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1 **Erosion in peatlands: recent research**
2 **progress and future directions**

3

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12

13

14 **Abstract**

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

37

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

39

40 **1. Introduction**

41 Peat is a slowly-accumulating organic-rich soil composed of poorly
42 decomposed remains of plant materials (Charman, 2002). Peatlands are
43 areas with a surface peat accumulation and they can be broadly subdivided
44 into bogs, fens and some types of swamps (Joosten, 2016). Bogs, which can
45 be subdivided into blanket peatlands and raised bog (Charman, 2002), are
46 ombrotrophic and receive water and nutrients primarily from precipitation.
47 Fens and swamps are minerotrophic and receive water and nutrients from
48 groundwater. To initiate and develop, peatlands require water-saturated
49 conditions. However, peatlands occur in a broad range of climatic conditions
50 from the warm tropics through to the cold, high latitudes and in total they
51 cover approximately 4.23 million km² (2.84%) of the world's land area (Xu et
52 al., 2018). Peatlands serve as important terrestrial carbon sinks, storing
53 carbon equivalent to more than two thirds of the atmospheric store (Yu et al.,
54 2010). Quantification of the carbon flux from peatland systems is therefore
55 vital to fully understand global carbon cycling (Evans and Warburton, 2007;
56 Pawson et al., 2008). In addition, peatlands provide a wide range of important
57 ecosystem services including water supply, recreation and biodiversity (Bonn
58 et al., 2009; Osaki and Tsuji, 2015). The conditions required for peatland
59 initiation and ongoing survival are relatively narrow and as a result they are
60 fragile ecosystems that are sensitive to a wide range of external and internal

61 pressures, including changes in topography due to peat growth, climate
62 change, atmospheric pollution, grazing, burning, artificial drainage,
63 afforestation and infrastructure (Fenner and Freeman, 2011; Holden et al.,
64 2007c; Ise et al., 2008; Noble et al., 2017; Parry et al., 2014).

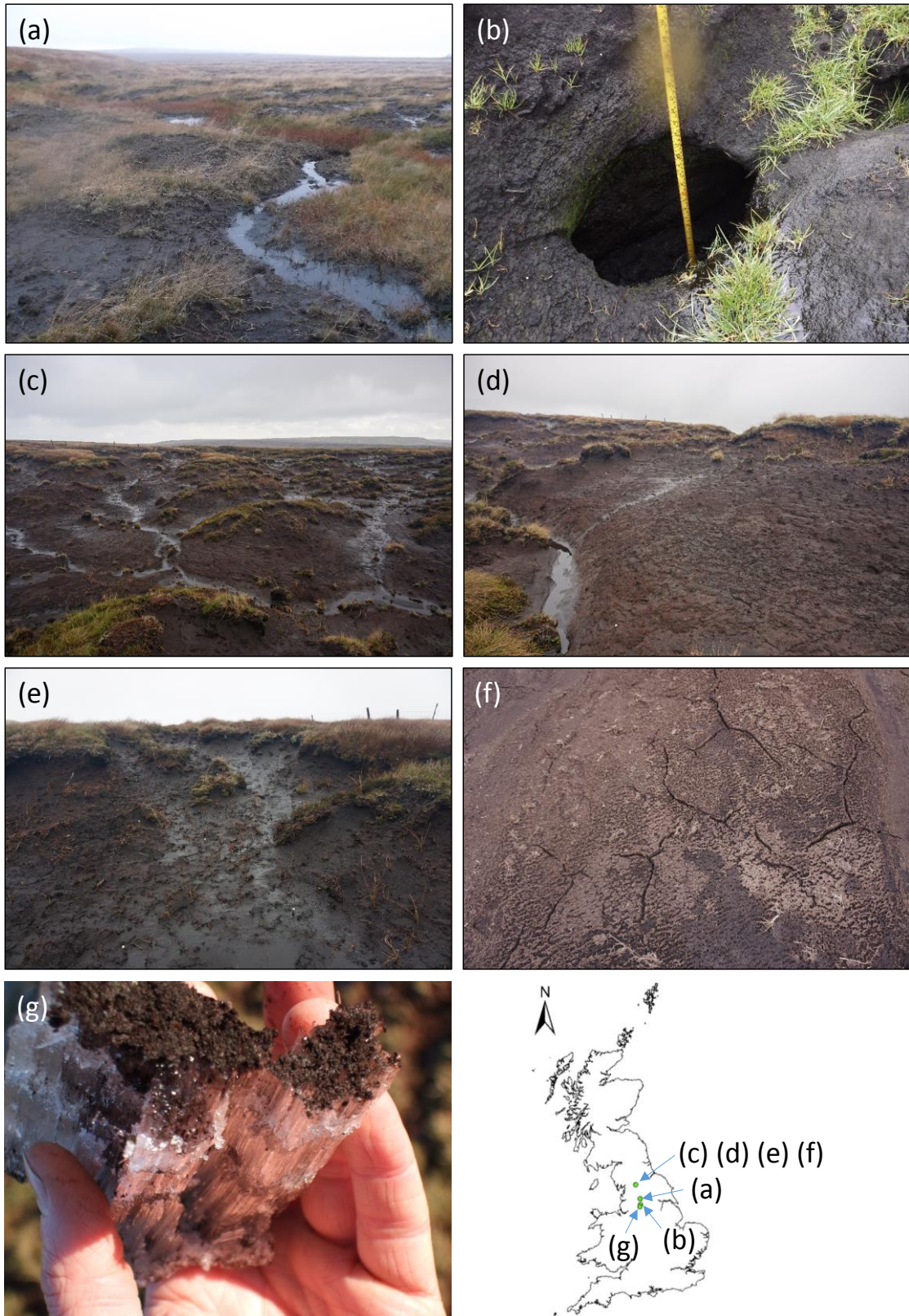
65

66 Peat erosion is a natural process driven primarily by actions of water and wind,
67 but slight changes in conditions driven by human action can lead to
68 accelerated erosion and degradation (Parry et al., 2014). Wind erosion can
69 occur where the peat surface is largely bare and is common in windy uplands
70 and peat mining areas (Foulds and Warburton, 2007a; Foulds and Warburton,
71 2007b). Erosion by water can occur through a number of different processes
72 (both on and below the surface), with the scale of erosion varying by peatland
73 type as well as how degraded they are. Rainsplash and runoff energy can
74 cause erosion on bare peat surfaces. Where flow accumulates, both in
75 artificial ditches and natural channels, further erosion can take place. In
76 peatlands that have been drained ditch erosion often occurs while channel
77 bank collapse may occur on all peatlands (Marttila and Kløve, 2010a). Erosion
78 under the peat surface can also occur with piping being common in many
79 peatlands globally (Jones, 2010).

80

81 Rain-fed blanket peatlands cover 105 000 km² of the Earth's surface (Li et al.,
82 2017a) and occur on sloping terrain, with slope angles as high as 15°. As a
83 result blanket peatlands are potentially more vulnerable to water erosion than
84 other types of peatlands occurring in landscapes with very little surface

85 gradient (Li et al., 2017a). It has been reported that many blanket peatlands
86 have experienced severe erosion (Evans and Warburton, 2007; Grayson et al.,
87 2012; Li et al., 2016b) and are under increasing erosion risk from future
88 climate change (Li et al., 2016a; Li et al., 2017a). The erosion of peat with
89 high carbon content will enhance losses of terrestrial carbon in many regions.
90 The main erosion processes affecting blanket peat can be broadly divided into
91 sediment supply processes (e.g., freeze–thaw and desiccation), sediment
92 transfer from hillslopes (e.g., interrill erosion, rill erosion and gully erosion),
93 bank failures and mass movement (Bower, 1961; Evans and Warburton, 2007;
94 Francis, 1990; Labadz et al., 1991; Li et al., 2018a; Warburton and Evans,
95 2011). Figure 1 shows some typical peat erosion features and processes in
96 the uplands of northern England.



97

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99

100

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.

101

102 Extensive erosion of many blanket peatlands potentially compromises their
103 ability to maintain ecosystem functions (Evans and Lindsay, 2010) and has
104 been found to have adverse impacts on landscapes (Holden et al., 2007c),
105 reservoir sedimentation (Labadz et al., 1991), water quality (Crowe et al.,
106 2008; Daniels et al., 2008; Rothwell et al., 2008a; Rothwell et al., 2008b;
107 Rothwell et al., 2010; Shuttleworth et al., 2015), carbon dynamics (Holden,
108 2005b; Worrall et al., 2011) and other ecosystem services (Osaki and Tsuji,
109 2015).

110

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

121

122 Despite peatland erosion having been studied for more than sixty years some
123 of the processes remain poorly understood (Bower, 1960; Evans and
124 Warburton, 2007; Li et al., 2016b). The prevention and control of peat erosion

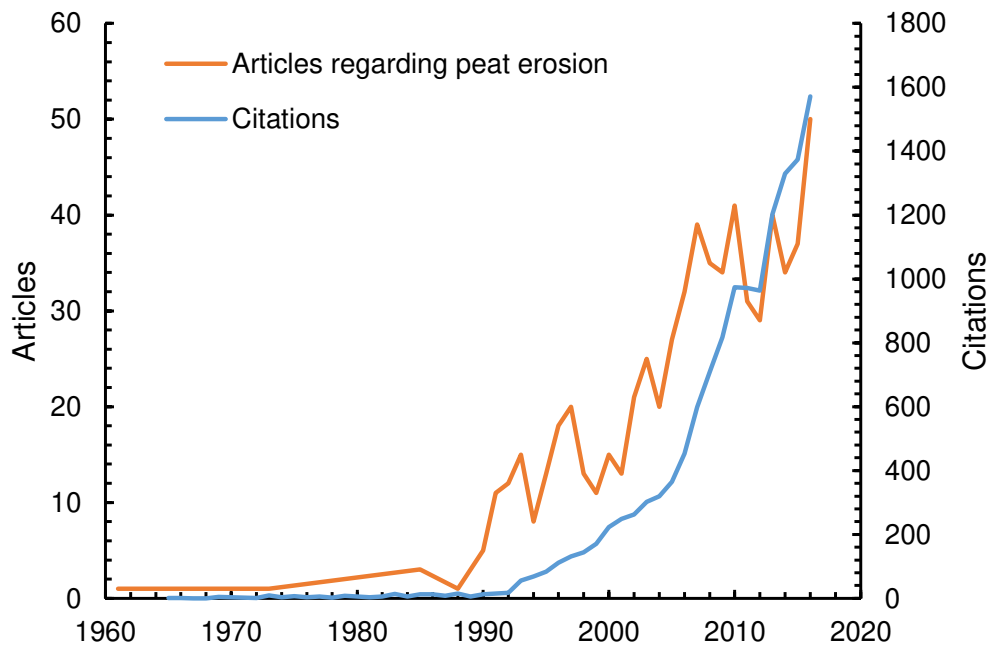
125 risk relies on designing and applying appropriate conservation strategies and
126 management techniques, which in turn requires a thorough understanding of
127 processes. Traditionally the bulk of soil erosion research has focussed on
128 understanding mineral soils, with much less known about erosion of organic
129 soils. While soil erosion remains a major concern in mineral agricultural soils
130 (Li et al., 2017c), erosion of peat is of particular concern due to the increased
131 risk of carbon loss to the atmosphere once peat sediment is moved from its
132 original location (Palmer et al., 2016).

133

134 On 12th November 2017, a bibliographic search was conducted to analyze the
135 evolution and trends in peatland erosion studies with the aim of identifying
136 new lines of investigation. The search used Thomson Reuters© Web of
137 Science© bibliographic databases. Using the key words 'peat' and 'erosion'
138 683 items were retrieved over the period 1900 to the present (12/11/2017).
139 The indexed articles cover both qualitative and quantitative investigations of
140 peat erosion processes, rates and the impacts of different factors on peat
141 erosion (Figure 2). Between 1960 and 1980 the number of peat erosion
142 related publications remained low, however since 1990 there has been a rapid
143 increase in associated research and resulting publications; this has resulted in
144 exponential growth in the number of citations. Evans and Warburton (2007)
145 synthesized our understanding of upland peat erosion at the time of their
146 monograph. Developments in direct and indirect methods for measuring soil
147 erosion processes and rates since 2007 and a greater appreciation for the
148 detrimental impacts of peat erosion have resulted in an increase in the
149 number of articles published annually, with a peak of 50 articles per year in

150 2016. Here we provide an updated review of recent developments. Our review
151 therefore focuses on new research over the last decade, but refers to older
152 research where necessary to provide background context or where that
153 material was not originally covered by Evans and Warburton (2007).

154



155

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

158

159 Although there may be some grey literature (unpublished research, theses or
160 reports), much of the recently published peat erosion literature is
161 geographically limited to blanket peatlands in the British Isles, and peatlands
162 in Finland, North America and tropical areas, primarily due to concerns over
163 peat erosion in these locations and programs to address these concerns.
164 Therefore this review of updates over the last decade will necessarily have
165 more concentrated information relating to those systems, however the findings

166 will have broader implications for peatlands globally. The literature covered in
167 this review primarily consists of peer-reviewed papers, books and book
168 chapters drawn from the Web of Science® database, but also includes
169 publically available academic theses and reports (e.g., IUCN UK Committee
170 Peatland Programme reports).

171

172 This paper is structured to provide the following:

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

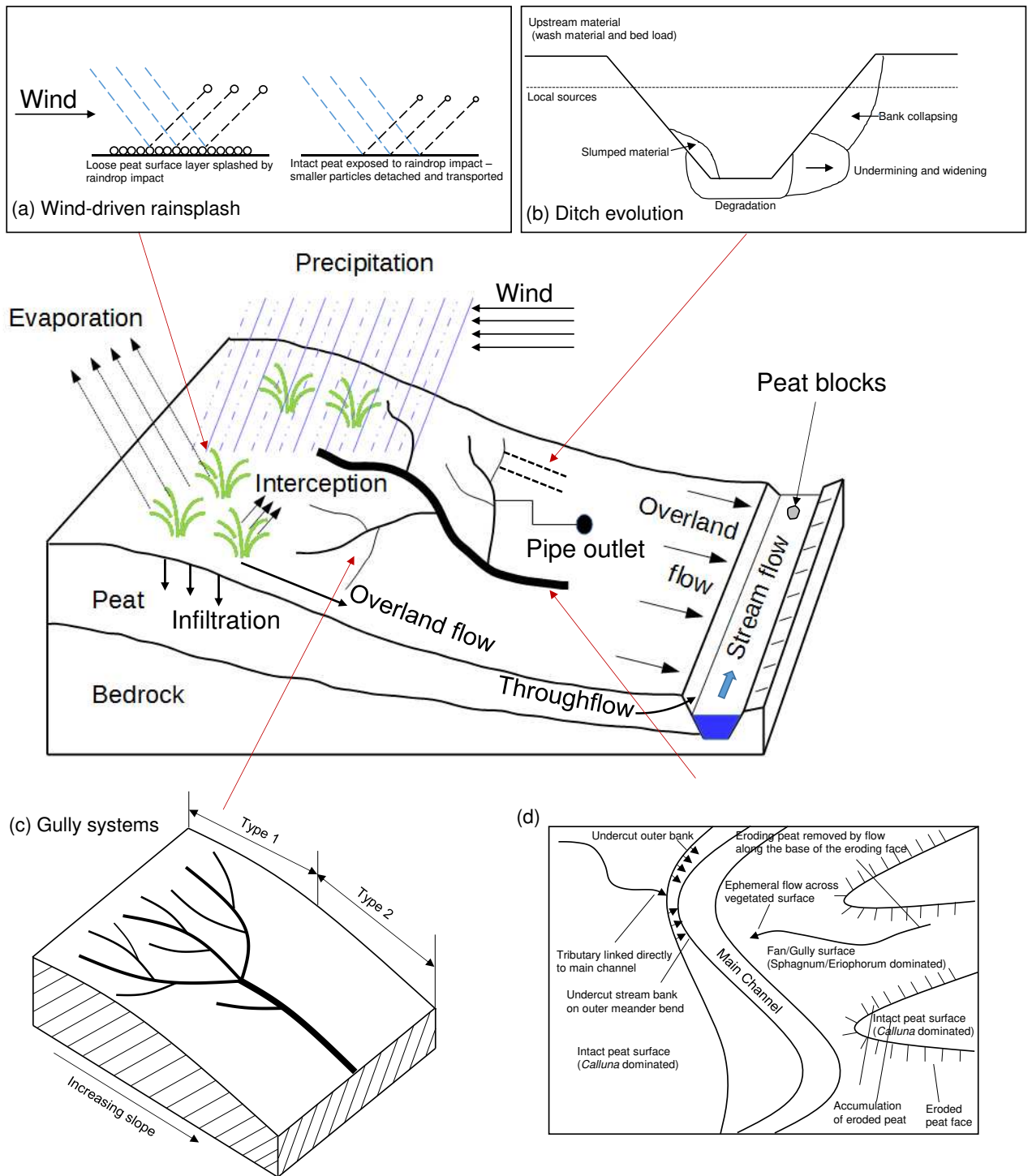
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181 **2. Peat erosion processes**

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

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

197



198

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

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

207

208 **2.1 Weathering processes**

209 **2.1.1 Frost action**

210 Frost weathering resulting from the freezing and thawing of water between
211 peat particles is common in cool high latitude or high altitude climates which
212 support many peatlands, and plays a vital role in breaking the peat surface
213 during winter months (Evans and Warburton, 2007; Francis, 1990; Labadz et
214 al., 1991; Li et al., 2018a). Compared to mineral soils peat has a higher
215 volumetric heat capacity but much lower conductivity and as a result has a
216 significantly different thermal response during wetting or drying periods
217 (FitzGibbon, 1981). On cold days, a strong thermal gradient can develop
218 between a cold peat surface and warmer peat at depth (Evans and Warburton,
219 2007) which together with an abundant moisture supply make ideal conditions
220 for needle ice formation (Figure 1 (g)) (Outcalt, 1971). Needle-ice is important
221 in producing eroding peat faces (Grab and Deschamps, 2004; Luoto and
222 Seppälä, 2000; Tallis, 1973) with ice crystal growth gradually weakening and
223 finally breaking peat soil aggregates and the subsequent warming and
224 thawing weakening or loosening the fractured peat. The growth of needle ice
225 can lead to a 'fluffy' peat surface that is loose and granular and vulnerable to
226 being flushed off by overland flow events (Evans and Warburton, 2007; Li et
227 al., 2018a).

228

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

245

246 **2.1.2 Desiccation**

247 Surface desiccation during extended periods of dry weather is another
248 important weathering process for producing erodible peat (Burt and Gardiner,
249 1984; Evans et al., 1999; Francis, 1990; Holden and Burt, 2002a). Desiccation
250 of surface peat can lead to development of hydrophobicity (Eggelsmann et al.,
251 1993). Where desiccation occurs the surface layer is typically platy with a
252 dried upper crust that is concave in shape and is detached from the intact

253 peat below (Evans and Warburton, 2007); this dry crust layer could impede
254 infiltration (Holden et al., 2014). On the other hand, a desiccated peat surface
255 can be susceptible to shrinkage and cracking (Holden and Burt, 2002a) that
256 actually promotes delivery of surface water to the subsurface hydrological
257 system (Holden et al., 2014).

258

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

267

268 **2.2 Sediment transport processes**

269 Transport of sediment from hillslopes to channels where it is more accessible
270 to fluvial processes is of great importance in geomorphology (Bryan, 2000a;
271 Evans and Warburton, 2007). Many erosional processes are active on peat
272 hillslopes (Figure 3), including water erosion (Bower, 1961), wind erosion
273 (Foulds and Warburton, 2007a; Foulds and Warburton, 2007b; Warburton,
274 2003) and mass movements such as peat slides and bog bursts (Crowe and
275 Warburton, 2007; Evans and Warburton, 2001; Evans and Warburton, 2007;
276 Warburton and Evans, 2011; Warburton et al., 2004). Bank erosion is an

277 important process in some peatlands, contributing to stream sediment loads
278 (Evans and Warburton, 2001). Peat transported within channels is typically in
279 the form of fine suspended sediment or larger low-density peat blocks which
280 may remain in situ until they float off in storms or roll along the bed and
281 quickly break up once mobilised (Evans and Warburton, 2007; Warburton and
282 Evans, 2011).

283

284 **2.2.1 Water erosion**

285 2.2.1.1 Interrill erosion processes

286 For interrill erosion, the dominant processes are detachment by raindrop
287 impact and transport by raindrop-impacted sheet flow (Kinnell, 2005).
288 Raindrops affect interrill erosion processes in two ways. First, raindrops
289 provide the primary force to initiate low-density peat particle detachment; with
290 the importance of raindrop impact on sediment detachment having been
291 shown under both laboratory and field conditions (Holden and Burt, 2002a;
292 Kløve, 1998; Li et al., 2018b). Li et al. (2018b) found that without raindrop
293 impact shallow interrill overland flow had little entrainment capacity, with
294 raindrop impact increasing peat surface erosion by 47% (Li et al., 2018b).
295 Second, raindrop impact is important in affecting overland flow hydraulics and
296 sediment transport as overland flow depths are typically shallow, in the order
297 of a few millimeters (Holden and Burt, 2002a; Holden et al., 2008a). Li et al.
298 (2018b) found that raindrop impacts increased flow resistance which reduced
299 overland flow velocities by 80–92%. Overland flow hydraulics as modified by
300 raindrop impact are important in defining and modelling overland flow erosion

301 processes (Bryan, 2000b); further work should be carried out to explore these
302 interactions.

303

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

315

316 Saturation-excess overland flow and near-surface throughflow are dominant in
317 many (but not all) types of peatland including blanket peatland (Evans et al.,
318 1999; Holden and Burt, 2002a; 2003c) and are a result of shallow water tables
319 and low hydraulic conductivity throughout most of the peat depth (Holden and
320 Burt, 2003a; Holden and Burt, 2003b; Rosa and Larocque, 2008). The
321 hydraulic conditions of overland flow (e.g., flow velocity, depth and resistance)
322 determine the erosive forces acting on the peat in interrill areas. Runoff
323 hydraulics including flow velocity, flow depth and friction coefficients, and their
324 empirical relationships have been reported at the plot scale on blanket peat

325 slopes (Holden et al., 2008a). Holden et al. (2008a) found a region of shallow
326 flows in which there is a gradual increase of roughness (reducing $f^{-0.5}$) with
327 depth, and a deeper region of flows with significantly decreasing roughness
328 (logarithmically) with depth.

329

330 2.2.1.2 Rill erosion processes

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

345

346 2.2.1.3 Pipe erosion

347 Piping is commonly found in peatlands (Holden, 2006; Holden and Burt,
348 2002c; Holden et al., 2012c; Norrström and Jacks, 1996; Price and Maloney,
349 1994; Rapson et al., 2006; Woo and DiCenzo, 1988). Peat pipes connect the
350 shallow and deep layers of the peat profile (Billett et al., 2012; Holden, 2005a;
351 Holden, 2005b) and act as significant sources and pathways for water, carbon
352 and sediment transport. In addition, pipe collapse is common, often being
353 associated with gully head retreat (Jones, 2004; Verachtert et al., 2011).
354 However, pipe erosion is less well studied compared with surface soil erosion
355 by water due to its subsurface nature (Holden, 2005a). Geophysical
356 techniques (e.g., ground-penetrating radar) (Holden et al., 2002) have helped
357 improve the identification of pipe networks, but studies have generally focuses
358 on pipe distribution and hydrology (Holden, 2005a; Holden, 2006; Holden,
359 2009a; Holden, 2009b; Holden and Burt, 2002c; Holden et al., 2012b; Holden
360 et al., 2012c; Smart et al., 2013). Holden and Burt (2002c) found that around
361 10% of stream discharge was derived from pipe networks in Little Dodgen Pot
362 Sike, a deep blanket peat catchment in the North Pennines of England. In the
363 nearby Cottage Hill Sike catchment, Smart et al. (2013) found that pipes
364 contributed 13.7% of the streamflow. Jones (2004) showed that piped areas
365 produced more sediment to the stream than areas without piping. Pipe outlets
366 delivered an amount of aquatic carbon equivalent to 22% of the aquatic
367 carbon flux at the outlet of Cottage Hill Sike catchment (Holden et al., 2012c)
368 with POC flux observed at the pipe outlets equivalent to 56-62 % of the annual
369 stream POC flux (Holden et al., 2012b; 2012c). Despite these valuable results,

370 quantification of the contribution of piping to peat loss is still limited to a few
371 case studies in a limited number of environments.

372

373 **2.2.2 Wind erosion**

374 Windy conditions are typical of many exposed peatland environments. The
375 impacts of wind action on peatlands differs between dry and wet conditions
376 (Evans and Warburton, 2007). During drought periods dry blow is of great
377 importance in transporting eroded peat as dry peat with a low density has a
378 high potential susceptibility to erosion and transport by wind (Campbell et al.,
379 2002; Foulds and Warburton, 2007a; 2007b; Warburton, 2003). In contrast
380 under wet and windy conditions, wind-driven rain is important in peat surface
381 erosion through the detachment and transport of peat particles (Foulds and
382 Warburton, 2007a; Warburton, 2003). Baynes (2012) identified a two-phase
383 erosion process of bare peat by wind-driven rain (Figure 3 (a)). Phase 1
384 includes large loose surface peat particles that are produced by frost action or
385 surface desiccation and are mobilized by raindrop impact and transported by
386 wind. The removal of the top layer exposes the intact peat surface to raindrop
387 impact which erodes smaller particles (Phase 2). Li et al. (2018b) found that
388 raindrop impact plays a key role in affecting overland flow, flow hydraulics and
389 soil loss under lower rainfall intensity conditions. However, more significant
390 effects could be expected with higher kinetic energy levels closer to those
391 experienced where natural rainfall is driven by strong wind. Future work could
392 examine overland flow interactions with wind-driven rainsplash erosion and its

393 contribution to total erosion, as rainfall on exposed peatlands is often
394 associated with strong winds (Evans and Warburton, 2007).

395

396 **2.2.3 Ditch erosion**

397 Artificial drainage on peatlands and the associated changes in peat structure,
398 hydrological flow paths and erosion have been widely reported in upland
399 Britain (Armstrong et al., 2009; Holden et al., 2004; Holden et al., 2006;
400 Holden et al., 2007b) and Finland (Haahti et al., 2014; Kløve, 1998; Marttila
401 and Kløve, 2008; Marttila and Kløve, 2010a; Stenberg et al., 2015a; Stenberg
402 et al., 2015b; Tuukkanen et al., 2016). Holden et al. (2007b) found that drain
403 networks that were well connected to stream channels were important
404 contributors of suspended sediment to the stream network. Ditch creation and
405 maintenance contribute to increased erosion and suspended sediment yields
406 by undermining and bank collapse (Marttila and Kløve, 2010a; Stenberg et al.,
407 2015a; Stenberg et al., 2015b; Tuukkanen et al., 2016). Field and laboratory
408 observations in Finland have shown that erosion of deposited peat sediment
409 from main ditches is the main suspended sediment source in peat extraction
410 areas during individual summer storm events (Marttila and Kløve, 2008;
411 Tuukkanen et al., 2014). Marttila and Kløve (2010a) presented a conceptual
412 model of the processes in the drainage channel, where suspended sediment
413 production in the channel is a result of flow erosion, sheet wash, sidewall
414 collapse and undercutting. Sediment from upstream areas can be stored in
415 the main drain during smaller flow events, indicating a physical process limited
416 by the transport capacity. The deposited sediment in the ditch bottom can be

417 released to be transported during larger flow events, and this process can
418 either be supply- or transport-limited (Marttila and Kløve, 2010a). Stenberg et
419 al. (2015a) outlined a conceptualisation where bank erosion occurs in the area
420 of a seepage face and the material is eroded due to different mechanisms (e.g.
421 seepage, gravitational forces, and freeze-thaw processes) and deposited on
422 the bottom of the ditch and the lower parts of the ditch bank. They concluded
423 that the main mechanism causing bank erosion was plausibly the seepage
424 and wetting-induced loosening of the peat material, as most of the erosion
425 took place during the time when groundwater levels were highest.

426

427 **2.2.4 Other erosion processes**

428 Other commonly observed erosion forms in peatlands are gully erosion, mass
429 movements and in-stream transport processes, and an extensive body of
430 literature has been published on these subjects (see Evans and Warburton
431 (2007) for a concise review). Little additional work has been published in the
432 last decade on these processes. Warburton and Evans (2011) found large
433 peat blocks in alluvial river systems could significantly contribute to stream
434 sedimentation, and this contribution might be greater than those from other
435 fluvial erosion forms such as rill and gully erosion, particularly over short
436 timescales and in a local context. The effects of peat blocks on downstream
437 sediment load were found to depend on channel width (Warburton and Evans,
438 2011). For narrow channels, peat blocks act as natural and economical dams
439 to block the flow and sediment pathways, which may lead to the upstream
440 accumulation of bed material; while for wider channels the blocks tend to be

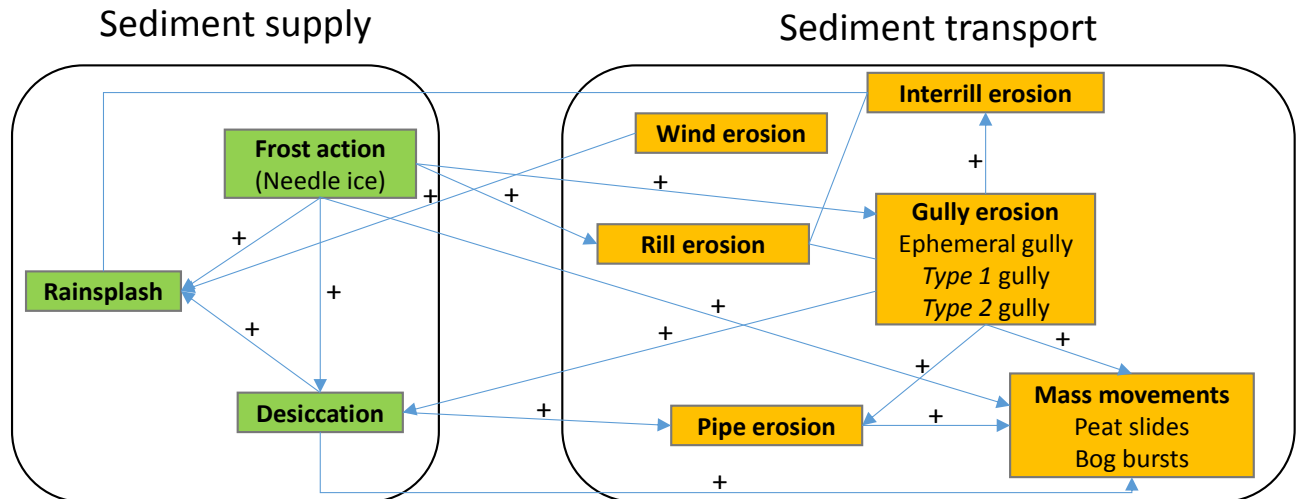
441 stored on the river bed in isolation and are of less importance in controlling
442 sedimentation (Warburton and Evans, 2011). Once peat blocks begin to move
443 they break down at a relatively rapid speed through abrasion and
444 disaggregation, which may release a large quantity of fine sediments in
445 stream systems (Evans and Warburton, 2001; Evans and Warburton, 2007).
446 Little is known about the hydraulic thresholds required for peat blocks to be
447 entrained, transported and deposited, nor the factors impacting the dispersal
448 and persistence of peat blocks in streams (Warburton and Evans, 2011).

449

450 **2.3 Interactions among different peat erosion processes**

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

462



463

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

466

467 Active sediment transport processes strongly interact with each other in some
 468 areas of peatlands (Figure 4). There are links between the development of
 469 interrill erosion and gully erosion. Interrill erosion is widely spread on summits
 470 of *Type 1* gully dissection systems, where large areas of bare peat are
 471 exposed (Bower, 1961). Once gullies develop, mass wasting and slope
 472 instability can be triggered and piping can also be enhanced. Holden et al.
 473 (2002) found through ground-penetrating radar survey of pipe frequency that
 474 pipes were often found at the head of gullies. Pipes have the potential to
 475 initiate or impact gully system development through roof collapse or channel
 476 extension (Higgins and Coates, 1990; Holden and Burt, 2002c; Tomlinson,
 477 1981). Pipe collapse is potentially associated with initiation of *Type 2* gullies
 478 (Evans and Warburton, 2007). However, there are no direct observations or
 479 quantitative analysis linking pipe features and gully initiation in peatlands.

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

482

483 Strong links would be expected between sediment supply and sediment
484 transport processes in peatland environments. For example, needle-ice
485 formation resulting from freeze–thaw cycles could result in damage to gully
486 walls (Evans and Warburton, 2007; Imeson, 1971). Freeze–thaw action would
487 also be associated with deep cracking on the bank face and peat mass failure
488 (Wynn et al., 2008). Desiccation cracking may promote delivery of surface
489 water to the subsurface hydrological system promoting elevated pore
490 pressures and peat mass failure (Hendrick, 1990). Gully systems are
491 particularly vulnerable to desiccation process, due to exposed faces drying
492 quickly and particles being rapidly removed by wind and gravity (Holden et al.,
493 2007a). The desiccation of the peat surface, has the potential to encourage
494 soil pipe development and pipe erosion (Holden, 2006; Jones, 2004). New
495 routes created by shrinking and cracking of the desiccated peat for bypassing
496 flow, may initiate the ephemerally flowing pipe networks, when abundant
497 sourcing water flows through the preferential flow pathways (Holden, 2006).

498

499 **2.4 Scale-dependency of peat erosion processes**

500 A conceptual model of the active sources and sinks of sediment in peatlands
501 can be developed based on De Vente and Poesen (2005). Different peat
502 erosion processes are active at different spatial scales. For example,
503 rainsplash, interrill and rill erosion are the dominant erosion processes studied

504 at fine scales (erosion plots) (Grayson et al., 2012; Holden and Burt, 2002a;
505 Holden et al., 2008a; Li et al., 2018a; Li et al., 2018b). For larger hillslope and
506 small and medium-size catchment scale, gully erosion and mass movements
507 become more important, yielding large quantities of sediment (Evans and
508 Warburton, 2005; Evans and Warburton, 2007; Evans et al., 2006). At the
509 large basin scale long-term erosion and sediment deposition processes are
510 more important due to large sediment sinks (footslopes and floodplains) (De
511 Vente and Poesen, 2005). Riverine POC is also potentially transformed to
512 DOC by in-stream degradation or mineralized to CO₂ during periods of
513 floodplain storage (Pawson et al., 2012).

514

515 **3 Methodological approaches for assessing erosion in** 516 **peatlands**

517 **3.1 Measurement techniques**

518 Numerous direct and indirect methods have been used to measure and
519 monitor peat erosion. Traditionally these have included: erosion pins (Grayson
520 et al., 2012), bounded plots (Holden et al., 2008a; Li et al., 2018a; Li et al.,
521 2018b), gauging stations, bathymetric surveys in reservoirs (Yeloff et al., 2005)
522 and some of these have been combined as part of sediment budgeting (Evans
523 and Warburton, 2005; Evans et al., 2006). However, more recently modern
524 high resolution topographic surveying methods have been applied to
525 peatlands to improve quantification of erosion (Evans and Lindsay, 2010;

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

528

529 **3.1.1 Erosion pins**

530 Erosion pins are widely used to measure erosion and deposition directly
531 through observed changes in the peat surface at a given point (Grayson et al.,
532 2012; Tuukkanen et al., 2016). Surface retreat rates measured by erosion
533 pins are the combined effects of wind erosion, water erosion and peat
534 wastage (oxidative peat loss) (Evans and Warburton, 2007; Evans et al., 2006;
535 Francis, 1990). Point measurements are usually interpolated over relatively
536 small areas. However, interpreting erosion rates based on erosion pins should
537 be treated with caution as the accuracy and precision can be affected by: i)
538 peat soil expansion and contraction during weathering processes (freeze-
539 thawing and wetting-drying cycles) (Kellner and Halldin, 2002; Labadz, 1988);
540 ii) significant spatial variation even over small areas (Grayson et al., 2012); iii)
541 increasing erosion or trapping eroded material (Benito and Sancho, 1992;
542 Couper et al., 2002); iv) interference from grazing animals like sheep; v)
543 disturbance and damage to the peat surface caused by installation and
544 repeated pin measurement.

545

546 **3.1.2 Erosion plots**

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

549 Holden and Burt, 2002a; Li et al., 2018b). Erosion plots include closed plots
550 that are usually less than 10 m², and open plots which are larger. Closed plots
551 are normally equipped with troughs, runoff and sediment collectors and are
552 employed together with rainfall simulation or upslope inflow simulation
553 experiments (Clement, 2005; Elaine, 2012; Holden and Burt, 2002a; Holden
554 and Burt, 2002b; Holden and Burt, 2003b; Holden et al., 2008a; Li et al.,
555 2018a; Li et al., 2018b). Closed plots have the advantages of allowing a
556 comparison of different responses at the same spatial scale (Boix-Fayos et al.,
557 2006). However, Holden and Burt (2002a) and Li et al. (2018b) showed that
558 closed erosion plots reduce erosion rates with rainfall simulation due to a
559 change from transport-limited to detachment-limited conditions. Open plots
560 are usually used in the field (Grayson et al., 2012) and they have the
561 advantage of better representation of natural conditions.

562

563 **3.1.3 Sediment transport measurements at gauging stations**

564 Sediment concentration measurements at gauging stations allow the
565 calculation of sediment yield rate and its temporal variability (Nadal-Romero et
566 al., 2011). A wide range of equipment and techniques (e.g., sediment traps,
567 sampling) are generally used to measure sediment flux at the catchment
568 outlet at larger spatial and temporal scales (Francis, 1990; Holden et al.,
569 2012c; Labadz et al., 1991; Pawson et al., 2012). Sediment sampling is
570 usually used in combination with the rating curve technique (Francis, 1990;
571 Labadz et al., 1991). It is important to consider sampling intervals as peat
572 systems often have flashy regimes and hence many sampling strategies (e.g.,

573 daily sampling) may miss important sediment transport events such as short-
574 lived storms (Pawson et al., 2008). Antecedent conditions and hysteresis in
575 the sediment – discharge relationship are also important factors to consider
576 when designing sampling campaigns. Turbidity meters have often been used
577 to measure suspended sediment concentrations in mineral catchments.
578 However, their application in peatland catchments should be treated with
579 caution and calibration is required since turbidity is sensitive to variations in
580 particle size distribution, water colour and the proportion of organic and
581 inorganic contents (Lewis, 1996; Marttila et al., 2010).

582

583 **3.1.4 Bathymetric surveys in reservoirs**

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

592

593 **3.1.5 Sediment budget**

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

596 (Parsons, 2011). Several studies have reported sediment budgets for blanket
597 peat catchments (Baynes, 2012; Evans and Warburton, 2005; Evans et al.,
598 2006). Evans and Warburton (2005) constructed a sediment budget over a
599 four-year monitoring period in the Rough Sike catchment that is an eroded but
600 partially re-vegetated system in north Pennines of England. They reported that
601 hillslope sediment supply to the catchment outlet was significantly reduced
602 due to re-vegetation of eroding gullies. Re-vegetation of the slope-channel
603 interface, which acts as a vegetated filter strip, reduced the sediment
604 connectivity between the hillslopes and channels. However, there may be a
605 limited capacity for how much sediment can be trapped over a given time
606 period as overland flow may still flush out redeposited sediment on vegetated
607 areas. More research is needed to evaluate the effectiveness of different
608 vegetative filter strip characteristics (e.g. vegetation type, width) in reducing
609 sediment delivery efficiency in peatland environments.

610

611 **3.1.6 Topographic surveys of soil surfaces**

612 Topographic surveys and fine-resolution topographic data allow the
613 determination of peat erosion or deposition (Glendell et al., 2017; Grayson et
614 al., 2012). Remote-sensing technologies employing high-resolution airborne
615 and terrestrial LiDAR (Light Detection and Ranging) for measuring peat
616 surface changes have been reported in blanket peatlands (Evans et al., 2005;
617 Evans and Lindsay, 2010; Evans and Lindsay, 2011; Grayson et al., 2012;
618 Rothwell et al., 2010). Grayson et al. (2012) compared the use of terrestrial
619 laser scanning and erosion pins across a blanket bog; contrasting results

620 were obtained from the two different methodologies. A net surface increase of
621 2.5 mm was calculated from the terrestrial laser scans (included areas of
622 erosion and deposition), compared with a net decrease in peat surface height
623 of 38 mm measured using pins (eroding areas only) during the same study
624 period (Grayson et al., 2012).

625

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

639

640 **3.2 Modelling techniques**

641 Blanket peat erosion has been estimated using numerical models such as the
642 Universal Soil Loss Equation (USLE) (May et al., 2010), Cellular Automaton
643 Evolutionary Slope and River (CAESAR) model (Coulthard et al., 2000) and

644 the grid version of the Pan-European Soil Erosion Assessment (PESERA-
645 GRID) model (Li et al., 2016b). May et al. (2010) applied USLE to model soil
646 erosion and transport in a typical blanket peat-covered catchment on the
647 northwest coast of the Ireland. Coulthard et al. (2000) used CAESAR model in
648 an upland catchment partially covered by peat to assess the effects of climate
649 and land-use change on sediment loss. The USLE model assumes that
650 entrainment is primarily caused by rainsplash energy while the CAESAR
651 model assumes that entrainment is caused by overland flow (Coulthard et al.,
652 2000). However, these models ignore the dominant weathering processes
653 such as freeze–thaw and desiccation in blanket peatlands. Li et al. (2016b)
654 developed a process-based model of peatland fluvial erosion (PESERA-PEAT)
655 by modifying the PESERA-GRID model (Kirkby et al., 2008) through the
656 addition of modules describing both freeze–thaw and desiccation.
657 Temperature and water table were chosen as indicators to parameterize
658 freeze–thaw and desiccation (Li et al., 2016b). PESERA-PEAT has been
659 shown to be robust in predicting blanket peat erosion (Li et al., 2016b) and it
660 has been successfully applied to examine the response of fluvial blanket peat
661 erosion to future climate change, land management practices and their
662 interactions at regional, national and global scales (Li et al., 2016a; Li et al.,
663 2016b; Li et al., 2017a; Li et al., 2017b).

664

665 **4. Factors affecting erosion in peatlands**

666 **4.1 Climatic conditions**

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

675

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

687

688 Peatland development is highly susceptible to climate change (Fenner and
689 Freeman, 2011; Ise et al., 2008; Parry et al., 2014). During the Medieval warm
690 period between AD 950 and 1100, a decrease in rainfall and an increase in
691 temperature resulted in drying of peat surfaces and promotion of erosion (Ellis
692 and Tallis, 2001; Tallis, 1997). Bioclimatic modelling suggests a retreat of
693 bioclimatic space suitable for blanket peatlands due to climatic change in the
694 21st century (Clark et al., 2010; Gallego-Sala et al., 2010; Gallego-Sala and
695 Prentice, 2013). Li et al. (2017a) found that future climatic change will begin to
696 affect sediment release from increasingly large areas of blanket peatland in
697 the Northern Hemisphere.

698

699 **4.2 Peat properties**

700 The physical properties of peat (e.g., degree of humification, shear strength,
701 bulk density) affect peat erosion and sediment delivery (Carling et al., 1997;
702 Marttila and Kløve, 2008; Svahnäck, 2007; Tuukkanen et al., 2014). Carling
703 et al. (1997) showed that intact peat (not yet loosened or weathered) is highly
704 resistant to water erosion, suggesting a high flow velocity of 5.7 m s⁻¹ was
705 needed for continuous erosion of unweathered peat material. Svahnäck
706 (2007) found a positive relationship between the degree of humification and
707 suspended sediment concentration (SSC) through sprinkler experiments in
708 the lab. Tuukkanen et al. (2014) examined whether peat physical properties
709 including the degree of humification, bulk density, ash content, and shear
710 strength affect peat erodibility and found that well-decomposed peat
711 generated higher SSC than slightly or moderately decomposed, fiber-rich peat.

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

719

720 Marttila and Kløve (2008) conducted laboratory flume experiments on peat
721 sediments and found that deposited sediment formed a loose layer overlaid by
722 more stabilized layers with stabilization time ranging from 15 minutes to 10
723 days. An increase in stabilization time resulted in increased erosion rates.
724 Critical shear stress was $0.01 \pm 0.002 \text{ N m}^{-2}$ for the loose surface peat layer,
725 and was $0.059 \pm 0.001 \text{ N m}^{-2}$ for the entire peat deposited peat sediment
726 (Marttila and Kløve, 2008). Two linear equations can be fitted to explain the
727 erosion across the critical shear stress. The critical shear stress for deposited
728 ditch sediment was about 0.1 N m^{-2} (Marttila and Kløve, 2008) which was
729 much lower than 0.6 N m^{-2} for well-decomposed peat and $4\text{-}6 \text{ N m}^{-2}$ for poorly
730 decomposed peat (Tuukkanen et al., 2014). The difference in critical shear
731 stress between intact soil and ditch sediment indicated that deposited ditch
732 sediment was much more susceptible to erosion than intact peat. Bulk density
733 affects peat erosion and sediment transport through changes in runoff
734 generation, rather than through its effect on peat erodibility (Tuukkanen et al.,
735 2014). The tendency for overland flow is greater in peat with higher bulk

736 density since the saturated hydraulic conductivity of peat often (but not always)
737 decreases with increasing bulk density (Chow et al., 1992).

738

739 Peat erodibility in the physically-based PESERA-PEAT model represents the
740 erodibility of available peat materials weathered by freeze–thaw and
741 desiccation (Li et al., 2016b). The erodibility of weathered peat was reported
742 to be 2–3 times that of intact peat (Mulqueen et al., 2006). In addition, Li et al.
743 (2018a) conducted physical overland flow simulation experiments on highly
744 frost-susceptible blanket peat with and without needle ice processes. They
745 defined peat anti-scourability capacity (*AS*) as the resistance of peat to
746 overland flow scouring. The higher the peat *AS*, the lower the peat erodibility,
747 with *AS* significantly increasing in treatments subjected to needle ice
748 processes, indicating that needle ice processes significantly increased peat
749 erodibility (Li et al., 2018a).

750

751 **4.3 Vegetation cover**

752 Vegetation cover in blanket peatlands is dominated by slow-growing vascular
753 plants and bryophytes (Holden et al., 2015), such as bog mosses (*Sphagnum*
754 spp.), cotton-grass (sedges) (*Eriophorum* spp.) and shrubs such as common
755 heather (*Calluna* spp.). These types of vegetation cover act as both indicators
756 and creators of blanket peat conditions. Vegetation cover impacts both
757 sediment supply and transport processes in peatlands (Li et al., 2016a).
758 Vegetation cover protects bare peat surface against weathering processes
759 (Holden et al., 2007b; Holden et al., 2007c; Lindsay et al., 2014; Shuttleworth

760 et al., 2015), rainsplash and overland flow erosion (Holden et al., 2008a), and
761 mass movements (Evans and Warburton, 2007; Warburton et al., 2004). The
762 removal of vegetation cover increases the thermal gradient between cold
763 surfaces and warmer peat at depth during winter (Brown et al., 2015), making
764 the peat surface susceptible to needle ice weathering processes (Li et al.,
765 2016b). Peat surfaces with sparse vegetation cover are also more vulnerable
766 to desiccation in summer (Brown et al., 2015).

767

768 In addition, vegetation cover reduces overland flow velocity (Holden et al.,
769 2007b; Holden et al., 2008a) and sediment connectivity from sediment source
770 zones to river channels (Evans and Warburton, 2007; Evans et al., 2006).
771 Holden et al. (2008a) demonstrated that vegetation cover dissipated overland
772 flow energy by imparting roughness, and therefore substantially reduced
773 velocity of running water across peat surface compared to bare peat surfaces.
774 Grayson et al. (2010) analyzed the long-term (1950s to 2010s) hydrograph
775 data from the Trout Beck blanket peat catchment, northern England, and
776 found that revegetation of eroded peat contributed to reduced flood peak, with
777 hydrographs being flashier and more narrow-shaped with higher peaks during
778 the more eroded periods. Recent modelling studies have also suggested that
779 surface vegetation cover is important in affecting the timing of the flood peaks
780 from upland peatlands (Ballard et al., 2011; Lane and Milledge, 2013). A
781 spatially-distributed version of TOPMODEL developed by Gao et al. (2015)
782 simulated how restoration and the associated land-cover change impact river
783 peak flow. They reported that a catchment with a cover of *Eriophorum* and

784 *Sphagnum* had much lower peak flows than that with bare peat (Gao et al.,
785 2015; Gao et al., 2016; Gao et al., 2017).

786

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

798

799 **4.4 Land management practices**

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

804

805 Grazing has received increasing attention due to its important impacts on peat
806 condition, vegetation and hydrological processes (Evans, 2005; Holden et al.,

807 2007a; Worrall and Adamson, 2008; Worrall et al., 2007a). Unsustainable
808 levels of grazing have adverse effects on peatland hydrological and erosion
809 processes. Meyles et al. (2006) reported increased hydrological connectivity
810 of hillslopes with channels resulting from grazing practices which led to
811 increased flood peaks. The high risk of vegetation damage and exposure of
812 bare soils by grazing make the bare peat surface vulnerable to weathering
813 processes (Evans, 1997). Compaction of soils by trampling decreases soil
814 infiltration and may enhance erosion sensitivity due to increased hydrological
815 connectivity by animal tracks (Meyles et al., 2006; Zhao, 2008).

816

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

831 exacerbated surface erosion (Holden et al., 2015; Holden et al., 2014; Pierson
832 et al., 2008; Smith and Dragovich, 2008).

833

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

854

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

864

865 **4.5 Peatland conservation techniques**

866 Numerous studies have examined the techniques available for restoring
867 degraded blanket peatlands (Armstrong et al., 2009; Crowe et al., 2008;
868 Holden et al., 2008b; Parry et al., 2014), and the role of conservation
869 techniques on stream peak flow (Gao et al., 2015; Gao et al., 2016; Gao et al.,
870 2017; Grayson et al., 2010; Lane and Milledge, 2013), water table and
871 hydrological processes (Allott et al., 2009; Holden et al., 2011; Wilson et al.,
872 2010; Worrall et al., 2007b) and sediment and particulate organic carbon
873 (Holden et al., 2007b; Holden et al., 2008a; Ramchunder et al., 2012;
874 Shuttleworth et al., 2015; Wilson et al., 2011). Restoration practices that result
875 in stabilisation and revegetation are recommended as vegetation cover is
876 capable of reducing erosion by: i) significantly reducing overland flow velocity
877 by 32-70% (Holden et al., 2008a); ii) reducing hydrological connectivity (Gao
878 et al., 2015; Gao et al., 2016; Gao et al., 2017) and sediment connectivity

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

886

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

894

895 Management techniques that aim to control channel processes are important
896 for reducing flow erosion, undercutting and ditch bank collapse (Holden et al.,
897 2007b; Marttila and Kløve, 2010a). Holden et al. (2007b) found that blocking
898 drains with periodic dams was successful at reducing sediment yield by more
899 than 50-fold. Practices such as peak runoff control dams (Kløve, 2000;
900 Marttila and Kløve, 2009) that allow temporarily ponding of water above
901 erodible bed deposits during low flows, have been found to be effective in
902 reducing peak flows, sediment and nutrient transport at peat harvesting sites

903 and in peatland forestry management (Kløve, 1998; Marttila and Kløve, 2008;
904 Marttila and Kløve, 2009; Marttila and Kløve, 2010b). In addition, treatment
905 wetland systems, or overland flow areas, are sometimes constructed
906 downstream to purify the peat extraction runoff by retaining sediment and
907 nutrient loads (Postila et al., 2014).

908

909 **5. A meta-analysis of peat erosion rates**

910 **5.1 Data collection and statistical analysis**

911 Data on peat erosion rates was searched for within the existing published
912 literature identified in the Web of Science described above. A total of 38
913 publications provided erosion rate data with 61 erosion rate records obtained
914 within these publications (Table 1). The dataset compiled included: (i) erosion
915 rates and/or peat loss; (ii) study area; (iii) spatial scale, (iv) temporal scale, (v)
916 measurement method. Erosion rates in the literature tend to be expressed as
917 $\text{mg m}^{-2} \text{h}^{-1}$ for data collected at very fine scale during short periods (minutes
918 or hours) (Arnaez et al., 2007; Morvan et al., 2008); and as mm yr^{-1} for data
919 collected at fine scale; or as $\text{t km}^{-2} \text{yr}^{-1}$ for data collected at hillslope and field
920 scales over longer periods (up to several years) (Cerdan et al., 2010;
921 Prosdocimi et al., 2016). We report data at these scales as presented in the
922 literature. However, it is worth noting that it is possible to convert between
923 units by using reported values of peat bulk density. While peat bulk density
924 varies, it is typically very low. Hobbs (1986) reported bulk density values for
925 British peats of $\sim 1 \text{ g cm}^{-3}$. Therefore, an erosion rate of $1 \text{ t km}^{-2} \text{yr}^{-1}$ is
926 equivalent to 10 mm of peat loss, or $0.5 \text{ t km}^{-2} \text{yr}^{-1}$ of carbon. Spatial scale is

927 classified as very fine (microplots < 1 m²), fine (1-1000 m²), hillslope (1000 m²
928 – 1 ha) and field (> 1 ha) scale (Boix-Fayos et al., 2006; Verheijen et al.,
929 2009). Temporal scale is classified as event (up to several days), monthly,
930 seasonal, long-term (> 1 year) scale. Methods used to obtain erosion data
931 included erosion pins, bounded plots, sediment transport measurements
932 through sampling or at gauging stations, bathymetric surveys in reservoirs,
933 topographic surveys and sediment budgeting. Correlation analysis and
934 regression analysis were used to identify the relationship between area and
935 sediment yield rate. Test results were considered significant at $p < 0.05$.

936

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) |

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

941 **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).

942 **5.2 Scale-dependency of peat erosion rates and the controls**

943 Figure 5a shows the median sediment yield measured at different spatial
944 scales based on the literature survey. Reported sediment yields ranged from
945 251 to 3711055 t km⁻² yr⁻¹ at the very fine scale, from -6600 to 73800 t km⁻² yr⁻¹
946 at fine scale, and from 3 to 213 t km⁻² yr⁻¹ at the catchment scale. The
947 significant range at the very fine scale is mainly associated with differences in
948 plot size, rainfall intensity and peat properties utilized in different studies
949 (Kløve, 1998; Li et al., 2018a; Li et al., 2018b). The sediment yields reported
950 at catchment scales tend to cluster quite closely, perhaps because of the
951 close range of climates within which peatlands are formed. A comparison of
952 sediment yields at different scales indicated significant differences between
953 scales, probably caused by extrapolating data from very fine and fine scales
954 to catchment scales. Different erosion processes are active at different spatial
955 scales, and different sediment sinks and sources appear from plot to
956 catchment scale. In addition, the processes at one spatial or temporal scale
957 interact with processes at another scale. Erosion or deposition rate measured
958 directly by pins are usually interpolated over relatively small areas. Measured
959 erosion rates from erosion plot studies ranged from 20.0 to 72061.8 mg m⁻²
960 min⁻¹ (Kløve, 1998; Li et al., 2018a; Li et al., 2018b). The temporal pattern of
961 erosion typically displays a positive hysteresis in the relationship between
962 suspended sediment concentration and overland rate, with peak sediment
963 concentration occurring during the rising limb of the overland flow hydrograph
964 (Clement, 2005; Holden and Burt, 2002a; Kløve, 1998; Li et al., 2018b). The
965 positive hysteresis is a result of sediment exhaustion (Li et al., 2018b). The
966 laboratory experiments by Li et al. (2018a) revealed that antecedent

967 conditions such as needle-ice formation is very important in controlling peat
968 erodibility and thus erosional response to a given rainfall event. In fact at the
969 plot scale, without the impacts of rainsplash and weathering processes
970 (freeze–thaw and desiccation), sheet or rill flow has limited effect on
971 increasing peat erosion (Li et al., 2018a; Li et al., 2018b). The presence or
972 absence of vegetation is considered as the other critical factor determining the
973 hydrological and erosion response at the finest temporal and spatial scales
974 (Clement, 2005; Holden and Burt, 2002a; Holden et al., 2008a).

975

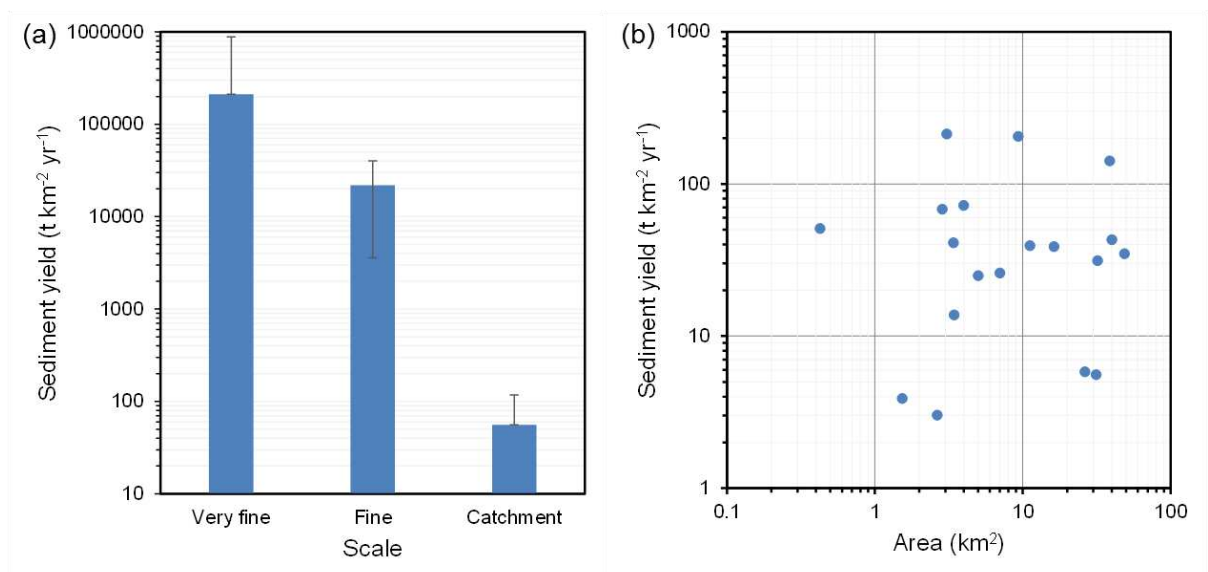
976 The spatial patterns of topography and vegetation are key factors controlling
977 the response of hillslopes to generation of runoff and the transfer of sediments.
978 Holden and Burt (2003c) found that the source area for overland flow on a
979 hillslope varied depending on the topography and time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

986

987 Catchment sediment yields reflect the combined effect of all active and
988 interacting erosion and sediment deposition processes. Figure 5b shows the
989 relationship between catchment area (A) and mean annual sediment yield (SY)
990 for a total of 19 catchments, based on published reservoir sedimentation

991 measurements (Labadz et al., 1991; Small et al., 2003; Yeloff et al., 2005);
992 there is wide variation and high degree of scatter, with no statistically
993 significant correlation (Spearman's correlation test, $p = 0.898$). It has been
994 widely reported that sediment yields decrease with increasing area (De Vente
995 et al., 2007) due to decreasing sediment delivery ratios (Walling and Webb,
996 1996). However, different behavior has been reported from upland peat
997 catchments (Small et al., 2003) with channel bank erosion being suggested as
998 the dominant sediment source. It can be inferred that gully and bank erosion
999 and mass movements form an important part of the catchment sediment
1000 budget in these environments. This is further confirmed by modelling, field
1001 measurement and tracer studies demonstrating a significant contribution to
1002 sediment yield from gully erosion, bank erosion and mass movements (Evans
1003 and Warburton, 2007; Evans et al., 2006). At the catchment scale where all
1004 erosion and sediment deposition processes are active and interactive,
1005 sediment yield can either increase or decrease with increasing area.

1006



1007

1008 Figure 5. (a) Erosion rates obtained from different spatial scales. The sediment yield data
1009 obtained from very fine and fine scales was directly extrapolated to a catchment scale for
1010 comparison purposes only; (b) Relationship between catchment area and sediment yield for
1011 catchment-scale peatland sediment studies.

1012

1013 **6. Main gaps and prospects in peat erosion research**

1014 Since peat erosion consists of complex interacting process that are variable in
1015 both space and time and are influenced by numerous internal and external
1016 factors, there are still many unanswered questions. More peat erosion
1017 research is required in three key areas: i) further study of the known basic
1018 peat erosion processes and their incorporation into peat erosion modelling; ii)
1019 studies of how peat erosion measurement techniques compare and what
1020 types of new information can be gleaned from new techniques; iii) more
1021 studies in a range of peatland environments on how erosion drivers or
1022 mitigation techniques influence peat erosion.

1023

1024 **6.1 Peat erosion processes and incorporation into peat** 1025 **erosion models**

1026 Some important issues that remain to be addressed include how basic erosion
1027 processes such as freeze–thaw weathering, wind-driven rainsplash and pipe
1028 erosion function and how they interact with each other. In addition,
1029 incorporating some of the important erosion processes into peat erosion
1030 models remains a challenge either due to difficulties in the parametrisation of
1031 processes that are not fully understood or, as is often the case, a lack of field

1032 data for model calibration and validation. For example, the contributions of
1033 wind erosion, gully erosion, bank erosion, pipe erosion and mass movements
1034 to catchment sediment budgets are usually under-represented in erosion
1035 models, although field data clearly demonstrate their importance (Li et al.,
1036 2016b). More attention should be focused on process-based studies of these
1037 erosion forms to directly inform future model development:

1038 (1) Needle ice production has been observed to be a vital agent of freeze–
1039 thaw weathering in producing erodible peat materials (Evans and
1040 Warburton, 2007; Grayson et al., 2012; Li et al., 2018a). Studies of the
1041 mechanisms controlling needle ice formation (e.g., cooling rate,
1042 freezing point, number and frequency of freeze–thaw cycles and
1043 moisture content at freezing) are urgently required to enhance the
1044 representation of freeze–thaw processes within peatland sediment
1045 supply models.

1046 (2) Limited attention has been given to quantitative study of rainsplash
1047 erosion, wind-driven rainsplash as well as interactions between rainfall-
1048 and flow-driven processes (Li et al., 2018b). Spatially-distributed
1049 models of peatlands which can incorporate these important controls for
1050 interrill erosion would be useful for predicting future slope development
1051 in peatlands. In addition, the effect of raindrop impact on detachment
1052 capacity is highly related to rainfall properties (e.g., rainfall type and
1053 intensity, drop size, velocity and kinetic energy and impact gradient of
1054 falling drops) (Salles and Poesen, 2000; Singer and Blackard, 1982;
1055 Torri and Poesen, 1992), that are usually modified by wind in many
1056 peatland environments (Foulds and Warburton, 2007a; Foulds and

1057 Warburton, 2007b; Warburton, 2003). These controls on rainsplash
1058 detachment should also be reflected in further peat erosion models
1059 development.

1060 (3) Piping has been widely observed in peatland landscapes. However, the
1061 complete understanding of pipe initiation mechanisms, the interaction
1062 of environmental factors controlling the development of pipe networks,
1063 roof collapse and gully development, and the influence of piping on
1064 catchment water and sediment response needs to be considered.

1065 (4) Despite the importance of wind erosion in upland peat, surprisingly few
1066 studies have examined aeolian erosion processes compared with those
1067 on fluvial processes in peatland landscapes. Of the few studies
1068 available most have focused on the UK north Pennines and are
1069 temporally limited with less than two years monitoring (Foulds and
1070 Warburton, 2007a; 2007b; Warburton, 2003). Future long-term
1071 observations of wind erosion are required in a range of
1072 geomorphological locations, to gain a full understanding of peatland
1073 aeolian system dynamics and erosion rates.

1074 (5) Floodplain sediment storage may be an important component of the
1075 carbon balance of eroding peatlands (Pawson et al., 2012). Future
1076 work is required to ascertain the fate of floodplain carbon (and the
1077 downstream fate of POC in the fluvial system more generally) in terms
1078 of rates and fluxes of loss to DOC or CO₂.

1079 (6) Peat erosion processes interact with one another. Further exploration
1080 of the combined effects of sediment supply (rainsplash, freeze–thaw
1081 and desiccation) and sediment transport (water erosion, wind erosion,

1082 mass movements) processes could be undertaken in future studies that
1083 couple laboratory-based experiments and field monitoring to reveal the
1084 relative importance of these controls.

1085 (7) Further research is needed on thresholds for connectivity of water and
1086 sediment flows at all scales and the role of streams as sediment
1087 sources and (temporal) sinks. Multi-scale studies to facilitate spatial
1088 upscaling of runoff and erosion rates and provide data on the spatial
1089 connections between different units at each scale are necessary.

1090 (8) Finally, peat erosion models should be coupled to peatland landform
1091 development models (e.g. DigiBog; Baird et al. (2012); Young et al.
1092 (2017)) that can be run under different climate, land management and
1093 topographic configurations so that predictions of peat mass growth and
1094 decay can include the erosion components.

1095

1096 **6.2 Peat erosion measurements**

1097 Traditional methods of peat erosion measurement using erosion pins,
1098 sediment traps and erosion plots have the disadvantage of disturbance and
1099 damage to the peat surface during installation and repeated measurements.

1100 Photogrammetric measuring techniques are instead recommended where
1101 possible. By using measurement techniques such as SfM (Glendell et al.,
1102 2017) or remote sensing (Evans and Lindsay, 2010; Evans and Lindsay, 2011;
1103 Grayson et al., 2012; Rothwell et al., 2010), micro-topographical changes can
1104 be compared by using time-series data and mapping important erosion

1105 processes (e.g., gully erosion) or erosion affected by needle ice production,
1106 desiccation or extreme rainfall events.

1107

1108 In addition, measuring peat erosion is restricted by the temporal scale
1109 involved as most monitoring programs are typically limited to a few years
1110 (Table 2). Short-term measurements may not be representative of long-term
1111 fluctuations (Boix-Fayos et al., 2006), such as seasonal and interannual
1112 variations in measured peat erosion rates at both the catchment (Evans and
1113 Warburton, 2007; Francis, 1990; Labadz et al., 1991) and plot scale (Holden
1114 and Burt, 2002a). Long-term systematic measurements under real field
1115 conditions are recommended to reduce the temporal uncertainty of erosion
1116 plot experiments and to provide numeric models (Li et al., 2016a) with reliable
1117 data. In addition, continuous and prolonged monitoring of peat erosion
1118 processes should utilize standardized procedures to allow comparisons of
1119 data obtained from different study areas (Prosdocimi et al., 2016).

1120

1121 Peat loss measured at one scale may not be representative of those at other
1122 scales. Therefore, direct extrapolation of plot scale interrill and rill erosion
1123 rates up the catchment scale can be problematic (De Vente and Poesen,
1124 2005; Parsons et al., 2006). There is a need for monitoring, experimental and
1125 modelling studies as a basis for scaling erosion rates from one specific area to
1126 larger or smaller areas.

1127

1128 **6.3 Factors (drivers or mitigation techniques) influencing peat**
1129 **erosion**

1130 **6.3.1 Effects of drivers**

1131 Changes in micro-climatic factors such as air temperature and moisture
1132 content impact the actions and interactions of freeze–thaw and wet–dry cycles
1133 and the associated weathering processes of the peat surface. Without
1134 intensive weathering processes, running water is unlikely to wash off large
1135 quantities of peat (Evans and Warburton, 2007; Li et al., 2018a). More direct
1136 investigations are required to reveal the importance of interactions between
1137 temperature and moisture controls on sediment supply processes.

1138

1139 In addition to the normally observed peat properties (e.g., degree of
1140 humification, shear strength, bulk density) that affect peat erosion (Carling et
1141 al., 1997; Marttila and Kløve, 2008; Svahnäck, 2007; Tuukkanen et al., 2014),
1142 other physical and geochemical properties (e.g., grain size distribution and
1143 form, moisture) also impact peat erodibility. For example, it has been
1144 hypothesized that peat particle size distribution and form impacts the
1145 resistance of peat to wind erosion process (Warburton, 2003). Any increase in
1146 moisture content is likely to enhance peat hillslope instability due to reduced
1147 cohesion and saturation of the basal peat (Evans and Warburton, 2007;
1148 Warburton et al., 2004). More attempts are needed to assess how these peat
1149 properties influence sediment yield and transport.

1150

1151 Numerous studies have demonstrated that vegetation cover can reduce peat
1152 erosion. However, there are several related research questions remaining
1153 unanswered. For example, what is the effectiveness of a plant cover in
1154 reducing splash erosion rates through interception of raindrops and by
1155 decreasing the kinetic energy of raindrops approaching the peat surface? Are
1156 weathering processes (freeze–thaw cycle and wet–drying cycle) for the bare
1157 soil surfaces different for vegetated peat surfaces? How does vegetation
1158 cover impact wind erosion by imparting roughness to the air flow and reducing
1159 the shear velocity of wind? To what extent does vegetation cover contribute to
1160 peat slope stability reducing mass movements?

1161

1162 In addition, management practices such as artificial drainage, prescribed
1163 burning and grazing can result in changes to vegetation cover and sediment
1164 connectivity from sources areas to channels (Evans et al., 2006). However,
1165 there have been limited measurements of how peatland hillslope erosion
1166 processes respond to changes of vegetation cover that are associated with
1167 these management practices (Li et al., 2016a; Li et al., 2017b). Integrated
1168 research into the interaction of peat hillslope erosion processes and different
1169 vegetation cover conditions that are associated with different states of
1170 degradation and re-vegetation will help inform future functioning of peatlands.

1171

1172 Local disturbances such as installation of infrastructure (e.g., windfarms,
1173 tracks, footpaths, pipelines) (Parry et al., 2014), may also affect peatland
1174 runoff and sediment production (Holden, 2005a; Robroek et al., 2010). More

1175 long term studies of peatland runoff and erosion are needed to understand the
1176 impacts of these land management practices.

1177

1178 **6.3.2** Effects of peatland conservation techniques

1179 In recent years there has been a significant increase in the number of
1180 peatland restoration projects and amount of funding to reduce the negative
1181 consequences of peatland degradation on ecosystem services (Holden et al.,
1182 2008b; Parry et al., 2014). Fewer studies have evaluated the effectiveness of
1183 conservation measures (e.g., check-dams in gullies and streams) at
1184 catchment or regional scales, therefore more attention is required in future
1185 studies, particularly to help ensure that erosion prevention is accounted for in
1186 carbon accounting processes as part of land management change (LULUCF,
1187 2014) under the United Nations Framework Convention on Climate Change.

1188

1189 **7. Conclusions**

1190 From this comprehensive review of peatland erosion research a number of
1191 research themes have emerged as requiring further attention in the near
1192 future. Firstly, there is a need to increase understanding of the basic erosion
1193 processes operating in peatlands (e.g., freeze–thaw weathering, wind-driven
1194 rainsplash, and piping erosion) and how they interact with one another.
1195 Secondly, it is important to establish long-term and multi-scale in-situ
1196 monitoring programmes that combine both traditional and new methods (e.g.
1197 SfM techniques) that offer improved resolution and spatial coverage. These
1198 should adopt standardized procedures to allow comparisons of data derived

1199 from different sites but should also be investigative to help our understanding
1200 of process dynamics. Process studies and new datasets will enable improved
1201 model parameterization through the incorporation of basic erosion processes
1202 that are currently under-represented in erosion models. Finally there is a need
1203 to collect more spatially-distributed data, across a wider range of peatland
1204 environments to help improve our understanding of the effects of
1205 environmental factors and land management practices on peat erosion
1206 processes and rates, not least as this will be beneficial for determining the
1207 most feasible and sustainable conservation techniques, and support reporting
1208 for LULUCF as part of UN climate change commitments.
1209

1210

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1214

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