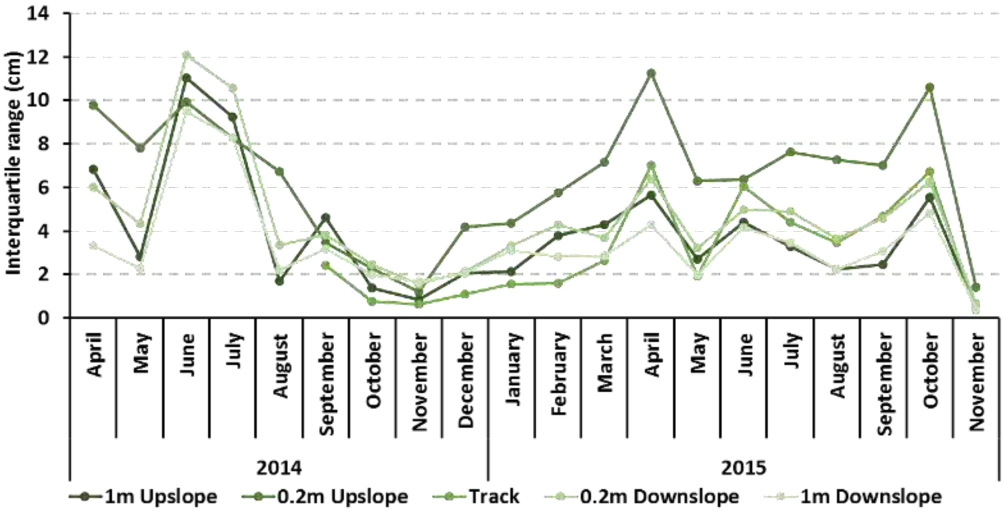

Figure 6.17 Interquartile range by month for mean daily water table in **PWEEK.AH**

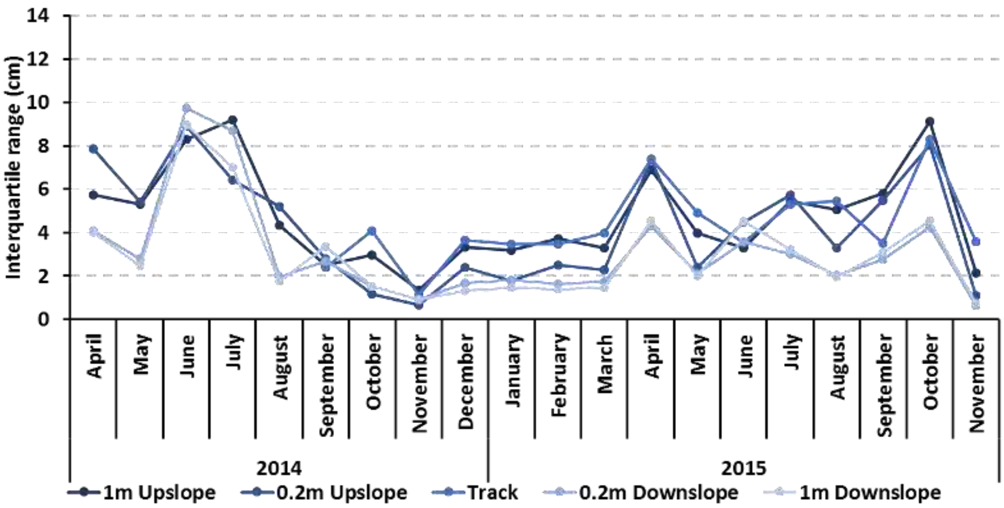

Figure 6.18 Interquartile range by month for mean daily water table in **PMONTH**

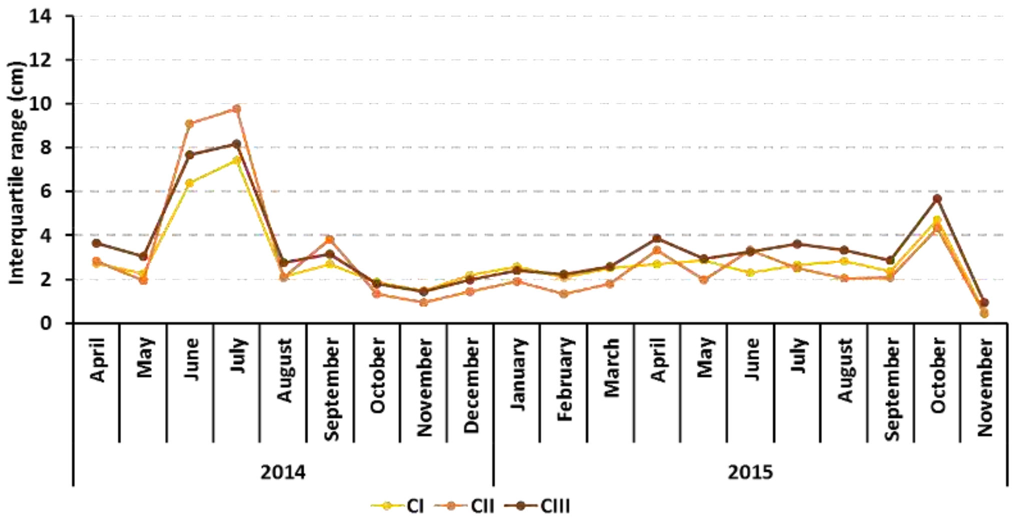

Figure 6.19 Interquartile range by month for mean daily water table in the control treatment (**C**).

6.3.1.3 Spatial Effect

Data from all 539 manual dipwells was used to examine spatial patterns in water-table depth around the track. At the mid-track sampling location, variation was observed in water-table depth between treatments at each individual topographic location. At topographic location S1, treatment **C** had the deepest median water table (12.4 cm), while the shallowest median water table (5.4 cm) was in treatment **PMONTH** (Figure 6.20a). At topographic location S2, however, **PWEEK.AH** had the shallowest water table (6.2 cm) whilst the deepest median water table was in treatment **PWEEK** (9.7 cm) (Figure 6.20b). Further, at topographic location S3, the shallowest median water table was 4.0 cm which was found in treatments **PDLEAYED** and **U**. Treatment **PWEEK.AL** had the deepest median mid-track water table (6.7 cm) (Figure 6.20c). Using linear mixed effects models (sampling date as a random factor), significant differences were found between treatments for mid-track water-table depth at topographic location S1 (p = 0.001), but not at topographic locations S2 (p = 0.133) and S3 (p = 0.251).

Differences in water-table depth on either side of the track at each topographic location (S1 and S2, Right vs Left; S3, Upslope vs Downslope) were statistically analysed using distance-weighted water table data in a linear mixed effects model, where sampling date was included as a random factor with treatment and side as nested variables. The p values from this analysis are presented in Table 6.5.

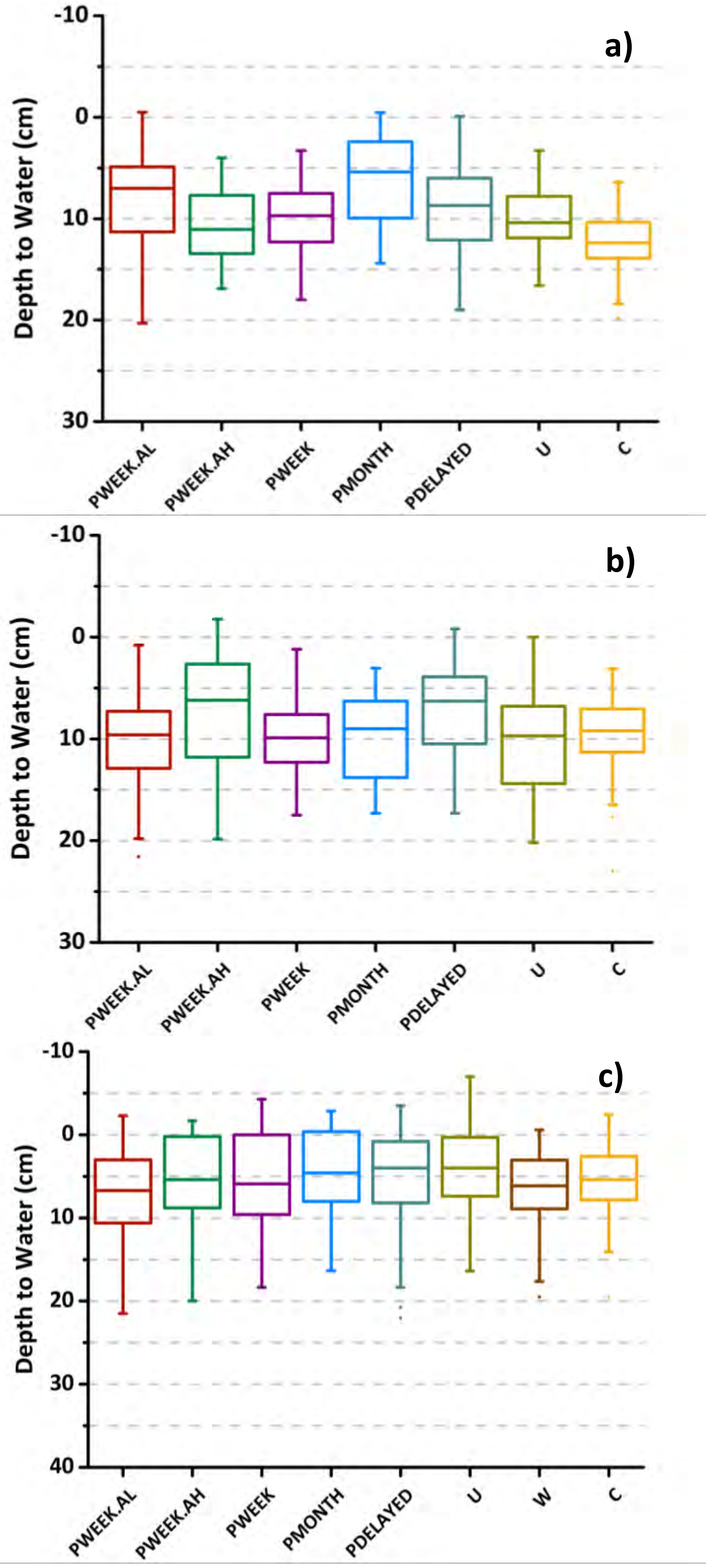

Figure 6.20 a-c Boxplot of water-table depth by treatment for mid-track location at topographic locations a) S1, b) S2, c)S3 and comparable control data at each topographic location. Note the addition of treatment **W** at topographic location S3. Boxplot shows median, interquartile range, and outliers which are values below Q1 – 1.5 x (Q3-Q1) and above Q3+1.5 x (Q3-Q1).

Table 6.5 *P* values from a linear mixed effects model testing the difference in water-table depth by treatment, side and treatment *x* side. Sampling date was included as a random factor. * = p ≤ 0.05. At topographic locations S1 and S2 side was Right vs Left, at topographic location S3 side was Upslope vs Downslope.

Factor	***P* value**		
	S1	**S2**	**S3**
Treatment	0.018*	<0.001*	0.013*
Side	0.161	0.123	0.288
Date (Treatment, Side)	<0.001*	<0.001*	<0.001*
Treatment *x* Side	0.083	0.002*	<0.001*

A significant difference was found in distance-weighted water-table depth between treatments at all topographic locations, however no significant difference was found between the two sides of the track (ignoring treatment) at each topographic location. It is potentially not surprising that a significant difference was not observed between the right and left sides of the tracks at topographic locations S1 and S2 given that the track was typically installed on the flat or perpendicular to the contours (i.e. direction of travel was straight up and down hill). Topographic location and by association the orientation of the track to the contours therefore have the potential to be influential to spatial effects on water-table depth. Further analysis was undertaken to investigate the significant interaction (treatment *x* side) yielded at topographic location S3 ($p < 0.001$), comparing the distance-weighted water-table depth on the upslope and downslope sides of the tracks for each treatment individually. *P* values are presented in Table 6.6.

Table 6.6 *P* values from linear mixed effects model testing the difference between the upslope and downslope distance-weighted water-table depth at topographic location S3 for each driven treatment. Date was included as a random factor to address the repeated measures. * = p ≤ 0.05.

Treatment	**Factors**	
	Side (Upslope vs Downslope)	Date (Treatment, Side)
PWEEK.AL	0.027*	<0.001*
PWEEK.AH	0.973	<0.001*
PWEEK	0.041*	<0.001*
PMONTH	0.139	<0.001*
PDELAYED	0.069	<0.001*
U	<0.001*	<0.001*
W	0.433	<0.001*

At topographic location S3, significant differences were only observed between the upslope and downslope distance-weighted water-table depth in treatments **PWEEK.AL**, **PWEEK** and **U**. From these, only treatment **PWEEK** exhibited significantly shallower water-table depth on the upslope side of the track relative to the downslope side. The control treatment (treatment **C**) also exhibited a statistically significant difference between the two sides of the assumed 'track', with deeper water-table depths on the 'upslope' relative to the 'downslope'. This therefore suggests spatial variation in water-table depth even without the presence of the track.

Analysis of water-table depth at individual distances from the track edge provided further evidence of spatial variation. Median water-table depth by topographic location and driving treatment is presented in table 6.7 (S1 and S2) and Table 6.8 (S3).

Table 6.7 Median water-table depth by distance from track and treatment for topographic locations S1 and S2. The shallowest median water-table depth is bold and the deepest median water-table depth is underlined for each distance for the track.

	S1					S2				
		Right		Left			Right		Left	
	n	1 m	0.2 m	0.2 m	1m	*n*	1 m	0.2 m	0.2 m	1m
PWEEK.AL	45	9.0	**8.5**	**6.0**	11.1	45	7.6	10.4	8.7	8.6
PWEEK.AH	45	11.0	10.9	10.2	9.8	45	**6.0**	**6.3**	7.9	12.2
PWEEK	45	9.7	10.0	9.4	13.3	45	10.1	8.8	9.3	12.1
PMONTH	45	**5.4**	11.1	7.4	7.9	45	9.1	11.1	11.4	8.4
PDELAYED	45	9.1	14.3	8.9	7.4	45	9.4	6.8	**5.0**	**5.1**
U	45	9.9	8.8	7.6	**7.3**	45	9.6	7.3	11.9	8.9

Table 6.8 Median water-table depth by distance from track and treatment for topographic location S3, where measurements were taken up to 10 m from the track edge. The shallowest median water-table depth is bold and the deepest median water-table depth is underlined for each distance for the track.

	n	10 m	5 m	2 m	1m	0.5 m	0.2 m
Upslope							
PWEEK.AL	75	11.3	8.1	5.8	9.8	8.7	8.0
PWEEK.AH	75	10.4	**2.6**	6.2	**4.7**	5.5	8.0 (*n* = 74)
PWEEK	75	4.4	3.9	6.1	5.4	6.8	**5.5**
PMONTH	75	7.9	2.8	7.8	5.1	8.0	8.4
PDELAYED	75	**4.0**	7.3	**5.0**	6.6	**4.7**	6.4
U	75	6.9	9.0	7.3	8.6	8.2	6.4
W	72	**4.0**	6.1	6.0	8.5	4.9	6.1
Downslope							
PWEEK.AL	75	7.4	6.7	5.6	10.2	**5.2**	8.0
PWEEK.AH	75	**3.1**	4.1	5.6	11.1	7.6	**5.2**
PWEEK	75	6.6	8.0	8.1	9.7	8.4	8.1
PMONTH	75	4.1	**4.0**	5.2	9.2	6.7	7.2
PDELAYED	75	7.9	7.1	5.6	9.5	5.4	7.5
U	75	5.6	6.5	4.6	**5.2**	7.1	**5.2**
W	72	7.4	6.5	**1.0**	12.6	7.2	5.9

At topographic location S3 only, a linear mixed effects model was used to test the difference in upslope and downslope water-table depth at each distance up to 10m from the track edge. Sampling date was included as a random factor. At the site scale, significant differences were observed between the upslope and downslope sides of the track 1m from the track edge and beyond (Table 6.9).

Table 6.9 *P* values from linear mixed effects model examining variation in water-table depth with distance from the track edge up to 10m at topographic location S3. * = $p \leq 0.05$.

Factor	Distance from Track Edge (*P* value)					
	0.2	**0.5**	**1**	**2**	**5**	**10**
Treatment	0.103	0.298	0.007*	0.012*	<0.001*	<0.001*
Side	0.157	0.052	0.486	0.042*	0.828	0.004*
Date (Treatment, Side)	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Treatment *x* Side	0.425	0.010*	<0.001*	0.001*	0.001*	<0.001*

There was variation in the distances which exhibited a significant difference between the upslope and downslope sides when compared within each treatment (Table 6.10, link with Table 6.8). At 0.2 m from the track edge only **PWEEK** exhibited a significantly shallower water table relative to the downslope. The control treatment also exhibited significant differences at 1 m ($p < 0.001$) and 5 m ($p < 0.001$), suggesting that spatial variation occurs independent of the presence of the track. Water-table depth was consistently significantly higher upslope of the track relative to the downslope at all comparative distances only in treatment **PWEEK** (Tables 6.8 and 6.10, Figure 6.21b). Given the lack of patterns it is not possible to determine whether the effects being observed were clearly the result of the presence and use of the track or natural spatial variation. There is no clear indication of an influence of track type or frequency of use on spatial patterns of water-table depth.

Table 6.10 *P* values from linear mixed effects model examining variation in water-table depth with distance from the track edge up to 10m at topographic location S3 by treatment. * = $p \leq 0.05$.

Factor	Distance from Track Edge (*P* value)					
	0.2	**0.5**	**1**	**2**	**5**	**10**
PWEEK.AL	0.301	0.050*	0.054	0.991	0.163	0.002*
PWEEK.AH	0.492	0.048*	0.024*	0.767	0.189	<0.001*
PWEEK	0.032*	0.006*	0.014*	0.041*	0.001*	0.006*
PMONTH	0.922	0.875	0.035*	0.061	0.391	0.001*
PDELAYED	0.312	0.697	0.977	0.371	0.794	<0.001*
U	0.694	0.914	<0.001*	0.003*	0.003*	<0.001*
W	0.641	0.055	0.496	0.004*	0.798	0.018*

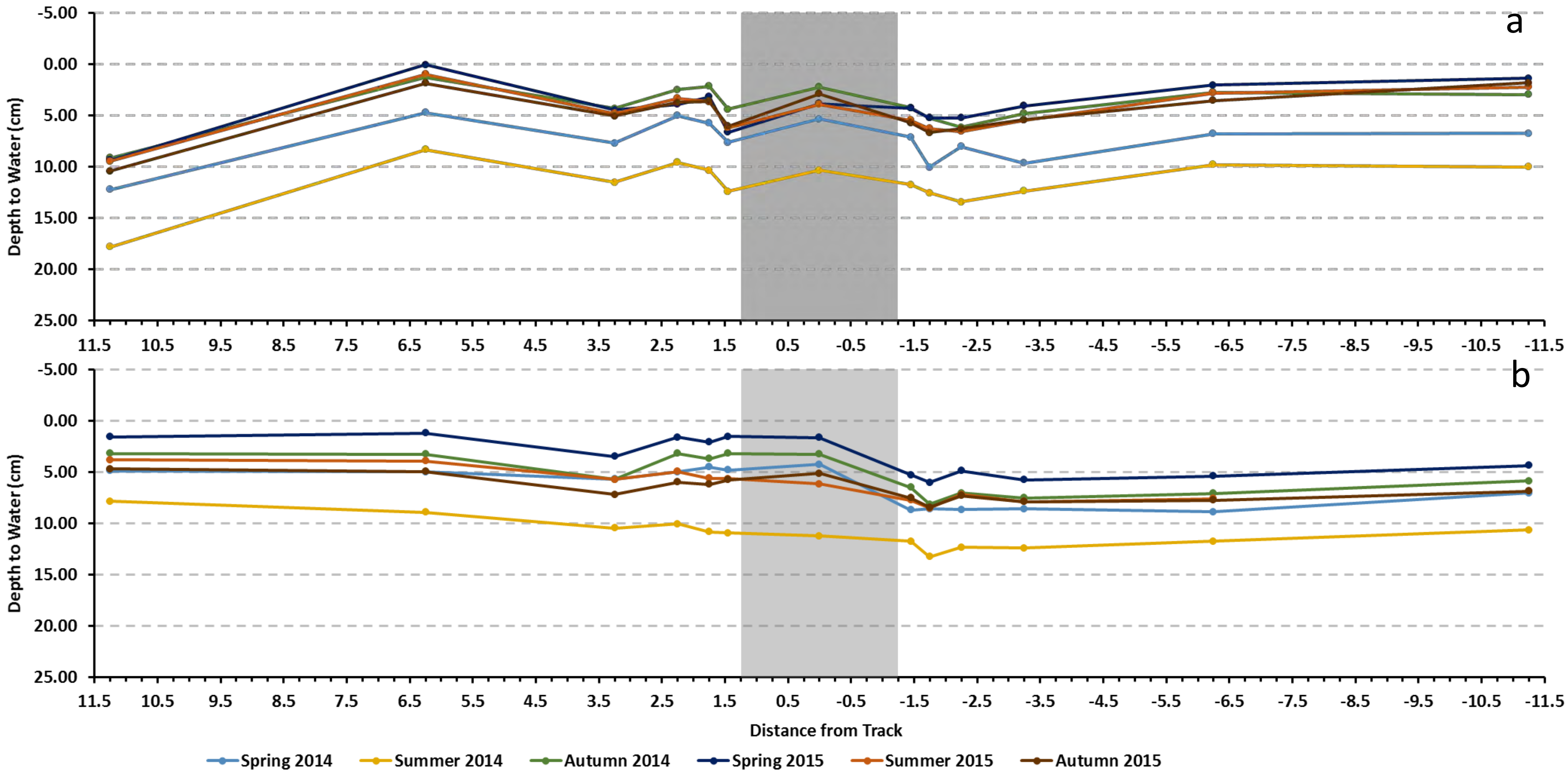

Figure 6.21 a–d (a-b on this page, c-d continued on page 174) Mean seasonal water-table depth for manual dipwells plotted by distance from track for treatments (a) **PWEEK.AH *x* S3** and (b) **PWEEK *x* S3**. Distances are given from the centre of the track (0). Location of track is shaded grey. Positive values are upslope, negative values are downslope.

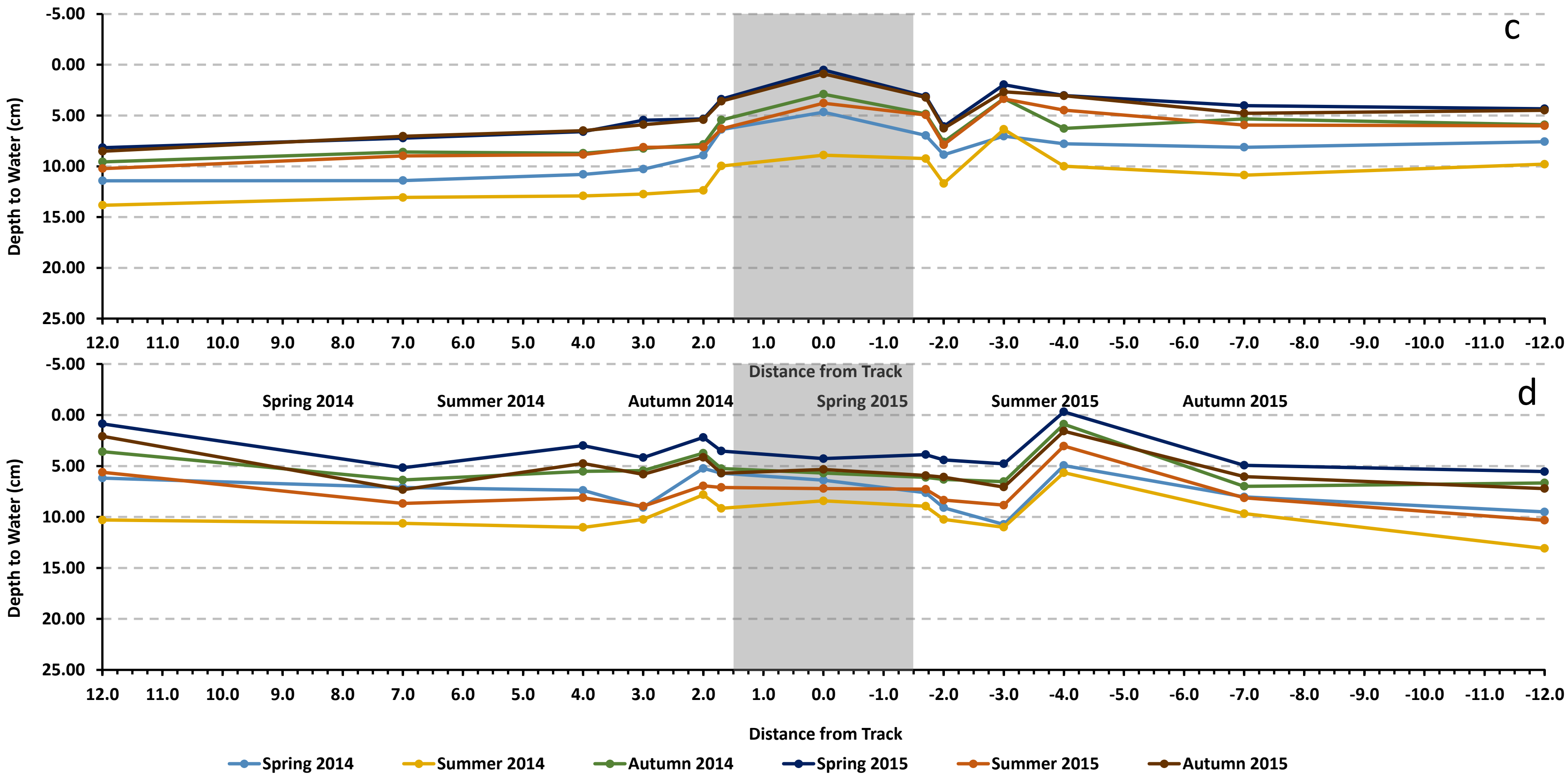

Figure 6.21 c-d Mean seasonal water-table depth for manual dipwells plotted by distance from track for treatments (c) **U *x* S3** and (d) **W**. Distances are given from the centre of the track (0). Location of track is shaded grey. Positive values are upslope, negative values are downslope

While there is clear spatial variation in water-table depth with distance from the track edge, graphical analysis showed in general spatial patterns in water-table depth remained similar within treatments over the monitoring period. Around the tracks areas of deeper water table remained deep and shallower water tables remained shallow; this was most obvious in the longer transects up to 10 m from the track edge installed at topographic location S3 in each treatment. Spatial patterns for selected treatments are shown in Figures 6.21a-d. One exception was the behaviour of the water table in the middle of the track in treatment **U** The range in water-table depth appeared to be large for this track type, when compared with the other treatments (Figure 6.20c). In addition, the water table appeared to be much shallower at this sampling location across all the seasons relative to the rest of the sampling locations in this treatment at this topographic location (Figure 6.21c). This is possibly an indication of compression of the surface peat under the track route.

Extended transects up to 50 m in **PWEEK.AH** and **PMONTH** also exhibited the same level of agreement between seasons. Greater variability, i.e. less agreement in spatial patterns of water-table depth between seasons, was observed at topographic locations S1 and S2. Measurements at these topographic locations were only taken up to 1 m from the edge of the track, and in the extended transects this was where the most variability was also observed in graphical analysis.

In addition, from treatment **C,** sampling dates which were several months apart but exhibited comparable water-table depths, were identified. Water-table patterns for the driven treatments were then examined for these dates to determine whether there had been a change in the behaviour of the water table around the tracks. Comparison of the data within the driven treatments for the comparable sampling dates showed the same extent of similarity as in the control. These results suggest that the water table was behaving in the same way over time around the track, with little evidence of track impact. Mean water-table depth for two selected dates (13.08.2014 and 11.03.2015) for two driven treatments **(PWEEK.AH** and **PMONTH**) and treatment **C** is shown in Figure 6.22.

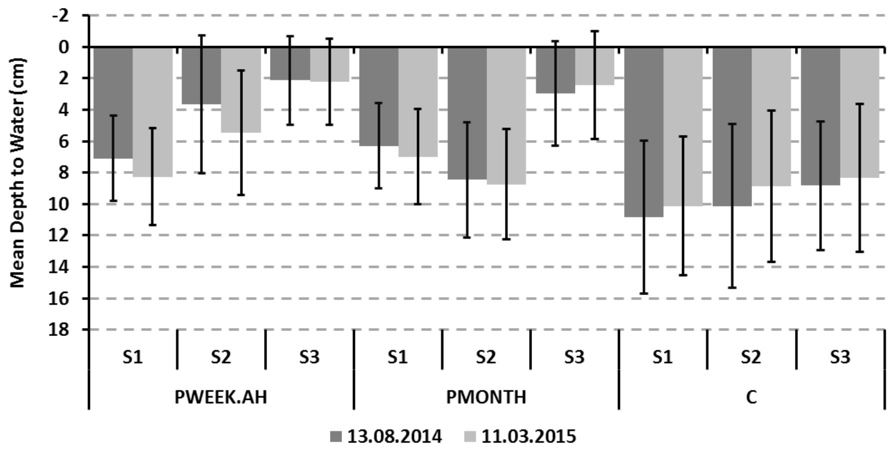

Figure 6.22 Mean water-table depth by topographic location for two driven treatments (**PWEEK.AH** and **PMONTH**) and treatment **C** for sampling dates with similar water-table depths several months apart. Error bars show ± standard deviation.

6.3.2 Overland Flow

Occurrence of overland flow was found to vary with topographic location unrelated to treatment. The highest frequency of overland flow occurrence was in location S3 with 58.5 % over the monitoring period. The lowest occurrence was in location S2 with 22.1 %. This topographic effect was found to occur in all treatments with the highest occurrence of overland flow in the bottom-slope (S3) locations. Between treatments the highest occurrence of overland flow was in **PMONTH** with 53.0 % whilst the lowest was in treatment **C** (21.3 %). Overland flow occurrence was second highest around treatment **W** at 49.0 %. While the results for all other treatments are based on five crest-stage samples at each topographic location, the results for treatment **W** are based on fifteen crest-stage samplers as it only covered one topographic location.

Spatial variation was observed in the occurrence of overland flow with sampling location in relation to the track. Using a chi-square test of association statistically significant differences were yielded at each separate topographic location ($p < 0.001$ in each case), indicating that there was some association between the occurrence of overland flow and sampling location around the track. Indeed at topographic locations S2 (Table 6.11) and S3 (Table 6.12), percent occurrence values indicated a higher occurrence of overland flow immediately on track and within 0.2 m of the track edge compared with 1m off track. When the data was further broken down by treatment at each topographic location this pattern did not always hold however (Tables 6.13 and 6.14).

Table 6.11 Percent occurrence of overland flow according to location of the crest-stage tube in relation to the track at topographic locations S1 and S2. All types of track are included and distances are given from the edge of the track (m).

	Right		Track	Left	
	1m	0.2 m		0.2m	1m
S1	32.8	30.7	29.5	40.2	12.3
S2	11.9	30.8	25.0	26.6	16.4

Table 6.12 Percent occurrence of overland flow according to location of the crest-stage tube in relation to the track at topographic location S3. All types of track are included and distances are given from the edge of the track (m).

	Upslope		Track	Downslope	
	1m	0.2 m		0.2m	1m
S3	55.6	70.6	61.8	66.4	37.9

Table 6.13 Percent occurrence of overland flow according to location of the crest-stage tube in relation to the track (distance from edge (m)) by topographic location (S1 and S2) and treatment.

	S1					S2				
	Right		Track	Left		Right		Track	Left	
	1	0.2		0.2	1	1	0.2		0.2	1
PWEEK.AL	8.6	82.9	97.1	22.9	5.7	5.7	65.7	11.4	14.3	25.7
PWEEK.AH	11.4	0	2.9	5.7	5.7	2.9	17.1	20	57.1	0
PWEEK	71.4	8.6	5.7	25.7	0	48.5	68.6	51.4	28.6	2.9
PMONTH	71.4	22.9	25.7	68.6	17.1	22.9	14.3	20	40	54.3
PDELAYED	0	0	0	14.7	2.9	0	20.6	73.5	38.2	8.8
U	0	80	74.3	48.6	51.4	2.9	22.9	0	8.6	22.9
C	65.7	20	0	94.3	2.9	0	5.7	0	0	0

Table 6.14 Percent occurrence of overland flow according to location of the crest-stage tube in relation to the track (distance from edge (m)) by topographic location (S3) and treatment.

	Upslope		Track	Downslope	
	1	0.2		0.2	1
PWEEK.AL	40	68.6	77.1	74.3	14.3
PWEEK.AH	77.1	77.1	80	80	62.9
PWEEK	82.9	85.7	71.4	71.4	48.6
PMONTH	71.4	88.6	97.1	88.6	91.4
PDELAYED	79.4	23.5	64.7	73.5	14.7
U	34.3	85.7	85.7	85.7	48.8
W	53.1	75.0	43.8	41.7	31.3
C	11.4	51.4	5.7	60	2.9

The occurrence of overland flow was compared for the same time periods (April to June and September to November) in 2014 and 2015, with a higher number of events recorded in 2015 compared with 2014 in both time periods. Within these time periods the highest occurrence of overland flow was in September to November 2015 (48.3 %). The results of a chi-squared test did not exhibit a significant difference in the occurrence of overland flow events for the April to June period from 2014 and 2015 ($p = 0.338$). However a statistically significant difference was observed for the September to November period ($p < 0.001$). When further analysed by treatment, variable patterns were observed depending on the time of year (Figures 6.23 and 6.24). By treatment, statistically significant differences in the occurrence of overland flow between years were only yielded in treatments **PDELAYED** (September to November, $p = 0.026$), **U** (April to June, $p = 0.012$, September to November, $p = 0.002$), and **C** (September to November, $p = 0.022$). The variation observed suggested that antecedent conditions, as well as impact of the track, were having an effect, with the additional rainfall in those periods during 2015 having an influence. This was further supported by the increase in the occurrence of overland flow observed in control treatment for both time periods.

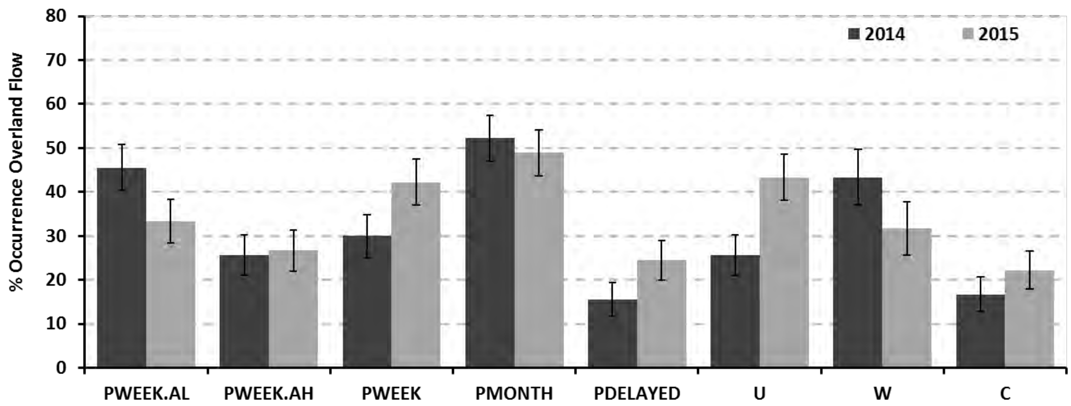

Figure 6.23 Comparison of occurrence of overland flow in 2014 and 2015 (April to June) for each treatment. Error bars show ± standard deviation.

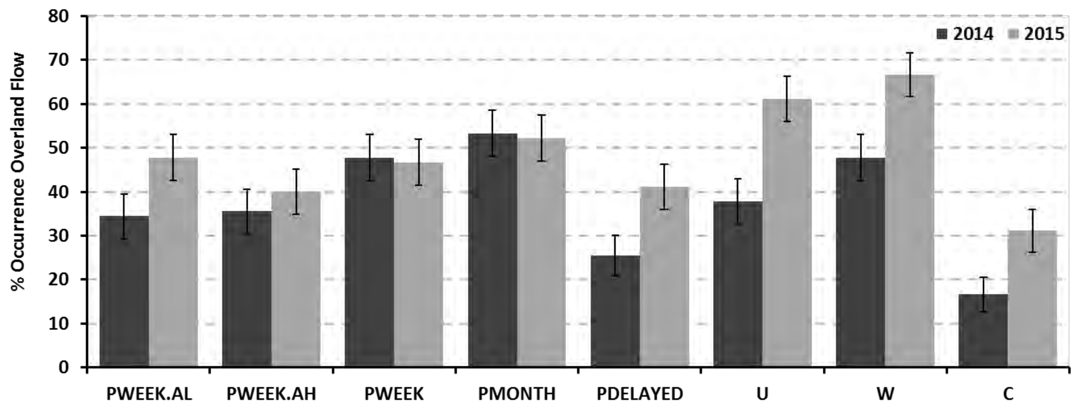

Figure 6.24 Comparison of occurrence of overland flow in 2014 and 2015 (September to November) for each treatment. Error bars show ± standard deviation.

6.4 Discussion

This study is the first to examine the impacts of unsurfaced tracks, plastic mesh tracks for low-ground pressure vehicles and articulated wooden tracking for 4x4 vehicles, on blanket peatland water-table depth and overland flow occurrence. The research tested the following hypotheses: (i) there will be evidence of a change over time in the water-table depth, (ii) there will be evidence of the water table becoming shallower upslope of the track and deeper downslope, (iii) there will be an increase in the occurrence of overland flow resulting from the track, and (iv) there will be evidence of spatial variation in the extent of track impact on blanket peat hydrology extending beyond the immediate footprint of the track. In addition to each of these questions I also wanted to ascertain: (i) the influence of track type, (ii) the influence of frequency of use, and (iii) the influence of topographic location, on the magnitude of impact.

6.4.1 Water Table

In general, the water table was shallow across all of the treatments, comparable with that of undisturbed blanket peatland reported elsewhere at Moor House (Evans et al., 1999). Median water-table depth was comparable between all treatments over the monitoring period ranging from 6.4 cm to 8.5 cm below the surface (Table 6.2). The water table was found to be slightly deeper in the control treatment, unlike other studies where the water table is usually shallowest in the undisturbed location (Daniels et al., 2008, Holden et al., 2011). This study was monitoring the immediate response of the water table to disturbance, where as other studies often compared the response of disturbed locations after a number of years (e.g. Holden et al., 2011) and therefore may explain some of the differences. In addition, dense *Calluna vulgaris* cover was found in treatment **C** which may have had an influence on water-table depth, such an effect was observed by Worrall et al. (2007a). Water-table data suggested a topographic gradient independent of treatment, S1 > S2 > S3, with S3 (bottom-slope) having the shallowest water table, in line with the findings of Holden and Burt (2003c)

For the plastic mesh track a gradient in the magnitude of impact was expected with the greatest impact in the most frequently used treatment (**PWEEK.AH**) and the lowest impact in the least frequently used treatment (**PMONTH**), with a possible order of **PWEEK.AH** > **PWEEK.AL** > **PWEEK** > **PDELAYED** > **PMONTH**. Treatment **W** also had intensive use (520 passes in total) and would therefore have a magnitude of impact similar to that of **PWEEK.AH**, whilst treatment **U** would potentially sit closer to **PWEEK** and **PDELAYED**. Although it had the lowest frequency of use (only 24 passes in total), the lack of track, and therefore protection to the peat, could have resulted in greater impacts being observed. Comparison of descriptive statistics did not exhibit such a pattern however at the side scale (Table 6.2). These results suggest that within the first 18 months of use, the track had not had a discernible impact on water-table depth.

6.4.1.1 Change Over Time

Significant differences were recorded in the mean daily water-table depth at topographic location S3 in treatments **PWEEK.AH** and **PMONTH** in spring, summer and autumn (2014 vs 2015), suggesting that a change over time had occurred (Table 6.4). There was little evidence of a clear pattern or trend in the significant differences with respect to treatment (**PWEEK.AH** or **PMONTH**) or the location of the dipwell in relation to the track, however. For example, while **PWEEK.AH *x* 1 m Upslope** exhibited a significant deepening of the water table across all three seasons, **PWEEK.AH *x* 0.2 m Upslope** only exhibited a significant deepening of the water table between spring 2014 and 2015. In the **PMONTH** treatment dipwells 1 m and 0.2 m upslope of the plastic mesh track showed the water table becoming significantly shallower between spring 2014 and 2015 but significantly deeper between autumn 2014 and 2015. A significant difference was also observed between two of the control dipwells between spring 2014 and 2015. Consequently hypothesis (i) was rejected as there was no clear consensus in the data of a change over time. In addition, the significant difference in the control suggests that changes may not be solely related to the presence of the track.

In the latter half of the monitoring period, one location, **PWEEK.AH *x* TRACK**, showed the water table becoming slightly shallower, i.e. the residual between the treatment and the control water-table depth became larger (it was not possible to test this observation statistically). It was interesting that this result was found in the most frequently used treatment (**PWEEK.AH**) and in the middle of the track where the greatest impact was expected (Figure 6.14). As this was one dipwell, however, it can only be stated that there was a suggestion of the track beginning to have an impact on water-table depth. Further work is needed to determine whether a shallower water table directly under the plastic mesh track was the result of a change in the dominant controls on the water table (evapotranspiration, free drainage) or due to compression of the peat. In the instance of peat compression, the water table would theoretically stay at the same relative height in the landscape and instead the peat surface would lower (e.g. Price and Schlotzhauer, 1999). Shallow water tables, however, are seen as a positive to peatland functioning, therefore it would be important to understand what other factors were being impacted to determine whether this effect of the track is positive or negative in a wider context.

6.4.1.2 Upslope-Downslope Gradient

Studies of linear disturbances (including roads) in Canadian boreal forest, fen and permafrost peatlands have shown alterations to flow pathways and consequently water-table depth around the roads, with shallower water tables upslope and deeper water tables downslope (e.g. Lieffers and Rothwell, 1987, Turchenek, 1990, Quinton et al., 2009, Moore et al., 2013, Williams et al., 2013, Bocking, 2015). The roads considered in these studies are constructed from stone and aggregate and the change in flow pathway is often the result of a reduction in permeability of the peat under the road as well as the creation of a barrier to surface flow. Such an effect has been visually observed around aggregate constructed roads over peatlands in the UK (Lindsay, 2007), however the scale of the effect is unknown.

At topographic locations S1 and S2, the plastic mesh and unsurfaced tracks were roughly on the flat or perpendicular to the contours (similar to installation on working estates) and therefore, in response to hypothesis (ii), evidence of an upslope-downslope effect on the water-table depth could not be tested. Statistical analysis did exhibit no significant difference in distance-weighted water table depth between the right and left sides of the plastic mesh and unsurfaced tracks however at either topographic location (Table 6.5). At topographic location S3, the track route was designed and installed in such a way that the track cut across the flow paths, i.e. was roughly parallel or diagonal to the contours (see Figure 3.7). Consequently at topographic location S3, hypothesis (ii) could be addressed using both the automated and manually collected water-table data.

Comparison of distance-weighted upslope versus downslope data (up to 10 m from the track edge) yielded significant differences at topographic location S3 in three driven treatments (**PWEEK.AL**, **PWEEK**, and **U**) and the control, where no track was present or driving occurred. Of these treatments **PWEEK** was only the only treatment to have significantly shallower water-table depths on the upslope side relative to the downslope side. Treatments **PWEEK.AL, U**, and **C** all had significantly deeper water table upslope and shallower water-table downslope.

Figure 6.21b suggests that upslope-downslope effect observed in treatment **PWEEK** was more obvious when the water table was shallower (spring 2014, 2015; autumn 2014); in summer 2014 when the water table was at its deepest in all treatments the upslope-downslope effect was not as clear. This could therefore suggest that the track has not had an impact on water table dynamics when the water table is deep, and that any impacts would be observed when the water table was in the top 10 cm of the peat. As the majority of flow is found within the top 10 cm of blanket peat (Holden and Burt, 2003c), it therefore suggests that any effect of the track to the hydrology would be predominantly focused within the surface peat. As the spatial pattern was consistent throughout the monitoring period it suggests that the effect could be the result of track installation.

The evidence from treatment **PWEEK** (two passes per week, 156 in total) supports hypothesis (ii), in that the presence and use of the track resulted in a shallower upslope-deeper downslope gradient for water-table depth, and could therefore be accepted. However, it would be prudent to consider the contradictory evidence from other treatments **PWEEK.AL** (which experienced a higher frequency of use) and **U,** and the lack of significant results from treatments **PWEEK.AH**, **PMONTH**, **PDELAYED** and **W**. As treatment **PWEEK** is the only treatment to exhibit such an effect at topographic location S3, hypothesis (ii) should be rejected overall. This conclusion is further supported by the lack of noticeable patterns of change in the mean daily water table at 1 m and 0.2 m upslope and downslope of the plastic mesh track in **PWEEK.AH** and **PMONTH** at topographic location S3. The general pattern in water-table depth variation between the different locations remained constant throughout the monitoring period, i.e. in **PMONTH**, 1m upslope was consistently shallower than 0.2 m upslope.

6.4.1.3 Spatial Effect on Water Table

Descriptive statistics (median water-table depth) exhibited spatial variation at individual distances from the track edge for all three track types (plastic mesh, articulated wooden, and unsurfaced), for all frequencies of use and at all topographic locations (Tables 6.7 and 6.8). Statistical analysis of water-table depth at comparative distances upslope and downslope for all treatments at topographic location S3 only exhibited statistically significant differences above -0.5 m distance from the track edge (Table 6.9). By treatment (track type and frequency of use), statistically significant differences were observed from 0.2 m onwards for treatment **PWEEK** and 1 m onwards for treatment **U**. The rest of the treatments only exhibited significant differences at specific distances, **PWEEK.AL** (0.5 m and 10 m), **PWEEK.AH** (0.5 m, 1 m and 10 m), **PMONTH** (1m and 10 m), **PDELAYED** (10 m) and **W** (2 m and 10m). In addition, the control treatment **(C)** exhibited statistically significant differences at 1 m and 5 m from the assumed 'track' edge. It is perhaps not surprising that sampling locations closer together were similar (i.e. within 0.2 m of the track edge). With the exception of treatment **PWEEK**, there was no clear evidence of the water-table being shallower upslope relative to the downslope at a specific distances (evidenced in Table 6.8). The consistency in the results from treatment **PWEEK** would suggest that there is potential for spatial impacts from the tracks. As this is only based on one treatment at one topographic location, however, caution should be taken in the interpretation of these results in relation to the spatial impact of plastic tracks. Rather, from the results yielded, it is difficult to differentiate between spatial impacts from the tracks and natural variation in the water-table depth (as shown in the control treatment data).

Graphical analysis of the seasonal average water-table depth by treatment (track type and frequency of use) *x* topographic location found slightly more variability between seasons in water-table closer to the track edge compared with further away, this alone would suggest that any track impact was limited to within ~1m of the track edge, for all track types. In general it was found that between seasons areas of shallow water table remained shallow and deeper water table remained deep, further suggesting that the variation observed through statistical analysis was the related to natural spatial variation in water-table depth. The pattern of water-table depth around the track in the different treatments did not obviously change when compared by season, especially with increasing distance from the track (Figures 6.21a-d).

At **PWEEK.AH** *x* **S3** and **PMONTH** *x* **S3** an extended transect was installed, with dipwells installed up to 50 m from the track edge (data not shown). At these distances there was no clear effect of the track on the water table. The results from this study are supported by Bradof (1992) who did not observe an impact of Highway 72 on water-table depth across Minnesota peatlands beyond 10 m from the track edge. However, this contradicts suggestions from other sources e.g. Lindsay (2007), that impacts could be observed up to 250 m from the track edge. These claims had not been measured however. The spatial variation found in water-table depth can be attributed to vegetation and microtopographic controls (Strack et al., 2006). Consequently hypothesis (iv) can only be partially accepted with respect to impacts to water-table depth, in that there is some evidence of a spatial effect around the track which is concentrated in the immediate vicinity ~1m from the edge of all track types at all topographic locations. Natural spatial variability in water-table depth may be masking the full extent of impacts at distances beyond 1m from the track edge measured at topographic location S3.

6.4.1.4 Influence of Frequency of Use

The expected gradient of difference between frequencies of use for the plastic mesh treatments especially, did not manifest itself in the median water table values. For example, data from directly the mid-track sampling location did not match the expected pattern of **PWEEK.AH** > **PWEEK.AL** > **PWEEK** > **PDELAYED** > **PMONTH** at any topographic location, indeed no significant difference was observed between the mid-track water table depth in the different treatments (track type and frequency of use) at topographic locations S2 and S3 (Figure 6.20a-c).

The monthly interquartile range for mean daily water table was found to generally be larger in **PWEEK.AH** and **PMONTH** when compared with the control treatment (**C**) (Figures 6.17-6.19), such an effect was also found in drained peatlands (Wilson et al., 2010), and suggests that the presence of the track is having some degree of effect on the water table behaviour. Holden et al. (2011) also observed a seasonal effect in variation in interquartile range in undisturbed peat, with a peak in late spring/summer due to evapotranspiration controlling water-table drawdown into deeper peat layers and then rapid water table recovery in response to summer rainfall events. Holden et al. (2011) showed that nearby drained peat had greater water-table variation but did not follow the same seasonal pattern as the undisturbed peat. In my study, a peak was observed in interquartile range in all three treatments in late spring/summer 2014; however the peak was not as evident for the same period in 2015. It should be noted that 2015 showed less variation in water-table depth and more consistently shallow water tables i.e. within the top 10 cm, which may therefore explain some of differences between years. The 'disturbed' treatments in this study,

PWEEK.AH (412 passes in total) and **PMONTH** (38 passes in total), still showed evidence of seasonality, with lower interquartile ranges in the winter months. Therefore suggesting that the response of the water table in the disturbed treatment still followed the same pattern as in the undisturbed treatment, hence the presence of the plastic mesh track and the different frequencies of use were not having a noticeable effect at topographic location S3.

Depth duration curves for mean daily water table showed the percent time the water table was above a certain depth for each automated dipwell in treatments **PWEEK.AH**, **PMONTH** and **C,** at topographic location S3. A steeper curve is indicative of large and more regular water-table fluctuation (Holden et al., 2011). Such curve shapes were observed for **PMONTH** *x* **1 m upslope** (Figure 6.7), **PWEEK.AH** *x* **0.2 m upslope** (Figure 6.8), and **PWEEK.AH** *x* **0.2 m downslope** (Figure 6.10) with the large water-table fluctuation at these locations highlighted in the respective time series plots (Figures 6.12, 6.13, and 6.15). As this was observed at different distances from the track edge and also in different treatments it is not clear whether this was evidence of track impact or just natural variation in water-table behaviour. Depth duration curves for the treatment **C** dipwells (Control I, Control II and Control III) were shallower and suggested that although there was still fluctuation in the water-table depth it was not as large as the dipwells with steeper duration curves. All treatment dipwell curves were plotted against the same control (Control I). Dipwells which shared a similar S-shaped curve with Control I, and therefore each other, included: **PWEEK.AH** *x* **1 m upslope** (Figure 6.7), **PMONTH** *x* **0.2 m downslope** (Figure 6.10), **PMONTH** *x* **1 m downslope (**Figure 6.11). **PWEEK.AH** *x* **TRACK** and **PMONTH** *x* **TRACK** were the only locations to have a markedly different shape to the curve. The shape of these curves can be attributed to the longer time periods the water table spent above the surface at these locations. This suggests that the behaviour of the water table was different at the mid- track location for the plastic mesh track and can be seen as an indication of a potential plastic mesh track effect, however there was no clear influence of frequency of use of the plastic mesh track influencing the shape of the curve at the different distances from the edge at topographic location S3.

6.4.1.5 Influence of Track Type

In contrast to expectations, the plastic mesh, articulated wooden and unsurfaced tracks at Moor House did not have a clear and consistent effect on water tables. Track type may have been an influential factor, and three aspects relating to track type: the material, construction method and time since installation will be discussed further here. Firstly, the track type/ material. In the case of existing Canadian and UK studies, the tracks were made from aggregate and suitable for transporting heavy vehicles such as tankers. In those instances the track alone exerted pressure on the peat resulting in compaction, even before the vehicles used it (Figure 6.1). Of the few studies measuring impacts under constructed tracks, Pilon (2015) recorded a reduction in under track hydraulic conductivity. In my study, however, low-ground-pressure vehicles were used in conjunction with the light weight plastic mesh which exerts little pressure on the peat surface. Even the heavier articulated wooden track would not exert as much pressure (see Table 3.2 for further details) as an aggregate track and the heaviest vehicle travelling over it was a 4x4. As less pressure was exerted on the peat from the track material, there was less chance for initial primary and secondary compression of the peat (Barden, 1968). It is the peat compaction which results in the change in peat structure and reduction in peat permeability in many cases (Chow et al., 1992). It should also be noted that aggregate tracks tend to be wider than the tracks studied at Moor House. Pilon (2015) studied a track 20 m wide, by comparison the tracks used in my study were 2.5-3 m wide, a tenth of the width.

Secondly, the method of construction could also be influential to flow pathways. For the installation of the plastic mesh and the wooden track in this study, the surface vegetation was removed and the track installed on the surface. In the case of the unmade track, nothing was done to the route prior to driving commencing. The installation of the track did not actively disturb the peat mass, as is the case with cut and fill roads. With cut and fill roads, the peat is removed, often to the mineral layer and back filled with aggregate (Munro, 2004) (further detail is provided in Chapter 1). The permeability of the back fill would influence how much water was able to move from the upslope to the downslope side of the track (Chimner et al., 2016). Floating roads, use another construction method, and are intended not to be destructive during construction as they are installed on the peat surface (Munro, 2004). As previously mentioned, the loading of the peat with aggregate leads to primary and secondary peat compression (Berry and Poskitt, 1972, Berry, 1983, Barry et al., 1992), which in turn reduces pore size and results in a change in peat structure (Chapter 5) and consequently could reduce the permeability of the peat. Hence, under the track this would create a zone of slower sub-surface flow and reduce delivery of water from one side of the track to the other (Figure 6.1).

Whereas with constructed aggregate tracks and roads the material and construction method placed pressure on the peat, this effect could be seen as minimal for the installation of plastic mesh and articulated wooden tracks. Therefore the real pressure for these track types comes from the intensity of driving over them; with respect to impacts to water-table depth I have found this to be a minimal effect. I also found that the presence of the track did not necessarily result in increased bulk density directly under the track or decrease in surface hydraulic conductivity (Chapter 5). This would suggest that movement of water was still possible under the track, and therefore delivery from the upslope to the downslope side was not impeded, as measured at topographic location S3 only. In the case of lateral sub-surface flow, horizontal hydraulic conductivity was found to increase following driving in some locations. The observed barrier to sub-surface water flow found under aggregate roads does not appear to exist here.

Construction method effects on surface flow have been found to result in ponding of water, and in extreme cases flooding, on the upslope side of roads (Lieffers and Rothwell, 1987, Bocking, 2015). Constructed aggregate roads are often built up above the surface, sometimes by up to 1 m. This therefore creates a barrier to the movement of water over the peat surface (the reader is referred to Figure 6.1). The plastic mesh, articulated wooden and unsurfaced tracks in this study could not have such effect. The plastic mesh was approximately 1 cm deep and, due to the uneven nature of the peat surface, was not in contact with the peat surface in all locations, this permitted space for movement of surface water under the track. The presence of holes in the plastic mesh would also allow water movement; it was not an impermeable barrier. Although the articulated wooden track was deeper (approximately 20 cm), the beams used to create the tracking had gaps between them meaning, theoretically, water would be able to flow between them and, unlike aggregate roads an impermeable barrier was not created.

Rather than creating barriers to surface flow however, the plastic mesh and unmade tracks used in this study had the potential to redirect water flowing from the upslope along the track route (the reader is referred to Figure 6.2). This was as a result of depression of the peat surface following driving (Chapter 5), so that immediately downslope of the track less surface water is received comparative to the upslope. Redirection of flow was observed at the Moor House site, predominantly at topographic location S3 (Figure 6.25), although monitoring has not clearly captured the impact of such an effect on water-table depth. Linking back to the change over time of the water table and spatial effects, there is currently little evidence to support this observation in the data.

Figure 6.25 Evidence of channelization and redirection of overland flow along track at experiment site.

Finally, time since installation may explain the difference between the magnitude of effects observed in existing studies and the minimal impacts to water-table depth observed here. In most existing studies, the tracks have been in place for a number of years, in the Canadian examples they range from 20 years (Bocking, 2015) to 50 years (Moore et al., 2015). A time since installation effect was also observed in the wider survey undertaken as part of this project (Chapter 4), with lower soil moisture content around older tracks. At the start of monitoring the constructed tracks on Moor House had been in place for eight full months (plastic mesh) and six full months (articulated wooden), by the end of the monitoring period they had been installed for 26 months (plastic mesh) and 24 months (articulated wooden) and experienced 18 months of driving. The unsurfaced track experienced just over one year of driving. Prolonged use of the plastic mesh, articulated wooden and unsurfaced tracks may result in more discernible impacts between the different treatments. Currently, it appears that the most important influence on water-table depth is topographic location independent of treatment.

6.4.2 Overland Flow

It was hypothesised that there would be an increase in the occurrence of overland flow resulting from the track (hypothesis iii). Within this hypothesis the potential influence of track type, frequency of use and topographic location on overland flow frequency were also considered. Visual observations of the occurrence of overland flow were found at various points along the track route, predominantly in bottom-slope locations (topographic location S3) for the plastic mesh and unsurfaced tracks. Here, there was clear evidence of water ponding along the track route in the ‘wheel-ruts’ and where there was a slight incline down the track there would be flow of the water. This was especially evident in treatments **PWEEK.AL**, **PWEEK.AH** and **PWEEK**. In some of these cases flow was being directed off track (see Figure 6.25).

In undisturbed blanket peatlands the generation of saturation-excess overland flow typically occurs when the water table is at or near the peat surface (Evans et al., 1999, Holden and Burt, 2003c). Across the whole site in this study, overland flow occurrence exhibited a topographic gradient, with the lowest occurrence of overland flow at topographic location S1 and the highest occurrence at topographic location S3, the percent of overland flow occurrence at location S2 was in between these. This pattern links with the topographic gradient observed in water-table depth where the deepest median water table was recorded at location S1 and the shallowest at location S3. In both cases these gradients were independent of treatment (frequency of use and track type) and sampling location in relation to the track. This result would suggest that at the site scale the presence of the plastic mesh, articulated wooden and unsurfaced tracks had minimal impact on the occurrence of overland flow.

Studies based on non-peat soils have suggested that a decrease in permeability following compaction of the soil may have led to increased generation of infiltration-excess overland flow (e.g. Ziegler and Giambelluca, 1997, Ziegler et al., 2001). A linear relationship was expected between the occurrence of overland flow and the frequency of use of the track due to a higher number of passes increasing the chance of compaction and reducing surface peat permeability. The results show, however, that the least frequently used treatment (**PMONTH**) had the highest occurrence of overland flow. In addition the changes to peat permeability have not been as expected (Chapter 5). Potential links between overland flow occurrence and changes in permeability will be considered further in Chapter 8. However, it is assumed that the overland flow captured in this study remains saturation-excess overland flow as opposed to infiltration-excess overland flow. Further work would be prudent to measure the chemical composition of the runoff water to determine if there was a change in overland flow type.

Treatment **C** was found to have the lowest occurrence of overland flow overall, although it did vary between topographic locations. Treatment **C** also exhibited some of the deepest median water-table depths. Especially at topographic locations S1 and S2, in relation to the other treatments, consequently this may have influenced the lower occurrence of overland flow in treatment **C**.

Relative to treatment **C** there was evidence that the presence of a track, irrespective of frequency of use, track type or topographic locations, had resulted in a higher occurrence of overflow. Caution should be taken when interpreting this result, however, given the spatial variation in overland flow occurrence and the deep water tables found in the control treatment. In addition to this, comparison of the occurrence of overland flow for the same periods (April to June and September to November) in 2014 and 2015 yielded different results in different treatments depending on the time of year, and only driven treatments **U** and **PDELAYED** (all topographic locations) exhibited statistically significant differences for the April to June (**U**) and September to November (**U** and **PDELAYED**) periods. Furthermore, the increase in the occurrence of overland flow in the control treatment (statistically significant for the September to November period), could lead to the suggestion that antecedent conditions were more important than the effect of the three track types or frequency of use. Had there not been a change in overland flow occurrence in the control it could have been suggested that the plastic mesh and unsurfaced tracks had an effect, and the effect was changing over time. No such effect occurred for the articulated wooden track given the lack of significant differences.

In their study of human trampled tracks on blanket peat, Robroek et al. (2010) found that the lowest occurrence of overland flow was along the control track because it was more vegetated. Such an effect was also observed in relation to the removal of vegetation following burning on blanket peat (Clay et al., 2009). It could therefore be suggested that the difference in the occurrence of overland flow in treatment **C** relative to the driven treatments could be related to change in vegetation cover following track installation. Links exist between the water balance of peatlands and vegetation cover, however there are two different outcomes which could occur: (i) the removal of vegetation cover would lead to reduced evapotranspiration and therefore a shallow water table, or (ii) the removal of vegetation would lead to an exposed peat surface which could get warmer leading to higher evapotranspiration and therefore a deeper water table (Holden, 2006). Potential links between vegetation cover and overland flow occurrence will be addressed further in Chapter 8.

The occurrence of overland flow was higher under and around the three track types compared with treatment **C**, therefore hypothesis (iii) could be accepted that there was an increase in overland flow in relation to the track. However, the occurrence of overland flow can be influenced by a number of factors including; water-table depth, near-surface permeability and vegetation cover. Water-table depth was found to be generally deeper in the control relative to the other treatments; however, there was also variation in the water-table depth between treatments. In addition, water-table depth did not show evidence of a change over time. This suggests that the location of the different treatments on the peatland and the antecedent water table conditions have more of an influence on the occurrence of overland flow than the presence of the plastic mesh, articulated wooden or unsurfaced track.

Statistical analysis of the occurrence of overland flow with sampling location across the three tracks combined did yield a significant difference at each topographic position. At this breakdown of the data the occurrence of overland flow was found to be higher in the centre and immediately off-track (within 0.2 m) at topographic locations S2 and S3 further supporting the visual observation (Figure 6.25). However, when the overland flow data was broken down by treatment *x* topographic location *x* sampling location (in relation to the track) (Table 6.13 and 6.14). This yielded few clear patterns in overland flow occurrence, thereby suggesting that local conditions e.g. microtopography and water-table depth were more of a contributing factor than track type or frequency of use. The topographic effect i.e. higher occurrence at topographic location S3 did hold true here however at this break down of the data, further supporting the idea that local conditions are important.

6.5 Chapter Summary

- This study is the first of its kind to monitor water-table depth and overland flow occurrence around plastic mesh, articulated wooden and unsurfaced tracks in peatlands over a wide spatial scale and extended time period, i.e. longer than the 3-4 month summer season found in many existing studies.

- Topography influences water-table depth and overland flow occurrence at the site scale independent from track type or frequency of use.
- Track orientation to the slope contour (particularly for the plastic mesh track) is influenced by topographic position, and in turn influenced how spatial patterns could be measured. An upslope-downslope effect could only be investigated at topographic location S3.
- There is no clear pattern in the magnitude of impact to water-table depth or overland flow occurrence with track type (plastic mesh, articulated wooden or unsurfaced) or frequency of use. A plastic mesh track treatment with a medium frequency of use (**PWEEK**) was the only one to show possible evidence of an effect of the track on water-table depth.
- Spatial patterns in water-table depth suggest that any impact of the three track types is most likely observed directly under the track (with particular reference to treatment **U** at topographic location S3) and within ~1 m of the track edge.
- Mean daily water-table depth showed evidence of change over time around the plastic mesh tracks under two different frequencies of use. There was no consistent pattern in the direction of change between months however.
- The expected upslope-downslope effect often referenced in relation to track impacts has only been observed for the plastic mesh track treatment with a medium frequency of use (**PWEEK**) at topographic location S3.
- Overland flow occurrence was different between driven treatments and the control. However, other factors are likely to be influential in the cause of this result, e.g. water-table depth and microtopography.
- In comparison with existing track studies, where the track was installed for a greater time period, it is likely that the time since installation could have had an influence on the minimal impacts observed.
- The variation in observed impacts can be related more to the location of specific track sections in the peatland.
- In relation to wider peatland functioning the water table has remained relatively shallow, there is evidence of overland flow occurrence and the spatial impacts are within short distance of the track. Initial effects of plastic mesh, articulated wooden and unsurfaced tracks do not appear to cause major alterations to the system with respect to water-table and overland flow properties. However, further work is needed to determine the longer-term trajectory of the system after prolonged track use.

CHAPTER 7: VEGETATION CHANGE IN RESPONSE TO PLASTIC MESH, ARTICULATED WOODEN, AND UNSURFACED TRACK USE ON BLANKET PEATLAND

7.1 Introduction

Vegetation is central to the development and functioning of peatlands. Vegetation composition varies within and between different peatland types, e.g. fen, blanket peat and raised bogs, usually in relation to the different environmental conditions found within them (Vitt, 2000). Influential environmental factors for vegetation composition include pH, C/N ratio, chemistry, water-table depth, water-table variation, peat depth and slope (Malmer, 1986, Cooper et al., 1997, Bubier et al., 2006, Sottocornola et al., 2008, Breeuwer et al., 2009, Andersen et al., 2011). Water-table depth has been found to be the primary influence on vegetation distribution in blanket peatlands (Cooper et al., 1997, Sottocornola et al., 2008). The relationship between these conditions is not one-way however, and multiple feedbacks exist within peatland systems. A conceptual arrangement is shown in Figure 7.1.

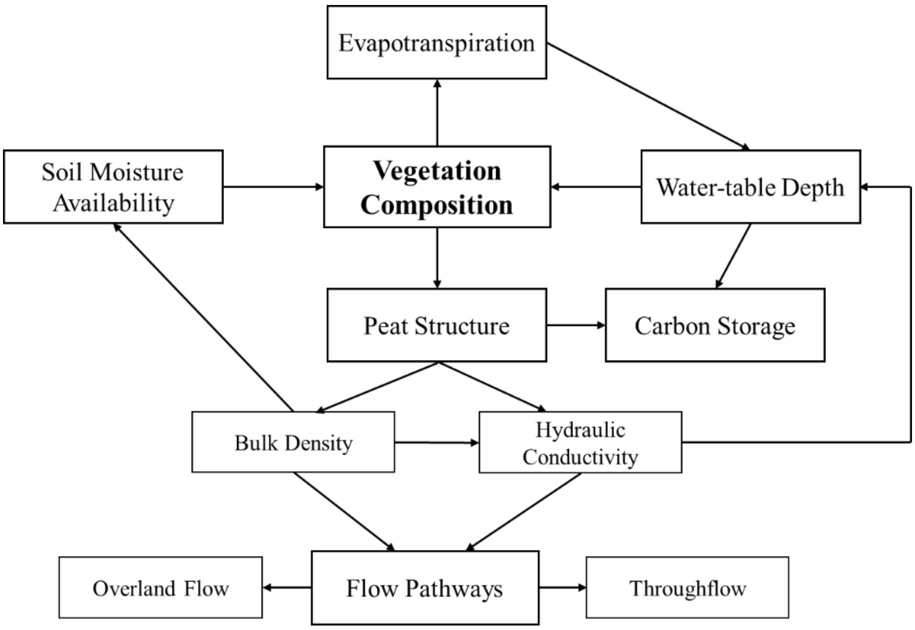

Figure 7.1 Conceptual diagram of the feedbacks which exist within peatland environments between vegetation composition and other aspects of peatland functioning.

Vegetation composition is not only influenced by the hydrology of peatlands but can also exert an influence on peatland hydrology through controlling the structure of peat during formation (Boelter, 1969). Furthermore, evapotranspiration, influenced by the vegetation, can govern the depth to the water table (Evans et al., 1999). Strong links exist between the role of peatlands as carbon stores and vegetation, directly and indirectly. Numerous studies have shown that vegetation type can exert controls on CO_2 and CH_4 fluxes (Bubier, 1995, Laine et al., 2007), and DOC production (Armstrong et al., 2012, Parry et al., 2015, Dunn et al., 2016). It has also been found that changes to vegetation composition can alter the size of carbon fluxes, with the potential to turn sinks into sources and vice-versa (Belyea and Malmer, 2004, Strack et al., 2006, Strack and Waddington, 2007).

Anthropogenic disturbances to peatlands are as influential on vegetation composition as abiotic factors and natural gradients (Lachance et al., 2004). It is therefore important to understand how anthropogenic disturbances to peatland environments can alter vegetation composition and consequently the complex feedbacks which exist. Disturbances such as grazing can result in vegetation changes in two ways: (i) through the selective removal of palatable species allowing others to grow back more abundantly (Smith et al., 2003, Groome and Shaw, 2015), and (ii) through trampling and associated changes in peat structure. Trampling (both through grazing and by humans) can result in a change in vegetation composition because of a change in water availability through reduced pore space and increased water stress (Price, 1997). In addition, the action of trampling can remove the surface vegetation cover and increase the occurrence of bare peat (Arnesen, 1999, Worrall et al., 2007a, Robroek et al., 2010). Drainage in peatlands has also resulted in a shift in species composition, with species preferring 'drier' conditions (e.g. *Rubeus chamaemorus*) observed immediately around the drains, in the area where water-table drawdown has occurred (Stewart and Lance, 1991, Wilson et al., 2011b).

The construction of tracks or their creation through off-road vehicle use on peatlands around the world is extensive. While measurements of vegetation change are more common than those of other peatland properties such as hydrology (Chapter 6), our understanding is still limited. Where unsurfaced tracks have been created, surveying typically occurs directly along the track route, using off-track locations as controls. Studies on organic soils, shallow peat and permafrost peatlands commonly show a loss of vegetation cover or a change in vegetation composition, with grasses and sedges often the first to grow back after disturbance (Sparrow et al., 1978, Abele et al., 1984, Kevan et al., 1995, Thurow et al., 1995, Hirst et al., 2003, Pickering et al., 2011). A greater loss of vegetation cover has also been found to occur with an increasing number of vehicle passes on both non-peat soils and peat (e.g. Kevan et al., 1995, Thurow et al., 1995, Hirst et al., 2003). In addition, differences in the magnitude of impact have been observed depending on whether the track was on flat or sloping ground, although no studies have reported findings from a sloping deep peat environment.

The impact of constructed roads on vegetation is typically associated with spatial impacts. At the large scale, roads across peatlands have been found to result in habitat fragmentation (Trombulak and Frissell, 2000) as they create a disjuncture across the peatland (Lindsay, 2007), and have the potential to reduce connectivity between the two sides of the track and introduce edge effects. The effects of chemical pollution from cars has been observed around a main arterial road crossing heathland in the New Forest, UK, with a decrease in *Calluna vulgaris* abundance (Angold, 1997). In this heathland study, edge effects were observed up to 200 m away.

Linear disturbances in Canadian boreal forested peatlands have caused tree dieback due to water impoundment upslope of roads and an increase in tree growth rate under drier conditions downslope of the road (Lieffers and Rothwell, 1987). In addition, Bocking (2015) observed an increase in hummock forming species with distance from the road on the upslope side, as conditions were wetter closer to the track and favoured by lawn forming species e.g. *Calamgrostis canadensis, Sphagnum squarrosum* and *Carex rostra*.

Within the UK the use of vehicles and creation of tracks in blanket peatlands is extensive. Until recently, vehicle tracks in these environments have been one of two main types: (i) constructed stone tracks or (ii) unsurfaced tracks where vehicles drive directly over the vegetation. Understanding of the impacts to vegetation in blanket peatlands is severely limited and often does not extend beyond the visual evidence of wheel ruts (Figure 7.2). To the author's knowledge there is no scientific literature set in blanket peatlands exploring the impacts of constructed tracks on vegetation. Charman and Pollard (1995) investigated the impact of military vehicle manoeuvres on vegetation composition, up to 24 years after their formation on blanket peat (as well as other soil types). They found that on-track vegetation recovery was very slow when compared with undisturbed off-track surveying locations. In addition, a shift from blanket peatland species to more heathland type species was observed along the military vehicle routes.

Figure 7.2 Evidence of snow lying in 'wheel ruts' of compressed vegetation following passage of a vehicle over unsurfaced blanket peat.

While the study of Charman and Pollard (1995) investigated the use of heavy military vehicles on unsurfaced tracks, there is widespread use of low-ground-pressure vehicles on UK peatlands, which also leads to the creation of unsurfaced tracks. Currently the effect of these vehicles on vegetation composition is also unknown in blanket peatland environments, beyond visual observations. In conjunction with the use of low-ground pressure-vehicles plastic mesh tracks are being trialled in moorland environments. The idea behind the plastic mesh is that it reinforces the peat surface and the holes in the plastic mesh permit the regrowth of vegetation which then helps to bind the track into place (further detail is provided in Chapter 3). Permitting the regrowth of vegetation through the track has potential positive benefits for the role of vegetation in carbon capture and storage in blanket peatland environments (Dunn et al., 2016) as new growth encourages the uptake of CO_2. In addition, new growth has the potential to buffer the effects of compaction caused by driving over the highly compressible peat and also to limit erosion of peat which is commonly associated with wheel rut formation along unsurfaced tracks (Arp and Simmons, 2012). A prototype articulated wooden track has also been developed for use with heavier vehicles such as 4x4s. Although more heavy duty than the plastic mesh, this type of tracking also works on the principle that vegetation is able to regrow through the gaps in the tracking. At present the impact of both plastic mesh and articulated wooden tracks on vegetation composition is unknown.

The aim of this study was to investigate the impact of three different track types (plastic mesh, articulated wooden and unsurfaced) on vegetation characteristics (composition and height) in a blanket peatland. To examine the impacts, two approaches were used: (i) a comparison of before and after surveys (all track types) and (ii) regular surveying with ongoing track use (unsurfaced track only). Greater impacts to vegetation cover and higher bare peat occurrence have been observed with a higher number of passes over tracks on non-peat soils. It was therefore important to consider the effect of track frequency of use in this study. In addition, it has been observed that impacts to vegetation can vary depending on whether the track is on flat or sloping ground. Blanket peatlands are unique compared to other peatland types in that they cover both flatter areas and steeper slopes, and these areas exhibit different wetness conditions and therefore vegetation composition. Some species may be more resistant than others and it was therefore important to address this with respect to both aims. Currently there are no published studies which take this into consideration.

The following hypotheses were tested: (i) vegetation change (composition and height) will vary with track type (plastic mesh, articulated wooden and unsurfaced) and frequency of use, with greatest impacts in the more frequently used treatments and lowest impacts in the least frequently used treatments; (ii) topographic location will influence vegetation change with drier mid-slopes showing less change than wetter bottom slopes; (iii) the occurrence of bare peat will be greatest in more frequently used treatments and lowest in least frequently used treatments; (iv) with an increasing number of passes over the unsurfaced track there will be a change in vegetation composition, a lowering in the height of the vegetation and an increase in the occurrence of bare peat, and (v) there will be evidence of greater impacts in the wheel routes compared with other locations across the track width.

7.2 Methodology

7.2.1 Vegetation Surveys

All vegetation surveys were designed and undertaken at Moor House NNR by Natural England staff and volunteers (for full site description see Chapter 3). According to NVC classification, Moor House is an M19 *Calluna vulgaris-Eriophorum vaginatum* dominated peatland (Averis et al., 2004). Key species found include *Calluna vulgaris*, *Eriophorum vaginatum*, *Sphagnum capillifolium*, *Cladonia* spp., *Empetrum nigrum*, *Hypnum jutlandicum*, *Plagiothecium undulatum* and *Pleurozium schreberi.* As described in Section 3.2.2, the vegetation was cut prior to track installation for treatments **PWEEK.AL**, **PWEEK.AH**, **PWEEK**, **PMONTH**, **PDELAYED,** and **W**. Vegetation surveys were undertaken for all driven treatments in May 2013 prior to track installation (where appropriate) and in May 2015 after 14 months of driving. No vegetation surveys were carried out in the control treatment. Extra vegetation surveys were undertaken in treatment **U** (unsurfaced track) after every driving event between April 2014 and May 2015. This approach was used to determine the level of impact of driving over the unsurfaced vegetation with an increasing number of passes. Vegetation surveys were undertaken at all three topographic locations (S1, S2, S3), with the exception of **PDELAYED** (S1 only) and **W** (S3 only).

There were three components to the vegetation surveys: (i) vegetation composition, (ii) vegetation height, and (iii) bare peat occurrence. Visual observations of vegetation change over the course of the monitoring period at Moor House were also recorded with photos regularly taken from the same locations along the track route on each visit. The surveys were undertaken by a representatives from Natural England and the same people may not always have surveyed the same sites. This therefore introduced error in the quantification of vegetation composition as some of the values recorded may be subjective.

7.2.1.1 Vegetation Composition

Vegetation composition was recorded from six 1 m^2 quadrats in each topographic location for each treatment. To locate the quadrats, a stake was positioned on the edge of the track at the start of each section (treatment *x* topographic location e.g. **PWEEK.AL** *x* **S1**). The first quadrat was then laid on the track route, 0.25 m in from the stake. The second quadrat was then laid in line with the first 0.25 m away. The next set of two quadrats were laid at a distance of 2 m from the first two and the final pair of quadrats 2 m away from the second set (Figure 7.3). Visual estimation of the percent cover of the different species was undertaken for each quadrat. Only living vegetation was included in the estimation. Vegetation cover was recorded as 0.5 %, where cover was greater than 0 but < 1 %. Vegetation cover was identified to species level in most cases with the exception of *Campylopus* spp., *Cladonia* spp., *Liverwort* spp. and *Lichen* spp. In addition, some *Sphagnum* species could not be identified to species level and were grouped as *Sphagnum* spp. (Natural England, *pers. Comm*.).

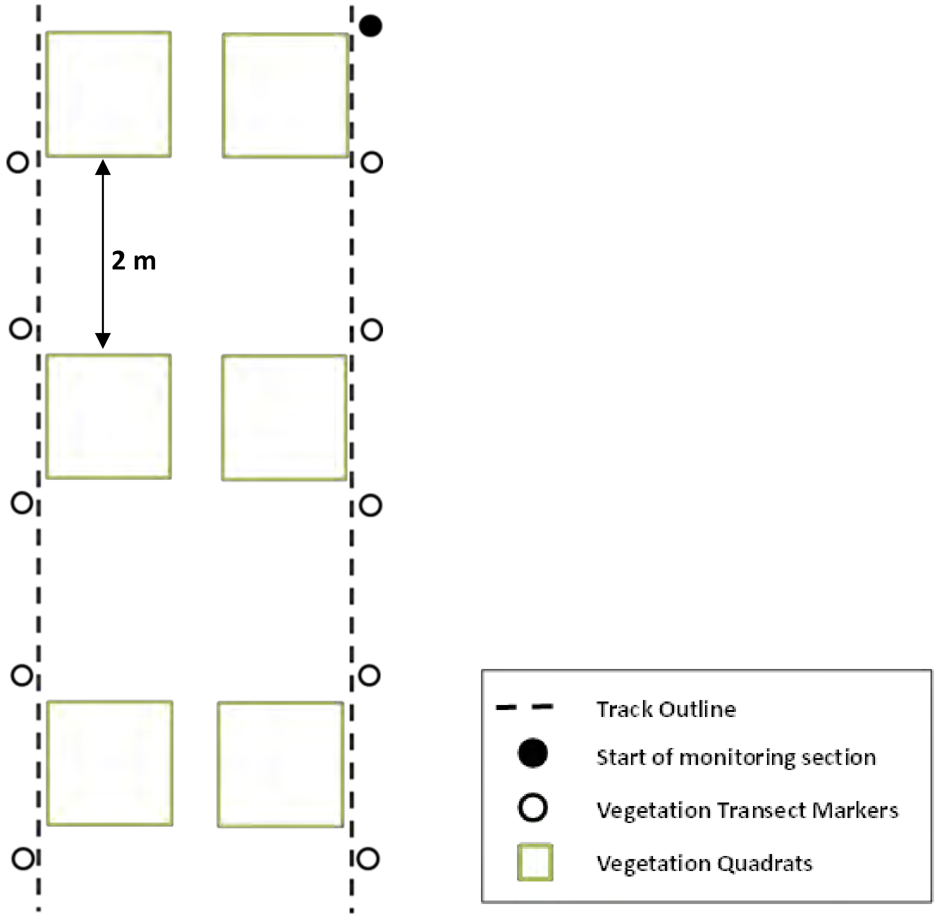

Figure 7.3 Schematic of the arrangement of vegetation composition survey quadrats and vegetation height transects within each treatment *x* topographic location.

7.2.1.2 Vegetation Height

Five transects were marked with stakes in each monitoring section (treatment *x* topographic location), the same as those used in the vegetation composition quadrat surveys (Figure 7.3). Vegetation height was recorded along each transect at 0.2 m intervals. Measurements were taken from the peat surface to the top of the vegetation using a sward stick, with height recorded in cm.

Average vegetation height from the five transects in each monitoring section was used in the analysis.

7.2.1.3 Occurrence of Bare Peat

Bare peat occurrence was measured using 50 cm^2 quadrats which were split into 100 5 x 5 cm grid squares. Five quadrats were surveyed across the track width, in line with the marked transects used for vegetation height measurements. The first quadrat was laid 0.25 m in from the transect stake and then subsequent quadrats were laid in line across the track width. In total there were twenty-five quadrats surveyed per treatment *x* topographic location. The location of the quadrats across the track splits the track width into five zones which roughly line up with the locations, across the track width, where the vehicle wheels have and have not travelled over (Figure 7.4). The occurrence of bare peat in each grid square was estimated visually and the peat was considered bare if there was no obvious vegetation at the surface, or if the vegetation was unrecognisable and ‘mushy’. If a grid square included bare peat it was recorded as 1 and if it did not it was recorded as 0, the grid squares containing peat were then counted to give percent cover.

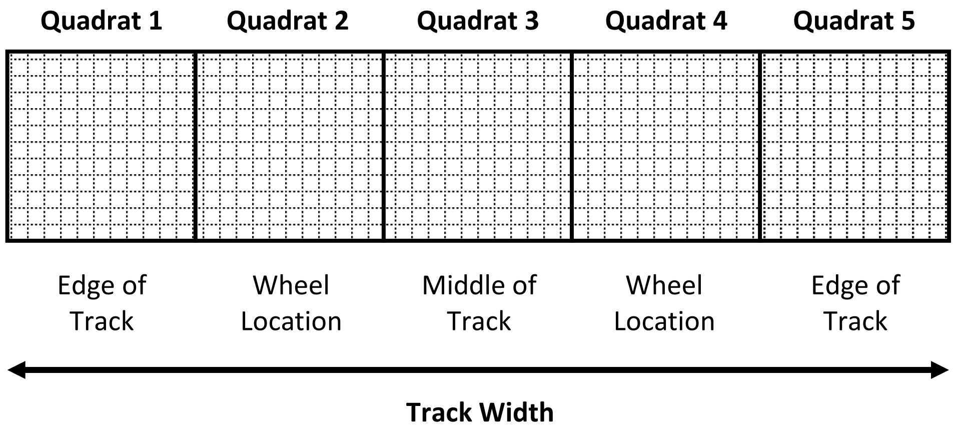

Figure 7.4 Schematic of arrangement of bare peat occurrence survey quadrats across the track width.

7.2.2 Statistical Analysis

Analyses were undertaken in R version 3.1.2 and Minitab version 17.1.0. Species composition, vegetation height and occurrence of bare peat were compared between and within the survey years. Non-metric multidimensional scaling (NMDS) was used to look at the dissimilarity between species composition dependent on year, treatment and topographic location using the Bray-Curtis measure of dissimilarity. Further dissimilarity analysis using the SIMPER function was also undertaken. SIMPER analysis reports how different communities are from each other, in addition to identifying the main species which are driving the differences. Graphical comparison of transect plots for vegetation height between years was undertaken, in addition to variation in species cover and bare peat occurrence with increasing number of passes. Differences in the percentage cover of key M19 blanket bog species (*C. vulgaris, E. vaginatum* and *S. capillifolium)* were tested for significance. The data was arcsine square root transformed prior to analysis (Bellamy et al., 2012). However, the data still did not meet the assumptions for parametric testing (normal and equal variance) and so non-parametric alternatives - Kruskall-Wallis and Mann-Whitney U statistical tests - were used.

7.3 Results

7.3.1 Weather Data

Monthly and annual rainfall totals and average temperatures for 2014 and 2015 are reported in Chapter 6. Initial vegetation surveys and the cutting of the vegetation for track installation occurred in 2013. Monthly and annual rainfall totals and average temperatures have therefore been included and are outlined in Table 7.1. Of the three years, 2013 had the lowest total rainfall and largest range in average monthly temperature from -2.1 °C in March to 14.5 °C in July.

Table 7.1 Monthly and annual total rainfall and average temperature for 2013 to 2015.Temperature and rainfall data courtesy of ECN.

	2013		**2014**		**2015**	
	Total Rain (mm)	Ave. Temperature (°C)	Total Rain (mm)	Ave. Temperature (°C)	Total Rain (mm)	Ave. Temperature (°C)
January	113.5	0.2	291	1.7	176	0.5
February	48	-0.8	335.5	1.7	80.5	0.3
March	39	-2.1	153	3.1	149.5	1.7
April	48	0.9	150	5.9	86	4.6
May	162.5	6.2	167	7.9	222	5.6
June	88	9.8	51.5	11.2	71	9.3
July	120.5	14.5	89.5	13.0	169	10.8
August	199	12.2	204	10.1	151.5	11.3
September	124.5	9.2	26.5	10.4	62.5	8.5
October	277	8.0	218.5	7.8	115	7.0
November	154.5	2.4	150.5	4.9	397.5	5.3
December	329.5	3.2	231	1.7	536.5	4.7
Annual	**1704**	**5.6**	**2068**	**6.6**	**2217**	**5.8**

7.3.2 Before Track Installation Vegetation Composition

In total, 41 species were identified prior to track installation, although not all were present in every treatment (Table 7.2). This illustrated natural spatial variation in vegetation composition independent of any disturbance through track installation or use. Species found to be present in all treatments before driving inlcuded *Calluna vulgaris*, *Empetrum nigrum*, *Eriophorum vaginatum*, *Plagiothecium undulatum*, *Pleurozium schreberi* and *Sphagnum capillifolium*.

Across the site the dominant species with >5 % cover in the surveyed quadrats included *Calluna vulgaris*, *Empetrum nigrum*, *Eriophorum vaginatum, Hypnum jutlandicum*, and *Sphagnum capillifolium*. These are known to be key species in an M19 classified bog, in addition to *Cladonia* spp., *Plagiothecium undulatum*, and *Pleurozium schreberi.* Prior to track installation *C. vulgaris* was the most dominant species with an average cover of 37 %, *E. vaginatum* and *S. capillifolium* had the next highest average cover at 23 % and 16 % respectively (Figure 7.5).

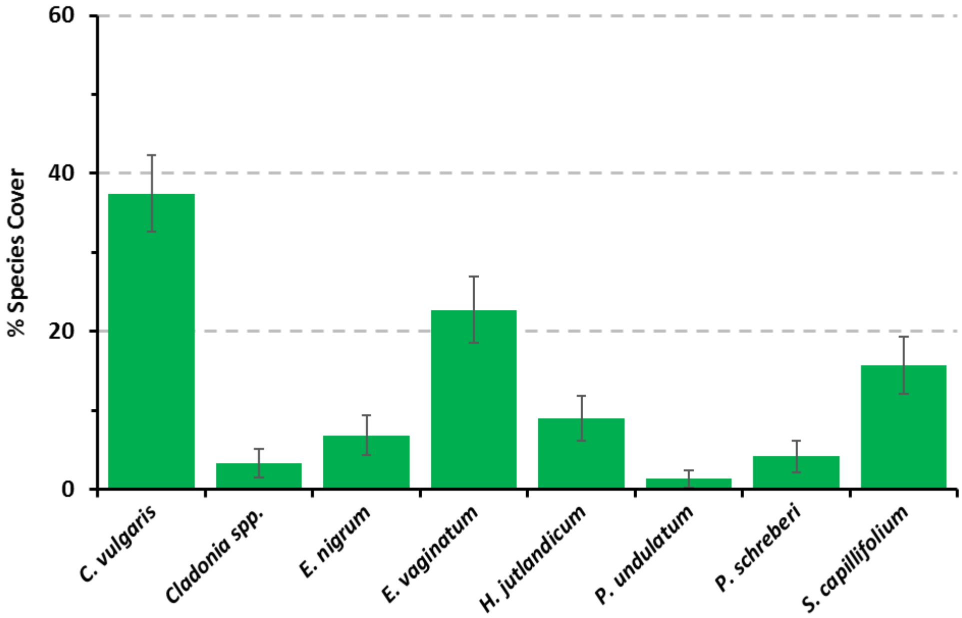

Figure 7.5 Average percent cover of key species in 2013 across all treatments prior to track installation. Error bars show ± standard deviation.

Table 7.2 Species present according to vegetation surveys undertaken in May 2013 prior to track installation (continued on page 201).

Species	PWEEK.AL	PWEEK.AH	PWEEK	PMONTH	PDELAYED	U	W
Bare Peat					✓		
Aulacomium palustre		✓	✓	✓	✓	✓	✓
Calluna vulgaris	✓	✓	✓	✓	✓	✓	✓
Campylopus spp.			✓				
Calypogeia Spp.		✓	✓	✓		✓	
Cephalozia bicuspidata		✓					
Cladonia Spp.	✓	✓	✓	✓		✓	
Dicranium scoparium	✓	✓		✓	✓		
Empetrum nigrum	✓	✓	✓	✓	✓	✓	✓
Erica tetralix	✓		✓				✓
Eriophorum angustifolium	✓	✓	✓	✓			
Eriophorum vaginatum	✓	✓	✓	✓	✓	✓	✓
Galium saxatile			✓				
Hylocomium splendens	✓		✓				
Hypnum cupressiforme	✓			✓			
Hypnum jutlandicum	✓	✓	✓	✓	✓	✓	
Neottia cordata	✓		✓			✓	
Liverwort Spp.	✓	✓	✓				
Lichen Spp.							✓
Lophocolea bidentata							✓
Narthecium ossifragum	✓						

Table 7.2 continued Species present according to vegetation surveys undertaken in May 2013 prior to track installation

Species	**PWEEK.AL**	**PWEEK.AH**	**PWEEK**	**PMONTH**	**PDELAYED**	**U**	**W**
Odontoschima sphagni			✓				
Plagiothecium undulatum	✓	✓	✓	✓	✓	✓	✓
Pleurozium schreberi	✓	✓	✓	✓	✓	✓	✓
Polytrichum alpinum				✓			
Polytrichum commune	✓	✓					
Pseudoscleropodium purum	✓						
Racomitrium lanuginosum					✓	✓	
Rhytidiadelphus loreus	✓	✓	✓	✓		✓	✓
Rhytidiadelphus squarrosus	✓	✓	✓	✓			
Rubus chamaemorus	✓	✓	✓	✓		✓	
Scirpus cespitosus	✓	✓					
Sphagnum capillifolium	✓	✓	✓	✓	✓	✓	✓
Sphagnum fallax	✓	✓		✓	✓	✓	✓
Sphagnum magellanicum			✓				✓
Sphagnum palustre				✓		✓	
Sphagnum papillosum	✓	✓		✓			
Sphagnum Spp.		✓					
Sphagnum tenellum		✓					
Vaccinium myrtillus	✓			✓	✓		
Vacinium vitisideaea					✓		

7.3.3 2013 compared with 2015

7.3.3.1 Species Composition

NMDS ordination analysis showed dissimilarity in monitored sites (treatment *x* topographic location *x* quadrat, *n* = 168) between 2013 and 2015 (Figure 7.6). The overlap evident in the plot suggests that the composition of some sites in 2015 was similar to sites measured in 2013. Some species were preferentially found to be associated with the 2013 survey, for example *E. tetralix,* while others showed closer association with the survey in 2015, for example bare peat (Figure 7.7). This suggests that most of the species which exhibited a preferential association with 2013 or 2015 were not present at survey sites in the alternate year. The species which were located around the centre of the plot (Figure 7.7) were present in both 2013 and 2015.

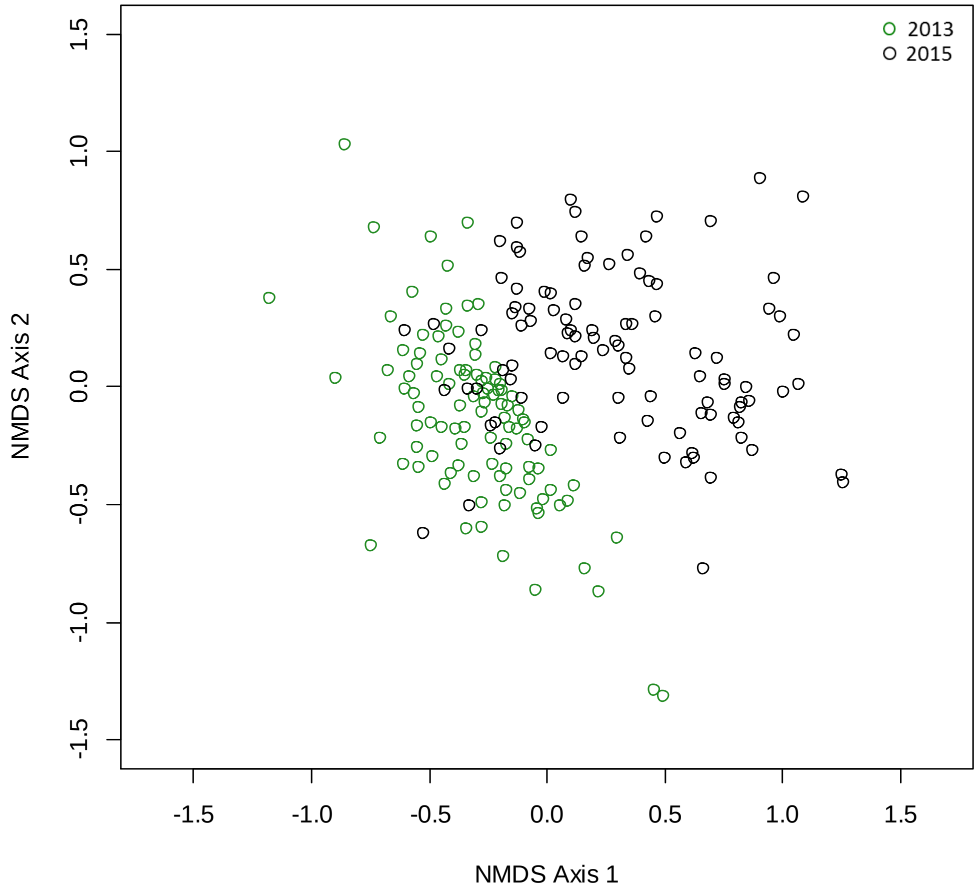

Figure 7.6 NMDS plot showing the location of sampling sites (treatment *x* topographic location *x* quadrat) by year. NMDS plots show the level of dissimilarity; sites which are further away from each other are more dissimilar than those which are closer together.

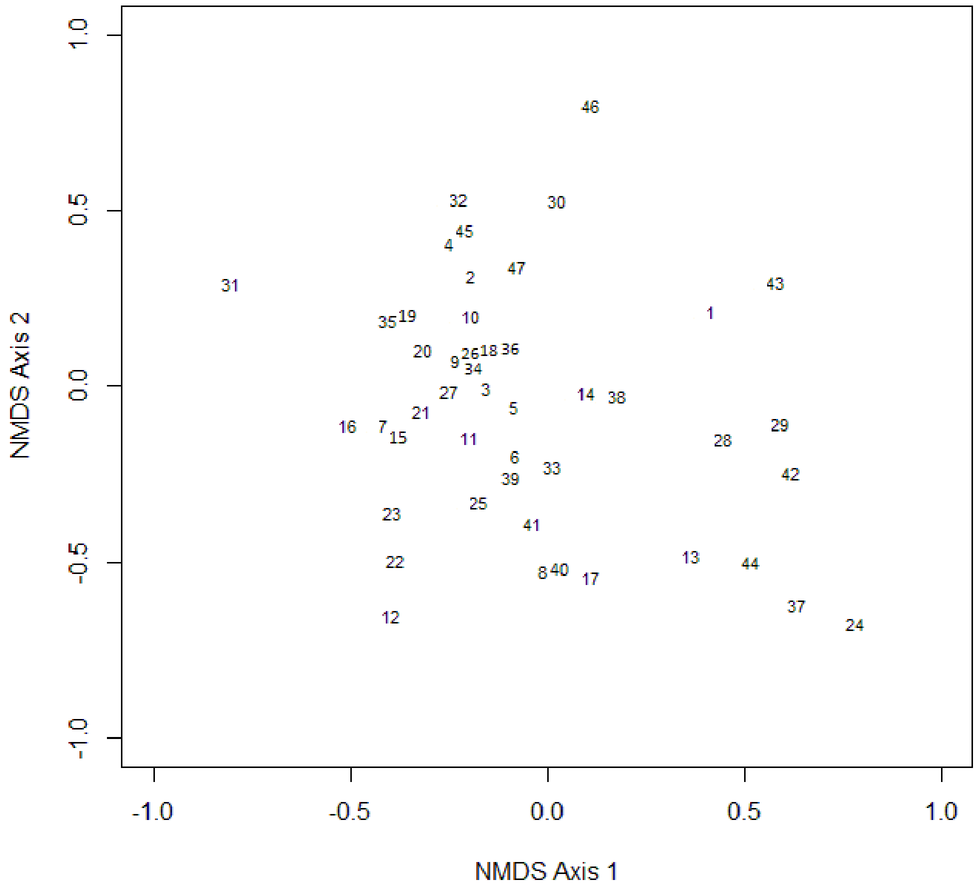

Figure 7.7 Species distribution in relation to sites according to NMDS analysis (Figure 7.6). Note the difference in scale on NMDS Axis 1 and NMDS Axis 2 compared with Figure 7.6. Species coding; 1.bare peat, 2.*Agrostis* spp., 3.*A.palustre*, 4.*B.media*, 5.*C.vulgaris*, 6.*Campylopus* spp., 7.*Calypogeia* spp., 8.*C.bicuspidata*, 9.*Cladonia* spp., 10.*D.scoparium*,11.*E.nigrum*, 12.*E.tetralix*, 13.*E.angustofolium*, 14.*E.vaginatum*, 15.*G.Saxatile*, 16.*H.splendens*, 17.*H.cupressiforme*, 18.*H.jutlandicum*, 19.*J.effusus*, 20.*N.cordata*, 21.*Liverwort* spp., 22.*Lichen* spp., 23.*L.bidentata*, 24.*N.ossifragum*, 25.*O.sphgani*, 26.*P.undulatum*, 27.*P.schreberi*, 28.*P.alpinum*, 29.*P.commune*, 30.*Polytrichum* spp., 31.*P.purum*, 32.*P.ciliare*, 33.*R.lanuginosum*, 34.*R.loreus*, 35.*R.squarrosus*, 36.*R.chamaerous*, 37.*S.cespitosus*, 38.*S.capillifolium*, 39.*S.fallax*, 40.*S.magellanicum*, 41.*S.palustre*, 42.*S.papillosum*, 43.*Sphganum* spp., 44.*S.tenellum*, 45.*V.myrtillus*, 46.*V.oxycoccus*, 47.*V.vitis-ideaea*.

Overall, SIMPER outputs showed the plant communities in 2013 and 2015 to be 61.1% dissimilar to each other. Dissimilarity was also found between the species composition when compared by topographic location (independent of treatment) prior to track installation (2013). This suggests spatial heterogeneity in variation of species composition associated with topographic location. There was an increase in dissimilarity between topographic locations in 2015 after track installation and driving over the track (Table 7.3).

Table 7.3 Percent dissimilarity in species composition between topographic locations for each surveying year. Before track installation (2013) and after driving (2015).

	2013	**2015**
S1 v S2	43.3	49.4
S1 v S3	44.5	56.3
S2 v S3	49.1	52.3

Before track installation, vegetation composition also exhibited dissimilarity between treatments (Table 7.4, 2013 comparison). A shift in the percent dissimilarity between treatments occurred following track installation and use. The results suggest that some treatments became more similar in composition in 2015 (a decrease in output value) while other became more dissimilar (an increase in output value). An increase in dissimilarity was particularly clear between treatment **U** and all other treatments, where there was evidence of a large increase in percent dissimilarity from 2013 to 2015 (Table 7.4, 2015 comparison). The results suggest an impact on species composition following disturbance by track installation and use.

Table 7.4 Percent dissimilarity in species composition between paired treatments by year, 2013 and 2015. Arrows indicate direction of change in dissimilarity between treatments in 2015 compared with 2013. ↑ = increase in dissimilarity, ↓ = decrease in dissimilarity.

	PWEEK.AL	**PWEEK.AH**	**PWEEK**	**PMONTH**	**PDELAYED**	**U**
2013						
PWEEK.AH	47.8	-	-	-	-	-
PWEEK	47.3	44.0	-	-	-	-
PMONTH	48.5	45.1	38.6	-	-	-
PDELAYED	54.2	54.6	46.0	46.6	-	-
U	46.4	52.0	35.5	36.8	42.9	-
W	59.7	58.1	48.5	50.1	49.4	47.0
2015						
PWEEK.AH	48.1 ↑	-	-	-	-	-
PWEEK	51.1 ↑	45.4 ↑	-	-	-	-
PMONTH	50.9 ↑	48.3 ↑	50.0 ↑	-	-	-
PDELAYED	54.8 ↑	48.3 ↓	48.3 ↑	54.2 ↑	-	-
U	62.6 ↑	60.7 ↑	65.3 ↑	52.2 ↑	68.6 ↑	-
W	53.6 ↓	46.8 ↓	54.5 ↑	47.2 ↓	53.1 ↑	52.8 ↑

According to the SIMPER function, the majority of dissimilarity between years, topographic locations, and treatments was driven by the following species: *C. vulgaris, S. capillifolium, E. vaginatum H. jutlandicum, E. nigrum* and *P. schreberi* and bare peat. A decrease in the average percent cover of most of the key species was observed from 2013 to 2015. Treatment **U**, where the vegetation was not cut, did not show the same amount of change between years. For a small number of species an increase in the average percent cover of key species was observed following track installation and use.

C.vulgaris, S. capillifolium, and *E. vaginatum* were the most abundant species before track installation (Figure 7.5). Further analysis of the influence of treatment and topographic location on vegetation recovery focused on these three species; the abundance of other key species was not large enough for meaningful statistical analysis. Table 7.5 outlines the results of a Mann-Whitney U test on the difference in percent cover of *C. vulgaris, E. vaginatum,* and *S. capillifolium* between 2013 and 2015 by treatment *x* topographic location.

Table 7.5 *P* values for difference in percent species cover between 2013 and 2015 for three key blanket peatland species in each treatment at three different topographic locations. S1 = Top-slope, S2 = Mid-slope, S3 = Bottom-slope. * = 2013 and 2015 data statistically significantly different, when $p \leq 0.05$.

	PWEEK.AL	PWEEK.AH	PWEEK	PMONTH	PDELAYED	U	W
S1							
C. vulgaris	0.010*	0.005*	0.005*	0.005*	0.056	0.416	-
E. vaginatum	0.066	0.005*	0.006*	0.041*	0.063	0.027*	-
S. capillifolium	0.005*	0.226	1.000	0.873	0.747	1.000	-
S2							
C. vulgaris	0.676	0.454	0.003*	0.005*	-	0.514	-
E. vaginatum	0.451	0.016*	0.040*	0.016*	-	0.575	-
S. capillifolium	0.809	0.471	0.630	0.936	-	0.128	-
S3							
C. vulgaris	0.005*	0.007*	0.004*	0.005*	-	0.371	0.063
E. vaginatum	0.042*	0.016*	0.241	0.683	-	0.298	0.063
S. capillifolium	0.334	0.628	0.044*	0.872	-	0.332	0.936

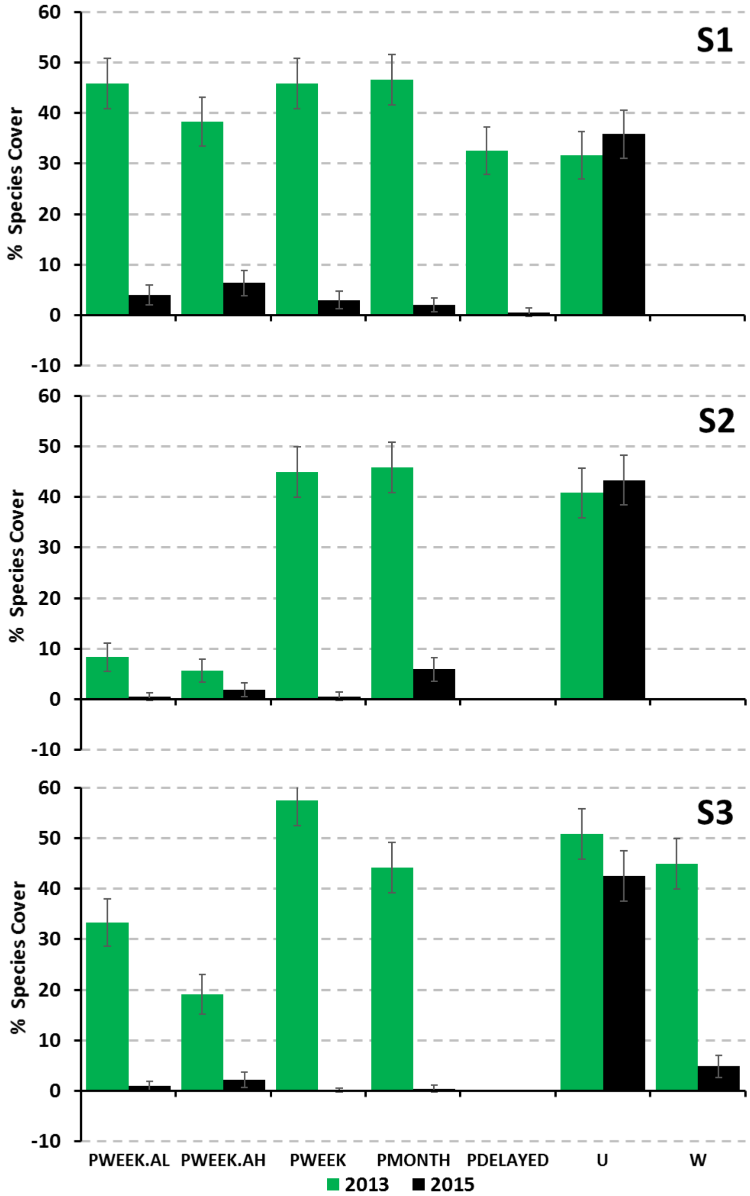

Figure 7.8 Average percent cover of *C. vulgaris* for 2013 and 2015 by treatment at each topographic location. Note that vegetation composition was only surveyed at topographic location S1 in **PDELAYED** and S3 in **W**. Error bars show ± standard deviation

A significant decrease was found in the percent cover of *C. vulgaris* between 2013 and 2015 in treatments **PWEEK** and **PMONTH** at all topographic locations. No significant difference was found in treatment **U** at any topographic location, or in treatments **PWEEK.AL** and **PWEEK.AH** at topographic location S2. Percent cover of *C. vulgaris* in treatments **PDELAYED** and **W** was marginally insignificant between 2013 and 2015 (p = 0.057 and p = 0.063 respectively) (Figure 7.8).

There appeared to be a consistent decrease in average percent cover of *E. vaginatum* between 2013 and 2015 in all treatments at topographic locations S1 and S3 (Figure 7.9), although these differences were not always statistically significant. Not all statistically significant differences between years were found at the same topographic location for the different treatments (Table 7.5). Treatment **PWEEK.AH** exhibited a statistically significant decrease in percent cover at all topographic locations. In treatment **U** a significant difference was found at topographic location S1 (p = 0.027), but not at topographic locations S2 and S3.

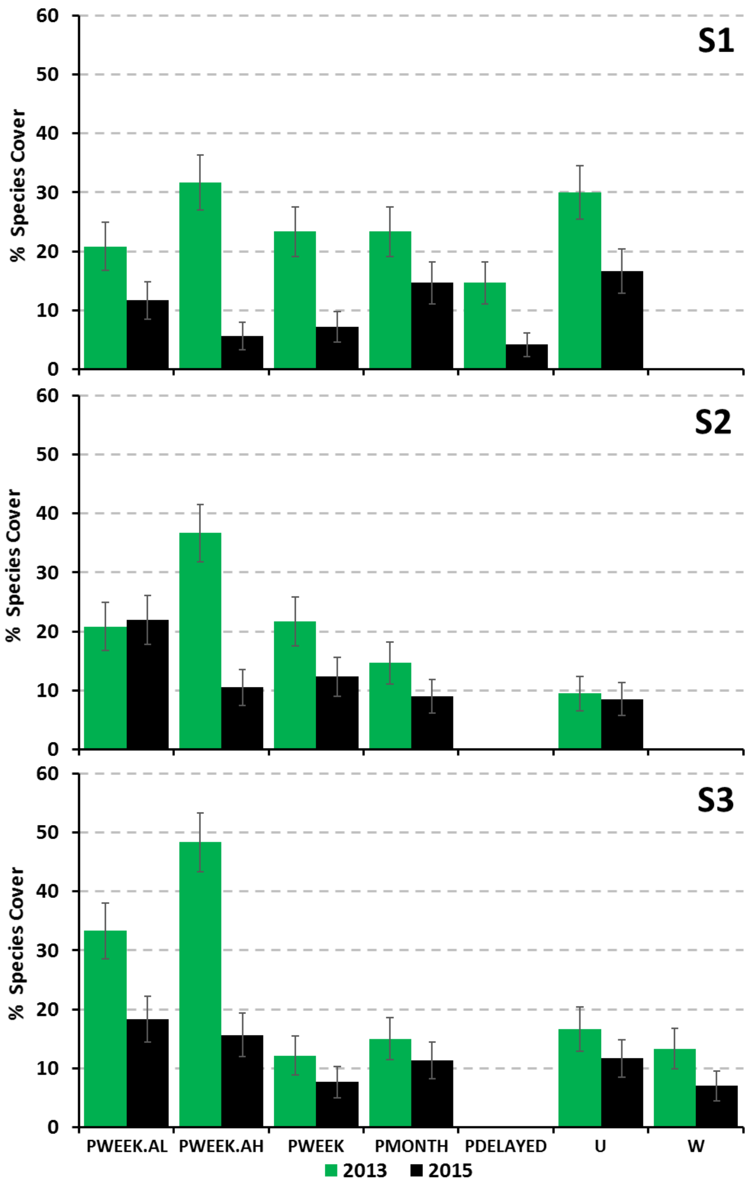

Figure 7.9 Average percent cover of *E. vaginatum* for 2013 and 2015 by treatment at each topographic location. Note that vegetation composition was only surveyed at topographic location S1 in **PDELAYED** and S3 in **W**. Error bars show ± standard deviation.

S.capillifolium had the least difference in average percent cover of the three species tested between 2013 and 2015 at the different topographic locations for each treatment (Figure 7.10). A statistically significant increase was found in percent cover of *S. capillifolium* between 2013 and 2015 at **PWEEK.AL** *x* **S1** (p = 0.005) and a decrease at **PWEEK** *x* **S3** (p = 0.044). All other differences were found not to be significant. In treatment **U** an increase in average percent cover was observed at topographic locations S2 and S3. In 2013 there was topographic variation in average percent cover of *S.capillifolium,* with the higher cover predominantly found at topographic location S3 for all treatments.

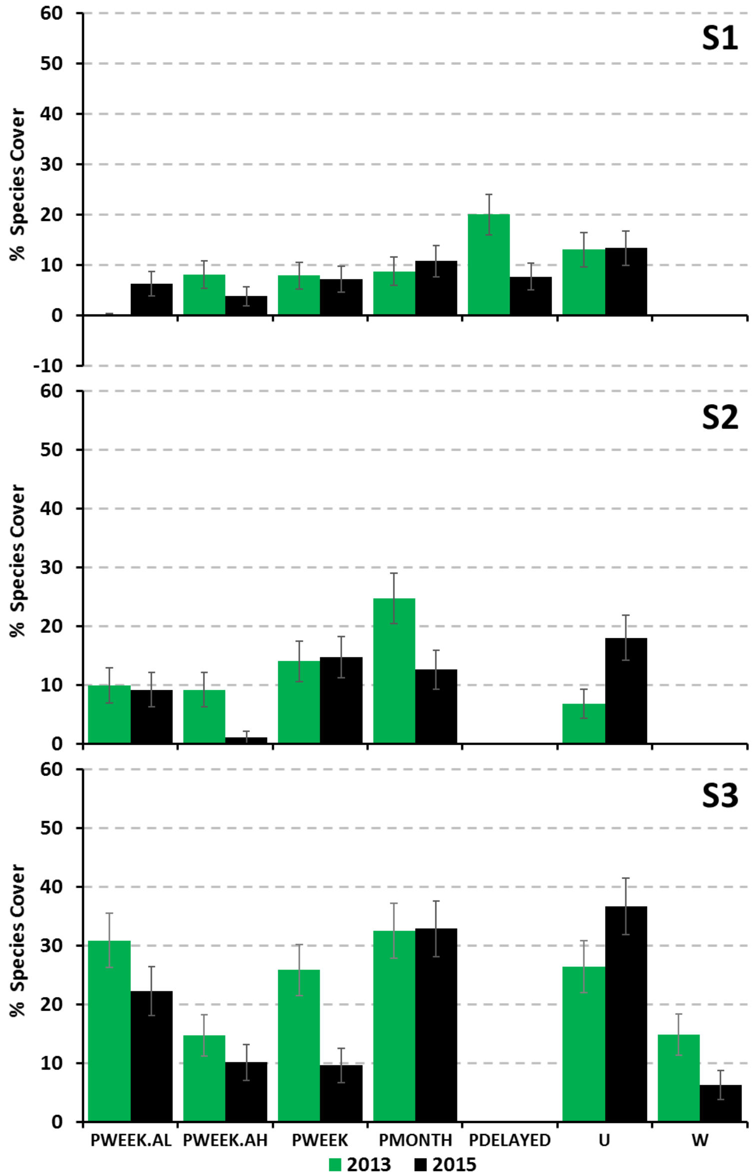

Figure 7.10 Average percent cover of *S. capillifolium* for 2013 and 2015 by treatment at each topographic location. Note that vegetation composition was only surveyed at topographic location S1 in **PDELAYED** and S3 in **W**. Error Bars show ± standard deviation.

The response of *C. vulgaris, E. vaginatum,* and *S. capillifolium* varied between species, treatments and topographic locations. There was a difference between the response of treatments where the vegetation was cut prior to track installation and treatment **U** where the vegetation had not been cut. However, there was no clear evidence that frequency of use of the track or topographic location had an impact on vegetation regrowth.

7.3.3.2 Vegetation Height

The height of the vegetation was lower in 2015 compared with 2013 in all treatments and at all topographic locations. Greatest regrowth occurred at the edge of the track in all treatments where the vegetation had been cut for track installation. Vegetation regrowth was lowest along wheel routes (Figure 7.11). There was no clear pattern in average vegetation height with topographic location or frequency of use for the plastic mesh track (Figure 7.12). In 2015, average vegetation height in treatment U was higher compared with the other treatments (Figure 7.12).

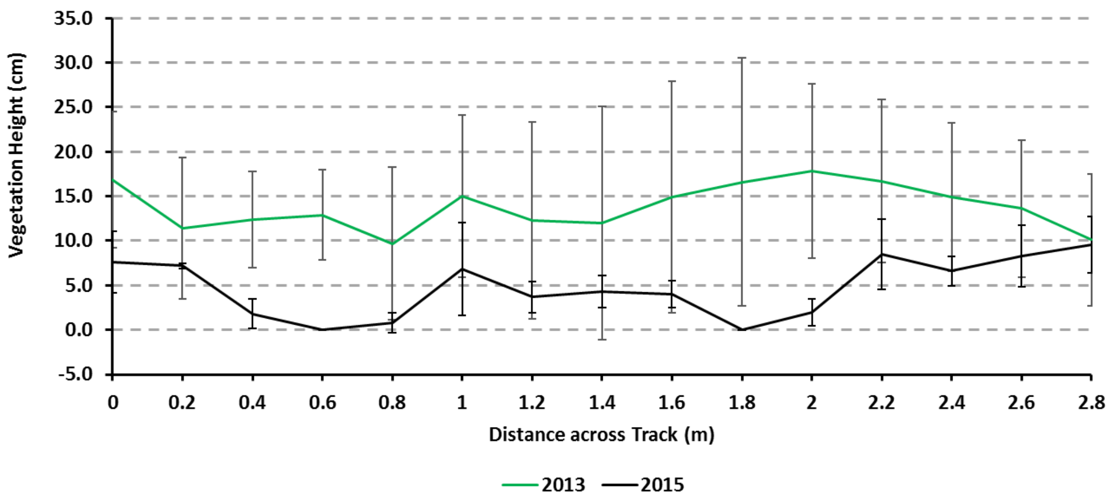

Figure 7.11 Example of vegetation height transects (average of five transects shown) for 2013 (before track installation) and 2015 (after track installation and driving) at **PWEEK.AL *x* S3**. Error bars show ± standard deviation.

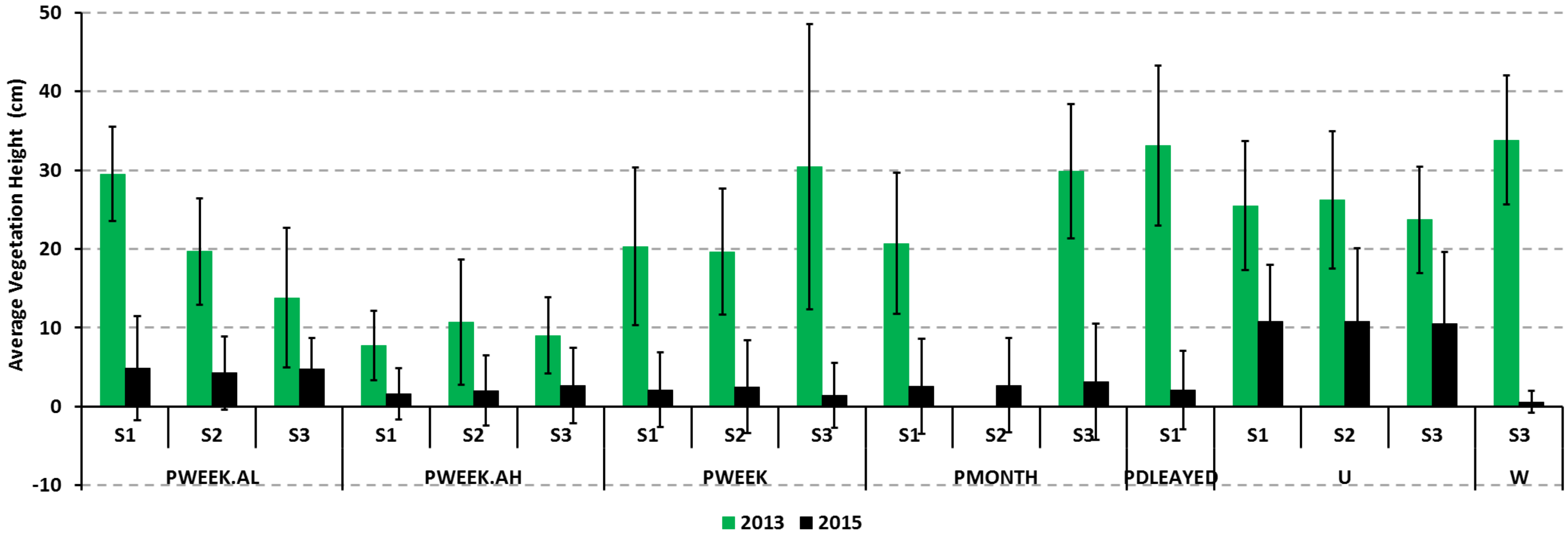

Figure 7.12 Average vegetation height (cm) in 2013 and 2015 across the track width at each topographic location. Error bars show ± standard deviation.

7.3.3.3 Bare Peat Occurrence

An increase in the occurrence of bare peat was observed across all treatments between 2013 and 2015 (0.02 % and 26 % respectively). Detailed analysis of average percent cover of bare peat in 2015 after 14 months of driving showed variation by treatment and topographic location. **PMONTH** had the highest percent cover of bare peat (16 %), treatment **U** had no bare peat. There was no data for treatment **W**. Bare peat cover was highest at topographic location S3 (15 %) and lowest at topographic location S1 (4 %). This pattern was not maintained at the treatment scale however (Table 7.6).

Table 7.6 Average percent occurrence of bare peat in 2015 by treatment and topographic location.

Treatment	Topographic Location		
	S1	S2	S3
PWEEK.AL	3	23	6
PWEEK.AH	2	5	18
PWEEK	3	12	14
PMONTH	6	2	39
PDELAYED	10	-	-
U	0	0	0

Spatial variation was also observed across the track at the whole site scale with the highest occurrence of bare peat in the middle of the track compared with the edge of the track (Figure 7.13). This pattern was maintained when data were further broken down by topographic location (Table 7.7) but only maintained in selected treatments when broken down when treatment. (Table 7.8). Further, when broken down by treatment *x* topographic location, the pattern was only maintained for the following: **PWEEK.AL** *x* **S3**, **PWEEK** *x* **S2**, **PWEEK** *x* **S3, PMONTH** *x* **S3** and **PDELAYED** (which was only surveyed at topographic location **S1)** .

Figure 7.13 Average percent cover of Bare Peat in 2015 by location across track for the following treatments combined: **PWEEK.AL**, **PWEEK.AH**, **PWEEK**, **PMONTH**, **PDELAYED,** and **U**. Error bars show ± standard deviation.

Table 7.7 Average percent cover of bare peat in 2015 by topographic location and sampling location across the track width.

Topographic Location	Location across Track Width				
	Edge of Track	Wheel Rut	Mid-Track	Wheel Rut	Edge of Track
S1	1	8	4	5	2
S2	2	10	13	10	6
S3	9	21	12	23	12

Table 7.8 Average percent cover bare peat in 2015 by treatment and sampling location across the track width.

Treatment	Location across Track Width				
	Edge of Track	Wheel Rut	Mid-Track	Wheel Rut	Edge of Track
PWEEK.AL	2	11	15	13	10
PWEEK.AH	6	9	4	15	8
PWEEK	4	20	8	14	3
PMONTH	7	22	17	20	12
PDELAYED	4	18	14	11	4

7.3.4 Treatment **U**

As has been discussed in section 7.3.3.1, there was minimal significant difference in percent cover for key species *C. vulgaris, E. vaginatum,* and *S. capillifolium* between 2013 and 2015 in treatment **U**. Only *E. vaginatum* showed a significant decrease at topographic location S1. Regular surveying of vegetation composition in treatment **U** after each driving event (2 passes per month) showed variation in average percent cover of key species but no clear pattern (Figure 7.14). There was no clear evidence that an increasing number of passes resulted in a decrease in percent cover of key species. The starting percent cover of *C.vulgaris* (0 passes) was 41 % while the final cover after 24 passes was 41 %. *E. vaginatum* exhibited a slight decrease in percent cover from 19 % at the start to 12 % at the end. *S. capillifolium* showed an increase from start to finish, with percent cover of 15 % and 23 % respectively. The lack of a clear pattern and evidence of a decrease with increasing number of passes was also observed when the data was broken down by topographic location. Topographic location had an influence on the percent cover of *S. capillifolium* with greater cover at topographic location S3. Driving was suspended on this treatment at the end of April 2015.

Average percent cover of bare peat was found to decrease between 8 passes over the route and 24 passes from 1 % to 0 % (Figure 7.15).

In general, vegetation height decreased with increasing number of passes in treatment **U** (Figure 7.16). The decrease in the height of the vegetation was greatest in the vehicular wheel routes (wheel ruts) at all topographic locations, although this effect was most prominent at topographic location S3. At topographic location S3, the average vegetation height across the track width prior to driving commencing was lower (22.3 ±6.4 cm) compared with locations S1 (28.4 ±4.0 cm) and S2 (29.5 ±6.3 cm). There was a suggestion of slight 'recovery' in the height of the vegetation at times during the monitoring period.

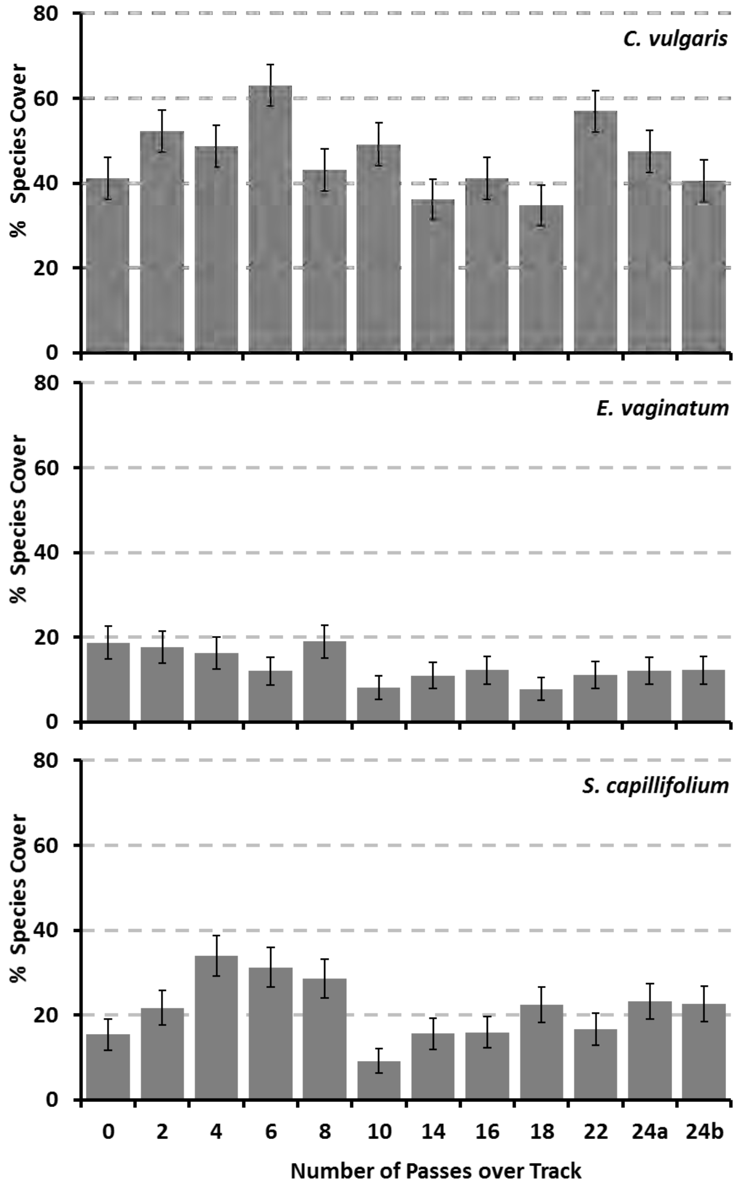

Figure 7.14 Average percent cover of *C. vulgaris, E.vaginatum*, and *S. capillifolium* by number of passes in treatment U. On the x-axis 24a survey marks the end of driving over the track (April 2015) while the 24b survey was undertaken in May 2015 in line with the rest of the treatments at the study site, when no further passes had been over this track. Error bars show ± standard deviation.

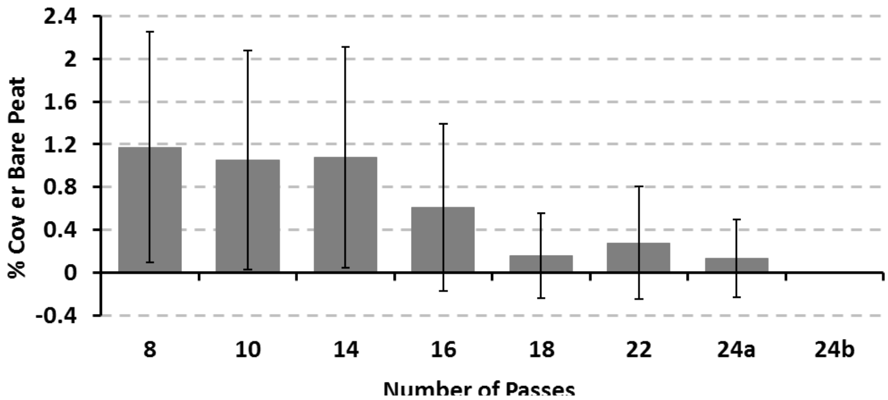

Figure 7.15 Average percent cover of bare peat by number of passes over treatment **U**. Note the small y-axis scale. The 24a survey marks the end of the driving (April 2015) while the 24b survey was undertaken in May 2015 in line with the rest of the treatments at the study site, when no further passes had been over this track. Error bars show ± standard deviation

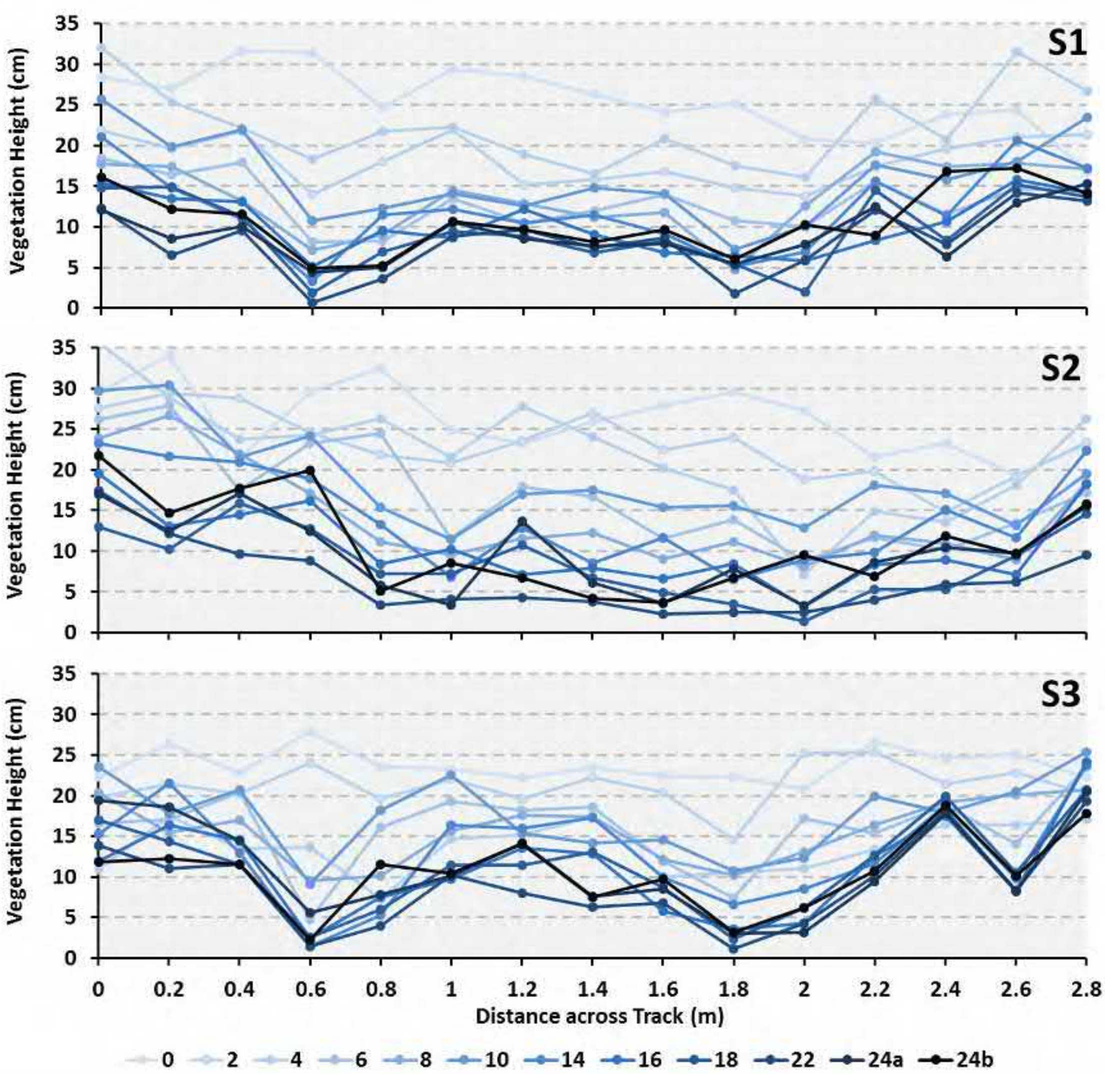

Figure 7.16 Change in vegetation height in treatment **U** with increasing number of passes by topographic location. The 24a survey marks the end of the driving (April 2015) while the 24b survey was undertaken in May 2015 in line with the rest of the treatments at the study site, when no further passes had been over this track.

7.4 Discussion

Change was observed in vegetation composition and height following track installation and use, relative to initial conditions recorded in May 2013. Prior to track installation, natural variation in species composition was found across the site, illustrated by the dissimilarity between treatments (track type and frequency of use) and topographic locations in the 2013 data (Tables 7.3 and 7.4). This reflects the fine scale heterogeneity of vegetation typical of blanket peatlands (Milne and Hartley, 2001, Sottocornola et al., 2008). For most treatments (track type and frequency of use) this dissimilarity was increased, however, following track installation and use, the dissimilarity between **PWEEK.AH** and **PDELAYED**, and **PMONTH** and **W**, showed a decrease in dissimilarity. Variation in the difference between initial and post-track vegetation composition and characteristics was observed with track type, frequency of use, topographic location and species. Table 7.9 summarises the hypotheses tested in this study and outlines which have been accepted or rejected. Hypotheses (i), (ii), (iii), and (v) were investigated through the before and after surveys, while hypothesis (iv) was investigated through the regular monitoring of treatment **U**.

Table 7.9 Summary of hypotheses and which have been accepted and which have been rejected.

Hypothesis	Accepted	Rejected
(i) Vegetation change will vary with track type (plastic mesh, articulated wooden and unsurfaced) and frequency of use	*For Track Type*	*For Frequency of Use*
(ii) Topographic position will influence vegetation change with drier slopes showing less change than wetter bottom slopes		✓
(iii) The occurrence of Bare Peat will be greatest in the most frequently used treatments		✓
(iv) With an increasing number of vehicle passes over the unsurfaced track there will be a change in vegetation composition, a lowering in the height of the vegetation and an increase in the occurrence of Bare Peat.	*For Vegetation Height*	*For Vegetation Composition and Occurrence of Bare Peat*
(v) Evidence of impacts will be greatest in line with the wheel routes compared with other locations across the track width	✓	

7.4.1 Influence of Track Type and Frequency of Use on Vegetation Composition and Height

Track type (plastic mesh, articulated wooden or unsurfaced) had a clear influence on vegetation composition and height relative to initial conditions. A probable explanation for this was the differences in route preparation for the three track types. While the vegetation was cut prior to the installation of the plastic mesh and articulated wooden tracks, no route preparation occurred in treatment **U** (unsurfaced tracks) prior to driving commencement. The large difference in vegetation height between 2013 and 2015 recorded in treatments **PWEEK.AL, PWEEK.AH, PWEEK, PMONTH, PDELAYED** and **W**, can be directly attributed to the effect of vegetation cutting.

The removal of vegetation cover through cutting can explain the increase in dissimilarity in vegetation composition observed between most treatments from 2013 to 2015 (Table 7.4). Relative to initial conditions, *C. vulgaris* showed the greatest difference in percent cover from 2013 to 2015, with a significant decrease for most treatments and topographic locations (exceptions **PDELAYED**, **PWEEK.AL** *x* **S2**, **PWEEK.AH** *x* **S2**, and **W**). In treatment **U** where the vegetation had not been cut there was no significant difference in percent cover of *C. vulgaris*. *E. vaginatum* also exhibited a significant decrease in cover for a number of treatments and topographic locations (exceptions **PWEEK.AL** *x* **S1**, **PDELAYED**, **PWEEK.AL** *x* **S2**, **U** *x* **S2**, **PWEEK** *x* **S3**, **PMONTH** *x* **S3**, **U** *x* **S3** and **W**). Visual observations made during the study monitoring period, however, found regrowth of *E. vaginatum* to be faster than that of *C. vulgaris*, with clear evidence of stems coming through the holes in the track by the start of driving in April 2014. Such a result is supported by studies of burning on peatlands, where *E. vaginatum* was one of the first species to come back following disturbance (Forrest, 1971, Rawes and Hobbs, 1979). It is suggested, therefore, that the impact of cutting the vegetation for the installation of the plastic mesh and wooden tracks was greatest on *C. vulgaris*.

Regrowth of *C. vulgaris* after cutting is influenced by a number of factors, including the age of the stand prior to cutting, the abundance of the seed bank and the magnitude of disturbance to the seed bank (Hobbs and Gimingham, 1984, Liepert et al., 1993). Regeneration of *C. vulgaris* can occur from a seed bank or be vegetative, i.e. regeneration from stems (Mohamed and Gimingham, 1970). *C. vulgaris* stands at the site were most likely in the mature to degenerate phase (c.f. Worrall et al., 2013) and it was observed by Mohamed and Gimingham (1970) that vegetative regrowth of more mature *C.vulgaris* was slower. In addition, the seed bank was often reduced in older stands. Since this work in the 1970s, however, layering of mosses has occurred at Moor House which has resulted in the regeneration of new *C. vulgaris* buds and a potentially large seed bank (J. Holden, *pers. Comm.*).

Percent cover of *S. capillifolium* was least impacted by installation and use of the three different tracks, with significant differences only being found at **PWEEK.AL** *x* **S1** and **PWEEK** *x* **S3**. Such a result could be indicative of one of two things: (i) *S. capillifolium* was not disturbed much during the installation of the track and therefore the small decrease in percent cover was due to track use and disturbance caused by the action of driving or (ii) *S. capillifolium* was disturbed during the installation of the plastic mesh and articulated wooden tracks, however the recovery of *Sphganum* spp. to initial conditions was faster than that of the vascular plants (*C. vulgaris* and *E. vaginatum*).

The slower recovery of vascular plants compared with *Sphagnum* was observed by Robroek et al. (2010), who noted a similar occurrence following human trampling on blanket peat. Here the dominant species were *S. magellanicum* and *S. rubellum,* although their individual response was not investigated in depth. Robroek et al. (2010) attribute the fast recovery of *Sphagnum* to a combination of factors including moisture conditions suitable for re-colonization (Chirino et al., 2006), the presence of macrospores and the sheltered position of the track which remained surrounded by vegetation. While dense vegetation remained either side of the track in my study, the tracks were 2.5-3 m wide, depending on type, and consequently there were exposed sections. Hence, the sheltering effect put forward by Robroek et al. (2010) for narrow human tracks is probably not an adequate explanatory factor in the case of wider vehicle tracks. Other studies considering track impacts (human trampled and unsurfaced vehicle tracks) on vegetation have observed an opposite effect with vascular plant regrowth to faster than that of bryophytes (Sparrow et al., 1978, Abele et al., 1984, Törn et al., 2006). These studies were typically on shallow peat or organic soils (arctic tundra) and the vehicles used were larger than those used in this study.

The route preparation for the different track types exhibited a clear impact on vegetation cover and height. Between the cut treatments, **PWEEK.AL, PWEEK.AH**, **PWEEK**, **PMONTH**, **PDELAYED** and **W**, further visual observations were made of differences in vegetation recovery over the course of the study monitoring period. In treatment **W** for example the peat under the track remained bare for a large part of the first year after installation. (Figure 7.17).

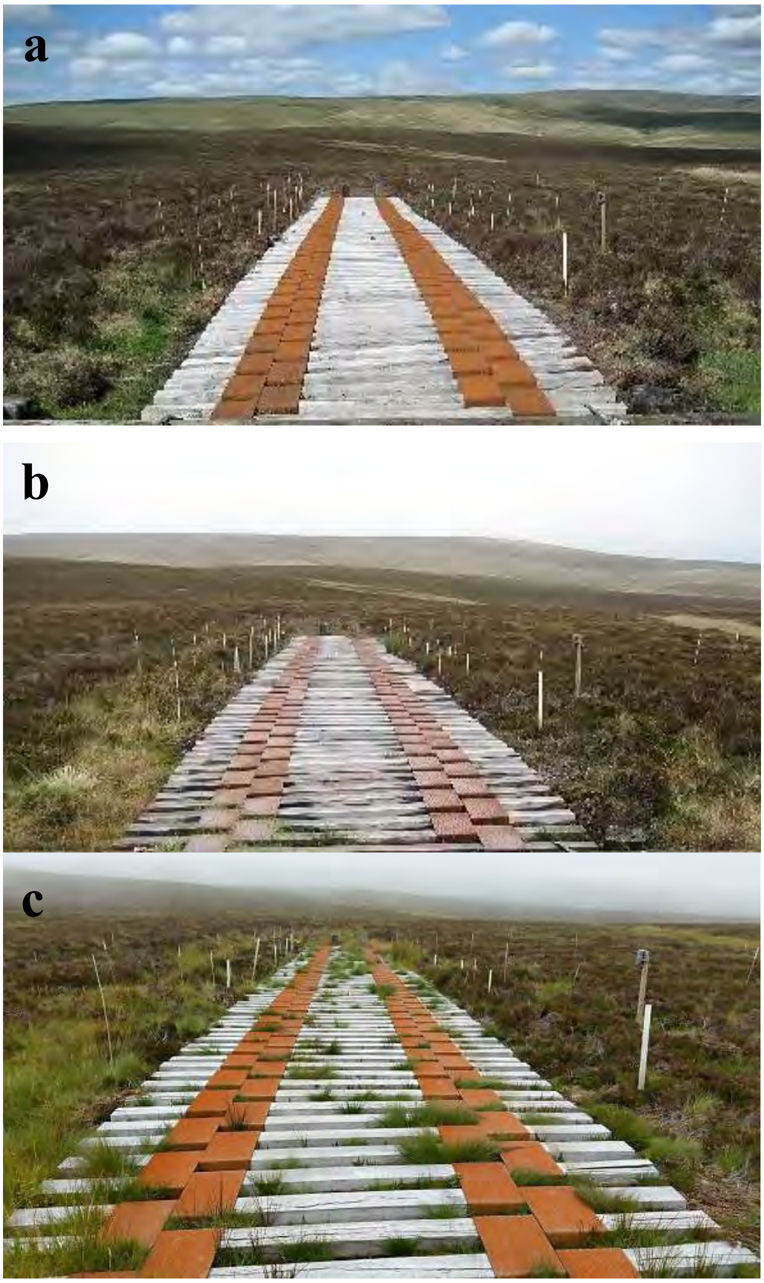

Figure 7.17 Vegetation regrowth on treatment **W**; a) May 2014 - 8 months after installation, b) November 2014 – 14 months after installation, c) September 2015 – 24 months after installation. The track was installed in September 2013.

Possible explanations for the slower recovery of vegetation in treatment **W** include: (i) the vegetation which was dominant in this treatment prior to cutting may have been different from the other treatments and therefore took longer to grow back; (ii) during route preparation a heavier cutting machine was used, compacting the surface peat more than under the plastic mesh tracks (Chapter 5), putting stress on vegetation regrowth (Charman and Pollard, 1995, Cooper et al., 2001); (iii) a closer cut of the vegetation to the peat surface created more bare peat, which has been found to take longer to recolonise (Robroek et al., 2010); (iv) the track itself was heavier and exerted pressure on the peat which made regrowth more difficult; and (v) time of year of track installation. The wooden track was not installed until September 2013. It has been suggested that cutting of blanket peat vegetation is best carried out in spring and avoided in autumn (MacDonald, 1996). While these visual observations did not translate into the measured change for *C. vulgaris*, *E. vaginatum*, and *S. capillifolium*, the difference in percent cover between 2013 and 2015 for *C. vulgaris* and *E. vaginatum* was marginally not significant ($p = 0.063$ for both). This suggests that while there was some effect from the articulated wooden track on vegetation it was not discernible in the data.

Greater impacts to vegetation cover have been linked with a higher number of passes (e.g. Kevan et al., 1995). It was therefore assumed that treatments in this study with a higher frequency of use (**PWEEK.AL, PWEEK.AH,** and **W**) would exhibit the largest decrease in percent vegetation cover (the slowest recovery) due to continued disturbance from driving. The smallest decrease would be in the least frequently used treatment (**PMONTH**) where vegetation recovery was possible between the driving events. Such a pattern was not observed in the statistical analysis, with some of the largest differences in *C. vulgaris* cover observed in treatment **PMONTH**, where there statistically significant decreases at all topographic locaitons. Reasons for this occurrence will be discussed further within section 7.4.2. Treatment **PDELAYED** had an intermediate frequency of use (two passes per week), however this treatment also had an extra growing season prior to driving commencing compared with the others. The difference in percent cover of *C. vulgaris* and *E. vaginatum* between 2013 and 2015 in treatment **PDELAYED** (topographic location S1 only) was marginally not significant for both species. Consequently, such a result provides no clear evidence that leaving this treatment for an additional 10 months resulted in a greater recovery of vegetation towards initial conditions

It has been suggested that the main control on vegetation regrowth is vegetation composition at a site pre-disturbance (Hobbs, 1984, Hobbs and Gimingham, 1984, Grant et al., 1985, Arnesen, 1999, Törn et al., 2006). The type of disturbance can also be important, whilst a return to a 'steady-state' *C. vulgaris-E. vaginatum* dominated peatland has been observed after burning, the same has not been found after grazing (Rawes and Hobbs, 1979). Groome and Shaw (2015) found that location, vegetation type and site wetness were important factors in determining the extent of impact.

Vegetation composition showed clear evidence of a change between 2013 and 2015 under the plastic mesh and wooden tracks, but not for the unsurfaced track. There was however no clear pattern to be found in vegetation recovery (*C. vulgaris*, *E. vaginatum*, *S. capillifolium*) with track frequency of use i.e. recovery was not clearly lowest under the highest frequency of use. Consequently, hypothesis (i) can be accepted with respect to the effect of track type on vegetation change but not accepted for the influence of track frequency of use with respect to the plastic mesh track.

Within existing track studies (human trampled and unsurfaced vehicle tracks) on peatlands, measurement of vegetation recovery and regrowth to baseline (undisturbed) conditions has occurred at various time intervals after disturbance. In the case of Charman and Pollard (1995) surveying of recovery was undertaken on tracks covering three different ages (times since abandonment), where the longest time since abandonment was 24 years. Arnesen (1999) surveyed recovery immediately after trampling ceased in 1981 and then again in 1982, 1984, 1990 and finally in 1995. Robroek et al. (2010) first looked at recovery in September 2008, one year after abandonment for one track and one month after abandonment for the other, a second set of surveying was undertaken in August 2009. In all these studies, vegetation recovery was not monitored until track use had ceased. In my study, however, recovery to initial conditions was measured while track use was ongoing (or just concluded in the case of treatment **U**). In addition, track use in this study had only occurred for 14 full months at the time of the 2015 surveys. Sustained track use may have resulted in clearer patterns with respect to the effect of frequency of use on vegetation recovery.

7.4.2 Influence of Topographic Location

It was hypothesised that vegetation change (composition, height, occurrence of bare peat) following track installation and use would be influenced by topographic location (hypothesis ii) i.e. the effect of the track on the vegetation regrowth and recovery would differ depending on whether it was at a top-, mid-, or bottom-slope location. Prior to disturbance (2013 data) variation was observed in species composition between topographic locations (Table 7.3). This could be related to the environmental gradients which influence vegetation composition (Andersen et al., 2011) and the preference of certain species to different conditions e.g. peat wetness. Of the key species *S. capillifolium* showed the highest percent cover at topographic location S3 in relation to S1 and S2.

Within individual treatments the difference between 2013 and 2015 percent cover of the key species, *C. vulgaris*, *E.vaginatum* and *S. capillifolium*, varied by topographic location (Figures 7.8 to 7.10). Spatial and temporal variation in the response of a single species to disturbance has been observed in other work (e.g. Milne and Hartley, 2001). There was no clear pattern that larger differences, which could be indicative of greater impact or slower recovery, occurred at specific topographic locations. At the site scale, topographic location exhibited an influence on the occurrence of bare peat, with the highest percent cover observed at topographic location S3 (bottom-slope). When broken down by treatment (track type and frequency of use), however, this pattern did not hold. Consequently, hypothesis (ii) was rejected as topographic location did not clearly influence recovery for the plastic mesh or unsurfaced track types which covered all three topographic locations.

7.4.3 Frequency of Use Influences Occurrence of Bare Peat

The occurrence of bare peat was associated with the 2015 sites compared with the 2013 sites in the NMDS plots (Figures 7.6 and 7.7) indicating that there had been an increase in the occurrence of bare peat with track installation and use. Several studies have suggested that there is a positive relationship between the occurrence of bare soil and an increasing number of passes (e.g. Payne et al., 1983, Kevan et al., 1995), probably due to the increased stress placed on the soil surface by vehicle movement or trampling. In this study, it was expected that the occurrence of bare peat would be of the order **PWEEK.AH** > **PWEEK.AL** > **PWEEK** > **PMONTH** > **PELAYED** for the plastic mesh treatments. However, the highest occurrence of bare peat was observed in the least frequently used treatment (**PMONTH**). In addition, there was no clear pattern in the occurrence of bare peat with frequency of use, with occurrence of bare peat of the order **PMONTH** > **PWEEK.AL** > **PDELAYED** > **PWEEK** > **PWEEK.AH** (data not shown). From these findings hypothesis (iii) was rejected for the plastic mesh track treatments. A possible explanation for this result was that more frequent driving over the track provided stimulation for vegetation regrowth, possibly disturbance of the seedbed, which was not able to happen with the infrequent driving on the less frequently used treatments (Natural England, *pers Comm*).

Ahlstrand and Racine (1993) found that vehicle weight rather than frequency of use influenced the occurrence of bare soil. However, there was little difference in the occurrence of bare peat between **PWEEK.AL** and **PWEEK.AH**, with 11% and 8% bare peat cover respectively. These treatments had the same number of passes but different vehicles weights. This therefore suggests that the plastic mesh of the track provides a buffer to surface disturbance from the vehicle wheels.

Caution should be taken in the interpretation of the occurrence of bare peat results, based upon visual observations made during the study monitoring period. While regrowth of vegetation had occurred along the track route, it was patchy and consequently the areas monitored may not have been fully representative of the impact of the plastic mesh track under the different frequencies of use.

7.4.4 Increasing Number of Passes on Unsurfaced Track Impacts Vegetation Composition and Height, and Bare Peat Occurrence

Studies of unsurfaced tracks on varying soil types investigating frequency of track use on vegetation have frequently found a decrease in abundance of vegetation and an increase in bare soil exposure (Gersper and Challinor, 1975, Sparrow et al., 1978, Abele et al., 1984, Ahlstrand and Racine, 1993, Arnesen, 1999). Frequency of use has been found to influence impacts in different ways with some studies of human trampled peat observing greatest impacts after the first passes which then plateau (Calais and Kirkpatrick, 1986), whilst others have found minimal change up to a threshold and then greater change after that threshold is reached (Whinam and Chilcott, 2003). It was therefore hypothesised that with an increasing number of passes over the unsurfaced track (treatment **U)** there would be a change in vegetation composition and height (hypothesis iv).

While variation was observed in percent cover for *C. vulgaris, E. vaginatum* and *S. capillifolium* with an increasing number of passes, there was no clear evidence of an overall decreasing trend in the percent cover of these species in treatment **U** (Figure 7.14). Only *E. vaginatum* yielded a significant decrease in percent cover between the 2013 and 2015 surveys in treatment **U**, but abundance showed variation through continuous monitoring. Some of this variation could be attributed to seasonal effects; peak abundance for *C. vulgaris* and *E. vaginatum* are at different times of year and out of step with each other (Forrest, 1971), thereby explaining the lack of clear seasonal patterns in the data.

Vegetation height exhibited greater evidence of an effect of the driving in treatment **U**, with clear evidence of overall lowering at all topographic locations (Figure 7.16). Although patterns in the plots implied 'recovery' at certain times, possibly an indication of new growth, the lowest vegetation heights were recorded after the highest number of passes over the track. The height of the vegetation never reached zero (peat surface) and could be attributed to the height and density of the vegetation prior to driving. In this treatment, the decrease in the height of the vegetation was probably related to the flattening and squashing of stems of *C. vulgaris* and *E. vaginatum*. Abele et al. (1984) observed one of the most obvious effects of driving over unsurfaced vegetation (arctic tundra) was compression of the vegetation and flattening of the micro-relief. It is likely that a similar effect was happening on the unsurfaced track within this study.

Linked with the minimal change in percent cover of the key species, there was no increase in the occurrence of bare peat with an increasing number of passes. Instead a decrease in the occurrence of bare peat was observed. Overall the occurrence of bare peat in treatment **U** was minimal, with the highest percent cover (1 %) recorded after eight passes and the lowest after 24 passes. As the vegetation height never reached zero, the peat surface was probably protected from the vehicle wheels. This may have mitigated against noticeable reductions in vegetation cover and increases in bare peat. Indeed, Sparrow et al. (1978) noted the crushing and grinding effects of wheels over the vegetation when the track was unsurfaced, however in that study the initial vegetation cover may not have been as dense as that in treatment **U**. Furthermore, as the vegetation height lowered, through the flattening of the taller vegetation, it could have covered any exposed peat that was surveyed, providing further explanation for minimal occurrence of bare peat observed in this treatment.

Based on these findings, using data from treatment **U** where vegetation composition and height and the occurrence of bare peat were recorded after every driving event over the treatment, hypothesis (iv) was rejected with respect to a change vegetation composition and increase in bare peat occurrence with an increased number of passes over the track. However, hypothesis (iv) was accepted with respect to vegetation height as there was evidence of a lowering in the height of the vegetation with an increasing number of passes.

7.4.5 Greater Impacts Observed in Wheel Ruts

With respect to existing unsurfaced vehicle track studies, the locations of greatest disturbance are typically in line with the vehicle wheels (e.g. Charman and Pollard, 1995). It was therefore hypothesised that the greatest impact to vegetation cover would be evident in the 'wheel ruts' relative to other locations across the track width, even with the presence of the plastic mesh track. Vegetation height and bare peat occurrence in the 2015 data both varied with sampling location across the track, with evidence of slower recovery in the wheel ruts compared with the rest of the track width, particularly in the plastic mesh track treatments. This linked with the results of the topographic surveys (Chapter 5).

Taller vegetation was measured at the edge of the track in all treatments, which indicated preferential regrowth. This was possibly influenced by the undisturbed vegetation off-track and the limited on-track disturbance at these locations following installation. The shortest vegetation was found in line with the wheel routes. Therefore, regrowth was slowed or prohibited at those points across the track. Such a pattern was not observed in treatment **W** where the vehicle wheels were not in direct contact with the peat surface.

In treatment **U**, where the vegetation had not been cut, the greatest lowering was found to occur in the centre of the track. At topographic location S3 in this treatment lowering of the height of the vegetation was enhanced in line with the wheel ruts. At the site scale, bare peat occurrence was also found to be greater in the middle of the track (plastic mesh in particularly) compared with the edges. In this study, however, the spatial patterns in both vegetation height and bare peat occurrence across track did not hold for every treatment *x* topographic location combination. This further supports the conclusion that the vegetation present prior to disturbance has a strong control over change relative to initial conditions and the rate of recovery. Hypothesis (v) can, however, be accepted in that greater impacts were observed in line with the wheel ruts where greatest pressure was applied, supported by data from the plastic mesh track treatments and treatment **U**.

7.5 Chapter Summary

- This study was the first to investigate the impact of plastic mesh, articulated wooden and unsurfaced vehicle tracks on blanket peatland vegetation. The study also differed from others in that use of the track was ongoing whilst surveying was undertaken.
- Natural variation was observed in vegetation composition across the site in surveys carried out prior to track installation, with dissimilarity between 38 % to 59 % yielded between the different treatments, and may have an influence on variation in levels of recovery observed across the site following plastic mesh, articulated wooden and unsurfaced track use.
- Track type was an important influence on vegetation composition, height and bare peat occurrence. This was related to the differences in ground preparation for the three track types, with the vegetation cut prior to plastic mesh and articulated wooden track installation. Where the vegetation was cut (plastic mesh and articulated wooden tracks), vegetation composition was significantly different, vegetation height was lower and bare peat occurrence was higher compared with the uncut treatment.
- In the treatments where the vegetation was cut, **PWEEK.AL**, **PWEEK.AH**, **PWEEK**, **PMONTH**, **PDELAYED** and **W**, a reduction in percent cover of key species *C. vulgaris, E. vaginatum* and *S. capillifolium* was observed. The differences were predominantly only significant for *C. vulgaris* and *E. vaginatum.* The results therefore show evidence of a slower recovery of/greater impact to vascular plants compared with bryophytes.
- The highest occurrence of bare peat was observed in the least frequently used treatment (**PMONTH**). At the site scale the highest occurrence of bare peat was found at topographic location S3 (bottom-slope). This pattern did not hold when broken down by treatment, where only treatments **PMONTH** and **PWEEK** exhibited such a pattern.
- Bare peat occurrence also exhibited spatial variation across the track width, the highest occurrence in line with wheel routes at the site scale. This did not translate at the treatment *x* topographic location breakdown of the data, where the spatial pattern was only observed in selected treatment *x* topographic location combinations (all for the plastic mesh track).
- Photographic evidence collected during the study showed recovery of vegetation along the track route. Not all treatments exhibited the same degree of regrowth. Treatment **W** exhibited some of the slowest regrowth of vegetation, with little evidence until 2015.
- In treatment **U** no track was installed and driving occurred over an unsurfaced route. Percent cover *C. vulagaris*, *E. vaginatum*, and *S. capillifolium* did not show a significant decrease between 2013 and 2015. There was also no clear effect of an increasing number of passes on vegetation composition. The height of the vegetation was found to become lower with an increasing number of passes. The occurrence of bare peat was minimal in this treatment and showed an unexpected decrease in percent cover with increasing number of passes. The stands

of *C. vulgaris* were mature and old, and the vegetation cover dense in this treatment prior to the creation of the track and may therefore have had an influence by providing greater protection to the peat surface.

- While track type exhibited a clear influence on vegetation change through track use, with a lowering of the vegetation height and reduction in the percent cover of key species associated with the plastic mesh and articulated wooden tracks, the influence of frequency of use did not exhibit any clear patterns. The magnitude of recovery of key species, height of vegetation regrowth or occurrence of bare peat did not exhibit a relationship with the number of passes over the plastic mesh track.
- The influence of topographic location appeared to be linked to the influence that it has on undisturbed species composition, i.e. the preference of species to different wetness conditions. This in turn has an influence on the rate of recovery of specific species, depending on their prevalence at a particular topographic location.
- Vegetation composition before disturbance and the installation method of a track appear to be the key influences on the impacts of tracks in blanket peatlands, where the vegetation cover is dense and mature.
- It is possible that *C. vulgaris-E. vaginatum* dominated bogs may be more resilient to disturbance from the tracks and peatlands dominated by other types of vegetation such as *Erica tertalix-Sphganum papillosum* could exhibit lower levels of resilience (Averis et al., 2004). Therefore results should be interpreted in the correct context.

CHAPTER 8: CONCLUSIONS

8.1 Research Overview

Tracks, constructed and unsurfaced, are a common feature of peatlands around the world. However, understanding of their impact on the functioning of these systems is very limited. This was highlighted through the review of existing literature undertaken in Chapter 2 which identified major gaps in our current knowledge. Previous work has often focused on the geotechnical issues of construction on peat, with some consideration given to impacts to vegetation. However, despite assumptions that such linear disturbances will interrupt the natural flow pathways within peatlands and consequently their hydrological functioning, there are very few studies which have attempted to capture these effects. Figure 8.1 revisits the conceptual diagram shown in Chapter 2, outlining the potential impacts of tracks in peatlands based on existing literature and highlighting the impacts to properties addressed through this thesis.

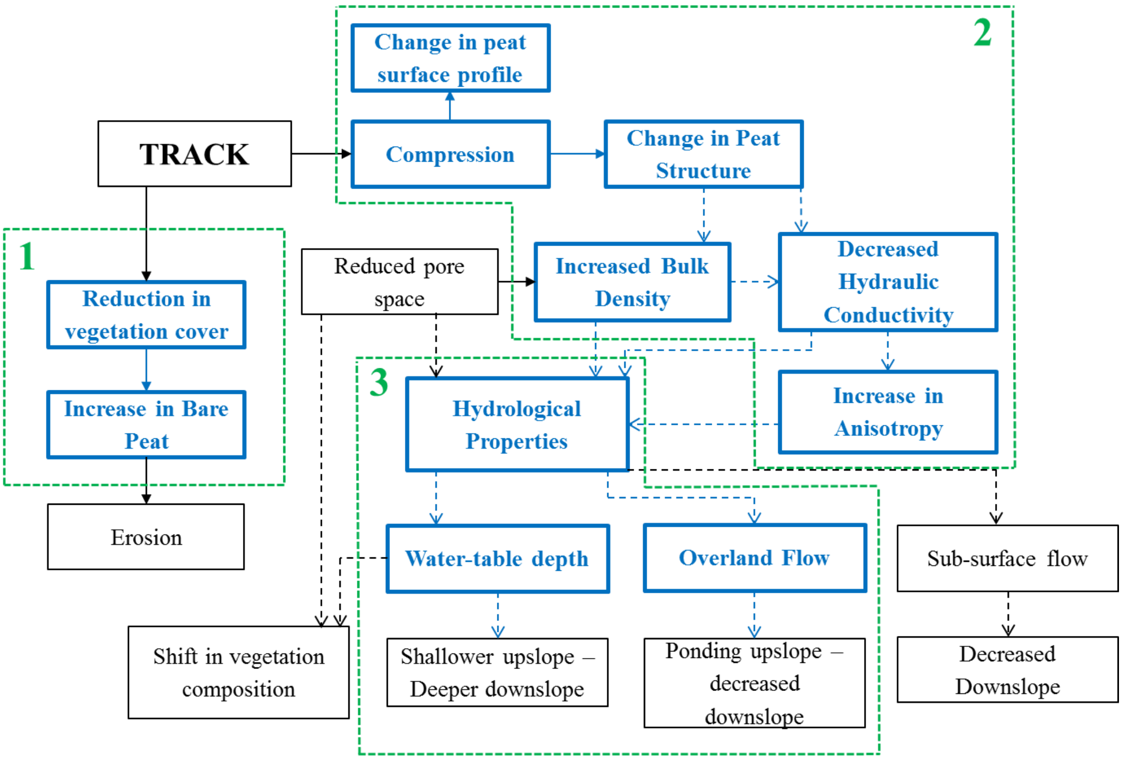

Figure 8.1 Conceptual diagram outlining the links between peatland properties following track construction and use. Solid lines indicate where current evidence exists, dotted black and blue lines indicate assumed impacts, those based on anecdotal evidence. Boxes highlighted in blue are those properties addressed in the thesis. Numbered green boxes inform the structure of section 8.2.

With respect to blanket peatlands specifically, knowledge of disturbance from tracks is almost non-existent, with scientific studies predominantly limited to the impacts of military vehicles on vegetation (Charman and Pollard, 1995) and human trampling on hydrochemistry and vegetation (Robroek et al., 2010). To the author's knowledge, there had been no studies of the impact of vehicle tracks on blanket peat hydrological properties until the current thesis. Blanket peatlands differ from other peatland types as they form on steeper slopes. Consequently, tracks have the potential for greater impact if they influence water flow paths on the slopes.

A two strand approach was used in this study, with the purpose of improving our wider understanding of the impact of tracks on blanket peat (the regional survey), and also investigating the impact of novel (plastic mesh and articulated wooden) and previously untested (unsurfaced) track types on varying blanket peatland properties and characteristics (the intensive study). These properties included bulk density, hydraulic conductivity, surface profile elevation, water-table depth, overland flow occurrence and vegetation composition and height. The research presented in this thesis is the first to investigate the impact of tracks on blanket peat ecohydrology and considered four key research areas: (i) the influence of track type, (ii) the spatial extent of impacts, (iii) the influence of topographic location, and (iv) the influence of frequency of use. In this chapter the results from the two strands of research, the regional study in the North Pennines and Cheviots (Chapter 4) and the intensive study at Moor House in the North Pennines (Chapter 5-7) are synthesised to provide a summary of key findings, address the limitations of the research and highlight areas for future research.

8.2 Synthesis of Key Findings

The research presented in this thesis has shown that tracks do have an impact on aspects of blanket peat ecohydrology, although the extent of impact is variable between properties measured. A summary of the outcomes related to each hypothesis tested in this thesis is presented in Table 8.1. For some peat properties there was clear change following disturbance (e.g. surface profile elevation, vegetation characteristics) while others exhibited little change (e.g. water-table depth). In both the regional survey and the intensive study, track type and topographic location were found to be key influential factors, when evidence of an impact was identified. Frequency of use was addressed within the intensive study and found to have minimal effect. Table 8.2 summarises where the properties measured exhibited differences in response with respect to the key influential factors. The extent of spatial effects varied between properties and is addressed in Table 8.1. This synthesis considers the results (as presented in Table 8.1) with respect to the assumptions of peatland track impacts in the current literature (Figure 8.1) and the four research areas outlined in Chapter 1. Links and feedbacks between the properties measured will also be addressed. The structure of the following sections is informed by the numbered green boxes in Figure 8.1.

Table 8.1 Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables. Continued on Pages 229 - 237

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 4: Regional Survey		
(i) Volumetric moisture content will be higher on the upslope side of the track relative to the downslope side of the track	- Of the parallel and diagonal plastic mesh tracks included in the regional survey there was no evidence of a higher upslope-lower downslope difference in volumetric moisture content around the tracks.	**Section 4.3.1**: **Table 4.6**
	- A significantly higher moisture content was observed on the upslope side of the parallel and diagonal stone tracks relative to the downslope.	**Section 4.3.1: Figure 4.7, Table 4.7**
	- In *post-hoc* testing parallel stone tracks still exhibited a higher moisture content upslope relative to the downslope, but the difference was not significant.	**Section 4.3.1: Table 4.7**
	- **Hypothesis (i) was rejected for plastic and stone tracks**	
(ii) There will be more pronounced differences between upslope and downslope volumetric moisture content in mid-slope locations compared with flatter top- and bottom-slope locations	- Significant differences between upslope and downslope volumetric moisture content were only found at top- and mid-slope positions for parallel stone tracks.	**Section 4.3.2 : Table 4.9**
	- **Hypothesis (ii) was accepted for stone tracks.**	

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 4: Regional Survey (continued)		
(iii) There will be more pronounced differences between upslope and downslope volumetric moisture content around older tracks	- Variation was observed with track age around plastic and stone tracks irrespective of orientation to the slope	**Section 4.3.3: Figure 4.6, Figure 4.7, Table 4.10, Table 4.11**
	- Around stone tracks (5-10 years and 15+ years) no significant difference was found between the upslope and downslope sides.	**Section 4.3.3**
	- Plastic tracks did not exhibit evidence of a pattern in the difference between the two sides of the track with track age	**Section 4.3.3**
	- **Hypothesis (iii) was therefore rejected for both track types.**	
(iv) A relationship will exist between volumetric moisture content and distance from the track edge.	- Relationship between plastic tracks and distance from track edge could not be tested.	
	- Moisture content showed large variation with distance from stone track edge at top-, mid- and bottom-slope locations.	**Section 4.4.4: Figure 4.8**
	- Suggestion of lower moisture content immediately downslope of stone tracks at top-slope topographic location.	
	- **Hypothesis (iv) was not tested for plastic tracks and rejected for stone tracks.**	

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 5: Physical Properties		
(i) There will be evidence of higher bulk density after driving compared with before	- Overall BD (0-30 cm) was found to be lower after driving compared with before for all track types and frequencies of use	**Section 5. 3.1: Figure 5.6, Table 5.3**
	- Track Type did have an influence –Treatment **U** had lowest After BD, Treatment **W** showed an increase in the surface peat After BD.	**Section 5.3.1: Figure 5.8, Figure 5.9, Table 5.5**
	- On-track After BD was higher that off-track After BD for selected treatments (**PWEEK.AL**, **PWEEK.AH**, **U** and **W**).	**Section 5.3.1**
	- Treatment **W** had higher After BD in top 5cm.	**Section 5.3.1: Figure 5.9, Table 5.6**
	- Suggestion of increased in BD between ~5 and 15 cm in profile after driving in selected treatments (**PWEEK.AL**, **PWEEK.AH**, and **PWEEK**)	**Section 5.3.1: Figure 5.9**
	- Bulk density did exhibit variability in treatment **C** suggesting not all of the impacts could be related to track installation and use.	**Section 5.3.1**
	- **Hypothesis (i) was rejected for overall BD**	
(ii) K will be lower after driving compared with before driving	- K_h was faster than K_v in Before and After samples	**Section 5.3.2: Figure 5.10**
	- After K_v was significantly lower than Before K_v, After K_h was higher than Before K_h (not significant)	**Section 5.3.2: Table 5.7**

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 5: Physical Properties (continued)		
(ii) *K* will be lower after driving compared with before driving (continued)	- Direction of change varied at treatment level (driven or control) and topographic level – suggestion of decrease in K_v and increase in K_h in driven treatments. - K_v and K_h showed variation from Before to After in Treatment **C** – suggesting natural variation. - **Hypothesis (ii) was only accepted for K_v**	**Section 5.3.2: Figure 5.13, Table 5.8** **Section 5.3.2: Figure 5.13, Table 5.8**
(iii) The peat surface profile will become lower with an increasing number of passes.	- Peat surface profile showed a lowering over time – although there was spatial variation in magnitude across track width - There was no clear pattern of increased lowering with increased number of passes - At most survey locations greatest lowering was recorded between April 2014 and October 2014. - Increase in elevation recorded at selected locations – indication of recovery or pushing up of peat - **Hypothesis (iii) was only partly accepted – lowering occurred but did not increase with an increasing number of passes.**	**Section 5.3.3: Figure 5.16, Table 5.11** **Section 5.3.3: Figure 5.16, 5.17** **Section 5.3.3:Figure 5.16** **Section 5.3.3: Figure 5.16**

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 6: Hydrological Properties		
(i) There will be evidence of a change over-time in water-table depth.	- Statistical analysis showed a significant difference in the residuals mean daily water-table depth for selected individual dipwells between years for each season (Spring, Summer and Autumn). - There was no clear trend in the change over time however. - Information only relates to water-table depth at topographic location S3. - **Hypothesis (i) was rejected due to lack of consensus in the data**	**Section 6.3.1.2 : Table 6. 4, Figures 6.12-6.16**
(ii) There will be evidence of the water table becoming shallower upslope of the track and deeper downslope, as with peatland drainage.	- Only applicable to topographic location S3 - At the site scale there was no significant difference between the upslope and downslope sides of the tracks	**Section 6.3.1.3: Table 6.5**
	- Only treatment **PWEEK** exhibited a significantly shallow water table upslope compared with the downslope.	**Section 6.3.1.3: Table 6.6**
	- The water table was significantly deeper upslope compared with downslope for treatments **PWEEK.AL**, **U** and the control (treatment **C**).	**Section 6.3.1.3: Table 6.6**

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 6 : Hydrological Properties (continued)		
(ii) There will be evidence of the water table becoming shallower upslope of the track and deeper downslope, as with peatland drainage. (continued)	- No significant difference was observed between the upslope and the downslope sides of the track for treatments **PWEEK.AH**, **PMONTH**, **PDELAYED** and **W**.	**Section 6.3.1.3: Table 6.6**
	- There was no clear effect of frequency of use or track type.	
	- **Hypothesis (iii) was rejected due to variation in the impacts observed**	
(iii) There will be evidence of an increase in overland flow resulting from the track.	- A significant increase was observed in the occurrence of overland flow for the September to October period from 2014 to 2015. This was not found for the April to June period.	**Section 6.3.2**
	- Treatment **U** exhibited a statistically significant increase in the occurrence of overland for both the April to June and September to October period from 2014 to 2015.	**Section 6.3.2: Figure 6.23, Figure 6.24**
	- Treatments **PDELAYED** and **C** exhibited a significant increase for the September to November period only.	**Section 6.3.2: Figure 6.24**
	- There is no clear indication that track type or frequency of use were influential. Topographic influence has not been considered here.	**Section 6.3.2**
	- Possible that increase is due to antecedent conditions given the significant increase in treatment **C**.	**Section 6.3.2: Figure 6.23, Figure 6.24**

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 6: Hydrological Properties (continued)		
(iii) There will be evidence of an increase in overland flow resulting from the track (continued)	- Higher occurrence of overland flow in middle of track relative to off-track (plastic mesh, unsurfaced and articulated wooden) could indicate increase in overland flow resulting from track. Especially at topographic locations S2 and S3. - **Hypothesis (iii) was rejected due to lack of agreement in the data.**	**Section 6.3.2: Table 6.13, Table 6.14**
(iv) There will be evidence of a spatial impact of the track on blanket peat hydrology, extending beyond its immediate footprint.	- Natural variation was observed in water-table depth around the three track types at all topographic positions.	**Section 6.3.1.3: Table 6.7, Table 6.8**
	- By treatment (track type and frequency of use), there was spatial variation in distances that were significantly different from each other on the upslope and downslope sides of the track.	**Section 6.3.1.3: Tables 6.9, Table 6.10.**
	- Only treatment **PWEEK** at topographic location S3 exhibited shallower upslope and deeper downslope water-table values at each distance.	**Section 6.3.1.3: Table 6.10**
	- Within other treatments difficult to disentangle effects of tracks from influence of natural spatial variation in water-table depth.	**Section 6.3.1.3: Table 6.10**

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 6: Hydrological Properties (continued)		
(iv) There will be evidence of a spatial impact of the track on blanket peat hydrology, extending beyond its immediate footprint. (continued)	- In general, over the monitoring period at topographic location S3 areas of shallower water-table remained shallow and deeper water-table remained deep. - Variation in water-table depth was greater within 1 m of the edge of all track types. Observed at all three topographic locations. - **Hypothesis (iv) partially accepted as greater variability was observed within ~1 m of track edge.**	**Section 6.3.1.3: Figure 6.21 a-d** **Section 6.3.1.3**
Chapter 7 : Vegetation		
(i) Vegetation change (composition and height) will vary with track type and frequency of use.	- A significant decrease in percent cover of key species (*C. vulgaris, E. vaginatum, S.capillifolium*) was found for the plastic mesh and articulated wooden tracks, but not the unsurfaced track. There was no clear effect of frequency of use. - Vegetation height was lower in 2013 compared with 2015 for all track types. There was no clear effect of frequency of use. - Bare peat occurrence increased from 2013 to 2015 across all treatments - **Hypothesis (i) was accepted for track type but not frequency of use**	**Section 7.3.3.1: Figures 7.8-7.10** **Section 7.3.3.2: Figure 7.12** **Section 7.3.3.3**

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 7 : Vegetation (continued)		
(ii) Topographic location will influence vegetation change with drier mid-slopes showing less change than wetter bottom-slopes.	- Topographic location did not appear to have an effect on vegetation change.	**Sections 7.3.3.1 & 7.3.3.2: Figures 7.8-7.10**
	- There was no clear pattern of an effect of topographic location on bare peat occurrence within each treatment	**Section 7.3.3.3**
	- **Hypothesis (ii) was rejected**	
(iii) The occurrence of bare peat will be greatest in more frequently used treatments and lowest in least frequently used treatments	- The occurrence of bare peat was not higher in the more frequently used treatments and lowest in the least frequently used treatments.	**Section 7.3.3.3**
	- **Hypothesis (iii) was rejected**	
(iv) With an increasing number of passes over the unsurfaced track there will a change in vegetation composition, a lowering in the height of the vegetation and an increase in the occurrence of bare peat.	- In treatment **U** there was no clear effect on vegetation composition for the key species.	**Section 7.3.4: Figure 7.14**
	- A lowering in the vegetation height was found at all three topographic locations in treatment **U** with an increasing number of passes.	**Section 7.3.4: Figure 7.16**
	- Bare peat occurrence did not show a decrease with increasing number of passes over treatment **U**.	**Section 7.3.4: Figure 7.15**
	- **Hypothesis (iv) was accepted for vegetation height but rejected for vegetation composition and bare peat**	

Table 8.1 continued Summary table of all hypotheses tested in this thesis listed by the Chapter they appear in. Outcomes relating to each hypothesis are also given in addition to the related section the results can be found in within the thesis and any relevant Figures and Tables.

Chapters and Hypotheses	Outcome	Related Section/ Figures/ Tables
Chapter 7 : Vegetation (continued)		
(v) There will be evidence of greater impacts in the wheel routes compared with other locations across the track width.	- Vegetation regrowth (height in 2015) exhibited a spatial pattern. Vegetation was taller at the edge and in the middle of the track compared with the wheel routes. This was observed in all treatments (track type and frequency of use) and topographic locations.	**Section 7.3.3.2: Figure 7.11 and Section 7.3.4: Figure 7.16**
	- At the whole site scale bare peat occurrence was highest in the wheel routes and lower at the track edges. This pattern held by topographic location but not by treatment.	**Section 7.3.3.3: Figure 7.13, Table 7.7, Table 7.8**
	- **Hypothesis (v) was accepted**	

Table 8.2 Summary of which influential factors led to variation in the impacts observed to the key properties measured. ✓ indicates variation in track impacts resulting from influential factor, X indicates there was no clear effect from influential factor on track impacts.

Key Properties Measured	Influence of Track Type	Influence of Topographic Position	Influence of Frequency of Use
Volumetric Moisture Content	✓	✓	n/a
Bulk Density	✓	n/a	X
Hydraulic Conductivity	n/a	✓	X
Surface Profile Elevation	✓	X	X
Water-table Depth	X	✓	X
Overland Flow Occurrence	X	✓	X
Vegetation	✓	X	X

8.2.1 Response of Blanket Peat Vegetation to Track Installation and Use

The noticeable reduction in cover of *Calluna vulgaris,* and in some treatments *Eriophorum vaginatum*, and the increase in the occurrence of bare peat indicated that the tracks had a negative impact on blanket peat vegetation composition, in line with current understanding (Figure 8.1 – Box 1). There was a clear influence of track type in this result, with the treatments which underwent vegetation cutting prior to track installation yielding reductions in percent cover of these characteristic blanket peatland species (see Table 8.1: Chapter 7 – Hypothesis (i)). In contrast, treatment **U,** which did not undergo ground preparation, showed minimal reduction in cover of *Calluna vulgaris* and *Eriophorum vaginatum*. However, clear lowering of the vegetation height was observed with an increasing number of vehicle passes in treatment **U**, indicating the potential for low-ground-pressure vehicles driving over unsurfaced peat to have an impact on the vegetation (Table 8.1: Chapter 7 – Hypothesis (iv)).

In all of the treatments, percent cover of *Sphagnum capillifolium* showed the least amount of change suggesting minimal disturbance (higher resilience) during track installation or faster recovery compared with *Calluna Vulgaris* and *Eriophorum vaginatum*. There was visual evidence of vegetation regrowth, predominantly *Eriophorum vaginatum* within the cut treatments, although the extent of recovery did vary between treatments and spatially across the track width. Recovery of vegetation was slowest in line with the wheel routes compared with the rest of the track width (Table 8.1: Chapter 7 – Hypothesis (v)). This suggests that continued disturbance limits the rate of recovery, yet overall some of the lowest rates of recovery were in treatment **PMONTH**, where the occurrence of driving was lowest and therefore continued disturbance minimal. Vegetation composition across the site did exhibit natural variation prior to disturbance and it is likely that the vegetation composition prior to disturbance influences the rate of recovery after disturbance (e.g. Hobbs, 1984, Hobbs and Gimingham, 1984, Arnesen, 1999). This may also explain the lack of influence of topographic location on vegetation recovery (cut treatments) (Table 8.1: Chapter 7 – Hypothesis (ii) and Table 8.2) or disturbance (treatment **U**).

Visual observations made during the regional survey showed that where vegetation was not cut prior to track installation recovery was more rapid, with many tracks being covered by a carpet of *Sphagnum* spp. within a couple of months (Figure 8.2), further indicating the influence of pre-disturbance vegetation composition.

Figure 8.2 Plastic mesh track, approximately 1 year after installation on a working estate where vegetation was not cut prior to installation.

With respect to constructed plastic mesh tracks, the presence of a track does not necessarily equate to the total loss of vegetation cover. This study has shown that there is variation in the magnitude of impact which could be related to the disturbance involved in track installation (Table 8.1: Chapter 7 – Hypothesis (i)). Change in vegetation composition was surveyed approximately two years after track installation and one year after driving in this study. Longer-term monitoring would provide an indication of the continued recovery of the vegetation and any longer lasting impacts that may become apparent.

Clearly, the regrowth of the vegetation has positive effects for the carbon storage potential of the peatland. In addition, it means that the bare peat is being covered and therefore limits the potential for widespread erosion along the track which could lead to the transportation of particulate organic carbon.

8.2.2 Response of Blanket Peat Physical Properties to Track Installation and Use

The installation and use of plastic mesh, articulated wooden and unsurfaced tracks on blanket peat led to peat compression (Figure 8.1 – Box 2), evidenced through a lowering of the surface profile elevation in all treatments (Table 8.1: Chapter 5 – Hypothesis (iii)). In addition, this compression was spatially variable across the track width, with greater lowering often observed in line with wheel routes. This suggests that, even with the presence of the plastic mesh track, there is potential for locations of greater pressure where the vehicle wheels are in close contact with the peat surface. Such an effect was not observed in treatment **W** where the travelling surface of the 4x4 vehicle was raised above the peat surface.

Surface bulk density (0-5 cm) exhibited a decrease rather than an increase in most treatments (plastic mesh and unsurfaced track) suggesting that compression of the peat resulting in the lowering of the surface elevation may have occurred at depths greater than 5 cm (Table 8.1: Chapter 5 – Hypothesis (i)). The exception to this was treatment **W**, where an increase in bulk density was observed in the upper 0-5 cm of the peat profile, suggesting that track type and installation methods were influential in the impacts observed. For both surface profile elevation and bulk density, track frequency of use did not exhibit a clear influence on the extent of impacts (Table 8.1: Chapter 5 – Hypotheses (i) and (iii) and Table 8.2).

For the first time, the response of *K* was considered in relation to plastic mesh track use on blanket peat. Surface *K* exhibited strong positive anisotropy before and after track installation and use (Table 8.1: Chapter 5 – Hypothesis (ii)), with the results adding to a currently sparse dataset on *K* in blanket peatlands. Following installation and use of the plastic mesh track, surface *K* (0-10 cm) was found to alter with decreased vertical *K* and increased horizontal *K* in both of the driven treatments included in the study (**PWEEK.AL** and **PMONTH**). Decreased vertical *K* further supports the notion of peat compression below 5 cm, while the change in horizontal *K* suggests a possible alteration in pore orientation. The response of *K* to plastic mesh track use could therefore be considered dependent on flow direction. Frequency of use did not exert a clear influence on *K*, yet topographic location of the samples collected did (Table 8.1: Chapter 5 – Hypothesis (ii) and Table 8.2). The lack of clear impacts within the top 5 cm of the peat profile has implications for the movement of water through the peat and will be addressed further in section 8.2.4.

8.2.3 Response of Blanket Peat Hydrological Properties to Track Installation and Use

Based on previous literature and theory it was assumed that tracks on blanket peat would interrupt natural flow pathways, resulting in differences in hydrological conditions on either side of a track (Figure 8.1 – Box 3). Chapter 4 showed that there was greater volumetric moisture content on the upslope side relative to the downslope side of parallel stone tracks, indicating a difference in hydrological conditions between the two sides of the tracks and a potential loss of connectivity (Table 8.1: Chapter 4 – Hypothesis (i)). In addition, the difference between the upslope and the downslope positions was more pronounced at the top- and mid-slope locations for the parallel stone tracks, suggesting an influence of topography on the magnitude of impact (Table 8.1: Chapter 4 – Hypothesis (ii)). Plastic tracks were typically installed perpendicular to the contours on steeper slopes for practical reasons and did not exhibit the same difference in volumetric moisture content either side of the track. Within the regional survey, moisture content was also measured around selected plastic mesh treatments at Moor House (intensive study site) and found to behave in a similar way as other plastic mesh tracks installed in the region.

Variation in the response of water-table depth and overland low occurrence was observed with respect to the plastic mesh, articulated wooden and unsurfaced tracks of the intensive study (Chapter 6), leading to the conclusion that within the time-scale of the intensive study there was no clear evidence of an impact of the tracks on water-table depth. Where the tracks were installed flat or perpendicular to the contours (topographic locations S1 and S2) there was no clear difference in water-table depth between the right and left sides of the plastic mesh and unsurfaced tracks (Table 8.1: Chapter 6 – Hypothesis (ii)), further supporting the observations of the regional survey. Where upslope-downslope sides to the track occurred (at topographic location S3), only one plastic mesh track treatment of medium use exhibited a shallower upslope-deeper downslope pattern in water-table depth (Table 8.1: Chapter 6 – Hypothesis (ii)). In addition, water-table depth was found to remain shallow across the intensive study site. While there was evidence of a change overtime in water-table depth at individual locations, the results were unclear with respect to the direction of change (Table 8.1: Chapter 6 – Hypothesis (i)). Furthermore, wider spatial analysis showed areas of deeper water table to remain deep and shallower water table to remain shallow (Table 8.1: Chapter 6 – Hypothesis (iv)).

Overland flow did exhibit evidence of a change over time. The effect of the track was difficult to disentangle from antecedent conditions however (Table 8.1: Chapter 6 – Hypothesis (iii)). There was however evidence of a greater occurrence along the track route compared with off-track for all track types (Table 8.1: Chapter 6 – Hypotheses (iii) and (iv)). In addition, at certain locations channelization of flow was found to occur, typically in line with wheel routes (see section 8.2.4). Therefore, with respect to the plastic mesh and unsurfaced tracks there is potential for zones of preferential flow to occur. Trampling by sheep on blanket peatlands has led to the creation of erosion scars, devoid of vegetation cover (Evans, 2005), which are also known to be hydrologically active conduits (Zhao, 2008). Further investigation in conjunction with the continued recovery of vegetation along the track route would be beneficial to determine the impact of such an occurrence with respect to vehicle tracks on blanket peat.

The results presented here are of particular significance given the importance that is assigned to limiting hydrological impacts during road construction and use on peatlands (Munro, 2004). The findings of Chapters 4 and 6 suggest that track type, topographic location and by association track orientation relative to the slope are influential on the extent of impact to hydrological properties (volumetric moisture content, water-table depth and overland flow occurrence) (Table 8.2).

Within the intensive study, frequency of use was not found to exert a clear influence on water-table depth or overland flow occurrence (Table 8.1: Chapter 6 and Table 8.2). The findings from Chapters 4 and 6 could be used by government agencies and land owners to inform the granting of permissions for track installation and provide advice on the appropriate location of tracks for minimal impact. Therefore, recommendations from this thesis are, taking into consideration expected track use: use plastic mesh tracks over stone tracks where possible; orientate tracks in relation to the slope so as to avoid creating upslope-downslope splits in flow paths; and install plastic mesh tracks on the driest areas of the peatland (areas with deepest water table) to avoid the channelization of overland flow.

8.2.4 Links between the Responses of Vegetation, and Physical and Hydrological Properties

The links between ecology and hydrology in peatland systems have long been recognised (Charman, 2002). Hence, the many feedbacks which exist between peatland ecological, hydrological and physical properties should be taken into consideration when interpreting impacts to peatland systems, with changes in one property likely to be evidenced or explained by changes in another. In this section potential links between the responses of vegetation and physical and hydrological properties following track installation and use that have been reported in this thesis are addressed.

8.2.4.1 Physical and Hydrological Properties

Figure 8.1 illustrates assumed links between the response of physical and hydrological properties following track construction and use. It has previously been assumed that there would be an upslope-downslope difference in water-table depth and overland flow occurrence as a result of a loss of connectivity between the two sides of the track, often stemming from a reduction in pore space in the peat directly under the track. As observed in the intensive study in this thesis, while there was evidence of compression of the peat and a decrease in vertical K, the top 5 cm of the peat remained relatively unaffected (Table 8.1: Chapter 5 – Hypothesis (i) and (ii)). Given that this is the zone where the greatest flow of water occurs within blanket peat (Holden and Burt, 2003c) it can be reasoned that the lack of impact observed in water-table depth and overland flow occurrence can be attributed to uninterrupted flow pathways. The decrease in vertical K directly under the plastic mesh track may have implications for overland flow resulting in a shift from saturation-excess to infiltration-excess. However, the suggested enhanced lamination of the peat structure, indicated by increased horizontal K in some locations implies that the lateral movement of water was still possible under the track. Further investigation would be required to determine whether this equated to improved connectivity between the sides of the track, as the horizontal orientation of the pores in relation to the track was not considered in this study.

Overland flow occurrence also exhibited links with the surface profile elevation results. Where surface profile elevation has shown a greater lowering in line with the wheel routes, there was channelization of overland flow along these depressions. It is not clear, however, from this study, whether the overland flow is a result of the reduced permeability in the wheel ruts or merely the creation of zones of preferential flow due to track depression.

8.2.4.2 Vegetation and Hydrological Properties

A link not included in the original conceptual diagram was that between vegetation cover and overland flow occurrence. Within the intensive study, between treatments, those with the highest occurrence of overland flow were often found to also have the lowest vegetation cover (slowest recovery). In addition, within treatments, overland flow occurrence was greatest where the vegetation had been cut, in the middle of the track and within 0.2m of the track edge, compared with 1m from the track edge. Furthermore, in treatment **U**, visual observations showed that there was greater evidence of overland flow and ponding where the vegetation was becoming compacted, a result of the increasing number of vehicle passes. This suggests a link between the vegetation cover and the occurrence of surface runoff. Vegetation cover has been found to influence the timing of streamflow at the catchment scale (e.g. Grayson et al., 2010). In addition, links have been observed between surface roughness, influenced by the extent and type of vegetation cover, and the velocity of overland flow (Holden et al., 2008). Hence, with continued vegetation recovery along the track routes, it would be useful to measure whether the occurrence of overland flow reduced or whether it was a function of the location of the track on the peatland.

8.2.4.3 Vegetation and Physical Properties

Vegetation influences the structure of peat and therefore characteristic physical properties such as bulk density and hydraulic conductivity. Bulk density measurements presented in Chapter 5 showed evidence of a decrease in the top 0-5 cm of the profile in many treatments. In addition, in a number of the samples collected for *K* analysis, a more open structure was observed in the top half of the samples (collected from 0-10 cm depth). Vegetation recovery was observed along the track route during the monitoring period via visual observations, and the lack of significant difference in the cover of *Sphagnum capillifolium* also suggests that recovery of some species has occurred. Given the links between vegetation and peat physical properties it is therefore possible that the observed and unexpected decrease in surface bulk density and increase in *K* are in part the result of vegetation regrowth and the formation of new peat.

8.2.5 The Impact of Tracks on Blanket Peat Ecohydrology

Figure 8.3 attempts to conceptualise the potential links which have been discussed above in relation to the intensive study and thereby illustrate the impact that tracks could have on blanket peat ecohydrology. It is clear that changes in one property have the potential to influence changes in another, and may even vary with track use. For example, a reduction in vegetation cover is linked with a higher occurrence of overland flow, while vegetation regrowth is linked with a lower occurrence of overland flow.

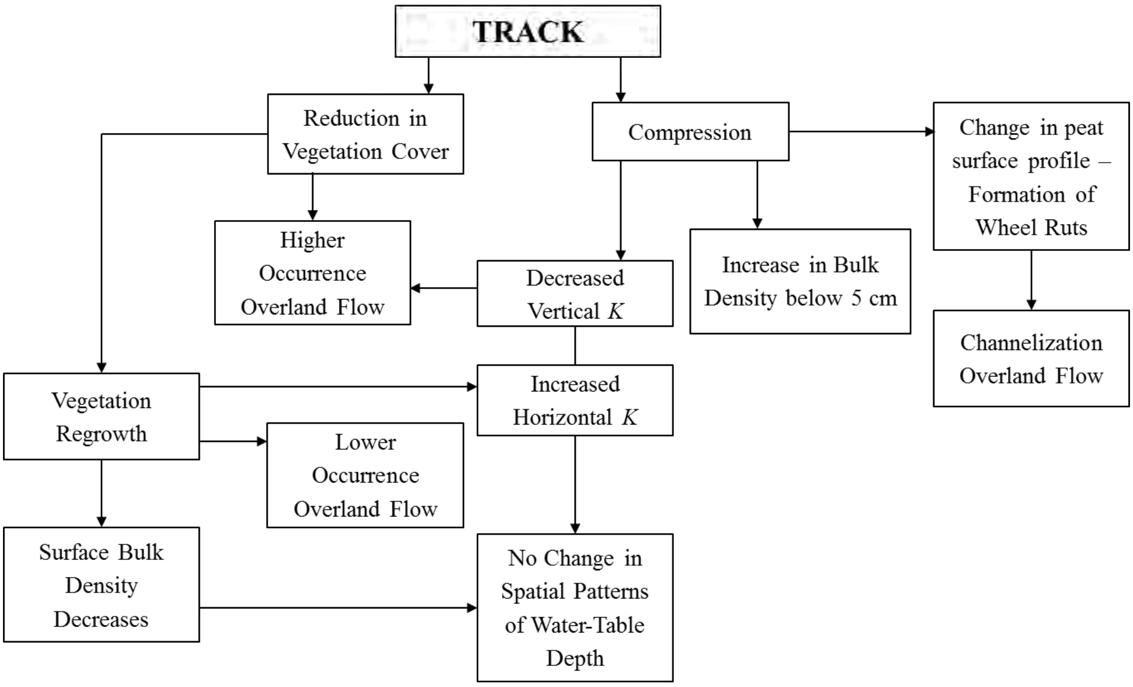

Figure 8.3 Conceptual diagram highlighting potential links between properties measured in the intensive study in this thesis, thereby illustrating the impacts of plastic mesh, articulated wooden and unsurfaced tracks on blanket peat ecohydrology.

8.3 Contextualising the Intensive Study

Within the regional survey, volumetric moisture content around the tracks was found to vary with track age, with a decrease in average volumetric moisture content observed with increasing age of track. Confounding variables such as track type and sampling date may have had some influence on the results observed, however the study suggested that the length of time a track is in place can influence the magnitude of impact. Consequently evidence of an impact from more recently installed (younger) tracks may be less noticeable. At the end of the monitoring period for the intensive study on Moor House the plastic mesh tracks had been *in-situ* for 27 full months and the articulated wooden track for 25 full months. In the context of the regional survey, plastic mesh tracks of the age grouping 1-5 years had high moisture content values relative to older tracks and showed no evidence of a difference between the upslope and downslope sides of the track (where they occurred). The tracks included in the intensive study therefore fit into this age group and it can be reasoned that the lack of clear evidence of an impact to some of the peat properties measured matches the findings of the extensive survey.

8.4 Limitations of Research

This study has contributed significant findings to a currently sparse evidence base regarding the impact of tracks on blanket peat. There are, however, limitations within the study which should be taken into consideration. While the results from the intensive study compare with those from the regional study with respect to the length of time since installation (section 8.3), the findings should be interpreted with the timescale of the study in mind. The results presented for the Moor House intensive study represents initial response to track installation and use (~2 years). However, peatlands develop and respond over decadal to centennial timescales so it is possible that with longer use the impact of the tracks included in the intensive study may become more apparent.

The results of the intensive study could be considered site specific. The installation of the track at the Moor House site required the cutting of vegetation due to its density; yet during the regional survey it was observed that the plastic mesh tracks were often installed directly onto the vegetation. The installation method may therefore have some influence on how the track performs and its impacts on the ecohydrological functioning of the peat and requires further study. In addition, Moor House is considered a relatively undisturbed site. On working estates it is unlikely that tracks would be installed on undisturbed peat and it is therefore possible that any hydrological impact of the tracks may interact with the effects of other management.

Ideally more plastic mesh, articulated wooden and unsurfaced tracks would have been included in the intensive study, incorporating blanket peatlands in different climatic locations (i.e. wetter and drier climate) and under different management conditions, for example burned or drained. In addition, the intensive study was located on a *Calluna vulgaris-Eriophorum vaginatum* dominated peatland. It is possible that with different types of vegetation cover the response of the ecohydrological properties to track use would be different. Low-ground-pressure vehicle type can vary and this may also have an influence on the observed impacts; especially with respect to the unsurfaced tracks as has been observed in other studies.

It should be noted, however, that this research was restricted by cost and timescale for the work. The plastic mesh track on Moor House cost £18,000 for 1.5 km and was laid specifically for this project to ensure a controlled set-up. Furthermore, the articulated wooden track was donated to the project and cost approx. £1000 per 10 m.

The research undertaken for this thesis was practically focused and consequently the input of the stakeholder advisory group was very important in determining the treatments and track route arrangement that was adopted in this study. With respect to the experimental design for the intensive study; while it was recognised that factors such as the presence of steeper slopes in blanket peatlands may be an influential factor on the magnitude of impacts from the track, the experiment was designed to meet the requirements of practically grounded research. Consequently the set-up needed to be reflective of 'real-world' situations. The set-up of the Moor House site was validated by observations made at the sites visited as part of the Regional Survey. By establishing the experiment design for practical application, it was not possible to test some of the hypotheses for all topographic locations. This was with particular reference to the hypotheses tested in Chapter 6 relating to upslope-downslope effects. The track was set-up in such a way that it only cut across flow pathways, producing upslope-downslope sides to the track, at topographic position S3. At topographic locations S1 and S2, the track was flat to the surface or ran perpendicular to the contours respectively. Consequently it should be recognised that the experiment design meant that the ability to fully test all of the hypotheses, derived from the literature and common assumptions, was limited.

8.5 Concluding Remarks and Further Work

The research presented in this thesis has furthered our understanding of the impact of tracks on blanket peat and contributed to the very limited evidence base for blanket peat environments. While some of the results have differed from those expected and outlined in the original conceptual diagram this thesis has highlighted that the impact of tracks does vary and is very much dependent on track type, topographic location and orientation of the track relative to the slope. Consequently, this thesis has provided important and useful information for decision-making with respect to the siting, installation and use of tracks. Given that this study was the first of its kind it has also allowed for the identification of areas of further research which include:

- To investigate the longer-term impacts of plastic mesh, articulated wooden and unsurfaced tracks by continuing driving and monitoring at the Moor House site. In addition, the research could be extended to other blanket peatlands, including those under differing management conditions, to determine whether the impacts observed were the effect of site specific factors or general effects.

- To investigate whether continued driving over the track may further change the physical properties and lead to water stress, which could further impact the vegetation composition and regrowth along the track route, and be particularly influential to *Sphagnum* spp. A study of the availability of water to plants under the track could be undertaken.

- Extend the regional survey to include a greater number of plastic and stone tracks, covering a broader climate range for blanket peatlands. In addition, the survey could be repeated at different times of year under differing antecedent conditions.

- To investigate impacts of tracks on water chemistry and how the presence of the track may affect dissolved and particulate organic carbon release.

- The removal of vegetation from the peat surface following burning has been found to influence the thermal regime of peat (Brown et al., 2015). Therefore further work could investigate impacts to the thermal regime of the peat directly under the track, where the vegetation has been removed and the peat compacted, compared with off-track and the influence this may have on carbon cycling.

- Tracks occur on blanket peatlands across the UK. The intensive study presented in this thesis was located on a *Calluna vulgaris-Eriophorum vaginatum* dominated blanket peatland. The dominant vegetation type varies between peatlands, often dependent on past management and climatic conditions. In order to fully understand the impact of tracks on blanket peat ecohydrology, further investigation should consider the influence of dominant vegetation type on track impacts.

- Channelization of water flow occurred in some locations along the track route. This could be studied further with a view to examining design features that could be installed to reduce negative impacts. In addition, further work is needed to determine whether the overland flow remains dominated by saturation-excess overland flow or whether there has been a shift to infiltration-excess overland flow following compression of the peat.

- Water-table depth measured within 1 m of the track edge often showed greater variability than those at distances greater than 1 m from the track edge, and automated water-table data from the driven treatments had large interquartile ranges compared with the control. Further study could investigate the response times of the water table in close proximity to the track compared with the water table at distance from the track edge, as well as in the undisturbed control, to further investigate whether there are lateral effects that were not captured in the larger spatial scale measurements.

- In the upper 10 cm of the peat, horizontal *K* was found to increase at some locations. Further research could investigate how pore orientation was affected following track use and the implications this may have for vertical and lateral hydrological connectivity within the upper peat.

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