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Erosion in peatlands: recent research progress and future directions

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Abstract

Peatlands cover approximately 2.84% of global land area while storing one third to one half of the world's soil carbon. While peat erosion is a natural process it has been enhanced by human mismanagement in many places worldwide. Enhanced peat erosion is a serious ecological and environmental problem that can have severe on-site and off-site impacts. A 2007 monograph by Evans and Warburton synthesized our understanding of peatland erosion at the time and here we provide an update covering: i) peat erosion processes across different scales; ii) techniques used to measure peat erosion; iii) factors affecting peat erosion; and iv) meta-analyses of reported peat erosion rates. We found that over the last decade there has been significant progress in studying the causes and effects of peat erosion and some progress in modelling peat erosion. However, there has been little progress in developing our understanding of the erosion processes. Despite the application of new peat surveying techniques there has been a lack of their use to specifically understand spatial and temporal peat erosion dynamics or processes in a range of peatland environments. Improved process understanding and more data on rates of erosion at different scales are urgently needed in order to improve model development and enable better predictions of future peat erosion under climate change and land management practices. We identify where further research is required on basic peat erosion processes, application of new and integrated measurement of different variables and the impact of drivers or mitigation techniques that may affect peat erosion.

Keywords: peatlands; erosion; processes; measurements; rates; restoration

1. Introduction

Peat is a slowly-accumulating organic-rich soil composed of poorly decomposed remains of plant materials (Charman, 2002). Peatlands are areas with a surface peat accumulation and they can be broadly subdivided into bogs, fens and some types of swamps (Joosten, 2016). Bogs, which can be subdivided into blanket peatlands and raised bog (Charman, 2002), are ombrotrophic and receive water and nutrients primarily from precipitation. Fens and swamps are minerotrophic and receive water and nutrients from groundwater. To initiate and develop, peatlands require water-saturated conditions. However, peatlands occur in a broad range of climatic conditions from the warm tropics through to the cold, high latitudes and in total they cover approximately 4.23 million km^2 (2.84%) of the world's land area (Xu et al., 2018). Peatlands serve as important terrestrial carbon sinks, storing carbon equivalent to more than two thirds of the atmospheric store (Yu et al., 2010). Quantification of the carbon flux from peatland systems is therefore vital to fully understand global carbon cycling (Evans and Warburton, 2007; Pawson et al., 2008). In addition, peatlands provide a wide range of important ecosystem services including water supply, recreation and biodiversity (Bonn et al., 2009; Osaki and Tsuji, 2015). The conditions required for peatland initiation and ongoing survival are relatively narrow and as a result they are fragile ecosystems that are sensitive to a wide range of external and internal pressures, including changes in topography due to peat growth, climate change, atmospheric pollution, grazing, burning, artificial drainage, afforestation and infrastructure (Fenner and Freeman, 2011; Holden et al., 2007c; Ise et al., 2008; Noble et al., 2017; Parry et al., 2014).

Peat erosion is a natural process driven primarily by actions of water and wind, but slight changes in conditions driven by human action can lead to accelerated erosion and degradation (Parry et al., 2014). Wind erosion can occur where the peat surface is largely bare and is common in windy uplands and peat mining areas (Foulds and Warburton, 2007a; Foulds and Warburton, 2007b). Erosion by water can occur through a number of different processes (both on and below the surface), with the scale of erosion varying by peatland type as well as how degraded they are. Rainsplash and runoff energy can cause erosion on bare peat surfaces. Where flow accumulates, both in artificial ditches and natural channels, further erosion can take place. In peatlands that have been drained ditch erosion often occurs while channel bank collapse may occur on all peatlands (Marttila and Kløve, 2010a). Erosion under the peat surface can also occur with piping being common in many peatlands globally (Jones, 2010).

Rain-fed blanket peatlands cover 105 000 km^2 of the Earth's surface (Li et al., 2017a) and occur on sloping terrain, with slope angles as high as 15°. As a result blanket peatlands are potentially more vulnerable to water erosion than other types of peatlands occurring in landscapes with very little surface gradient (Li et al., 2017a). It has been reported that many blanket peatlands have experienced severe erosion (Evans and Warburton, 2007; Grayson et al., 2012; Li et al., 2016b) and are under increasing erosion risk from future climate change (Li et al., 2016a; Li et al., 2017a). The erosion of peat with high carbon content will enhance losses of terrestrial carbon in many regions. The main erosion processes affecting blanket peat can be broadly divided into sediment supply processes (e.g., freeze–thaw and desiccation), sediment transfer from hillslopes (e.g., interrill erosion, rill erosion and gully erosion), bank failures and mass movement (Bower, 1961; Evans and Warburton, 2007; Francis, 1990; Labadz et al., 1991; Li et al., 2018a; Warburton and Evans, 2011). Figure 1 shows some typical peat erosion features and processes in the uplands of northern England.

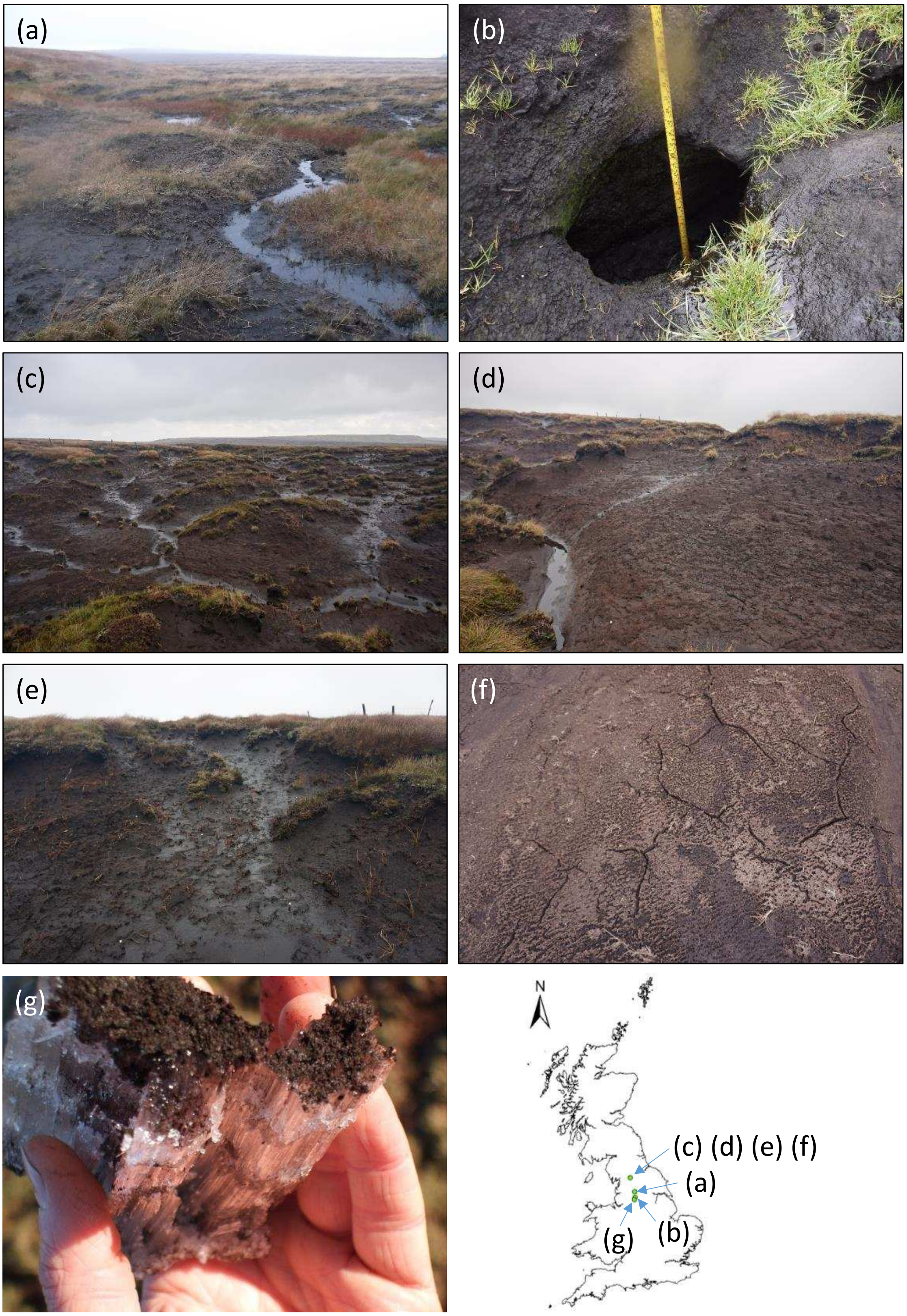

Figure 1. Examples of erosion features and processes in blanket peatlands of northern England: (a) rill erosion; (b) pipe erosion; (c) eroded bare hillslopes; (d) gully wall; (e) gully head; (f) desiccation; (g) needle ice production.

Extensive erosion of many blanket peatlands potentially compromises their ability to maintain ecosystem functions (Evans and Lindsay, 2010) and has been found to have adverse impacts on landscapes (Holden et al., 2007c), reservoir sedimentation (Labadz et al., 1991), water quality (Crowe et al., 2008; Daniels et al., 2008; Rothwell et al., 2008a; Rothwell et al., 2008b; Rothwell et al., 2010; Shuttleworth et al., 2015), carbon dynamics (Holden, 2005b; Worrall et al., 2011) and other ecosystem services (Osaki and Tsuji, 2015).

As a proportion of dry mass, blanket peat is typically around 50 % carbon (e.g. Dawson et al. (2004)). Thus sediment loss from peatlands also represents a significant removal of carbon. However, most research on peatland carbon budgets has focussed on gas flux with less effort on aquatic carbon fluxes from peatlands (Holden et al., 2012c). Where aquatic carbon fluxes from peatlands have been measured, the dissolved organic carbon (DOC) flux tends to be several times greater than that of particulate organic carbon (POC) (e.g. Hope et al. (1997); Dinsmore et al. (2010); Holden et al. (2012c)). However, in more severely eroding peatlands the POC flux has been shown to be greater than that of DOC (Pawson et al., 2012; Pawson et al., 2008).

Despite peatland erosion having been studied for more than sixty years some of the processes remain poorly understood (Bower, 1960; Evans and Warburton, 2007; Li et al., 2016b). The prevention and control of peat erosion risk relies on designing and applying appropriate conservation strategies and management techniques, which in turn requires a thorough understanding of processes. Traditionally the bulk of soil erosion research has focussed on understanding mineral soils, with much less known about erosion of organic soils. While soil erosion remains a major concern in mineral agricultural soils (Li et al., 2017c), erosion of peat is of particular concern due to the increased risk of carbon loss to the atmosphere once peat sediment is moved from its original location (Palmer et al., 2016).

On 12th November 2017, a bibliographic search was conducted to analyze the evolution and trends in peatland erosion studies with the aim of identifying new lines of investigation. The search used Thomson Reuters© Web of Science® bibliographic databases. Using the key words ‘peat’ and ‘erosion’ 683 items were retrieved over the period 1900 to the present (12/11/2017). The indexed articles cover both qualitative and quantitative investigations of peat erosion processes, rates and the impacts of different factors on peat erosion (Figure 2). Between 1960 and 1980 the number of peat erosion related publications remained low, however since 1990 there has been a rapid increase in associated research and resulting publications; this has resulted in exponential growth in the number of citations. Evans and Warburton (2007) synthesized our understanding of upland peat erosion at the time of their monograph. Developments in direct and indirect methods for measuring soil erosion processes and rates since 2007 and a greater appreciation for the detrimental impacts of peat erosion have resulted in an increase in the number of articles published annually, with a peak of 50 articles per year in

2016. Here we provide an updated review of recent developments. Our review therefore focuses on new research over the last decade, but refers to older research where necessary to provide background context or where that material was not originally covered by Evans and Warburton (2007).

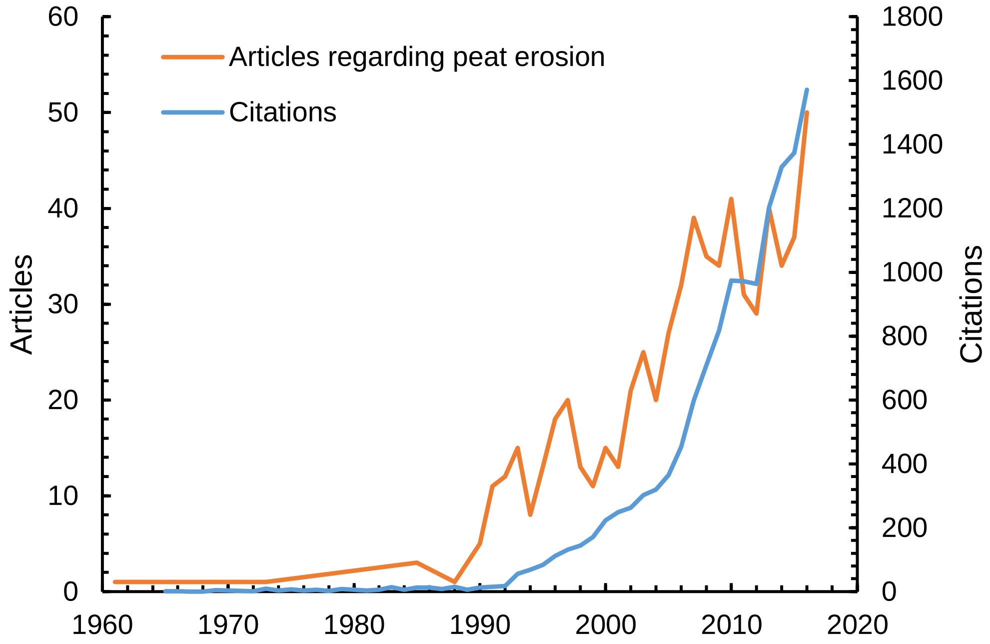

Figure 2. Annual evolution of the number of publications on peat erosion from 1960 to 2017 (indexed in Web of Science 12/11/2017) and the number of citations.

Although there may be some grey literature (unpublished research, theses or reports), much of the recently published peat erosion literature is geographically limited to blanket peatlands in the British Isles, and peatlands in Finland, North America and tropical areas, primarily due to concerns over peat erosion in these locations and programs to address these concerns. Therefore this review of updates over the last decade will necessarily have more concentrated information relating to those systems, however the findings will have broader implications for peatlands globally. The literature covered in this review primarily consists of peer-reviewed papers, books and book chapters drawn from the Web of Science® database, but also includes publically available academic theses and reports (e.g., IUCN UK Committee Peatland Programme reports).

This paper is structured to provide the following:

1. Review of the dominant erosion processes at a range of scales and their interactions in peatland environments.
2. Review of the techniques used to measure peat erosion.
3. A discussion of the factors affecting erosion processes in peatlands.
4. A database and meta-analyses of peat erosion rates measured at different temporal and spatial scales.
5. A synthesis of unanswered research questions on peat erosion.

2. Peat erosion processes

A discussion of the characteristics of critical erosion processes active in peatlands is essential in predicting and mitigating the effects of erosion. Peat erosion can be seen as a two-phase process that consists of: 1) the supply of erodible peat particles by weathering processes, and; 2) their subsequent transport by agents such as water and wind (Li et al., 2016b). Weathering processes such as freeze–thaw and desiccation (Figure 1 (f)-(g)) are important for producing a friable and highly erodible peat surface layer for transport by water and wind (Evans and Warburton, 2007; Li et al., 2018a;

Lindsay et al., 2014). Rainsplash and runoff energy are active erosion agents for water erosion processes involving splash erosion, interrill erosion, rill erosion, pipe erosion and ditch/channel erosion (Evans and Warburton, 2007; Holden, 2006; Li et al., 2018b). Dry peat with a low density is potentially highly susceptible to erosion and transport by wind through dry blow or wind-driven rainsplash (Evans and Warburton, 2007; Foulds and Warburton, 2007a; Foulds and Warburton, 2007b; Warburton, 2003).

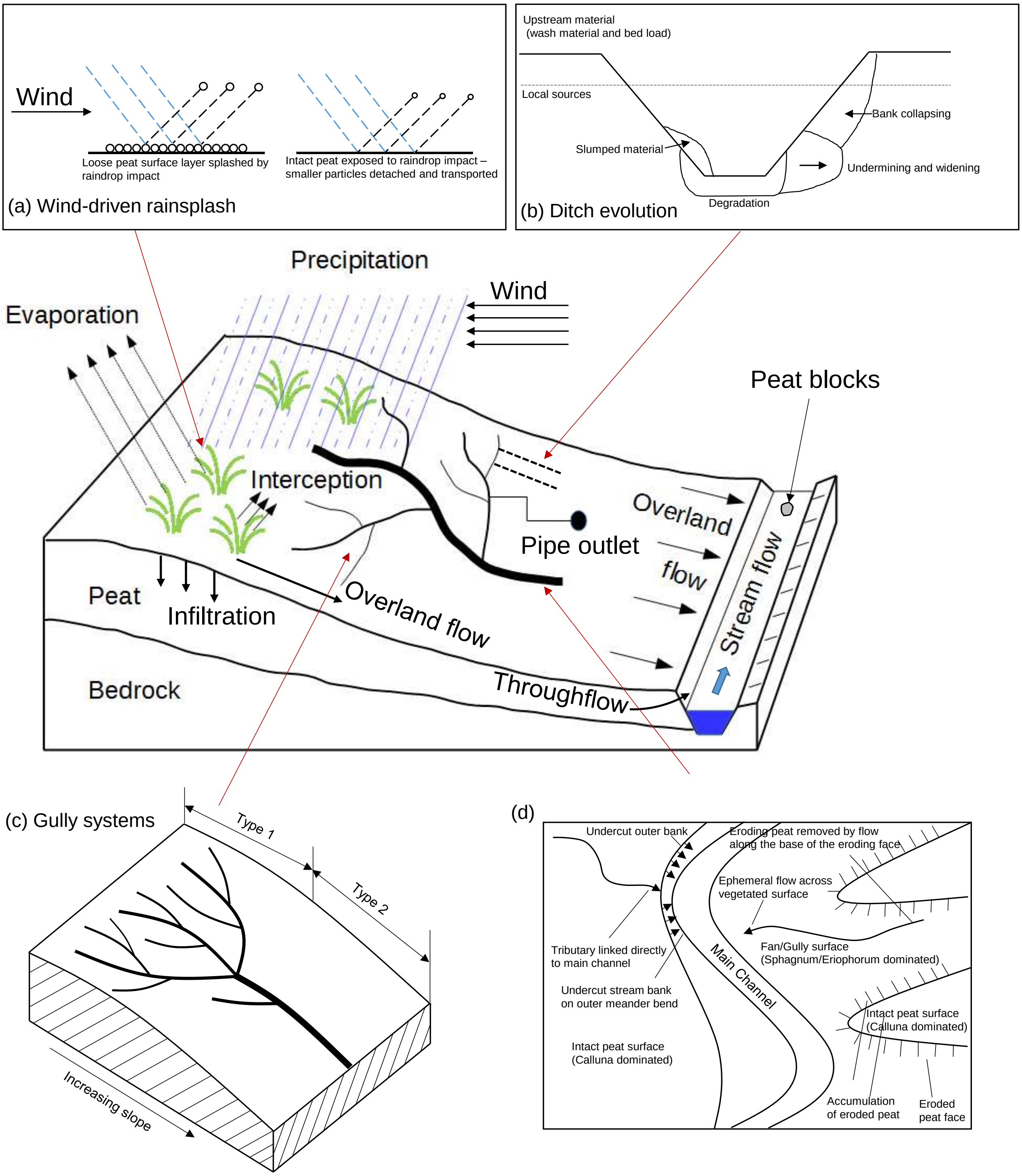

Figure 3. Sketch illustrating water flow paths and main water and wind erosion processes on peatland systems: (a) Conceptual diagram showing two-phase mechanism of bare peat erosion by wind-driven rain, deduced from the particle size and shape (after Baynes (2012)); (b) Conceptual model of drainage channel evolution, and sediment and erosion dynamics in a peatland forest ditch (after Marttila and Kløve (2010a)). (c) Type 1 and Type 2 dissection of gully systems (after Bower (1961)); (d) Diagram showing the main channel of a stream in an

eroding peatland with erosion and revegetation processes operating in the catchment (after Evans and Burt (2010)).

2.1 Weathering processes

2.1.1 Frost action

Frost weathering resulting from the freezing and thawing of water between peat particles is common in cool high latitude or high altitude climates which support many peatlands, and plays a vital role in breaking the peat surface during winter months (Evans and Warburton, 2007; Francis, 1990; Labadz et al., 1991; Li et al., 2018a). Compared to mineral soils peat has a higher volumetric heat capacity but much lower conductivity and as a result has a significantly different thermal response during wetting or drying periods (FitzGibbon, 1981). On cold days, a strong thermal gradient can develop between a cold peat surface and warmer peat at depth (Evans and Warburton, 2007) which together with an abundant moisture supply make ideal conditions for needle ice formation (Figure 1 (g)) (Outcalt, 1971). Needle-ice is important in producing eroding peat faces (Grab and Deschamps, 2004; Luoto and Seppälä, 2000; Tallis, 1973) with ice crystal growth gradually weakening and finally breaking peat soil aggregates and the subsequent warming and thawing weakening or loosening the fractured peat. The growth of needle ice can lead to a ‘fluffy’ peat surface that is loose and granular and vulnerable to being flushed off by overland flow events (Evans and Warburton, 2007; Li et al., 2018a).

Despite the important role of needle-ice formation in preparing the peat surface for erosion, very little has been done to understand the actual process and quantify the effects on erosion (Li et al., 2018a). Li et al. (2018a) conducted physical overland flow simulation experiments on peat with needle ice treatments. Using a cooling rate of −1.3 °C hr^{-1} to a minimum of −1.0 °C, Li et al. (2018a) successfully formed needle-ice within the upper layer of peat blocks and provided the first quantitative analysis demonstrating that needle-ice production and thaw is a primary process contributing to upland peat erosion by enhancing peat erodibility during runoff events following thaw. It should be noted that Li et al. (2018a) used simulated upslope inflow and excluded responses to raindrop impact, while under natural rainfall conditions raindrops provide the primary force to initiate peat particle detachment (Li et al., 2018b). Thus, more significant effects of freeze–thaw on increasing peat erosion could be expected under combined rainfall and overland flow conditions and exploration of these processes could be undertaken in future work.

2.1.2 Desiccation

Surface desiccation during extended periods of dry weather is another important weathering process for producing erodible peat (Burt and Gardiner, 1984; Evans et al., 1999; Francis, 1990; Holden and Burt, 2002a). Desiccation of surface peat can lead to development of hydrophobicity (Eggelsmann et al., 1993). Where desiccation occurs the surface layer is typically platy with a dried upper crust that is concave in shape and is detached from the intact peat below (Evans and Warburton, 2007); this dry crust layer could impede infiltration (Holden et al., 2014). On the other hand, a desiccated peat surface can be susceptible to shrinkage and cracking (Holden and Burt, 2002a) that actually promotes delivery of surface water to the subsurface hydrological system (Holden et al., 2014).

Li et al. (2016a) modelled the effect of future climate change on UK peatlands and found that peat shrinkage and desiccation may become more important in blanket peatlands as a result of warmer summers and the resulting lowering of water tables. Given projected global climate change, desiccation of the peat surface might be exacerbated across many low-latitude peatland areas (Li et al., 2017a). In addition, field observations have shown that desiccation of the peat surface contributes to increasing surface roughness (Smith and Warburton, 2018).

2.2 Sediment transport processes

Transport of sediment from hillslopes to channels where it is more accessible to fluvial processes is of great importance in geomorphology (Bryan, 2000a; Evans and Warburton, 2007). Many erosional processes are active on peat hillslopes (Figure 3), including water erosion (Bower, 1961), wind erosion (Foulds and Warburton, 2007a; Foulds and Warburton, 2007b; Warburton, 2003) and mass movements such as peat slides and bog bursts (Crowe and Warburton, 2007; Evans and Warburton, 2001; Evans and Warburton, 2007; Warburton and Evans, 2011; Warburton et al., 2004). Bank erosion is an important process in some peatlands, contributing to stream sediment loads (Evans and Warburton, 2001). Peat transported within channels is typically in the form of fine suspended sediment or larger low-density peat blocks which may remain in situ until they float off in storms or roll along the bed and quickly break up once mobilised (Evans and Warburton, 2007; Warburton and Evans, 2011).

2.2.1 Water erosion

2.2.1.1 Interrill erosion processes

For interrill erosion, the dominant processes are detachment by raindrop impact and transport by raindrop-impacted sheet flow (Kinnell, 2005). Raindrops affect interrill erosion processes in two ways. First, raindrops provide the primary force to initiate low-density peat particle detachment; with the importance of raindrop impact on sediment detachment having been shown under both laboratory and field conditions (Holden and Burt, 2002a; Kløve, 1998; Li et al., 2018b). Li et al. (2018b) found that without raindrop impact shallow interrill overland flow had little entrainment capacity, with raindrop impact increasing peat surface erosion by 47% (Li et al., 2018b). Second, raindrop impact is important in affecting overland flow hydraulics and sediment transport as overland flow depths are typically shallow, in the order of a few millimeters (Holden and Burt, 2002a; Holden et al., 2008a). Li et al. (2018b) found that raindrop impacts increased flow resistance which reduced overland flow velocities by 80–92%. Overland flow hydraulics as modified by raindrop impact are important in defining and modelling overland flow erosion processes (Bryan, 2000b); further work should be carried out to explore these interactions.

For interrill erosion areas, soil detachment and sediment transport are simultaneously influenced by rainfall-driven and flow-driven erosion processes and their interaction (Li et al., 2018b). However, rather limited attention has been given to the importance of the interaction between rainfall- and flow-driven processes and the interaction is usually ignored when modelling interrill processes (May et al., 2010). Li et al. (2018b) found a negative interaction, with the total sediment concentration for both rainfall and runoff treatments being lower than the sum of the combined rainfall and runoff treatments. This interaction substantially reduced sediment concentration as a result of significantly increased flow resistance caused by the retardation effect of raindrops on shallow overland flow.

Saturation-excess overland flow and near-surface throughflow are dominant in many (but not all) types of peatland including blanket peatland (Evans et al., 1999; Holden and Burt, 2002a; 2003c) and are a result of shallow water tables and low hydraulic conductivity throughout most of the peat depth (Holden and Burt, 2003a; Holden and Burt, 2003b; Rosa and Larocque, 2008). The hydraulic conditions of overland flow (e.g., flow velocity, depth and resistance) determine the erosive forces acting on the peat in interrill areas. Runoff hydraulics including flow velocity, flow depth and friction coefficients, and their empirical relationships have been reported at the plot scale on blanket peat slopes (Holden et al., 2008a). Holden et al. (2008a) found a region of shallow flows in which there is a gradual increase of roughness (reducing $f^{-0.5}$) with depth, and a deeper region of flows with significantly decreasing roughness (logarithmically) with depth.

2.2.1.2 Rill erosion processes

Rill processes are affected by concentrated flow and soil resistance (Govers et al., 2007; Knapen et al., 2007). Li et al. (2018a) conducted laboratory flume experiments on blanket peat with and without needle ice processes. The physical overland flow simulation experiments showed that rills were not produced in intact peat without needle ice production and thaw. However, visual observations of the needle ice treatments showed that micro-rills and headcuts occurred and caused localized micro-waterfalls (Li et al., 2018a). For the needle-ice treatments with rill initiation, stepwise linear regression showed that stream power was the only factor that predicted erosion (Li et al., 2018a). Although recent research has focused on the mechanisms of peat interrill and rill erosion (Li et al., 2018a; Li et al., 2018b) little is known about the threshold hydraulic conditions for the transition from interrill to rill processes. There is a dearth of evidence on how the two erosive agents interact with each other, and how their interactions impact on peatland hillslope development.

2.2.1.3 Pipe erosion

Piping is commonly found in peatlands (Holden, 2006; Holden and Burt, 2002c; Holden et al., 2012c; Norrström and Jacks, 1996; Price and Maloney, 1994; Rapson et al., 2006; Woo and DiCenzo, 1988). Peat pipes connect the shallow and deep layers of the peat profile (Billett et al., 2012; Holden, 2005a; Holden, 2005b) and act as significant sources and pathways for water, carbon and sediment transport. In addition, pipe collapse is common, often being associated with gully head retreat (Jones, 2004; Verachtert et al., 2011). However, pipe erosion is less well studied compared with surface soil erosion by water due to its subsurface nature (Holden, 2005a). Geophysical techniques (e.g., ground-penetrating radar) (Holden et al., 2002) have helped improve the identification of pipe networks, but studies have generally focuses on pipe distribution and hydrology (Holden, 2005a; Holden, 2006; Holden, 2009a; Holden, 2009b; Holden and Burt, 2002c; Holden et al., 2012b; Holden et al., 2012c; Smart et al., 2013). Holden and Burt (2002c) found that around 10% of stream discharge was derived from pipe networks in Little Dodgen Pot Sike, a deep blanket peat catchment in the North Pennines of England. In the nearby Cottage Hill Sike catchment, Smart et al. (2013) found that pipes contributed 13.7% of the streamflow. Jones (2004) showed that piped areas produced more sediment to the stream than areas without piping. Pipe outlets delivered an amount of aquatic carbon equivalent to 22% of the aquatic carbon flux at the outlet of Cottage Hill Sike catchment (Holden et al., 2012c) with POC flux observed at the pipe outlets equivalent to 56-62 % of the annual stream POC flux (Holden et al., 2012b; 2012c). Despite these valuable results, quantification of the contribution of piping to peat loss is still limited to a few case studies in a limited number of environments.

2.2.2 Wind erosion

Windy conditions are typical of many exposed peatland environments. The impacts of wind action on peatlands differs between dry and wet conditions (Evans and Warburton, 2007). During drought periods dry blow is of great importance in transporting eroded peat as dry peat with a low density has a high potential susceptibility to erosion and transport by wind (Campbell et al., 2002; Foulds and Warburton, 2007a; 2007b; Warburton, 2003). In contrast under wet and windy conditions, wind-driven rain is important in peat surface erosion through the detachment and transport of peat particles (Foulds and Warburton, 2007a; Warburton, 2003). Baynes (2012) identified a two-phase erosion process of bare peat by wind-driven rain (Figure 3 (a)). Phase 1 includes large loose surface peat particles that are produced by frost action or surface desiccation and are mobilized by raindrop impact and transported by wind. The removal of the top layer exposes the intact peat surface to raindrop impact which erodes smaller particles (Phase 2). Li et al. (2018b) found that raindrop impact plays a key role in affecting overland flow, flow hydraulics and soil loss under lower rainfall intensity conditions. However, more significant effects could be expected with higher kinetic energy levels closer to those experienced where natural rainfall is driven by strong wind. Future work could examine overland flow interactions with wind-driven rainsplash erosion and its contribution to total erosion, as rainfall on exposed peatlands is often associated with strong winds (Evans and Warburton, 2007).

2.2.3 Ditch erosion

Artificial drainage on peatlands and the associated changes in peat structure, hydrological flow paths and erosion have been widely reported in upland Britain (Armstrong et al., 2009; Holden et al., 2004; Holden et al., 2006; Holden et al., 2007b) and Finland (Haahti et al., 2014; Kløve, 1998; Marttila and Kløve, 2008; Marttila and Kløve, 2010a; Stenberg et al., 2015a; Stenberg et al., 2015b; Tuukkanen et al., 2016). Holden et al. (2007b) found that drain networks that were well connected to stream channels were important contributors of suspended sediment to the stream network. Ditch creation and maintenance contribute to increased erosion and suspended sediment yields by undermining and bank collapse (Marttila and Kløve, 2010a; Stenberg et al., 2015a; Stenberg et al., 2015b; Tuukkanen et al., 2016). Field and laboratory observations in Finland have shown that erosion of deposited peat sediment from main ditches is the main suspended sediment source in peat extraction areas during individual summer storm events (Marttila and Kløve, 2008; Tuukkanen et al., 2014). Marttila and Kløve (2010a) presented a conceptual model of the processes in the drainage channel, where suspended sediment production in the channel is a result of flow erosion, sheet wash, sidewall collapse and undercutting. Sediment from upstream areas can be stored in the main drain during smaller flow events, indicating a physical process limited by the transport capacity. The deposited sediment in the ditch bottom can be released to be transported during larger flow events, and this process can either be supply- or transport-limited (Marttila and Kløve, 2010a). Stenberg et al. (2015a) outlined a conceptualisation where bank erosion occurs in the area of a seepage face and the material is eroded due to different mechanisms (e.g. seepage, gravitational forces, and freeze-thaw processes) and deposited on the bottom of the ditch and the lower parts of the ditch bank. They concluded that the main mechanism causing bank erosion was plausibly the seepage and wetting-induced loosening of the peat material, as most of the erosion took place during the time when groundwater levels were highest.

2.2.4 Other erosion processes

Other commonly observed erosion forms in peatlands are gully erosion, mass movements and in-stream transport processes, and an extensive body of literature has been published on these subjects (see Evans and Warburton (2007) for a concise review). Little additional work has been published in the last decade on these processes. Warburton and Evans (2011) found large peat blocks in alluvial river systems could significantly contribute to stream sedimentation, and this contribution might be greater than those from other fluvial erosion forms such as rill and gully erosion, particularly over short timescales and in a local context. The effects of peat blocks on downstream sediment load were found to depend on channel width (Warburton and Evans, 2011). For narrow channels, peat blocks act as natural and economical dams to block the flow and sediment pathways, which may lead to the upstream accumulation of bed material; while for wider channels the blocks tend to be stored on the river bed in isolation and are of less importance in controlling sedimentation (Warburton and Evans, 2011). Once peat blocks begin to move they break down at a relatively rapid speed through abrasion and disaggregation, which may release a large quantity of fine sediments in stream systems (Evans and Warburton, 2001; Evans and Warburton, 2007). Little is known about the hydraulic thresholds required for peat blocks to be entrained, transported and deposited, nor the factors impacting the dispersal and persistence of peat blocks in streams (Warburton and Evans, 2011).

2.3 Interactions among different peat erosion processes

The three most common sediment supply processes affecting peatlands (e.g., frost action, desiccation and rainsplash) seldom occur independently of each other (Figure 4). Peat is usually 'puffed up' by frost in winter, contracted by desiccation in summer, and buffeted year-round by wind-driven rain (Warburton, 2003). Rainsplash plays an important role in detaching peat particles for flow transport (Li et al., 2018b). However, antecedent conditions such as antecedent freeze–thaw or desiccation activity are very important in controlling peat erodibility and thus erosional response to a given rainfall event. In addition, desiccation is closely related to the frost effect in terms of the formation of segregation ice at the peat surface and this could initiate desiccation of the surface layer (Evans and Warburton, 2007).

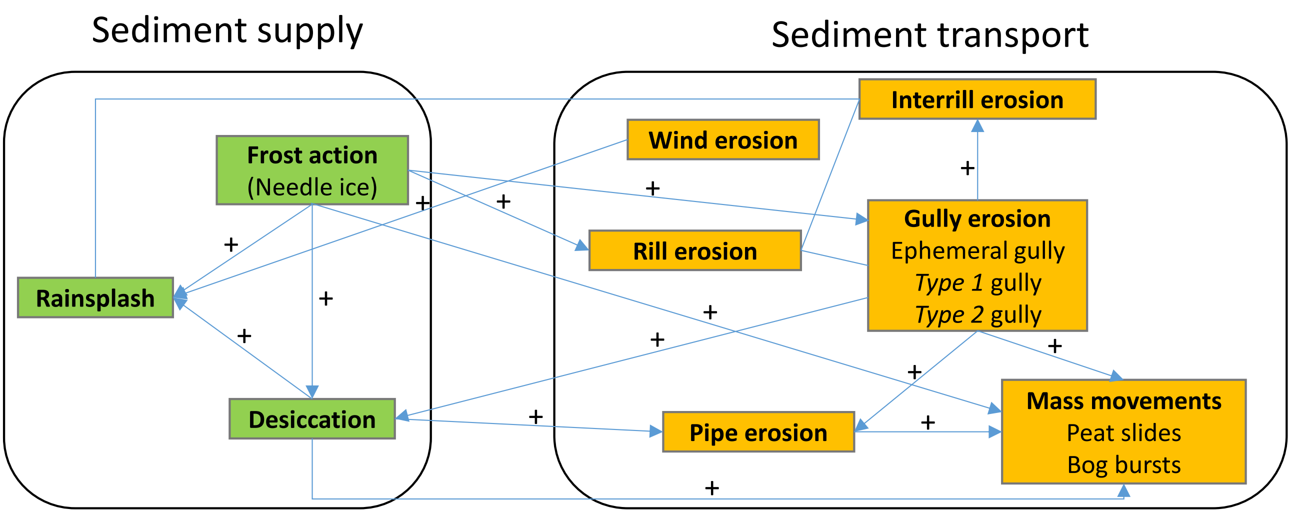

Figure 4. Interactions among sub-processes of sediment supply and sediment transport processes in peatlands.

Active sediment transport processes strongly interact with each other in some areas of peatlands (Figure 4). There are links between the development of interrill erosion and gully erosion. Interrill erosion is widely spread on summits of Type 1 gully dissection systems, where large areas of bare peat are exposed (Bower, 1961). Once gullies develop, mass wasting and slope instability can be triggered and piping can also be enhanced. Holden et al. (2002) found through ground-penetrating radar survey of pipe frequency that pipes were often found at the head of gullies. Pipes have the potential to initiate or impact gully system development through roof collapse or channel extension (Higgins and Coates, 1990; Holden and Burt, 2002c; Tomlinson, 1981). Pipe collapse is potentially associated with initiation of Type 2 gullies (Evans and Warburton, 2007). However, there are no direct observations or quantitative analysis linking pipe features and gully initiation in peatlands.

Peat mass movements have also been linked to gully formation (Evans and Warburton, 2007)

Strong links would be expected between sediment supply and sediment transport processes in peatland environments. For example, needle-ice formation resulting from freeze–thaw cycles could result in damage to gully walls (Evans and Warburton, 2007; Imeson, 1971). Freeze–thaw action would also be associated with deep cracking on the bank face and peat mass failure (Wynn et al., 2008). Desiccation cracking may promote delivery of surface water to the subsurface hydrological system promoting elevated pore pressures and peat mass failure (Hendrick, 1990). Gully systems are particularly vulnerable to desiccation process, due to exposed faces drying quickly and particles being rapidly removed by wind and gravity (Holden et al., 2007a). The desiccation of the peat surface, has the potential to encourage soil pipe development and pipe erosion (Holden, 2006; Jones, 2004). New routes created by shrinking and cracking of the desiccated peat for bypassing flow, may initiate the ephemerally flowing pipe networks, when abundant sourcing water flows through the preferential flow pathways (Holden, 2006).

2.4 Scale-dependency of peat erosion processes

A conceptual model of the active sources and sinks of sediment in peatlands can be developed based on De Vente and Poesen (2005). Different peat erosion processes are active at different spatial scales. For example, rainsplash, interrill and rill erosion are the dominant erosion processes studied at fine scales (erosion plots) (Grayson et al., 2012; Holden and Burt, 2002a; Holden et al., 2008a; Li et al., 2018a; Li et al., 2018b). For larger hillslope and small and medium-size catchment scale, gully erosion and mass movements become more important, yielding large quantities of sediment (Evans and Warburton, 2005; Evans and Warburton, 2007; Evans et al., 2006). At the large basin scale long-term erosion and sediment deposition processes are more important due to large sediment sinks (footslopes and floodplains) (De Vente and Poesen, 2005). Riverine POC is also potentially transformed to DOC by in-stream degradation or mineralized to CO_2 during periods of floodplain storage (Pawson et al., 2012).

3 Methodological approaches for assessing erosion in peatlands

3.1 Measurement techniques

Numerous direct and indirect methods have been used to measure and monitor peat erosion. Traditionally these have included: erosion pins (Grayson et al., 2012), bounded plots (Holden et al., 2008a; Li et al., 2018a; Li et al., 2018b), gauging stations, bathymetric surveys in reservoirs (Yeloff et al., 2005) and some of these have been combined as part of sediment budgeting (Evans and Warburton, 2005; Evans et al., 2006). However, more recently modern high resolution topographic surveying methods have been applied to peatlands to improve quantification of erosion (Evans and Lindsay, 2010;

Evans and Lindsay, 2011; Glendell et al., 2017; Grayson et al., 2012; Rothwell et al., 2010).

3.1.1 Erosion pins

Erosion pins are widely used to measure erosion and deposition directly through observed changes in the peat surface at a given point (Grayson et al., 2012; Tuukkanen et al., 2016). Surface retreat rates measured by erosion pins are the combined effects of wind erosion, water erosion and peat wastage (oxidative peat loss) (Evans and Warburton, 2007; Evans et al., 2006; Francis, 1990). Point measurements are usually interpolated over relatively small areas. However, interpreting erosion rates based on erosion pins should be treated with caution as the accuracy and precision can be affected by: i) peat soil expansion and contraction during weathering processes (freeze-thawing and wetting-drying cycles) (Kellner and Halldin, 2002; Labadz, 1988); ii) significant spatial variation even over small areas (Grayson et al., 2012); iii) increasing erosion or trapping eroded material (Benito and Sancho, 1992; Couper et al., 2002); iv) interference from grazing animals like sheep; v) disturbance and damage to the peat surface caused by installation and repeated pin measurement.

3.1.2 Erosion plots

Erosion plots are one of the most widely applied methods for measuring peat erosion rates over short and medium time periods (Grayson et al., 2012;

Holden and Burt, 2002a; Li et al., 2018b). Erosion plots include closed plots that are usually less than 10 m^2, and open plots which are larger. Closed plots are normally equipped with troughs, runoff and sediment collectors and are employed together with rainfall simulation or upslope inflow simulation experiments (Clement, 2005; Elaine, 2012; Holden and Burt, 2002a; Holden and Burt, 2002b; Holden and Burt, 2003b; Holden et al., 2008a; Li et al., 2018a; Li et al., 2018b). Closed plots have the advantages of allowing a comparison of different responses at the same spatial scale (Boix-Fayos et al., 2006). However, Holden and Burt (2002a) and Li et al. (2018b) showed that closed erosion plots reduce erosion rates with rainfall simulation due to a change from transport-limited to detachment-limited conditions. Open plots are usually used in the field (Grayson et al., 2012) and they have the advantage of better representation of natural conditions.

3.1.3 Sediment transport measurements at gauging stations

Sediment concentration measurements at gauging stations allow the calculation of sediment yield rate and its temporal variability (Nadal-Romero et al., 2011). A wide range of equipment and techniques (e.g., sediment traps, sampling) are generally used to measure sediment flux at the catchment outlet at larger spatial and temporal scales (Francis, 1990; Holden et al., 2012c; Labadz et al., 1991; Pawson et al., 2012). Sediment sampling is usually used in combination with the rating curve technique (Francis, 1990; Labadz et al., 1991). It is important to consider sampling intervals as peat systems often have flashy regimes and hence many sampling strategies (e.g., daily sampling) may miss important sediment transport events such as short-lived storms (Pawson et al., 2008). Antecedent conditions and hysteresis in the sediment – discharge relationship are also important factors to consider when designing sampling campaigns. Turbidity meters have often been used to measure suspended sediment concentrations in mineral catchments. However, their application in peatland catchments should be treated with caution and calibration is required since turbidity is sensitive to variations in particle size distribution, water colour and the proportion of organic and inorganic contents (Lewis, 1996; Marttila et al., 2010).

3.1.4 Bathymetric surveys in reservoirs

Repeat bathymetric surveys of reservoirs or check dams provide insights into sediment yield at the catchment scale over long periods of time (Nadal-Romero et al., 2011). Compared to other techniques, analyzing reservoir sedimentation is generally a cheaper and more reliable way to estimate net erosion rate (Verstraeten et al., 2006). However, the bathymetric survey method is constrained by determinations of trap efficiency, floor sediment density and spatial analysis being rather challenging (Boix-Fayos et al., 2006; Verstraeten and Poesen, 2002).

3.1.5 Sediment budget

Sediment budgeting within a catchment acts as a framework for identifying sediment yield processes, sediment transport processes and linkages

(Parsons, 2011). Several studies have reported sediment budgets for blanket peat catchments (Baynes, 2012; Evans and Warburton, 2005; Evans et al., 2006). Evans and Warburton (2005) constructed a sediment budget over a four-year monitoring period in the Rough Sike catchment that is an eroded but partially re-vegetated system in north Pennines of England. They reported that hillslope sediment supply to the catchment outlet was significantly reduced due to re-vegetation of eroding gullies. Re-vegetation of the slope-channel interface, which acts as a vegetated filter strip, reduced the sediment connectivity between the hillslopes and channels. However, there may be a limited capacity for how much sediment can be trapped over a given time period as overland flow may still flush out redeposited sediment on vegetated areas. More research is needed to evaluate the effectiveness of different vegetative filter strip characteristics (e.g. vegetation type, width) in reducing sediment delivery efficiency in peatland environments.

3.1.6 Topographic surveys of soil surfaces

Topographic surveys and fine-resolution topographic data allow the determination of peat erosion or deposition (Glendell et al., 2017; Grayson et al., 2012). Remote-sensing technologies employing high-resolution airborne and terrestrial LiDAR (Light Detection and Ranging) for measuring peat surface changes have been reported in blanket peatlands (Evans et al., 2005; Evans and Lindsay, 2010; Evans and Lindsay, 2011; Grayson et al., 2012; Rothwell et al., 2010). Grayson et al. (2012) compared the use of terrestrial laser scanning and erosion pins across a blanket bog; contrasting results were obtained from the two different methodologies. A net surface increase of 2.5 mm was calculated from the terrestrial laser scans (included areas of erosion and deposition), compared with a net decrease in peat surface height of 38 mm measured using pins (eroding areas only) during the same study period (Grayson et al., 2012).

The cost-effective and flexible photogrammetric surveying technique called ‘Structure-from-Motion’ (SfM) provides a cheaper alternative to the established airborne and terrestrial LiDAR (Smith et al., 2016; Smith and Vericat, 2015). Currently, through the SfM technique, it is possible to produce high-resolution DEMs from multi-stereo images without expert knowledge in photogrammetry, by using consumer-grade digital cameras, including those compatible with unmanned aerial vehicles (UAVs) (Glendell et al., 2017). UAVs allow large areas to be covered without disturbing the investigated plot (Glendell et al., 2017). High-resolution topographic data obtained from SfM techniques may provide new insights into erosion dynamics that affect peatlands at field scales (Glendell et al., 2017; Smith and Warburton, 2018). Wider application of the SfM technique is recommended to enable a better understanding of erosion processes and their spatial and temporal dynamics.

3.2 Modelling techniques

Blanket peat erosion has been estimated using numerical models such as the Universal Soil Loss Equation (USLE) (May et al., 2010), Cellular Automaton Evolutionary Slope and River (CAESAR) model (Coulthard et al., 2000) and the grid version of the Pan-European Soil Erosion Assessment (PESERA-GRID) model (Li et al., 2016b). May et al. (2010) applied USLE to model soil erosion and transport in a typical blanket peat-covered catchment on the northwest coast of the Ireland. Coulthard et al. (2000) used CAESAR model in an upland catchment partially covered by peat to assess the effects of climate and land-use change on sediment loss. The USLE model assumes that entrainment is primarily caused by rainsplash energy while the CAESAR model assumes that entrainment is caused by overland flow (Coulthard et al., 2000). However, these models ignore the dominant weathering processes such as freeze–thaw and desiccation in blanket peatlands. Li et al. (2016b) developed a process-based model of peatland fluvial erosion (PESERA-PEAT) by modifying the PESERA-GRID model (Kirkby et al., 2008) through the addition of modules describing both freeze–thaw and desiccation. Temperature and water table were chosen as indicators to parameterize freeze–thaw and desiccation (Li et al., 2016b). PESERA-PEAT has been shown to be robust in predicting blanket peat erosion (Li et al., 2016b) and it has been successfully applied to examine the response of fluvial blanket peat erosion to future climate change, land management practices and their interactions at regional, national and global scales (Li et al., 2016a; Li et al., 2016b; Li et al., 2017a; Li et al., 2017b).

4. Factors affecting erosion in peatlands

4.1 Climatic conditions

Climatic conditions are important for peatland stability. Li et al. (2016b) found via modeling work and sensitivity analysis that with a climate scenario of the annual rainfall total being initially low, annual peat erosion increases if climate change causes increased precipitation, whereas for a scenario whereby annual precipitation is initially high, annual erosion decreases with increased annual precipitation. This demonstrates that when rainfall is above a threshold value there is a shift from supply-limited to transport-limited erosion patterns (Li et al., 2016b).

Modelled erosion rate in cold months (from October to February in Great Britain) has been found to decrease with increasing air temperature, while in warm months (from March to September) erosion increased with increasing temperature (Li et al., 2016a). The effects of temperature are associated with its significant control on freeze–thaw and desiccation weathering processes. Holden and Adamson (2002) showed that a small change in the mean annual temperature at Moor House, from 5.2 ˚C (1931-1979) to 5.8 ˚C (1991-2000), led to a decrease in the mean number of freezing days from 133 to 101 per year. Therefore, a minor change in near-surface air temperature has the potential to significantly impact sediment availability (Holden, 2007) due to the vital preparatory role of freeze–thaw cycles.

Peatland development is highly susceptible to climate change (Fenner and Freeman, 2011; Ise et al., 2008; Parry et al., 2014). During the Medieval warm period between AD 950 and 1100, a decrease in rainfall and an increase in temperature resulted in drying of peat surfaces and promotion of erosion (Ellis and Tallis, 2001; Tallis, 1997). Bioclimatic modelling suggests a retreat of bioclimatic space suitable for blanket peatlands due to climatic change in the 21st century (Clark et al., 2010; Gallego-Sala et al., 2010; Gallego-Sala and Prentice, 2013). Li et al. (2017a) found that future climatic change will begin to affect sediment release from increasingly large areas of blanket peatland in the Northern Hemisphere.

4.2 Peat properties

The physical properties of peat (e.g., degree of humification, shear strength, bulk density) affect peat erosion and sediment delivery (Carling et al., 1997; Marttila and Kløve, 2008; Svahnbäck, 2007; Tuukkanen et al., 2014). Carling et al. (1997) showed that intact peat (not yet loosened or weathered) is highly resistant to water erosion, suggesting a high flow velocity of 5.7 m s^{-1} was needed for continuous erosion of unweathered peat material. Svahnbäck (2007) found a positive relationship between the degree of humification and suspended sediment concentration (SSC) through sprinkler experiments in the lab. Tuukkanen et al. (2014) examined whether peat physical properties including the degree of humification, bulk density, ash content, and shear strength affect peat erodibility and found that well-decomposed peat generated higher SSC than slightly or moderately decomposed, fiber-rich peat.

The degree of humification affects peat erodibility and sediment transport in two ways. First, the critical shear stress required for peat particle entrainment decreases with increasing degree of humification. Second, there is a higher risk of rill formation in well-decomposed peat extraction areas (Tuukkanen et al., 2014). As a consequence, well-decomposed peat with low fibre content is more likely to cause increased transport of organic suspended matter, compared with poorly decomposed peat (Tuukkanen et al., 2014).

Marttila and Kløve (2008) conducted laboratory flume experiments on peat sediments and found that deposited sediment formed a loose layer overlaid by more stabilized layers with stabilization time ranging from 15 minutes to 10 days. An increase in stabilization time resulted in increased erosion rates. Critical shear stress was 0.01 ± 0.002 N m^{-2} for the loose surface peat layer, and was 0.059 ± 0.001 N m^{-2} for the entire peat deposited peat sediment (Marttila and Kløve, 2008). Two linear equations can be fitted to explain the erosion across the critical shear stress. The critical shear stress for deposited ditch sediment was about 0.1 N m^{-2} (Marttila and Kløve, 2008) which was much lower than 0.6 N m^{-2} for well-decomposed peat and 4-6 N m^{-2} for poorly decomposed peat (Tuukkanen et al., 2014). The difference in critical shear stress between intact soil and ditch sediment indicated that deposited ditch sediment was much more susceptible to erosion than intact peat. Bulk density affects peat erosion and sediment transport through changes in runoff generation, rather than through its effect on peat erodibility (Tuukkanen et al., 2014). The tendency for overland flow is greater in peat with higher bulk density since the saturated hydraulic conductivity of peat often (but not always) decreases with increasing bulk density (Chow et al., 1992).

Peat erodibility in the physically-based PESERA-PEAT model represents the erodibility of available peat materials weathered by freeze–thaw and desiccation (Li et al., 2016b). The erodibility of weathered peat was reported to be 2–3 times that of intact peat (Mulqueen et al., 2006). In addition, Li et al. (2018a) conducted physical overland flow simulation experiments on highly frost-susceptible blanket peat with and without needle ice processes. They defined peat anti-scouribility capacity (AS) as the resistance of peat to overland flow scouring. The higher the peat AS, the lower the peat erodibility, with AS significantly increasing in treatments subjected to needle ice processes, indicating that needle ice processes significantly increased peat erodibility (Li et al., 2018a).

4.3 Vegetation cover

Vegetation cover in blanket peatlands is dominated by slow-growing vascular plants and bryophytes (Holden et al., 2015), such as bog mosses (Sphagnum spp.), cotton-grass (sedges) (Eriophorum spp.) and shrubs such as common heather (Calluna spp.). These types of vegetation cover act as both indicators and creators of blanket peat conditions. Vegetation cover impacts both sediment supply and transport processes in peatlands (Li et al., 2016a). Vegetation cover protects bare peat surface against weathering processes (Holden et al., 2007b; Holden et al., 2007c; Lindsay et al., 2014; Shuttleworth et al., 2015), rainsplash and overland flow erosion (Holden et al., 2008a), and mass movements (Evans and Warburton, 2007; Warburton et al., 2004). The removal of vegetation cover increases the thermal gradient between cold surfaces and warmer peat at depth during winter (Brown et al., 2015), making the peat surface susceptible to needle ice weathering processes (Li et al., 2016b). Peat surfaces with sparse vegetation cover are also more vulnerable to desiccation in summer (Brown et al., 2015).

In addition, vegetation cover reduces overland flow velocity (Holden et al., 2007b; Holden et al., 2008a) and sediment connectivity from sediment source zones to river channels (Evans and Warburton, 2007; Evans et al., 2006). Holden et al. (2008a) demonstrated that vegetation cover dissipated overland flow energy by imparting roughness, and therefore substantially reduced velocity of running water across peat surface compared to bare peat surfaces. Grayson et al. (2010) analyzed the long-term (1950s to 2010s) hydrograph data from the Trout Beck blanket peat catchment, northern England, and found that revegetation of eroded peat contributed to reduced flood peak, with hydrographs being flashier and more narrow-shaped with higher peaks during the more eroded periods. Recent modelling studies have also suggested that surface vegetation cover is important in affecting the timing of the flood peaks from upland peatlands (Ballard et al., 2011; Lane and Milledge, 2013). A spatially-distributed version of TOPMODEL developed by Gao et al. (2015) simulated how restoration and the associated land-cover change impact river peak flow. They reported that a catchment with a cover of Eriophorum and

Sphagnum had much lower peak flows than that with bare peat (Gao et al., 2015; Gao et al., 2016; Gao et al., 2017).

Vegetation removal driven by land management practices (e.g., burning, overgrazing) (Parry et al., 2014) and atmospheric pollution (Smart et al., 2010) is normally associated with the first stage of the onset of blanket peat erosion (Lindsay et al., 2014; Parry et al., 2014; Shuttleworth et al., 2015). In modelling peat erosion using PESERA-GRID, a vegetation growth module was used to estimate gross primary productivity, soil organic matter and vegetation cover based on the biomass carbon balance (Kirkby et al., 2008; Li et al., 2016b). Li et al. (2016a) found that modelled peat erosion increased significantly with decreased vegetation coverage. For example, predicted peat erosion for the Trout Beck study catchment increased by 13.5 times when vegetation coverage was totally removed as a scenario (Li et al., 2016a).

4.4 Land management practices

Peatlands can be destabilized by changes in hydrology that may be brought about by a wide range of land management practices, including peat extraction, artificial drainage, grazing, burning (prescribed burning or wild fire), afforestation and infrastructure (Parry et al., 2014; Ramchunder et al., 2009).

Grazing has received increasing attention due to its important impacts on peat condition, vegetation and hydrological processes (Evans, 2005; Holden et al., 2007a; Worrall and Adamson, 2008; Worrall et al., 2007a). Unsustainable levels of grazing have adverse effects on peatland hydrological and erosion processes. Meyles et al. (2006) reported increased hydrological connectivity of hillslopes with channels resulting from grazing practices which led to increased flood peaks. The high risk of vegetation damage and exposure of bare soils by grazing make the bare peat surface vulnerable to weathering processes (Evans, 1997). Compaction of soils by trampling decreases soil infiltration and may enhance erosion sensitivity due to increased hydrological connectivity by animal tracks (Meyles et al., 2006; Zhao, 2008).

Fire is a common occurrence in peatlands throughout the world (Ramchunder et al., 2013; Turetsky et al., 2015), both naturally and for management purposes. Prescribed burning has been practiced in many peatlands to mitigate wildfire risks (Hochkirch and Adorf, 2007; Holden et al., 2007c), to clear land for plantations or agriculture (Gaveau et al., 2014) and to promote changes in heather structure for food production to support grouse habitats and the rural gun-sports industry (Grant et al., 2012; Holden et al., 2012a; Ramchunder et al., 2013). Managed fire practice attempts to avoid consumption of the underlying peat by keeping the fire under control (Holden et al., 2015). However, the soil properties and surface conditions can be affected in the aftermath of the fire with enhanced surface drying, increased bulk density and associated water retention in the near-surface peat (Brown et al., 2015; Holden et al., 2015). This may lead to decreased evapotranspiration (Bond-Lamberty et al., 2009), enhanced overland flow production and exacerbated surface erosion (Holden et al., 2015; Holden et al., 2014; Pierson et al., 2008; Smith and Dragovich, 2008).

There have been several recent studies examining the effects of prescribed burning on peatland vegetation communities (Noble et al., 2017), hydrological processes (Clay et al., 2009a; Holden et al., 2015; Holden et al., 2014), thermal regime of the soil mass (Brown et al., 2015), soil solution chemistry (Clay et al., 2009b; Worrall et al., 2007a) and fluvial carbon loads (Holden et al., 2012a; Worrall et al., 2013; Worrall et al., 2011). Imeson (1971) reported that burning not only exposed the peat surface to erosion and accelerated the loss of surface material, but also increased the rate and intensity of infiltration and throughflow that promotes gully formation and development (e.g. Maltby et al. (1990)). Rothwell et al. (2007) found that approximately 32% of the total lead export from a peatland catchment may have been released during a discrete erosion event soon after a wildfire, and accidental wildfires and the subsequent release of highly contaminated peat may increase under future climate change. Worrall et al. (2011) measured the POC release from peat-covered sites after restoration, following degradation by past wildfires. They found that unrestored, bare peat sites had mean POC flux at 181 t C km^{-2} yr^{-1} which was much higher than that of the restored sites (18 t C km^{-2} yr^{-1}) and the intact vegetated control sites without wildfire impact (21 t C km^{-2} yr^{-1}). Note that as peat sediment consists of around half organic carbon, then, crudely, the above values can be doubled to estimate sediment flux.

Several recent modelling studies have been conducted to examine the effects of land-management practices on controlling erosion. Li et al. (2016a) found that a shift in land-management practices that reduce drainage density, grazing and vegetation burning intensity can mitigate the impacts of future climate change on blanket peat erosion, and promote the resilience of systems. Li et al. (2017b) used land-management scenarios including intensified and extensified grazing, artificial drainage and prescribed burning in modelling blanket peat erosion, and found that less intensive management reduced erosion but potentially enhanced the risk of more severe wildfires.

4.5 Peatland conservation techniques

Numerous studies have examined the techniques available for restoring degraded blanket peatlands (Armstrong et al., 2009; Crowe et al., 2008; Holden et al., 2008b; Parry et al., 2014), and the role of conservation techniques on stream peak flow (Gao et al., 2015; Gao et al., 2016; Gao et al., 2017; Grayson et al., 2010; Lane and Milledge, 2013), water table and hydrological processes (Allott et al., 2009; Holden et al., 2011; Wilson et al., 2010; Worrall et al., 2007b) and sediment and particulate organic carbon (Holden et al., 2007b; Holden et al., 2008a; Ramchunder et al., 2012; Shuttleworth et al., 2015; Wilson et al., 2011). Restoration practices that result in stabilisation and revegetation are recommended as vegetation cover is capable of reducing erosion by: i) significantly reducing overland flow velocity by 32-70% (Holden et al., 2008a); ii) reducing hydrological connectivity (Gao et al., 2015; Gao et al., 2016; Gao et al., 2017) and sediment connectivity

(Evans and Warburton, 2007; Evans et al., 2006); iii) protecting peat surfaces from the effects of rainsplash (Li et al., 2018b), freeze-thaw action and desiccation (Brown et al., 2015; Li et al., 2016b); and iv) enhancing the organic matter and microbiological function of peat. In turn, areas with enhanced peat erosion and good hydrological connectivity would make it more difficult for the peat to host vegetation as seeds or small plants would be readily washed away during rainfall events (Holden, 2005b).

Traditional techniques for controlling gully erosion are the establishment of check dams to slow down water flows and control the expansion of the gully network, and reprofiling of the sides of gullies to reduce the slope steepness of gully walls (Parry et al., 2014). Following reprofiling, revegetating gully sides (natural or artificial revegetation) is frequently used to decrease the sediment connectivity of the landscape, resulting in reduced sediment delivery to the channel system (Evans and Warburton, 2005; Parry et al., 2014).

Management techniques that aim to control channel processes are important for reducing flow erosion, undercutting and ditch bank collapse (Holden et al., 2007b; Marttila and Kløve, 2010a). Holden et al. (2007b) found that blocking drains with periodic dams was successful at reducing sediment yield by more than 50-fold. Practices such as peak runoff control dams (Kløve, 2000; Marttila and Kløve, 2009) that allow temporarily ponding of water above erodible bed deposits during low flows, have been found to be effective in reducing peak flows, sediment and nutrient transport at peat harvesting sites and in peatland forestry management (Kløve, 1998; Marttila and Kløve, 2008; Marttila and Kløve, 2009; Marttila and Kløve, 2010b). In addition, treatment wetland systems, or overland flow areas, are sometimes constructed downstream to purify the peat extraction runoff by retaining sediment and nutrient loads (Postila et al., 2014).

5. A meta-analysis of peat erosion rates

5.1 Data collection and statistical analysis

Data on peat erosion rates was searched for within the existing published literature identified in the Web of Science described above. A total of 38 publications provided erosion rate data with 61 erosion rate records obtained within these publications (Table 1). The dataset compiled included: (i) erosion rates and/or peat loss; (ii) study area; (iii) spatial scale, (iv) temporal scale, (v) measurement method. Erosion rates in the literature tend to be expressed as mg m^{-2} h^{-1} for data collected at very fine scale during short periods (minutes or hours) (Arnaez et al., 2007; Morvan et al., 2008); and as mm yr^{-1} for data collected at fine scale; or as t km^{-2} yr^{-1} for data collected at hillslope and field scales over longer periods (up to several years) (Cerdan et al., 2010; Prosdocimi et al., 2016). We report data at these scales as presented in the literature. However, it is worth noting that it is possible to convert between units by using reported values of peat bulk density. While peat bulk density varies, it is typically very low. Hobbs (1986) reported bulk density values for British peats of ~ 1 g cm^{-3}. Therefore, an erosion rate of 1 t km^{-2} yr^{-1} is equivalent to 10 mm of peat loss, or 0.5 t km^{-2} yr^{-1} of carbon. Spatial scale is classified as very fine (microplots < 1 m^2), fine (1-1000 m^2), hillslope (1000 m^2 – 1 ha) and field (> 1 ha) scale (Boix-Fayos et al., 2006; Verheijen et al., 2009). Temporal scale is classified as event (up to several days), monthly, seasonal, long-term (> 1 year) scale. Methods used to obtain erosion data included erosion pins, bounded plots, sediment transport measurements through sampling or at gauging stations, bathymetric surveys in reservoirs, topographic surveys and sediment budgeting. Correlation analysis and regression analysis were used to identify the relationship between area and sediment yield rate. Test results were considered significant at $p < 0.05$.

Table 1. Erosion rates in peatlands reported in publications since 1957.

Region	Spatial scale	Temporal scale	Methods*	Erosion rate**	Reference
Strines Reservoir, S Pennines, England	Catchment (11.15 km^2)	Long-term (87 years)	d	SY1: 39.4	Young (1957)
Catcleugh Reservoir, N England	Catchment (40 km^2)	Long-term (4 years)	d	SY1: 43.1	Hall (1967)
Moor House, N Pennines, England	Catchment (0.83 km^2)	Long-term (1 year)	c	SY1: 110.8 SRR: 10.0	Crisp (1966)
Featherbed Moss, N England	Catchment (0.03 km^2)	Long-term (1 year)	c	SY1: 12.0-40.0	Tallis (1973)
North York Moors, N England	Fine	Long-term (2 years)	a	SRR: 40.9	Imeson (1974)
Hopes Reservoir, SE Scotland	Catchment (5 km^2)	Long-term (35 years)	d	SY1: 25.0	Ledger et al. (1974)
North Esk Reservoir, S Scotland	Catchment (7 km^2)	Long-term (121 years)	d	SY1: 26.0	Ledger et al. (1974)
North York Moors, N England	Catchment	-	-	SY1: 2.0-30.0	Arnett (1979), cited in Robinson and Blyth (1982)
Snake Pass, S Pennines, England	Fine	Long-term (1 year)	a	SRR: 7.8	Philips et al. (1981)
Moor House, N Pennines, England	Fine	Long-term (1 year)	a	SRR: 10. 5	Philips et al. (1981)
Holme Moss, S Pennines, England	Fine	Long-term (1 year)	a	SRR: 73. 8	Philips et al. (1981)
Snake Pass, S Pennines, England	Fine	Long-term (1 year)	a	SRR: 5.4	Philips et al. (1981)
Coalburn, N England	Catchment (1.5 km^2)	Long-term (1.5 year)	c	SY1: 3.0	Robinson and Blyth (1982)
Holme Moss, S Pennines, England	Fine	Long-term (2 years)	a	SRR: 33.5	Tallis and Yalden (1983)
Cabin Clough, S Pennines, England	Fine	Long-term (2 years)	a	SRR: 18.5	Tallis and Yalden (1983)
Doctors Gate, S Pennines, England	Fine	Long-term (2 years)	a	SRR: 9.6	Tallis and Yalden (1983)
Glenfarg reservoir, Scotland	Catchment (5.82 km^2)	Long-term (56 years)	d	SY1: 26.3	McManus and Duck (1985)

Region	Spatial scale	Temporal scale	Methods*	Erosion rate**	Reference
Glenquey reservoir, Scotland	Catchment (5.58 km^2)	Long-term (73 years)	d	SY1: 31.3	McManus and Duck (1985)
Peak District Moorland, N England	Fine	Long-term (1 year)	a	SRR: 18.4-24.2	Anderson (1986)
Monachyle, C Scotland	Catchment (7.7 km^2)	-	c	SY1: 43.8	Stott et al. (1986)
Plynlimon, Mid Wales	Fine	Long-term (5 years)	a	SRR: 30.0	Robinson and Newson (1986)
Wessenden Moor, S Pennines, N. England	Catchment	-	c	SY1: 55.0	Labadz (1988)
Chew Reservoir, S Pennines, N. England	Catchment (3.06 km^2)	-	d	SY1: 212.7	Labadz (1988)
Mid Wales	Fine	Long-term (1.4 years)	a	SRR: 23.4	Francis and Taylor (1989)
Ceunant Ddu, Mid Wales	Catchment (0.34 km^2)	Seasonal	c	SY1: 3.7	Francis and Taylor (1989)
Ceunant Ddu (Ploughing), Mid Wales	Catchment (0.34 km^2)	Seasonal	c	SY1: 9.0	Francis and Taylor (1989)
Nant Ysguthan, Mid Wales	Catchment (0.14 km^2)	Long-term (1.4 years)	c	SY1: 1.1	Francis and Taylor (1989)
Nant Ysguthan (Ploughing), Mid Wales	Catchment (0.14 km^2)	Seasonal	c	SY1: 3.1	Francis and Taylor (1989)
Earlsburn Reservoir, Scotland	Catchment (2.85 km^2)	-	d	SY1: 68.2	Duck and McManus (1990)
North Third Reservoir, Scotland	Catchment (9.31 km^2)	-	d	SY1: 205.4	Duck and McManus (1990)
Carron Valley Reservoir, Scotland	Catchment (38.7 km^2)	-	d	SY1: 141.9	Duck and McManus (1990)
Pinmacher Reservoir, Scotland	Catchment (0.425 km^2)	-	d	SY1: 50.9	Duck and McManus (1990)
Holl Reservoir, Scotland	Catchment (3.99 km^2)	-	d	SY1: 72.3	Duck and McManus (1990)
Harperleas Reservoir, Scotland	Catchment (3.44 km^2)	-	d	SY1: 13.8	Duck and McManus (1990)
Drumain Reservoir, Scotland	Catchment (1.53 km^2)	-	d	SY1: 3.9	Duck and McManus (1990)
Plynlimon, Mid Wales	Fine	Long-term (2 years)	a	SRR: 16.0	Francis (1990)

Region	Spatial scale	Temporal scale	Methods*	Erosion rate**	Reference
Upper Severn, Mid Wales	Catchment (0.94 km^2)	Long-term (2 years)	c	SY1: 34.4	Francis (1990)
Abbeystead Reservoir, N. England	Catchment (48.7 km^2)	Long-term (2 years)	d	SY1: 34.8	Labadz et al. (1991)
Wessenden Head Moor, N. England	Catchment (2.4 km^2)	Long-term (2 years)	c	SY1: 38.8	Labadz et al. (1991)
Shetland, N. Scotland	Fine	Long-term (5 years)	a	SRR: 10.0~40.0	Birnie (1993)
Forest of Bowland, N. England	Fine	Long-term (1 year)	a	SRR: 20.4	Mackay and Tallis (1994)
Howden Reservoir, N. England	Catchment (32.0 km^2)	Long-term (75 years)	d	SY1: 128.0	Hutchinson (1995)
Abbeystead Reservoir, N. England	Catchment (48.7 km^2)	Long-term (140 years)	d	SY1: 35.5	Rowan et al. (1995)
77 Reservoirs in Yorkshire, N. England	Catchment	-	d	SY1: 124.5	White et al. (1996)
Harrop Moss, Pennines, N. England	Fine	Long-term (7 years)	a	SRR: 13.2	Anderson et al. (1997)
Monachyle, C. Scotland	Fine	Long-term (2 years)	a	SRR: 59.0	Stott (1997)
Haapasuo peat mine, C. Finland	Fine	Event	b	SY2: 20.0-7060.6	Kløve (1998)
Burnhope Reservoir, N. England	Catchment (17.8 km^2)	Long-term (62 years)	d	SY1: 33.3	Holliday (2003)
Moor House, N. Pennines, N. England	Fine	Long-term (4 years)	a	SRR: 19.3	Evans and Warburton (2005)
Moor House, N. Pennines, N. England	Catchment (0.83 km^2)	Long-term (4 years)	f	SY1: 44.6	Evans and Warburton (2005)
Upper North Grain, S. Pennines, N. England	Catchment (0.38 km^2)	Long-term (1 year)	c	SY1: 161.6	Yang (2005)
March Haigh Reservoir, N. England	Catchment	-	d	SY1: 2-28	Yeloff et al. (2005)
Upper North Grain, S. Pennines,	Fine	Long-term (1 year)	a	SRR: 34.0	Evans et al. (2006)

Region	Spatial scale	Temporal scale	Methods*	Erosion rate**	Reference
England					
Upper North Grain, S. Pennines, England	Catchment (0.38 km^2)	Long-term (1 year)	f	SY1: 195.2	Evans et al. (2006)
Oughtershaw Beck, N. England	Catchment	Long-term (1 year)	c	SY1: 16.9	Holden et al. (2007b)
Flow Moss, N. Pennines, N. England	Fine	Seasonal	a	SRR: 1.03	Baynes (2012)
Harthope Head, N. England	Fine	Seasonal	a	SRR: 38.0	Grayson et al. (2012)
Harthope Head, N. England	Fine	Seasonal	e	SRR: -6.6~-2.5	Grayson et al. (2012)
Cottage Hill Sike, Moor House, N. England	Catchment (0.17 km^2)	Long-term (3 years)	c	SY1: 2.8	Holden et al. (2012c)
Moor House, N. Pennines, N. England	Very fine	Event	b	SY2: 188.8-72061.8	Li et al. (2018b)
Moor House, N. Pennines, N. England	Very fine	Event	b	SY2: 28.6-299.2	Li et al. (2018a)

*Methods used: a = erosion pins; b = bounded plots; c = sediment transport measurements through sampling or at gauging stations; d = bathymetric surveys in reservoirs; e = topographic surveys; f = sediment budgeting.

**Erosion rates are summarized in forms of sediment yield (SY1, t km^{-2} yr^{-1} and SY2, mg m^{-2} h^{-1}) or surface retreat rate (SRR, mm yr^{-1}).

5.2 Scale-dependency of peat erosion rates and the controls

Figure 5a shows the median sediment yield measured at different spatial scales based on the literature survey. Reported sediment yields ranged from 251 to 3711055 t km^{-2} yr^{-1} at the very fine scale, from -6600 to 73800 t km^{-2} yr^{-1} at fine scale, and from 3 to 213 t km^{-2} yr^{-1} at the catchment scale. The significant range at the very fine scale is mainly associated with differences in plot size, rainfall intensity and peat properties utilized in different studies (Kløve, 1998; Li et al., 2018a; Li et al., 2018b). The sediment yields reported at catchment scales tend to cluster quite closely, perhaps because of the close range of climates within which peatlands are formed. A comparison of sediment yields at different scales indicated significant differences between scales, probably caused by extrapolating data from very fine and fine scales to catchment scales. Different erosion processes are active at different spatial scales, and different sediment sinks and sources appear from plot to catchment scale. In addition, the processes at one spatial or temporal scale interact with processes at another scale. Erosion or deposition rate measured directly by pins are usually interpolated over relatively small areas. Measured erosion rates from erosion plot studies ranged from 20.0 to 72061.8 mg m^{-2} min^{-1} (Kløve, 1998; Li et al., 2018a; Li et al., 2018b). The temporal pattern of erosion typically displays a positive hysteresis in the relationship between suspended sediment concentration and overland rate, with peak sediment concentration occurring during the rising limb of the overland flow hydrograph (Clement, 2005; Holden and Burt, 2002a; Kløve, 1998; Li et al., 2018b). The positive hysteresis is a result of sediment exhaustion (Li et al., 2018b). The laboratory experiments by Li et al. (2018a) revealed that antecedent conditions such as needle-ice formation is very important in controlling peat erodibility and thus erosional response to a given rainfall event. In fact at the plot scale, without the impacts of rainsplash and weathering processes (freeze–thaw and desiccation), sheet or rill flow has limited effect on increasing peat erosion (Li et al., 2018a; Li et al., 2018b). The presence or absence of vegetation is considered as the other critical factor determining the hydrological and erosion response at the finest temporal and spatial scales (Clement, 2005; Holden and Burt, 2002a; Holden et al., 2008a).

The spatial patterns of topography and vegetation are key factors controlling the response of hillslopes to generation of runoff and the transfer of sediments. Holden and Burt (2003c) found that the source area for overland flow on a hillslope varied depending on the topography and time since rainfall. Gentle slopes, especially footslopes, are dominated by saturation-excess overland flow, whereas steeper midslope sections are dominated by shallow subsurface flow (Holden, 2005b). The majority of sediment produced by interrill and rill erosion on hillslopes is usually deposited at the foot of hillslopes or trapped by vegetation surrounding bare peat areas, and therefore does not reach the channel systems.

Catchment sediment yields reflect the combined effect of all active and interacting erosion and sediment deposition processes. Figure 5b shows the relationship between catchment area (A) and mean annual sediment yield (SY) for a total of 19 catchments, based on published reservoir sedimentation measurements (Labadz et al., 1991; Small et al., 2003; Yeloff et al., 2005); there is wide variation and high degree of scatter, with no statistically significant correlation (Spearman's correlation test, $p = 0.898$). It has been widely reported that sediment yields decrease with increasing area (De Vente et al., 2007) due to decreasing sediment delivery ratios (Walling and Webb, 1996). However, different behavior has been reported from upland peat catchments (Small et al., 2003) with channel bank erosion being suggested as the dominant sediment source. It can be inferred that gully and bank erosion and mass movements form an important part of the catchment sediment budget in these environments. This is further confirmed by modelling, field measurement and tracer studies demonstrating a significant contribution to sediment yield from gully erosion, bank erosion and mass movements (Evans and Warburton, 2007; Evans et al., 2006). At the catchment scale where all erosion and sediment deposition processes are active and interactive, sediment yield can either increase or decrease with increasing area.

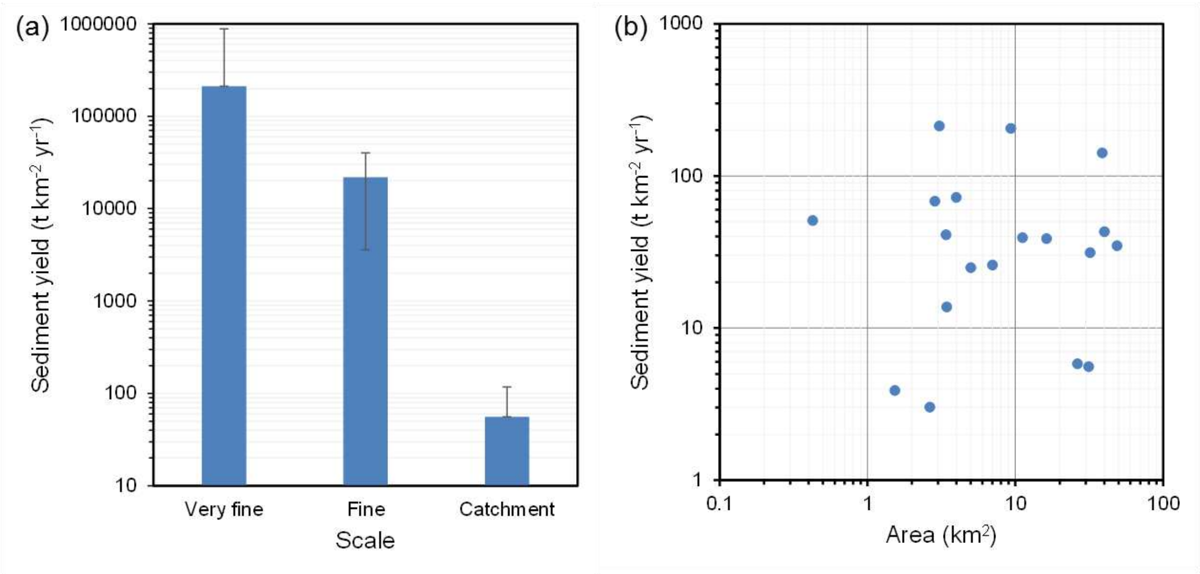

Figure 5. (a) Erosion rates obtained from different spatial scales. The sediment yield data obtained from very fine and fine scales was directly extrapolated to a catchment scale for comparison purposes only; (b) Relationship between catchment area and sediment yield for catchment-scale peatland sediment studies.

6. Main gaps and prospects in peat erosion research

Since peat erosion consists of complex interacting process that are variable in both space and time and are influenced by numerous internal and external factors, there are still many unanswered questions. More peat erosion research is required in three key areas: i) further study of the known basic peat erosion processes and their incorporation into peat erosion modelling; ii) studies of how peat erosion measurement techniques compare and what types of new information can be gleaned from new techniques; iii) more studies in a range of peatland environments on how erosion drivers or mitigation techniques influence peat erosion.

6.1 Peat erosion processes and incorporation into peat erosion models

Some important issues that remain to be addressed include how basic erosion processes such as freeze–thaw weathering, wind-driven rainsplash and pipe erosion function and how they interact with each other. In addition, incorporating some of the important erosion processes into peat erosion models remains a challenge either due to difficulties in the parametrisation of processes that are not fully understood or, as is often the case, a lack of field data for model calibration and validation. For example, the contributions of wind erosion, gully erosion, bank erosion, pipe erosion and mass movements to catchment sediment budgets are usually under-represented in erosion models, although field data clearly demonstrate their importance (Li et al., 2016b). More attention should be focused on process-based studies of these erosion forms to directly inform future model development:

(1) Needle ice production has been observed to be a vital agent of freeze–thaw weathering in producing erodible peat materials (Evans and Warburton, 2007; Grayson et al., 2012; Li et al., 2018a). Studies of the mechanisms controlling needle ice formation (e.g., cooling rate, freezing point, number and frequency of freeze–thaw cycles and moisture content at freezing) are urgently required to enhance the representation of freeze–thaw processes within peatland sediment supply models.

(2) Limited attention has been given to quantitative study of rainsplash erosion, wind-driven rainsplash as well as interactions between rainfall- and flow-driven processes (Li et al., 2018b). Spatially-distributed models of peatlands which can incorporate these important controls for interrill erosion would be useful for predicting future slope development in peatlands. In addition, the effect of raindrop impact on detachment capacity is highly related to rainfall properties (e.g., rainfall type and intensity, drop size, velocity and kinetic energy and impact gradient of falling drops) (Salles and Poesen, 2000; Singer and Blackard, 1982; Torri and Poesen, 1992), that are usually modified by wind in many peatland environments (Foulds and Warburton, 2007a; Foulds and

Warburton, 2007b; Warburton, 2003). These controls on rainsplash detachment should also be reflected in further peat erosion models development.

(3) Piping has been widely observed in peatland landscapes. However, the complete understanding of pipe initiation mechanisms, the interaction of environmental factors controlling the development of pipe networks, roof collapse and gully development, and the influence of piping on catchment water and sediment response needs to be considered.

(4) Despite the importance of wind erosion in upland peat, surprisingly few studies have examined aeolian erosion processes compared with those on fluvial processes in peatland landscapes. Of the few studies available most have focused on the UK north Pennines and are temporally limited with less than two years monitoring (Foulds and Warburton, 2007a; 2007b; Warburton, 2003). Future long-term observations of wind erosion are required in a range of geomorphological locations, to gain a full understanding of peatland aeolian system dynamics and erosion rates.

(5) Floodplain sediment storage may be an important component of the carbon balance of eroding peatlands (Pawson et al., 2012). Future work is required to ascertain the fate of floodplain carbon (and the downstream fate of POC in the fluvial system more generally) in terms of rates and fluxes of loss to DOC or CO_2.

(6) Peat erosion processes interact with one another. Further exploration of the combined effects of sediment supply (rainsplash, freeze–thaw and desiccation) and sediment transport (water erosion, wind erosion,

mass movements) processes could be undertaken in future studies that couple laboratory-based experiments and field monitoring to reveal the relative importance of these controls.

(7) Further research is needed on thresholds for connectivity of water and sediment flows at all scales and the role of streams as sediment sources and (temporal) sinks. Multi-scale studies to facilitate spatial upscaling of runoff and erosion rates and provide data on the spatial connections between different units at each scale are necessary.

(8) Finally, peat erosion models should be coupled to peatland landform development models (e.g. DigiBog; Baird et al. (2012); Young et al. (2017)) that can be run under different climate, land management and topographic configurations so that predictions of peat mass growth and decay can include the erosion components.

6.2 Peat erosion measurements

Traditional methods of peat erosion measurement using erosion pins, sediment traps and erosion plots have the disadvantage of disturbance and damage to the peat surface during installation and repeated measurements. Photogrammetric measuring techniques are instead recommended where possible. By using measurement techniques such as SfM (Glendell et al., 2017) or remote sensing (Evans and Lindsay, 2010; Evans and Lindsay, 2011; Grayson et al., 2012; Rothwell et al., 2010), micro-topographical changes can be compared by using time-series data and mapping important erosion processes (e.g., gully erosion) or erosion affected by needle ice production, desiccation or extreme rainfall events.

In addition, measuring peat erosion is restricted by the temporal scale involved as most monitoring programs are typically limited to a few years (Table 2). Short-term measurements may not be representative of long-term fluctuations (Boix-Fayos et al., 2006), such as seasonal and interannual variations in measured peat erosion rates at both the catchment (Evans and Warburton, 2007; Francis, 1990; Labadz et al., 1991) and plot scale (Holden and Burt, 2002a). Long-term systematic measurements under real field conditions are recommended to reduce the temporal uncertainty of erosion plot experiments and to provide numeric models (Li et al., 2016a) with reliable data. In addition, continuous and prolonged monitoring of peat erosion processes should utilize standardized procedures to allow comparisons of data obtained from different study areas (Prosdocimi et al., 2016).

Peat loss measured at one scale may not be representative of those at other scales. Therefore, direct extrapolation of plot scale interrill and rill erosion rates up the catchment scale can be problematic (De Vente and Poesen, 2005; Parsons et al., 2006). There is a need for monitoring, experimental and modelling studies as a basis for scaling erosion rates from one specific area to larger or smaller areas.

6.3 Factors (drivers or mitigation techniques) influencing peat erosion

6.3.1 Effects of drivers

Changes in micro-climatic factors such as air temperature and moisture content impact the actions and interactions of freeze–thaw and wet–dry cycles and the associated weathering processes of the peat surface. Without intensive weathering processes, running water is unlikely to wash off large quantities of peat (Evans and Warburton, 2007; Li et al., 2018a). More direct investigations are required to reveal the importance of interactions between temperature and moisture controls on sediment supply processes.

In addition to the normally observed peat properties (e.g., degree of humification, shear strength, bulk density) that affect peat erosion (Carling et al., 1997; Marttila and Kløve, 2008; Svahnbäck, 2007; Tuukkanen et al., 2014), other physical and geochemical properties (e.g., grain size distribution and form, moisture) also impact peat erodibility. For example, it has been hypothesized that peat particle size distribution and form impacts the resistance of peat to wind erosion process (Warburton, 2003). Any increase in moisture content is likely to enhance peat hillslope instability due to reduced cohesion and saturation of the basal peat (Evans and Warburton, 2007; Warburton et al., 2004). More attempts are needed to assess how these peat properties influence sediment yield and transport.

Numerous studies have demonstrated that vegetation cover can reduce peat erosion. However, there are several related research questions remaining unanswered. For example, what is the effectiveness of a plant cover in reducing splash erosion rates through interception of raindrops and by decreasing the kinetic energy of raindrops approaching the peat surface? Are weathering processes (freeze–thaw cycle and wet–drying cycle) for the bare soil surfaces different for vegetated peat surfaces? How does vegetation cover impact wind erosion by imparting roughness to the air flow and reducing the shear velocity of wind? To what extent does vegetation cover contribute to peat slope stability reducing mass movements?

In addition, management practices such as artificial drainage, prescribed burning and grazing can result in changes to vegetation cover and sediment connectivity from sources areas to channels (Evans et al., 2006). However, there have been limited measurements of how peatland hillslope erosion processes respond to changes of vegetation cover that are associated with these management practices (Li et al., 2016a; Li et al., 2017b). Integrated research into the interaction of peat hillslope erosion processes and different vegetation cover conditions that are associated with different states of degradation and re-vegetation will help inform future functioning of peatlands.

Local disturbances such as installation of infrastructure (e.g., windfarms, tracks, footpaths, pipelines) (Parry et al., 2014), may also affect peatland runoff and sediment production (Holden, 2005a; Robroek et al., 2010). More long term studies of peatland runoff and erosion are needed to understand the impacts of these land management practices.

6.3.2 Effects of peatland conservation techniques

In recent years there has been a significant increase in the number of peatland restoration projects and amount of funding to reduce the negative consequences of peatland degradation on ecosystem services (Holden et al., 2008b; Parry et al., 2014). Fewer studies have evaluated the effectiveness of conservation measures (e.g., check-dams in gullies and streams) at catchment or regional scales, therefore more attention is required in future studies, particularly to help ensure that erosion prevention is accounted for in carbon accounting processes as part of land management change (LULUCF, 2014) under the United Nations Framework Convention on Climate Change.

7. Conclusions

From this comprehensive review of peatland erosion research a number of research themes have emerged as requiring further attention in the near future. Firstly, there is a need to increase understanding of the basic erosion processes operating in peatlands (e.g., freeze–thaw weathering, wind-driven rainsplash, and piping erosion) and how they interact with one another. Secondly, it is important to establish long-term and multi-scale in-situ monitoring programmes that combine both traditional and new methods (e.g. SfM techniques) that offer improved resolution and spatial coverage. These should adopt standardized procedures to allow comparisons of data derived from different sites but should also be investigative to help our understanding of process dynamics. Process studies and new datasets will enable improved model parameterization through the incorporation of basic erosion processes that are currently under-represented in erosion models. Finally there is a need to collect more spatially-distributed data, across a wider range of peatland environments to help improve our understanding of the effects of environmental factors and land management practices on peat erosion processes and rates, not least as this will be beneficial for determining the most feasible and sustainable conservation techniques, and support reporting for LULUCF as part of UN climate change commitments.

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