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3 **Botanical and geotechnical characteristics of blanket peat at three Irish**

4 **bogflows**

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23

24 **Abstract**

25

26 Systematic investigations of instability and failure of peat covered hillslopes began in the late 1990s and quickly

27 identified the potential importance of botanical controls on the properties and behaviour of the blanket peat involved in

28 the failures. However, attempts to unravel some of these controls did not begin for several years. During 2010-12

29 investigations of the blanket peat at three relatively recent bogflows in northwest Ireland were done with the aim of

30 establishing some form of relationship between botanical or paleoecological characteristics and standard physical and
31 geotechnical properties, assuming the latter to be meaningful but recognising that this may not be the case. In-situ
32 measurements and investigations at all three sites were followed by extensive laboratory characterisation of small core,
33 block and monolith samples.

34
35 The botanical composition of the peat could not be fully determined due to the very high degree of decomposition.
36 However, analysis of macrofossils allowed distinct depth-related patterns of several key botanical indicators to be
37 determined. In particular the monocotyledon fragments, dominated by *Eriophorum vaginatum*, showed distinct and
38 potentially useful distributions throughout the peat profiles. Overall results showed that the basal peat at one of the sites
39 was discernibly different from the other two sites having fewer monocotyledons, fewer fibres, higher dry bulk density
40 and higher saturated hydraulic conductivity. This approach therefore offers a potential basis for developing a means of
41 assessing peat mass characteristics from small auger samples.

42
43 **Key words** Fabric/structure of soils, Landslides, Strength & testing of materials

44
45 **Notation**

46 F fibre content
47 F_m fine fibre fraction of the peat (fragment of plant tissue 0.15-1.00 mm in any dimension)
48 R_m coarse fibre fraction of the peat (fragment of plant tissue > 1 mm in any dimension)
49 F_t total fibre fraction of the peat (all fibres > 0.15 mm in any dimension)
50 F_h humus fraction of the peat (all particles < 0.15 mm in any dimension)
51 FVS field vane strength
52 M_{Ft} mass of the total fibre fraction (g)
53 M_{Fh} mass of the humus fraction (g)
54 M_s mass of oven-dried (105°C) peat sample – mass of ash (g)

55
56 **1. Introduction**

57
58 Records of failures of peat bogs go back around 500 years to the collapse of Chat Moss near Manchester,
59 northwest England, in 1526 (Crofton 1902). However, until the late 1990s the occasional studies of isolated
60 examples of peatland failures were largely descriptive with estimates of geometric characteristics and

61 occasionally reports of the living plant assemblages present at the time of failure. Systematic investigations
62 began into the stability of blanket peat-covered slopes following significant peat landslides in Northern
63 Ireland (Dykes and Kirk 2001; Kirk 2001) and northern England (Mills 2002; Warburton et al. 2003, 2004).
64 The potential importance of the botanical composition as a controlling factor for the properties and
65 geotechnical behaviour of peat was highlighted earlier by Hobbs (1986), not least because of the widespread
66 adoption by engineers of the von Post scheme for classifying peat deposits (e.g. Landva and Pheaney 1980;
67 Carlsten 1993) which requires the estimation of relative frequencies of fibres and wood/shrub fragments as
68 well as the degree of decomposition of the plant matter (i.e. the humification). The need for research into
69 botanical controls on peat properties was further emphasised with respect to blanket peat instability by Kirk
70 (2001), Dykes (2008a) and O’Kelly (2017) in response to findings from their investigations of physical and
71 geotechnical properties thus far. Indeed, O’Kelly (2017) highlighted the scarcity of published works on the
72 topic and the contradictory findings from the few such studies. The present research (Foteu Madio et al.
73 2012; Foteu Madio 2013) arose directly from this dearth of previous studies.

74
75 The aim of this paper is to examine whether physical and geotechnical properties of Irish blanket peat can be
76 causally associated with measurable botanical characteristics. It does so by presenting and analysing data
77 representing the properties and characteristics of the peat at the sites of three significant bogflows in
78 northwest Ireland, obtained from a combination of field and laboratory investigations. The importance of this
79 study is to provide the basis for more efficient and reliable methods for assessing the stability of peat with
80 respect to planned interventions such as construction of access roads for windfarms or other purposes.

81 82 **2. Blanket Bog Failures in Ireland**

83
84 The topic of peat mass movements (as distinct from geotechnical engineering of peat) emerged from an
85 esoteric scientific by-way to become a mainstream theme in engineering geology and geomorphology
86 following several major events in late 2003. On 19 September 2003, two entirely independent extreme
87 rainfall events in Co. Mayo, Ireland, and South Shetland, Scotland, triggered multiple failures of peat-
88 covered hillslopes (Dykes and Warburton 2007a, 2008a,b). More significantly for civil engineering, four
89 weeks later the 450,000 m³ Derrybrien Windfarm landslide occurred (Lindsay and Bragg 2005). By that time

90 it had already become clear that the Irish blanket bogs were failing in several slightly different ways, giving
91 rise to morphologically distinctive types of failures (Dykes and Warburton 2007b). Most involve shearing of
92 mineral soil beneath the peat ('peaty-debris slides'), shearing at the peat-mineral interface ('peat slides'), or
93 shearing entirely within the basal peat ('bog slides'). 'Peat flows', a term reserved for failures resulting
94 primarily from head-loading, appear to be effectively bearing capacity failures with small areas of shear
95 surface within the basal peat having been observed in the Derrybrien and Ballincollig Hill landslides (Long
96 2005; Dykes and Jennings 2011).

97
98 All of the available evidence relating to 'bog bursts' and 'bogflows' indicate that these failures involved
99 some sort of in-situ liquefaction of the lower or basal peat, with this (semi-)liquid peat slurry then breaking
100 out from beneath a stronger confining acrotelm layer (or from cut faces through the margins of raised bogs)
101 (Dykes and Warburton 2007b). The precise mechanisms of strength loss are unknown. One hypothesis, for
102 example, is that the basal peat fails like 'quick clay' with an initial small shear failure creating a disturbance
103 that propagates rapidly. As such a bogflow may simply be a bog slide involving weaker and wetter peat – but
104 there is a clear distinction because these two types of failure have different peat depth vs. gradient
105 characteristics (A P Dykes, unpublished data). A parallel hypothesis is that in some of these failures the
106 lower layer of the peat deposit was always a fluid body, for example if peat grew over a large pond so as to
107 eventually entirely bury it.

108
109 In almost all cases of failures of (blanket) peat-covered slopes in Ireland, landslide morphologies and runout
110 characteristics display clear evidence of relatively rapid development of failure associated with very high
111 volumes of rainwater, with eyewitness accounts of some recent events (e.g. the Derrybrien peat flow in 2003,
112 the Croaghan peat slide in 2014) corroborating these interpretations. Warburton et al. (2004) discussed the
113 various hydrological processes giving rise to, or controlling, such failures. It is likely that the peaty-debris
114 slides are triggered by pore pressure effects, in part due to subsurface storm runoff being confined beneath a
115 saturated and effectively impermeable peat cover. Peat slides (interface failures) probably occur for the same
116 reason. Failure within the peat is a more complex issue because of the dual influences of effectively
117 impermeable and normally saturated but weak catotelm peat material and the internal structure of the peat
118 mass (sensu 'rock mass' considerations) that may experience high turbulent flows and even artesian

119 conditions within networks of natural peat pipes and (relict) desiccation cracks (Dykes and Warburton
 120 2007a, 2008a; Gilman and Newson 1980; Holden and Burt 2003). Given the rates of deformation and then
 121 movement and the saturated hydraulic conductivity of the intact peat mass through which any shear surface
 122 may develop, the focus of our research is on the undrained strength characteristics of basal peat.

123

124 *2.1 Study sites*

125 We identified three locally significant bogflows (sensu Dykes and Warburton 2007b) for this study, located
 126 within the same region of northwest Ireland: Straduff Townland (hereafter referred to as ‘ST’), Slieve
 127 Anierin (‘SA’) and Slieve Rushen (‘SR’) (Fig. 1). Site and landslide characteristics are summarised in Table
 128 1 and illustrated in Fig. 2. All were relatively recent, thus limiting the degree of post-failure degradation, and
 129 two sites (though not the same landslide at one of these sites) had been investigated previously which
 130 provided a cross-check for the peat characterisation results from this study. Furthermore, although the peat at
 131 all three sites was generally very similar, one site (Slieve Anierin, below) was noted by Yang and Dykes
 132 (2006) to be slightly but nevertheless distinctly different from others including a bogflow at Straduff
 133 Townland adjacent to the one used for this study. We anticipated that the results of this new research would
 134 also show this.

135

136

137 **Table 1.** Summary of site details and characteristics of the study bogflows.

Bogflow	County	Latitude	Longitude	Elevation (m)	Geology (Carboniferous)	Geomorphological Context	Length (m)	Slope (°)	Depth ^a (m)	Volume (m)
ST	Sligo	54°7.2’N	8°12.9’W	405	Lackagh Sandstone	Escarpment failure	200	5.5 (top) 3 (mid) 6 (lower)	2.5	35,000
SR	Cavan	54°8.9’N	7°38.5’W	390	Glenade Sandstone	Basin slope failure	175	5.5	2.0	20,000
SA	Leitrim	54°6.3’N	7°58.7’W	440	Lackagh Sandstone	Escarpment failure	190	4	2.2	22,000

138 Note

139 ^a Indicative average depth of in-situ peat immediately adjacent to the landslide source area

140

141

142 < FIGURE 1 >

143 **Figure 1.** Location of the study area in northwest Ireland, showing the distribution of peatlands (after Hammond 1979).
144 The outlined rectangle is enlarged to show the locations of the three bogflows: (left to right) ST = Straduff Townland,
145 SA = Slieve Anierin, SR = Slieve Rushen. Modified from Yang and Dykes (2006).

146

147 < FIGURE 2 >

148 **Figure 2.** General views of the three study areas. (A) Straduff Townland bogflow, looking downslope from above the
149 head (July 2010). (B) Slieve Rushen bogflow, looking across at the failed slope from the other side of the peat basin
150 into which its displaced peat flowed (July 2010). (C) Slieve Anierin bogflow from the air (Nov. 1998, photo by APD).

151

152

153 ST, the Straduff Townland landslide, occurred overnight or early morning on 14 August 2008 during very
154 heavy rain. The dominant morphology is that of a bogflow. However, a basal shear surface around 20 mm
155 above the base of the peat was visible in two small parts of the source area (Dykes 2009; Dykes and Jennings
156 2011). Although the latter observation corresponds with a ‘bogslide’ (Dykes and Warburton 2007b), we will
157 refer to this failure as a bogflow. It involved an area of intact blanket peat between the source areas of
158 bogflows dating from 1945 and 1991, leaving narrow strips of minimally displaced peat separating the
159 failures. The physical characteristics of the peat at the 1991 bogflow, just a few metres from the margin of
160 the later failure, were determined by Yang and Dykes (2006). SA (the Slieve Anierin bogflow) is thought to
161 have occurred during 1998, based on its visible condition when first seen from a light aircraft in November
162 1998 and a conversation with a local resident in 2011. It was described, and the physical characteristics of
163 the peat reported, by Yang and Dykes (2006). The date of SR (the Slieve Rushen bogflow) is uncertain, but
164 the condition of the failure when first inspected in September 2004 was consistent with an age of only a few
165 years, i.e. it most likely occurred during the 1990s (Dykes 2008b).

166

167 **3. Methods**

168

169 The three bogflows were investigated using the same general methodology as previous studies of peat
170 landslides (e.g. Yang and Dykes 2006). All had previously been surveyed in detail by Dykes (2008b, 2009).

171 The focus for this study was to obtain samples for laboratory testing from a carefully prepared and fully
172 described vertical profile through the full depth of undisturbed *in situ* peat. Most peat failures leave irregular
173 sub-vertical peat profiles with varying amounts of peat debris covering the lower layers, around several parts
174 of the source area margins. A single study profile (hereafter referred to as the ‘study profile’ or ‘Sampling
175 Point’) was selected at each landslide according to the feasibility of creating a clean vertical profile through
176 the full thickness of the peat, i.e. involving the minimum manual excavation of loose peat debris, but
177 ensuring the in-situ peat was undisturbed and not within a few metres of any tension cracks. Safety was
178 ensured by having wide open access to the prepared profile from within the evacuated source area of each
179 landslide, with one person maintaining active watch over the cut face while the other person worked there.

180

181 **3.1 Field investigations**

182 Around each bogflow source area, stratigraphic and topographic surveys were carried out in order to estimate
183 the morphology of the peat deposit and the variability of the peat within it prior to failure. The stratigraphy
184 and maximum depth of the *in situ* peat was determined on a coarse but regular grid using a 20 mm diameter
185 gouge auger. Maximum peat depths were measured at additional locations by probing with a metal rod. Peat
186 surface elevations were then surveyed at all the stratigraphy and peat depth measurement points by levelling,
187 with the mineral surface elevations being measured within the landslide source areas and calculated for the
188 peat-covered areas around the source areas from the measured peat depths.

189

190 Prior to sampling, a detailed description of the full thickness of the peat at each Sampling Point was recorded
191 according to the von Post (von Post, 1922, as presented by Landva and Pheeney 1980, and Hobbs 1986) and
192 Troels-Smith (Troels-Smith 1955) peat classification schemes. Several sets of samples were obtained from
193 each landslide. Most of the physical/geotechnical samples were obtained from the basal peat at each
194 Sampling Point. Samples were also obtained from the surface and middle peat at the Sampling Point at
195 bogflow ST to provide some indication of depth variations, assuming it to be representative of all three sites.
196 In addition, a Geonor H-60 field shear vane was used to measure the ‘field vane strength’ (FVS) of the in-
197 situ basal peat ~1 m behind each Sampling Point. For palaeoecological (or simply ‘botanical’) analyses,
198 monolith samples were extracted that included most of the thickness of the peat profile at each Sampling
199 Point (missing the uppermost part at SR and SA). In addition, 10 mm cubes of peat were carefully cut from
200 the auger samples from SR at approximately 200 mm depth intervals (Fig. 5 in Section 4 shows results from
201 this component of the work). Table 2 summarises the samples collected.

202 **Table 2.** Samples extracted from the study bogflows.

Landslide / position in peat profile	Physical properties – small cores 50 mm dia. × 51 mm length	Tensile strength – blocks 120×120×70 mm	Triaxial – 38 mm dia. cores	Shear strength (direct shear) – blocks 120×120×70 mm	Monoliths for botanical data 730×100×100 mm
ST see right	6 at ~650 mm depth 6 at ~1150 mm depth	3 at 10-80 mm depth 3 at 890-960 mm depth	--	3 at 10-80 mm depth 3 at 890-960 mm depth	1 at 400-1130 mm depth
ST base ^a	9	6	6	12	2
SA 300-1030 mm depth	--	--	--	--	1
SA base ^a	9	6	6	12	2
SR 100-830 mm depth	--	--	--	--	1
SR base ^b	9	6	6	12	2

203 Notes

204 ^a 1600-1700 mm depth below the surface of the peat, 970-1700 mm depth for the lower monoliths

205 ^b 1900-2000 mm depth, 1270-2000 mm depth for the lower monoliths

206

207

208 **3.2 Laboratory testing**

209 Some physical properties of peat can give a rough indication of the state or condition of the peat (Hobbs,
 210 1986). Therefore, standard methods were used to determine the water content and bulk density (oven-drying
 211 for 24 h at 105°C: O’Kelly 2017), loss on ignition (550°C for 3h: Skempton and Petley 1970; Andrejko et al.
 212 1983; Jarrett 1983; Hobbs 1986) and saturated hydraulic conductivity (‘constant head’ method) to provide
 213 reference details for correlation with the results of the botanical and geotechnical analyses. There has been
 214 some debate in recent years regarding the appropriate drying temperature for water content determination,
 215 including evidence of the possibility of charring of the peat at temperatures higher than 80-90°C (O’Kelly
 216 2014). Further, O’Kelly (2014) found experimentally that the possible additional loss of mass due to charring
 217 is negligible compared with the mass of any retained water due to incomplete drying, particularly
 218 intracellular water within peat fibres that may constitute a significant proportions of the peat mass (Foteu
 219 Madio 2013), and so recommended following the standard specification for mineral soils of 105°C as used
 220 by many previous workers including Skempton and Petley (1970) and Hobbs (1986). We adopted the latter
 221 approach for the demonstrated reasons of standardisation and comparability of results.

222

223 For the constant head method we used a laboratory permeameter arrangement as described by, for example,
224 Klute and Dirksen (1986) or Head (1994). Undisturbed core samples collected in thin-walled tubes 50 mm
225 long \times 50.5 mm diameter were trimmed to size, saturated in tap water and mounted vertically to form a
226 permeameter maintaining a constant head of 0.15 m of water on the top of the sample. Water that passed
227 through the sample was collected underneath and measured. The constant head saturated hydraulic
228 conductivity was calculated according to Darcy's Law.

229

230 The proportion of intracellular and interparticle water depends upon the structure and morphology of the
231 various plants present and on the degree of humification of peat (Hobbs 1986). Microfossils, including pollen
232 grains, may not represent the original in situ vegetation because they are small enough to be transported by
233 the wind, possibly over long distances. Therefore we investigated the fibres, macrofossil content and the
234 degree of humification of the peat. The latter influences the water holding capacity, pore sizes and fibre
235 quantities and properties, all of which could influence the peat strength. The fibres and macrofossils are
236 likely to directly affect the strength and other geotechnical properties.

237

238 *3.2.1 Humification*

239 Humification was quantitatively determined in the laboratory followed a modified version of the Bahnson
240 colorimetric method (Aaby and Tauber 1974; Blackford and Chambers 1993; Chambers et al. 1997).

241 Subsamples taken contiguously at every 10 mm from the monoliths were tested. The measurements were
242 obtained using a Hatch 2500 spectrometer set up at 540 nm. Results are expressed as 'raw' percentages of
243 light transmission through the diluted peat solution. The more light passes through the peat solution, the less
244 humified the sample.

245

246 *3.2.2 Fibres*

247 The fibre content (F) is an important characteristic that influences peat stability (Long and Jennings, 2006) as
248 it affects the peat structure and its strength properties. To explore this effect, we firstly re-defined the
249 different fractions as follows: (i) a 'fine fibre' (Fm) is a fragment or piece of plant tissue between 0.15 and
250 1.00 mm in any dimension including length; and (ii) a 'coarse fibre' (Rm) is a fragment or piece of plant

251 tissue > 1 mm in any dimension. In line with the ASTM's (2008) standard for determining the fibre content
252 of peat, the 'total fibre fraction' (Ft) is defined as all fibres ≥ 0.15 mm in any dimension. The humus
253 fraction (Fh) is defined as all particles < 0.15 mm in any dimension. We recognise that it is difficult to
254 determine a specific shape of some fibres and that, depending on the orientation of the fibre, any dimension
255 of a fibre or particle of a particular shape (e.g. elongated fibres) can prevent it passing through a hole in the
256 sieve, so further refinements to this methodology are likely to be needed in the future.

257

258 The Fm and Rm fibre fractions were estimated in the field based on the von Post system as presented by
259 Hobbs (1986, p.79): Fine fibres (Fm) are 'fibres and stems smaller than 1 mm in diameter or width' and
260 coarse fibres (Rm) are 'fibres, stems, and rootlets greater than 1 mm in diameter or width'. To both of these
261 definitions we added 'or any plant particle' and took the size boundary as '< or > 1 mm in all directions'.
262 The von Post scheme uses a four point scheme from 0 'nil' to 3 'high content' but without a microscope it is
263 difficult to be certain that there are no fragments of fibre present. Consequently we removed '0' and assessed
264 the quantity according to a five point scale: 1 = very low content (VL), 2 = low content (L), 3 = medium
265 content (M), 4 = high content (H) and 5 = very high content (VH). All of the other fractions defined above
266 were determined in the laboratory and recorded using a similar 5-point scheme:

267 1 = fibre content $\leq 40\%$

268 2 = fibre content > 40 and $\leq 60\%$

269 3 = fibre content > 60 and $\leq 80\%$

270 4 = fibre content > 80 and $\leq 95\%$

271 5 = fibre content > 95%

272 Differentiating peat in this way enabled field estimates to be corrected with measurements obtained from
273 laboratory tests, and this simple 5-point scale allowed cluster analyses of the results to be carried out in a
274 consistent way.

275

276 For the laboratory determinations, duplicate subsamples of known masses were taken every 70 mm from
277 along the lowest monolith sample from each site. These were analysed differently in order to separate the
278 peat into different fractions, the initial part of the procedure following ASTM (2008) but with a much
279 smaller initial sample mass. Thus the fibre contents of the lowest 0.7 m of the peat profile at each landslide's

280 Sampling Point were fully quantified. The first subsample was soaked in a dispersing agent (5% sodium
281 hexametaphosphate) for approximately 15 hours and then the peat was gently washed through a 0.15 mm
282 mesh size sieve using tap water. The fibrous material retained on the sieve was washed through a further 1
283 mm sieve and the fine fraction that passed through was collected. The fibres retained on the 1 mm sieve
284 comprised the coarse fraction. Both fractions were oven-dried at 105°C until constant masses were achieved.
285 The masses of fine and coarse fibres were combined to obtain the total mass of fibres. The mass of humus
286 was obtained from the difference between the mass of total fibres and the initial dry mass of peat determined
287 from the second subsample. The second subsample was dried at 105°C for 24 h and the mass ratio of dry to
288 wet peat determined. The duplicate peat samples had slightly different masses and assuming that their
289 respective mass ratios of dry to ‘field wet’ peat were equal, the corresponding initial mass of the sample used
290 for fibre content testing was established. The fibre (Ft) and humus (Fh) fractions (without any mineral
291 matter) were then expressed as percentages of the initial dry mass (M_s) as follows:

$$292 \quad F_t = (M_{F_t} / M_s) \times 100$$

$$293 \quad F_h = (M_{F_h} / M_s) \times 100$$

294 where M_{F_t} and M_{F_h} are the masses (g) of the fibre and humus fractions, respectively, after drying at 105°C to
295 constant mass then subtracting the mass of ash, and M_s is the mass (g) of the initial peat sample after drying
296 at 105°C to constant mass less the mass of ash.

297

298 3.2.3 *Macrofossils*

299 The heterogeneity of peat is due to the variability of factors and environmental gradients that influence its
300 initiation and development (Moore, 1984; Charman, 2002). The original plant composition of peat
301 influences its structure and is assumed to affect its geotechnical properties. We used macrofossil analysis to
302 assess these botanical factors. 10 mm cubes of peat were obtained from the along the length of each monolith
303 sample, with 40–80 mm separation except within the basal peat where the cubic subsamples were
304 contiguous. Analysis was undertaken using the ‘Quadrat and Leaf Count Macrofossil Analysis technique’
305 (QLCMA) developed at the Southampton Palaeoecology Laboratory (Barber et al. 1994). The method
306 estimates the percentage coverage of all macrofossil types with the aid of a 10 × 10 grid graticule in the
307 eyepiece of a stereomicroscope. Monocotyledon epidermis tissues and *Sphagnum* branch leaves were
308 examined further at a magnification of ×400 under transmitted light. Daniels and Eddy (1990) (for

309 *Sphagnum*), Smith (2004) (for other bryophytes), Grosse-Brauckmann (1972) and Katz et al. (1977) (for
310 vascular plants) were used to identify the remains.

311

312 The additional small cubic samples obtained from SR were further investigated using the method developed
313 by Walker and Walker (1961), in which on a scale of 0 to 5, 0 indicates absence and 5 indicates that the
314 sample consisted largely of a particular macrofossil. This was done to check that peat at the Sampling Point
315 was representative of the entire blanket bog.

316

317 *3.2.4 Shear strength*

318 The mechanism of failure of in-situ peat in natural landslides is uncertain and indeed there may be different
319 mechanisms operating in different contexts. Examples of these are outlined in Section 2. Our tests focused
320 on undrained shear strength because of the documented rapid development of failures compared with the
321 measured very low permeability of Irish catotelm peat (e.g. 10^{-6} to 10^{-9} m s⁻¹: see Section 4.2.1). We used a
322 direct shear apparatus with a 100 mm × 100 mm shearbox to try to obtain reproducible values of shear
323 strength using normal stresses representing in-situ conditions, i.e. typically less than 5 kPa (after Dykes
324 2008a). Samples were sheared at normal stresses of 0.7, 1.2, 1.7, 2.2, 3.2, 4.2 and 5.6 kPa using the method
325 outlined by Dykes (2008a), i.e. no pre-consolidation, but with a slightly higher shear rate of 1 mm min⁻¹
326 (2×10^{-5} m s⁻¹) to represent moderate failure (IUGS, 1995) with the associated likelihood of undrained
327 shearing effects.

328

329 The triaxial tests were intended to give an indication of the undrained shear strength and associated stress-
330 strain behaviour of the peat by means of rapid unconsolidated-undrained tests on standard 38 mm diameter ×
331 76 mm high samples (carried out according to Head (1994)) at a range of cell pressures at the lowest end of
332 what was possible with the available equipment, i.e. 50, 100 and 200 kPa. To minimise membrane effects we
333 used thinner membranes, samples were allowed to saturate before the axial load was applied at 1 mm min⁻¹
334 as for the direct shear tests. After each test, the sample was visually inspected to assess the failure
335 mechanism or any other deformation. The bi-linear correction of the deviator stress due to membrane
336 stiffness was not applied to the results because although the effect may be significant, (i) there is no
337 consensus on appropriate corrections given complex peat-membrane interactions, and (ii) this was primarily

338 a comparative study that was not necessarily expected to determine the exact value of the shear strength of
339 peat.

340

341 *3.2.5 Tensile strength*

342 The tensile strength of block samples of undisturbed peat was measured using the equipment (Fig. 3C) and
343 procedure described by Dykes (2008c). This involved applying a tensile load, in 100 g increments, to half of
344 the cross-sectional area of each 100 × 100 mm test sample by means of five 10 mm wide steel fingers (Fig.
345 3A), the tensile resistance being provided by the four 12.5 mm wide strips of peat between the fingers (Fig.
346 3B). Tensile stress and strain were recorded 30 s after the application of each load increment until the sample
347 failed. Although results obtained using this method have been found to be reproducible and consistent, two
348 key limitations are recognised: (i) the apparatus does not allow a vertical load to be placed on the sample to
349 replicate the condition of the basal peat in-situ; and (ii) significant sample disturbance may occur during
350 installation due to large fibres or woody fragments (Dykes 2008c).

351

352

353 < FIGURE 3 >

354 **Figure 3.** Measuring the tensile strength of the peat: (A) the two sets of steel ‘fingers’ that are pushed through the
355 centre of a cut block of undisturbed peat 100 mm high × 100 mm wide and 40-60 mm thick; (B) one half of a sample
356 following tensile failure, still adhering to one set of ‘fingers’; (C) the testing apparatus, showing: *centre* – the ‘fingers’
357 assembly installed (without a sample); *right* – the force proving ring; *lower far left* – the hanger for applying the
358 weights that apply the load just visible beside the end of the cupboards. Details of the design and development of this
359 apparatus are provided in Dykes (2008c).

360

361

362 **4. Results**

363

364 *4.1 Field descriptions of the peat*

365 The peat at the three landslides showed remarkably little variability in terms of structure and macrofossil
366 content. Four major stratigraphic units were identified at each site. The first unit (starting at the top),

367 including the living roots near the surface, comprised slightly humified peat, with each unit below being
368 progressively more humified and the fourth unit at the base having highly humified and/or greasy peat,
369 sometimes with bitumen or sludge like patches (Table 3; e.g. Fig. 4). The identifiable plant material in the
370 peat was predominantly monocotyledon ('monocot') remains ('*Turfa herbacea*' in the Troels-Smith scheme)
371 including undifferentiated roots, stems and leaves (Fig. 5). This general lack of variation between (Table 3)
372 and within (Fig. 5) sites allowed us to consider one Sampling Point as being broadly representative of each
373 landslide site.

374

375

376 < FIGURE 4 >

377 **Figure 4.** Peat stratigraphy across the slope above the head of the Slieve Rushen bogflow. This linear transect was
378 located 7.5 m upslope of the source area head at the closest point. Modified from Foteu Madio (2013).

379

380

381 < FIGURE 5 >

382 **Figure 5.** Results of macrofossil analyses of samples obtained from across the Slieve Rushen bogflow. Labels A1, A5,
383 etc. refer to sampling positions: A1 to A9 are shown in Fig. 5; E1/E3 and E4/E7 are located either side of the downslope
384 extent of the source area. The materials found at each position are from, and in the same order as, this list: Charcoal
385 (0.5-1 mm); Charcoal (less than 0.5 mm); Ericales; *Eriophorum vaginatum*; Monocot fragments (Monocot leaves at
386 E4), Roots; *Sphagnum*; Unidentified organic matter. Source: Foteu Madio (2013).

387

388

389 ***4.2 Physical and mechanical properties of the peat***

390

391 ***4.2.1 Geotechnical characteristics***

392 The basic physical properties of the peat at the three landslides are summarised in Table 4. These are broadly
393 consistent with previous results obtained from Straduff Townland (the 1997 bogflow adjacent to ST) and SA
394 by Yang and Dykes (2006). Uncorrected field shear vane readings from depths between 1.25 and 2.00 m
395 were between 6.6 and 14.0 kPa at all sites and there were insufficient results from which to identify any

396 patterns in the data. No corrections were applied because this was intended as a comparative study and the
397 shear vane is known to be inappropriate for the determination of the undrained strength of peat due to the
398 effects of fibres, although it can be used to identify patterns of peat strength variation with depth.

399

400 Results from the experimental low-stress direct shear tests (without consolidation prior to shearing) are
401 shown in Fig. 6. These are consistent with results obtained from basal peat at another landslide in
402 northwestern Ireland (identified as 'E6' by Kirk (2001): Dykes 2008a). The surface peat at ST clearly
403 demonstrates a higher strength due to the greater density, and probably strength, of less humified fibres.
404 Samples inevitably consolidate under even these small loads as shearing takes place. Straight line
405 approximations in the normal stress range 2-5 kPa would all give cohesion intercepts of 1-4 kPa (Fig. 6). If
406 the peat was overconsolidated by up to 10-15 kPa as seems to be the general case (O'Kelly 2017), such low
407 shear stress values within this range of applied normal loads should not be expected.

408

409 Results from the unconsolidated-undrained triaxial tests similarly demonstrate the inherently low shear
410 strength of the basal peat with all three sites in the range 1.5-2.5 kPa (Fig. 7). Slight variations in the
411 diameters of the Mohr's circles arise from the heterogeneity of the peat mass, as also observed in raised bog
412 peat by Hanrahan (1954), but may also result from gas in the peat causing variations in pore water pressures
413 within the samples. Hanrahan (1954) found that the gas content of Irish *Sphagnum* peat may be considerably
414 in excess of 5% of the volume and that significant volumes of gases such as sulphuretted and phosphorated
415 hydrogen (phosphine), as well as methane, could be emitted during construction involving the compression
416 of peat. Therefore the possibility of gas affecting both permeability and pore pressures must be allowed for
417 when interpreting results.

418

419 Fig. 8 shows the tensile strengths obtained from this and previous studies using the same methodology
420 (Dykes 2008c). The tensile strengths of the basal peat at the three landslides in this study are all less than 3
421 kPa except where locally reinforced by matted woody fragments. With the exception of two outliers, which
422 arose from the respective samples containing significant fragments of decomposing roots or woody stems,
423 there is an apparent trend of reducing tensile strength with depth. Although this trend arises from combined
424 results from several locations in Ireland, the similarities of all other measured peat properties between all of

425 these sites (Dykes 2008c; Dykes and Warburton 2008a; Dykes and Jennings 2011) means that this general
426 trend is probably real. At individual sites it is possible that such a trend of decreasing tensile strength with
427 depth may not always be found, although there are insufficient relevant data to be able to comment further.

428

429 Helenelund (1967) suggested that the fibre contents, types and orientations – which depend on the
430 morphology and the mode of growth of the original plant assemblage that formed the peat – may have major
431 influences on the tensile strength. The macrofossil analyses of peats from our study sites revealed remains of
432 sedges, the degree of humification of which increase with depth. In such monocotyledon peat, fibres are the
433 remains of vascular bundles formed from the root systems that grow perpendicularly to the ground surface.
434 The resulting tensile strength will therefore be related to the resisting force produced by the fibres, the
435 frequency of which decreases with depth and is inversely proportional to the degree of humification. The
436 tensile strength results obtained by Helenelund (1967) from *Sphagnum* bog peat, which has very few fibres,
437 are comparable with the lowest of our results, showing that the monocotyledon peats at our sites generally
438 have higher tensile strengths than *Sphagnum* bog peat. Due to the effect of compression during the
439 accumulation of the peats, some fibres that were originally distributed vertically through the peat become
440 squashed progressively into a horizontal alignment as pressure increases. The degree of inclination of these
441 fibres toward the horizontal plane should therefore also increase with depth. The tensile strength values
442 presented in this study were measured in a horizontal plane, intended to represent the effect of the peat mass
443 pulling apart above a basal (shear?) failure zone. The effect of fibre orientation should be to increase the
444 tensile strength with depth since horizontal breaking up of a failing peat mass is resisted by sometimes
445 significant lengths of fibres adhering to amorphous colloidal matrix material. However, the role of living and
446 minimally decomposed roots within the near-surface acrotelm layer combined with the very high degree of
447 humification below the acrotelm appears to entirely override the fibre orientation effect.

448

449

450 < FIGURE 6 >

451 **Figure 6.** Results from experimental low-stress direct shear tests of basal peat from all three landslides and from around
452 10-60 mm depth at Straduff Townland. Previous results from bog slide ‘E6’ at Cuilcagh Mountain, Co. Cavan, obtained
453 using the same methodology, are also shown. Modified from Foteu Madio et al. (2012), after Dykes (2008a).

454

455

456 < FIGURE 7 >

457 **Figure 7.** Mohr's Circles (total stresses) obtained from unconsolidated-undrained triaxial tests on peat samples from the
458 three landslides: (A) ST– Straduff Townland; (B) SR – Slieve Rushen; (C) SA – Slieve Anierin. Source: Foteu Madio
459 (2013).

460

461

462 < FIGURE 8 >

463 **Figure 8.** Tensile strength results obtained from the three landslides in this study and from previous studies using the
464 same methodology. MHA-00s refers to the Maghera bogflow, Co. Galway; SDF-08 is bogflow ST in this study; BHW-
465 08 is the Ballincollig Hill peat flow, Co. Kerry; DCM-03 is the collective reference for the 40 landslides that occurred
466 on Dooncarton Mountain, Co. Mayo on 19 September 2003, the results here being obtained from peat slide 'SE5'.
467 Modified from Foteu Madio (2013).

468

469

470

471 *4.2.2 Humification and fibres*

472 The results of the quantitative determination of humification, recorded as the 'raw' percentage of light
473 transmission through the peat, showed no significant differences between the mean values for the three sites.
474 However, only the results from ST showed a clear reduction in light transmission (i.e. increase in degree of
475 humification) with depth (Fig. 9).

476

477

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482

483 **Table 3.** Summary description of the peat at each landslide Sampling Point (Foteu Madio 2013). The four major
 484 stratigraphic units are separated by the solid lines of the Table.

Depth (m)	Peat profile description at ST
0.00-0.40	Light brown fibrous peat, slightly humified, mainly monocotyledon fine fibres and low amorphous material, moderate horizontal tensile strength.
0.40-0.78	Black and moderately humified, mainly monocotyledon fine fibre peat and moderate amorphous material, moderate horizontal tensile strength.
0.78-1.22	Light brown with dark patches, very weak and moderately humified peat. Monocotyledon fine fibre limited. Low horizontal tensile strength.
1.22-1.60	Brown, moderately to strongly humified peat. Monocotyledon fine fibre present. Low horizontal tensile strength.
1.60-1.80	Dark grey, greasy, highly humified and amorphous peat. Rare and very fine monocotyledon fragments. Low to zero horizontal tensile strength.
>1.80	<i>Sandstone in clay matrix, 5YR 3/1 on the Munsell soil colour chart.</i>
Depth (m)	Peat profile description at SR¹
0.00-0.15	Brown fibrous peat with moderately humified, mainly monocotyledon fine fibres and low amorphous material, moderate horizontal tensile strength.
0.15-0.36	Brown, less fibrous peat with moderately humified, mainly monocotyledon fine fibre peat and moderate amorphous material, moderate horizontal tensile strength.
0.36-0.58	Dark brown humified peat with monocotyledon fragments. Low horizontal tensile strength.
0.58-0.88	Dark brown decomposing peat with monocotyledon fragments. Low horizontal tensile strength.
0.88-1.58	Dark grey, highly humified and amorphous peat. Very fine monocotyledon fragments. Low to zero horizontal tensile strength.
1.58-1.64	Dark grey, greasy, highly humified and amorphous peat. Very fine monocotyledon fragments. Low to zero horizontal tensile strength.
>1.64	<i>Sandstone in clay matrix, 5YR 3/1 on the Munsell soil colour chart.</i>
Depth (m)	Peat profile description at SA
0.00-0.76	Dark fibrous peat, slightly humified, mainly monocotyledon fine fibres, low amorphous material and moderate horizontal tensile strength.
0.76-1.56	Light brown less fibrous peat with moderately humified, mainly monocotyledon fine fibre peat, moderate amorphous material and moderate horizontal tensile strength.
1.56-1.76	Black humified peat with monocotyledon fragments. Low horizontal tensile strength.
1.76-1.78	Dark grey, greasy, highly humified and amorphous peat. Very fine monocotyledon fragments. Low to zero horizontal tensile strength.
>1.78	<i>Sandstone in clay matrix, 5YR 3/1 on the Munsell soil colour chart.</i>

485 Note

486 ¹ Recorded in July 2010 prior to the moorland fire.

487

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493

494 **Table 4.** Summary of physical properties of peat at the three landslides, including previous data from Yang and Dykes
 495 (2006)*.

	Water content ^{a,b} (% mass fraction)	Loss on Ignition ^c (%)	Saturated bulk density ^e (Mg m ⁻³)	Dry bulk density ^e (Mg m ⁻³)	Saturated hydraulic conductivity ^{h,i} (m s ⁻¹)
ST	700-900 *620-860	94.5-95.6 *97.8-98.8	1.00 ^f *1.06	0.10-0.20 *0.13	10 ⁻⁹ to 10 ⁻⁸ * < 10 ⁻¹¹
SR	600-700	94.6-97.2 ^d	1.00	0.10-0.20	10 ⁻⁹ to 10 ⁻⁶
SA	600-700 *600-740	95.0 *97.7-98.5	1.00 *1.05	0.20 ^g *0.15	10 ⁻⁸ to 10 ⁻⁶ * < 10 ⁻¹¹

496 Notes

497 ^a There was negligible difference between field-wet and saturated water contents at all sites

498 ^b Indicative ranges of mean values from 256-319 samples per site

499 ^c Indicative ranges of mean values from 123-196 samples per site

500 ^d The basal peat at Slieve Rushen was noticeably higher in organic matter than any other sampled peat

501 ^e Mean values from 20-26 samples per site

502 ^f The basal peat at Straduff Townland was noticeably higher (~1.10 Mg m⁻³) than any other sampled peat

503 ^g The peat at Slieve Anierin had higher dry bulk densities throughout its depth

504 ^h Indicative ranges of mean values from 19-26 samples per site, obtained using a 'constant head' method

505 ⁱ Results obtained using a 'falling head' method were consistently 10²-10³ m s⁻¹ higher than the respective 'constant
 506 head' values

507

508

509 The mean 'total fibre fraction' (Ft) of the lowest 0.7 m of the peat profile at each landslide Sampling Point,
 510 based on 70 depth-consecutive measurements per site, was 68% at ST, 71% at SR and 56% at SA. As Fig. 10
 511 shows, the latter appears to indicate a small but consistent difference from the other two, having slightly
 512 fewer coarse fibres throughout the sampled depth range. At all three sites there is a general trend of reducing
 513 coarse fibre content with depth but the fine fibre content seems to increase slightly towards the base of SR.

514

515

516 < FIGURE 9 >

517 **Figure 9.** 'Raw' percentage of light transmission at the Straduff Townland bogflow (ST).

518

519 < FIGURE 10 >

520 **Figure 10.** Depth variations of fibre contents throughout the lower half of the peat profile at each landslide: (A)
 521 Straduff Townland, (B) Slieve Rushen, (C) Slieve Anierin. Source: Foteu Madio (2013).

522

523

524 **4.3 Peat stratigraphy according to macrofossil results**

525 The blanket bog at the Sampling Point at each landslide mostly comprised the remains of monocotyledon
526 plants, particularly *E. vaginatum* (Fig. 11). Monocotyledon contents were lowest within the basal peat zones
527 (as defined by cluster analysis) and, at ST, immediately above the basal zone.

528

529

530 < FIGURE 11 >

531 **Figure 11.** Macrofossil content of the peat monolith from the three landslides: (a) ST, (b) SR, (c) SA. Parameter values
532 are raw counts for charcoal and *E. vaginatum* spindles, otherwise percentages. The figure shows the dendrogram
533 produced from unconstrained incremental sum square cluster analysis of strata analysed. Dashed lines separate clusters
534 corresponding to zones in the diagram. Source: Foteu Madio (2013).

535

536

537 **4.4 Comparing botanical and geotechnical characteristics**

538 The results were examined in order to identify any statistical associations (using Pearson's 'r' correlation
539 coefficient) between physical/geotechnical parameters, and then between geotechnical characteristics and
540 botanical results, that may have physical explanations potentially exploitable for predictive purposes. In this
541 study, only significant ($p < 0.05$) correlations with $|r| > 0.7$ at all three landslides were interpreted as possibly
542 indicating a causal relationship because the study was based on a single monolith per study site.

543 Furthermore, the full depth of the peat at each site was not analysed for most of the parameters investigated.

544 The only significant associations with $|r| > 0.7$ that were found between physical/geotechnical parameters at
545 all three sites were between: (i) the humus fraction, Fh, and the total fibre content, Ft (Fig. 12A); (ii) the total
546 fibre content, Ft, and the coarse fibre fraction, Rm (Fig. 12B); (iii) the humus fraction, Fh, and the coarse
547 fibre fraction, Rm; and (iv) the coarse fibre fraction, Rm – and therefore also the total fibre content and the
548 humus fraction – and the field water content (Fig. 12C).

549

550 Figs. 12D and 12E show the only consistently high correlations ($p < 0.05$) between macrofossil data and
551 physical/geotechnical properties of peat, i.e. between: (i) the total fibre content and the proportion of
552 monocot fragments; and (ii) the von Post degree of humification and the percentage of unidentified organic
553 matter. This may arise from the QLCMA method used for macrofossil analyses probably being more
554 appropriate for *Sphagnum* peat with small leaves that can be easily counted, compared with monocotyledon
555 peat with larger original plant fragments. The general lack of strong or consistent associations correlations
556 between the physical/geotechnical and botanical parameters at the three landslides suggests that these
557 physical properties cannot be used as indicators of peat mass structure and, thus, of potential peat instability.
558 However, the method used to quantify the fibre contents (Section 3.2.2, above) may be useful for
559 investigating relationships between the structural properties of failed Irish blanket peats in order to classify
560 peat for stability assessments.

561

562 The macrofossil analyses at the three landslides showed that the original plant assemblage was
563 predominantly monocotyledons, especially *Eriophorum vaginatum*. Therefore, the undrained strengths
564 obtained at the three landslides were plotted against the other properties (e.g. coarse fibre content in Fig.
565 12F) in order to investigate any possible relationship that may exist. The statistical analyses revealed no
566 significant correlation coefficients ($p < 0.05$).

567

568 Fig. 13 shows the thickness of a weak basal layer at each site identified by cluster analyses of the results (e.g.
569 Fig. 11). If all three landslides failed in a similar manner (i.e. by initial basal shearing), then it appears that
570 field observations of shear surfaces within a few tens of mm above the peat-mineral interface can be
571 explained in terms of formation of a failure zone (a) within the weakest layer of the peat profile, and (b) at
572 the lowest elevation within that weakest layer giving a continuous plane above the level of any large stones
573 or woody remnants that would resist shearing within the basal peat. The mean thickness of this layer based
574 on cluster analyses of the data (e.g. Fig. 11) is around 170 mm, but this is clearly overestimated because of
575 the lack of a clear depth-related trend in the quantitative humification results ('raw' % light transmission)
576 from Straduff Townland and is probably less than 140 mm in reality.

577

578

579 < FIGURE 12 >

580 **Figure 12.** Correlations between physical/geotechnical parameters and between botanical characteristics of the peat. (A)
581 Total fibre content vs. humus fraction. (B) Total fibre content vs. coarse fibre fraction. (C) Coarse fibre fraction vs. field
582 water content. (D) Monocot fragments vs. total fibre content. (E) Unidentified organic matter vs. von Post humification.
583 (F) Undrained shear strength (including 'field vane strength') vs. total fibre content. In (A) to (E), solid line = ST, long
584 dashed line = SR and the thin broken line = SA. After Foteu Madio (2013).

585

586

587 < FIGURE 13 >

588 **Figure 13.** Variation of mean thickness of basal peat depths according to specific physical properties at all three
589 landslides.

590

591

592 **5. Discussion**

593

594 The three sites investigated for this study were remarkably similar in terms of the characteristics of their
595 blanket peat. Slieve Anierin had a lower fraction of identifiable monocot fragments and a correspondingly
596 higher fraction of unidentified organic matter, but this may simply reflect greater decomposition of the same
597 plants rather than being evidence of different constituents. The smaller proportion of coarse fibres throughout
598 the peat at this site, and particularly towards the base, supports the interpretation of more advanced
599 decomposition. However, the higher dry bulk density and slightly higher saturated hydraulic conductivities
600 (Table 4) perhaps indicate a very slightly different composition. One tensile strength measurement at this site
601 was significantly out of line with the others (Fig. 8) due to a high density of woody remains within one test
602 sample, but the other measures of shear strength were entirely consistent with the other two sites. Therefore
603 we suggest that this site has essentially the same palaeoenvironmental history of peat accumulation as the
604 others. Furthermore, the similarity between these results and some obtained from other landslide sites
605 throughout northwestern and western Ireland and Northern Ireland (e.g. Kirk 2001; Yang and Dykes 2006;
606 Dykes 2008c; Dykes and Warburton 2008a; Dykes and Jennings 2011) and indeed eastern Ireland (e.g.

607 Boylan and Long 2010) strongly suggests that the general geotechnical characteristics of upland blanket peat
608 throughout the island of Ireland are very similar everywhere.

609

610 Much of the present vegetation of Ireland's blanket bogs is dominated by sedges (e.g. *E. vaginatum*),
611 heathers (*Ericaceae*, including *Calluna vulgaris*) and some *Sphagnum* and other mosses. These are all
612 represented in the analyses, with the sedges dominating the identifiable macrofossils (Fig. 10). In many
613 places there are the remains of trees at the base of the peat, which act like fragments of weathered bedrock to
614 resist movement of the peat over the in situ ground. However, at these three sites, separated by up to 20 km,
615 there is a weak basal layer around 150 mm thick that can be clearly distinguished from the peat above on the
616 basis of the properties measured for this study. Intriguingly, a higher proportion of the macrofossils can be
617 identified as monocot fragments in this layer, which somewhat contradicts the idea of greater decomposition.
618 On the other hand, fibre contents reduce sharply towards this basal layer (Fig. 10). O'Kelly (2017) suggested
619 that the properties of fibrous peat depend on the fibre content, but we suggest that these Irish blanket peats
620 cannot be considered to be 'fibrous' in the same sense, since even the acrotelm layer may contain relatively
621 few identifiable fibres. The issue is in any case unclear. Previous studies have found that higher fractions of
622 coarse fibres had no effect on measured strength compared with lower coarse fibre contents (Zhang and
623 O'Kelly 2014; Hendy et al. 2014); Price et al. (2005) found that fibre content was not related to
624 compressibility, and Lee et al. (2015) concluded that the effect of fibre orientation on frictional shearing
625 resistance was not clear. However, Boylan and Long (2010) undertook a quantitative analysis of fibre
626 contents adjacent to peat slides in Co. Wicklow and found lower fibre contents with depth. We therefore
627 conclude that the occurrence of failure in upland Irish blanket bogs must be at least in part due to the lower
628 fibre content, as well as higher overall degree of decomposition, towards the base of the peat.

629

630 We found some relationships between measured properties of the peat we analysed. The very strong
631 association ($|r| > 0.95$) between the humus fraction, coarse fibre fraction and total fibre content at the three
632 landslides mean that only one of these parameters may be needed to investigate other properties of peat. This
633 association can be explained by the fact that with increasing plant decomposition, the size and amount of
634 organic particles decrease, resulting in low fibre contents (Fig. 12A). When the fibre content decreases, the
635 water content also decreases (Fig. 12C) because the voids within the fibres, which contain the largest amount

636 of water (MacFarlane and Radforth 1968), also decrease. The coarse fibres influence peat structure and
637 possibly strength (see above) and may be used for stability assessments given that at all three sites they were
638 similarly abundant and showed high ($|r| > 0.9$) correlations with other properties. However, the apparent
639 uniformity of the peat across these sites precludes any suggestion that this may form the basis of a
640 generalised approach, in the absence of further studies from different peatlands (e.g. Northern England or
641 Scotland). Figs. 12D and 12E merely highlights the effect of humification in that if there are more fibres
642 remaining then there should also be more macrofossils that have not yet decomposed too far to be identified.
643 Fig. 12F shows that whichever method of strength determination is used (excluding the field vane), the
644 (shear) strength of the basal peat appears to be around 2 kPa. This is consistent with stability analyses of
645 landslides involving failure within the peat (i.e. bog slides, bogflows and some peat flows *sensu* Dykes and
646 Warburton 2007b) as reported by Dykes (2008c), Dykes and Jennings (2011) and Farrell (2012) and with test
647 results obtained from other similar studies in Ireland (e.g. Dykes 2008c; Dykes et al. 2008).

648

649 Two of the characteristics identified as being slightly different at Slieve Anierin, i.e. the monocot content and
650 the coarse fibre content, can be readily determined from small auger samples because they are quantified
651 with respect to the dry mass. A hand auger capable of cutting ‘intact’ core samples, notwithstanding issues of
652 sample deformation due to compression or fibres not being cut cleanly (Long and Boylan 2013; Hendy et al.
653 2014), could in principle provide samples for simple determination of dry bulk density and possibly saturated
654 hydraulic conductivity, i.e. the other two slightly distinctive characteristics. However, given that the
655 measured strengths at this site were no different from the others, we cannot say whether measurement of
656 those characteristics would be useful for peats formed from significantly different plant assemblages. It is not
657 possible to generalise any implications of our results for peatlands in general, and notwithstanding previous
658 comments we cannot assume that any of our correlations between botanical and geotechnical characteristics
659 will apply throughout Ireland. There is thus a clear necessity for comprehensive laboratory testing of peat
660 from the site of any proposed development, probably requiring excavation of trial pits for the extraction of
661 appropriate undisturbed samples. However, general recommendations for the most appropriate tests – and
662 testing procedures suitable for peat – will probably take some time to emerge from ongoing research
663 programmes.

664

665 Finally, the very low shear strength indicated above demands some consideration with respect to water
666 conditions within the peat. Blanket bogs in the British Isles may experience water table variations of up to
667 0.5–1.0 m, but these are occasional reductions below the surface during warm periods of summer weather
668 (Evans et al. 1999; Holden and Burt 2003). The usual condition for these deposits is to be fully saturated to
669 the surface, i.e. with normal effective stress ≈ 0 and maximum pore water pressure most of the time. Periods
670 of summer drying may increase the normal effective stress by a few kPa due to the reduced pore water
671 pressure, i.e. temporarily increasing the effective shear strength. Failure within the peat cannot, therefore, be
672 the result of raised pore water pressures throughout the peat matrix due to heavy rainfall (although it could
673 due to external loading). The hydraulic effects of water-filled pipes, cracks and other voids (e.g. Dykes, this
674 volume – in review) may play significant roles in the initiation of failure, i.e. peat mass effects, are thought
675 to be more important than simply the peat matrix (shear) strength, but much more research is needed to test
676 this hypothesis.

677

678 **6. Conclusions and Future Work**

679

680 The upland blanket bogs of northwestern Ireland appear to be formed from essentially the same assemblages
681 of plant species, dominated by sedges (mostly represented by *Eriophorum vaginatum*), and therefore having
682 similar physical and botanical characteristics. The data describing those characteristics show a statistically
683 distinct basal layer around 150 mm thick characterised by, in particular, a sharp reduction in the coarse – and
684 total – fibre content. Tensile strength, experimental low stress direct shear and unconsolidated undrained
685 triaxial compression measurements of peat strength converge on a value of around 2 kPa which is consistent
686 with stability back-analyses requiring undrained shear strengths of around 2 kPa for FS = 1.0. Contrary to
687 some published accounts, it appears that the lack of coarse fibres may be a contributory factor in the
688 incidence of peat slope failures. Some relationships between measured properties suggest that there may be
689 usable indicators of peat strength and stability conditions, possibly obtainable by means of samples from
690 hand augers, but the apparent uniformity of the peat at these three locations precludes any definitive proposal
691 of useful new methodologies at present.

692

693 It has been recognised for some time that the development of methods for reliably estimating the shear
694 strength of peat is likely to require some detailed investigations of botanical controls on relevant
695 geotechnical properties (e.g. Dykes 2008a). More recently, O’Kelly (2017, p.21) stated that: ‘More extensive
696 testing of peats with different botanical compositions is recommended to confirm relationships between
697 tensile strength, other strength parameters and humification level’. All of these issues are now starting to be
698 addressed more systematically by a few researchers in several countries. However, more extensive
699 integrative research is needed, perhaps involving palaeoecologists alongside geotechnical engineers, to
700 explore the causes and geotechnical effects of different peat accumulation scenarios. Detailed measurements
701 of all possible characteristics, such as presented in this study, are required for several known sites of peat
702 landslides in each of several different biogeographical zones such as Dartmoor (SW England), North
703 Pennines (N England), Isle of Skye (W Scotland), Shetland Islands (N Scotland), ideally including full depth
704 variations at each study location in order to generate sufficient data for reliable statistical analyses.

705

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707

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713

714 **References**

- 715 Aaby B and Tauber H (1974) Rates of peat formation in relation to degree of humification and local environment as
716 shown by studies of a raised bog in Denmark. *Boreas* (Oslo) 4(1), 1-18.
- 717 Andrejko MJ, Fiene F and Cohen AD (1983) Comparison of ashing techniques for determination of the inorganic
718 content of peats. In *Testing of Peats and Organic Soils* (Jarrett PM (ed)). ASTM Special Technical Publication, 820.
719 American Society for Testing and Materials, Philadelphia, pp.5-20.
- 720 ASTM (2008) D1997-91: Standard test method for laboratory determination of the fiber content of peat samples by dry
721 mass. American Society for Testing and Materials, Philadelphia.

- 722 Barber KE, Chambers FM, Maddy D, Stoneman R and Brew JS (1994) A sensitive high resolution record of late
723 Holocene climatic change from a raised bog in northern England. *The Holocene* 4, 198-205.
- 724 Blackford JJ and Chambers FM (1993) Determining the degree of peat decomposition for peat based palaeoclimatic
725 studies. *International Peat Journal* 5, 7-24.
- 726 Boylan N and Long M (2010) An investigation of two peat slope failures in the Wicklow mountains. *Biology and*
727 *Environment: Proceedings of the Royal Irish Academy* 110B (3), 173-184.
- 728 Carlsten P (1993) Peat - Geotechnical Properties and Up-to-Date Methods of Design and Construction. State-of-the-Art-
729 Report. Linköping: Swedish Geotechnical Institute.
- 730 Chambers FM, Barber KE, Maddy D and Brew JS (1997) A 5500-year proxy-climate and vegetation record from
731 blanket mire at Talla Moss, borders, Scotland. *The Holocene* 7, 391-399.
- 732 Charman DJ (2002) *Peatlands and Environmental Change*. Wiley, Chichester.
- 733 Crofton HT (1902) How Chat Moss broke out in 1526. *Transactions of the Lancashire and Cheshire Antiquarian*
734 *Society* **XX**, 139-144.
- 735 Daniels RE and Eddy A (1990) *Handbook of European Sphagna*. Institute of Terrestrial Ecology, Natural Environment
736 Research Council. HMSO, London.
- 737 Dykes AP (2008a) Properties of peat relating to instability of blanket bogs. In *Landslides and Engineered Slopes*,
738 Volume 1 (Chen ZY, Zhang J, Li Z, Wu A and Ho K (eds)). Taylor and Francis, London, UK, pp.339-345.
- 739 Dykes AP (2008b) Geomorphological maps of Irish peat landslides created using hand-held GPS. *Journal of Maps*
740 v2008, 258-276.
- 741 Dykes AP (2008c) Tensile strength of peat: laboratory measurement and role in Irish blanket bog failures. *Landslides*
742 5(4), 417-429.
- 743 Dykes AP (2009) Geomorphological maps of Irish peat landslides created using hand-held GPS - Second Edition.
744 *Journal of Maps* v2009, 179-185.
- 745 *Dykes AP (this issue? – still being revised) New insights from a recent peat slide at Croaghan, Co. Antrim, Northern*
746 *Ireland*.
- 747 Dykes AP and Jennings P (2011) Peat slope failures and other mass movements in western Ireland, August 2008.
748 *Quarterly Journal of Engineering Geology and Hydrogeology* 44(1), 5-16.
- 749 Dykes AP and Kirk KJ (2001) Initiation of a multiple peat slide on Cuilcagh Mountain, Northern Ireland. *Earth Surface*
750 *Processes and Landforms* 26, 395-408.
- 751 Dykes AP and Warburton J (2007a) Significance of geomorphological and subsurface drainage controls on failures of
752 peat-covered hillslopes triggered by extreme rainfall. *Earth Surface Processes and Landforms* 32, 1841-1862.

753 Dykes AP and Warburton J (2007b) Mass movements in peat: A formal classification scheme. *Geomorphology* 86(1-2),
754 73-93.

755 Dykes AP and Warburton J (2008a) Failure of peat-covered hillslopes at Dooncarton Mountain, Co. mayo, Ireland:
756 Analysis of topographic and geotechnical factors. *Catena* 72, 129-145.

757 Dykes AP and Warburton J (2008b) Characteristics of the Shetland Islands (UK) peat slides of 19 September 2003.
758 *Landslides* 5, 213-226.

759 Dykes AP, Gunn J and Convery (Née Kirk) KJ (2008) Landslides in blanket peat on Cuilcagh Mountain, northwest
760 Ireland. *Geomorphology* 102, 325-340.

761 Evans MG, Burt TP, Holden J, Adamson JK (1999) Runoff generation and water table fluctuations in blanket peat:
762 evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology* 221, 141-160.

763 Farrell ER (2012) Organics/peat soils. In *ICE Manual of Geotechnical Engineering: Volume 1, Geotechnical*
764 *Engineering Principles, Problematic Soils and Site Investigation* (Burland J, Chapman T, Skinner H and Brown M
765 (eds)). ICE Publishing, London, UK, pp.463-479.

766 Foteu Madio ES (2013) Botanical and geotechnical influences on peat instability. Unpublished PhD thesis, Kingston
767 University, UK.

768 Foteu Madio ES, Dykes AP, Waller MP, Hughes P and Grant MJ (2012) Botanical and geotechnical influences on peat
769 instability. In *Landslides and Engineered Slopes: Protecting Society through Improved Understanding* (Vol. 2)
770 (Eberhardt E, Froese C, Turner AK and Leroueil S (eds)). *Proceedings of the 11th International and 2nd North*
771 *American Symposium on Landslides and Engineered Slopes*. CRC Press, London, pp.421-427.

772 Gilman K, Newson MD (1980) *Soil Pipes and Pipeflow: a Hydrological Study in Upland Wales*, British
773 *Geomorphological Research Group Monograph 1*. Geobooks: Norwich.

774 Grosse-Brauckmann G (1972) Über pflanzliche Makrofossilien mitteleuropäischer Torfe - I. Gewebereste krautiger
775 Pflanzen und ihre Merkmale. *Telma*2, 19-55.

776 Hammond RF (1979) *The Peatlands of Ireland*. Survey Bulletin No. 35. An Foras Talúntais, Dublin

777 Hanrahan ET (1954) An investigation of some physical properties of peat. *Géotechnique* 4, 108-123.

778 Head KH (1994) *Manual of Soil Laboratory Testing, Permeability, Shear Strength and Compressibility Testing*.
779 Volume 2. Wiley, New York.

780 Helenelund KV (1967) Vane tests and tension tests on fibrous peat. *Proceedings of the Geotechnical Conference, Oslo*,
781 Vol. 1, 199-203.

782 Hendy MT, Barbour SL and Martin CD (2014) Evaluating the effect of fiber reinforcement on the anisotropic undrained
783 stiffness and strength of peat. *Journal of Geotechnical and Geoenvironmental Engineering*, published on-line at
784 doi:10.1061/(ASCE)GT.1943-5606.0001154.

785 Hobbs NB (1986) Mire morphology and the properties and behaviour of some British and foreign peats. Quarterly
786 Journal of Engineering Geology 19, 7-80.

787 Holden J, Burt TP (2003) Hydrological studies on blanket peat: the significance of the acrotelm–catotelm model.
788 Journal of Ecology 91: 103–113.

789 IUGS – International Union of Geological Sciences Working Group on Landslides (1995) A suggested method for
790 describing the rate of movement of landslides. Bulletin International Association of Engineering Geology 52, 75-78.

791 Jarrett PM (1983) Summary. In Testing of Peats and Organic Soils (Jarrett PM (ed)). ASTM Special Technical
792 Publication, 820. American Society for Testing and Materials, Philadelphia, pp.233-237.

793 Katz NJ, Katz SV and Skobeyeva EI (1977) Atlas of plant remains in peat soil. Nedra [In Russian].

794 Kirk KJ (2001) Instability of blanket bog slopes on Cuilcagh Mountain, N.W. Ireland. Unpublished PhD thesis.
795 University of Huddersfield, UK.

796 Klute A, Dirksen C (1986) Hydraulic conductivity and diffusivity: laboratory methods. Methods of Soil Analysis
797 Part 1. Physical and Mineralogical Methods. Agronomy Monograph (2nd edition), Vol. 9. Soil Science Society
798 of America, Madison, pp. 687– 734.

799 Landva AO and Pheeney PE (1980) Peat fabric and structure. Canadian Geotechnical Journal 17(3), 416-435.

800 Lee J-S, Seo S-Y and Lee C (2015) Geotechnical and geophysical characteristics of muskeg samples from Alberta,
801 Canada. Engineering Geology 195, 135-141.

802 Lindsay R, Bragg O (2005) Wind farms and blanket peat: a report on the Derrybrien bog slide (2nd edition). Derrybrien
803 Development Cooperative Ltd., Gort.

804 Long M (2005) Review of peat strength, peat characterisation and constitutive modelling of peat with reference to
805 landslides. Studia Geotechnica et Mechanica XXVII, 67-90.

806 Long M and Boylan N (2013) Predictions of settlement in peat soils. Quarterly Journal of Engineering Geology and
807 Hydrogeology 46, 303-322.

808 Long M and Jennings P (2006) Analysis of the peat slide at Pollatomish, County Mayo, Ireland. Landslides 3(1), 51-61.

809 MacFarlane IC and Radforth NW (1968) Structure as a basis of peat classification. National Research Council of
810 Canada (Ottawa). Reprinted from Proceedings, Third International Peat Congress held in Quebec, Canada, 18-23
811 August 1968, pp.91-97.

812 Mills AJ (2002) Peat slides: morphology, mechanisms and recovery. Unpubl. PhD thesis. University of Durham, UK.

813 Moore PD (1984) The classification of mires: An introduction. In European Mires (Moore PD (ed)). Academic Press,
814 London, pp.1-10.

815 O’Kelly BC (2014) Drying temperature and water content–strength correlations. Environmental Geotechnics 1 (EG2),
816 81-95.

817 O'Kelly BC (2017) Measurement, interpretation and recommended use of laboratory strength properties of fibrous peat.
818 Geotechnical Research, published on-line at <http://dx.doi.org/10.1680/jgere.17.00006>.

819 Price JS, Cagampan J and Kellner E (2005) Assessment of peat compressibility: is there an easy way? *Hydrological*
820 *Processes* 19, 3469-3475.

821 Skempton AW and Petley DN (1970) Ignition loss and other properties of peats and clays from Avonmouth, Kings
822 Lynn and Cranberry Moss. *Geotechnique* 20(4), 343-356.

823 Smith AJE (2004) *The moss flora of Britain and Ireland* (2nd edition). Cambridge University Press, Cambridge.

824 Troels-Smith J (1955) Karakterisering af lose jordarter (Characterisation of unconsolidated sediments). *Denmarks*
825 *Geologiske Undersogelse* 4(3), 1-73.

826 von Post L (1922) Sveriges geologiska undersoknings torvinventering och nagre av dess hittills vunna resultat, sr.
827 mosskulturfor. *Tidskr* 1, 1-27.

828 Walker D and Walker PM (1961) Stratigraphic evidence of regeneration in some Irish bogs. *Journal of Ecology* 49,
829 169-185.

830 Warburton J, Higgitt D and Mills A (2003) Anatomy of a Pennine peat slide, northern England. *Earth Surface Processes*
831 *and Landforms* 28(5), 457-473.

832 Warburton J, Holden J and Mills AJ (2004) Hydrological controls of superficial mass movements in peat. *Earth-Science*
833 *Reviews* 67(1-2), 139-156.

834 Yang J and Dykes AP (2006) The liquid limit of peat and its application to the understanding of Irish blanket bog
835 failures. *Landslides* 3(3), 205-216.

836 Zhang L and O'Kelly BC 2014 The principle of effective stress and triaxial compression testing of peat. *Geotechnical*
837 *Engineering* 167, 40-50.

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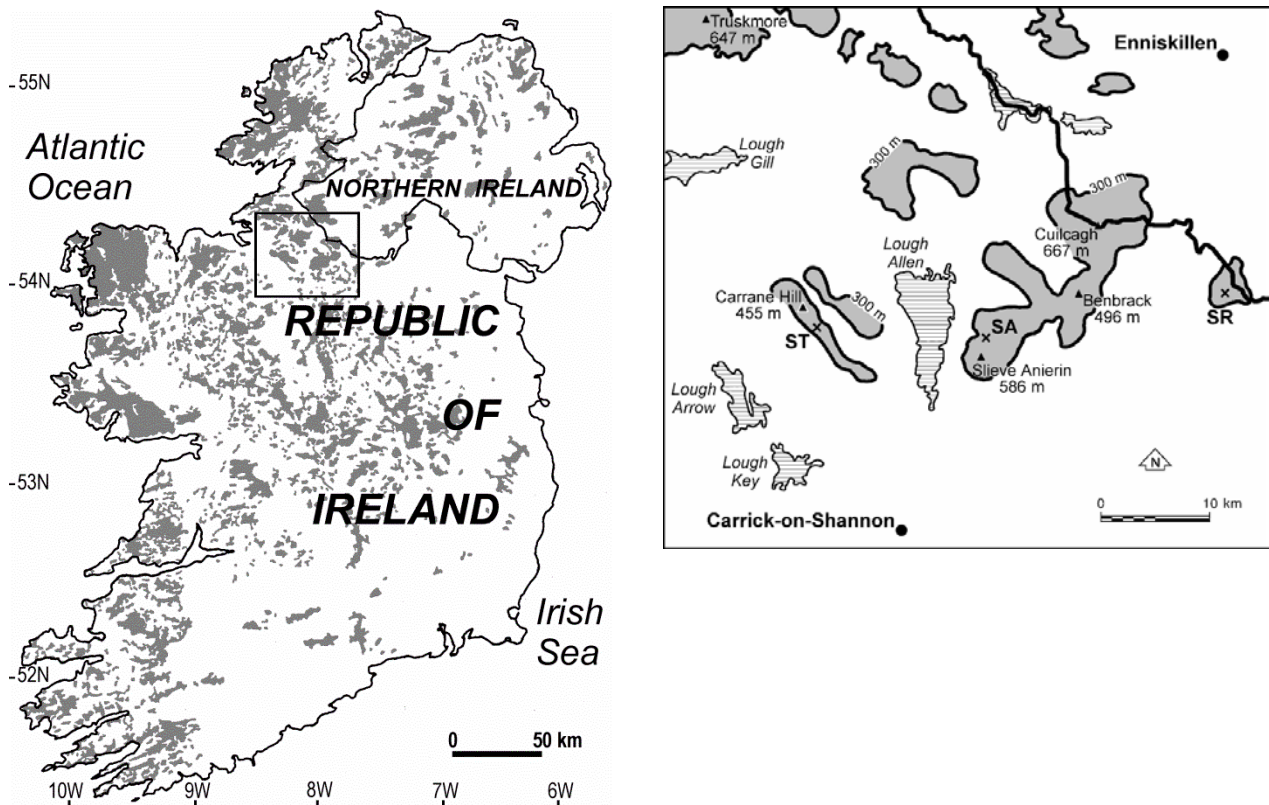
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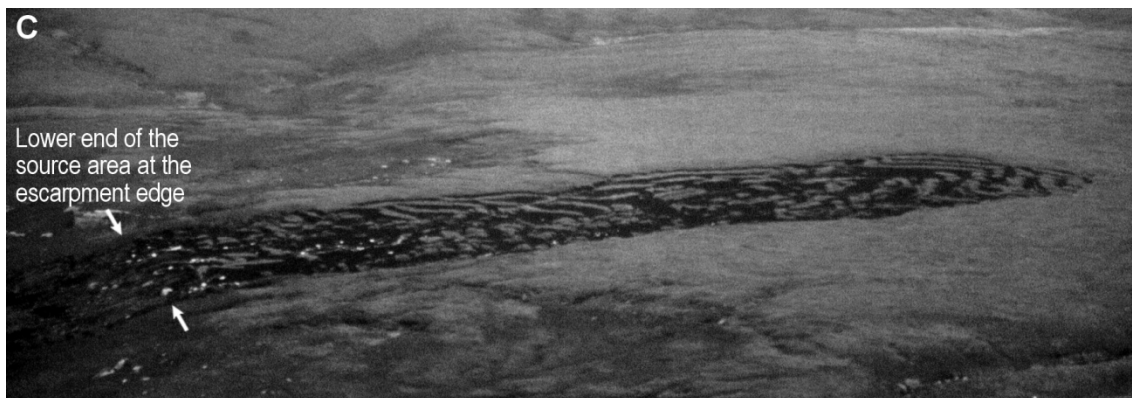
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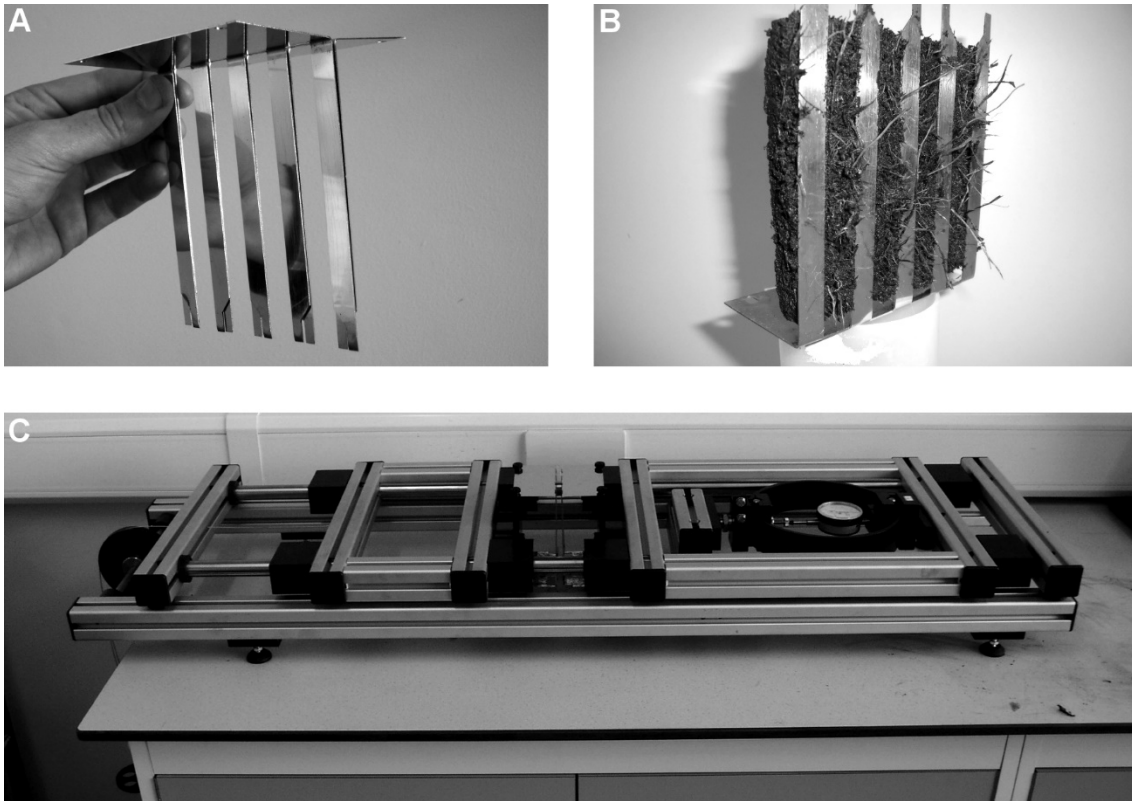
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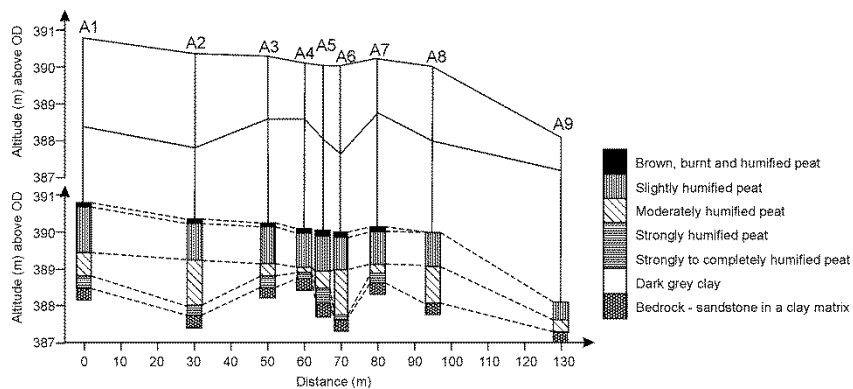
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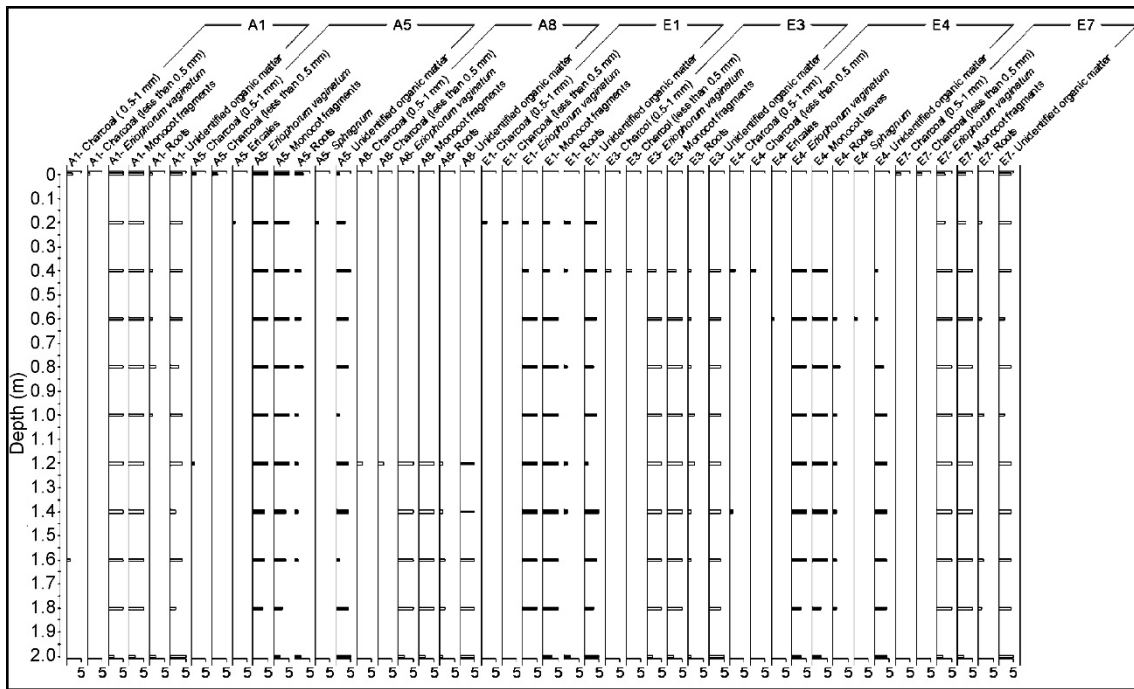
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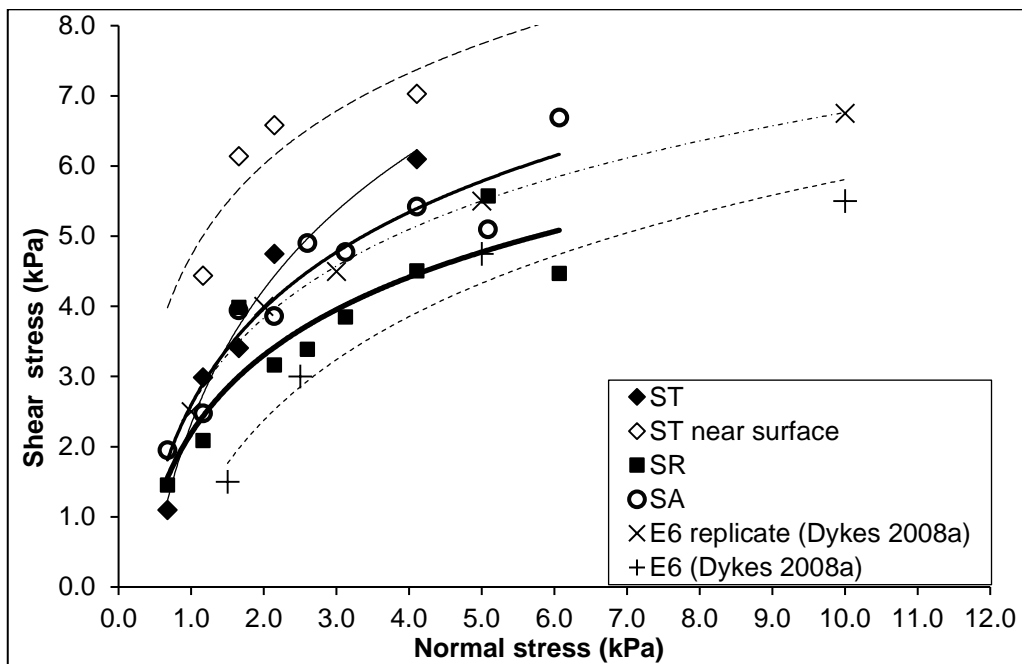
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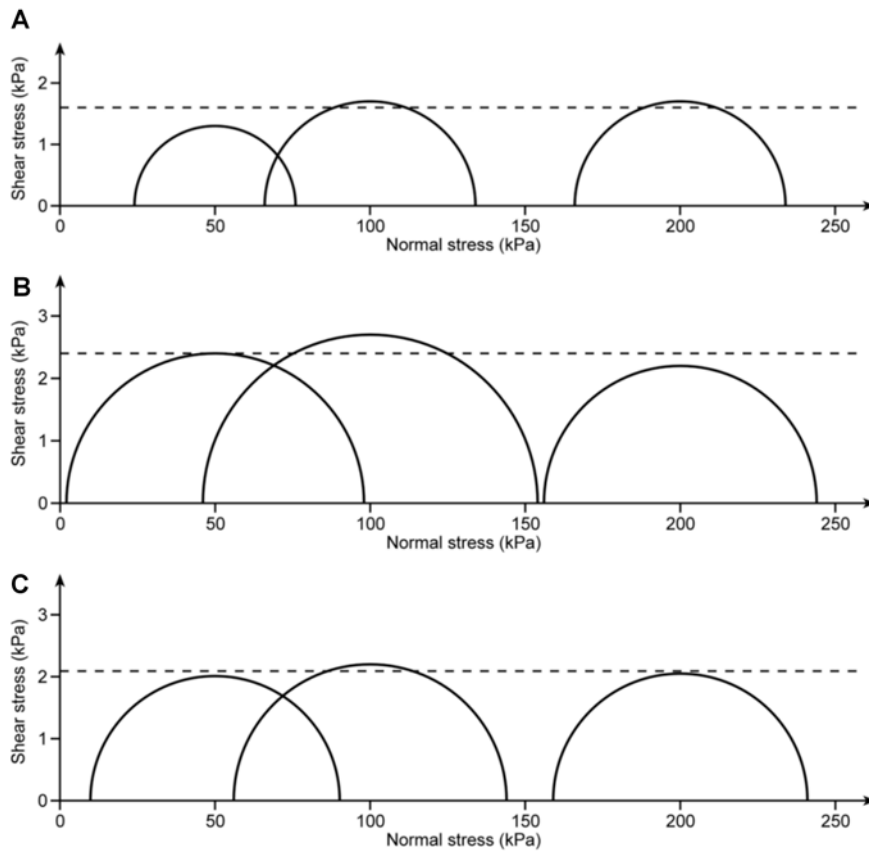
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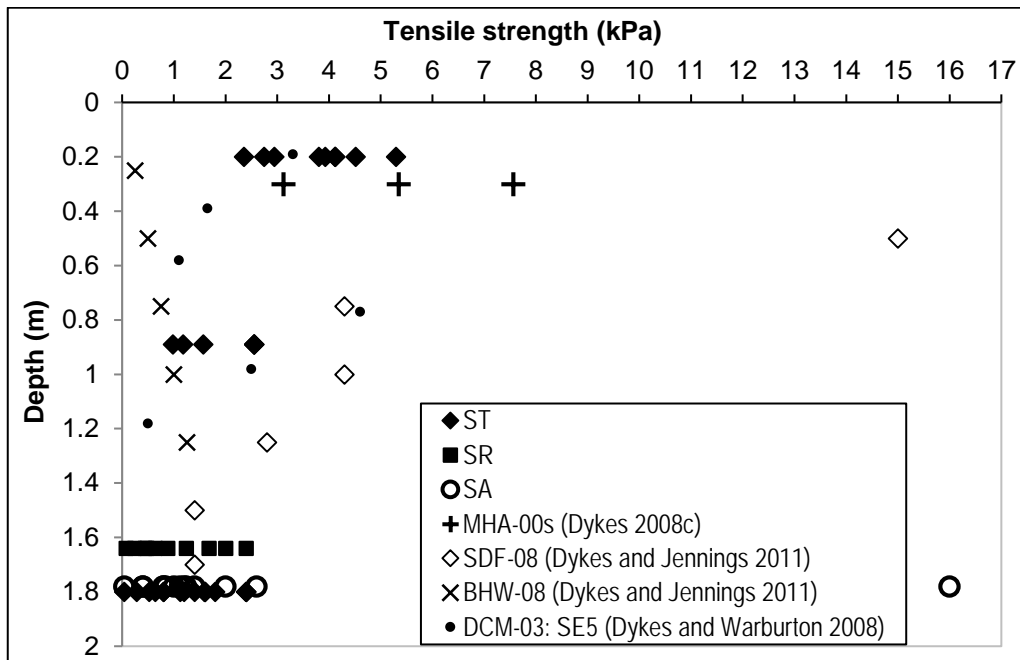
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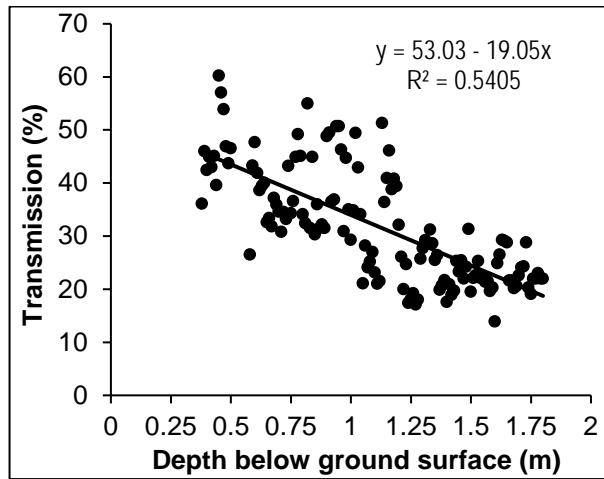
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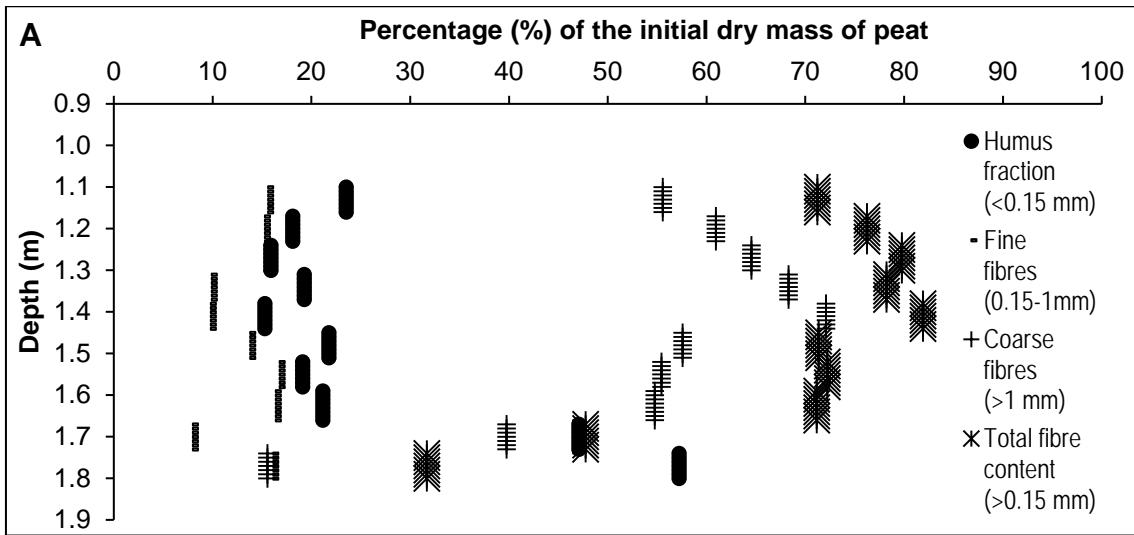
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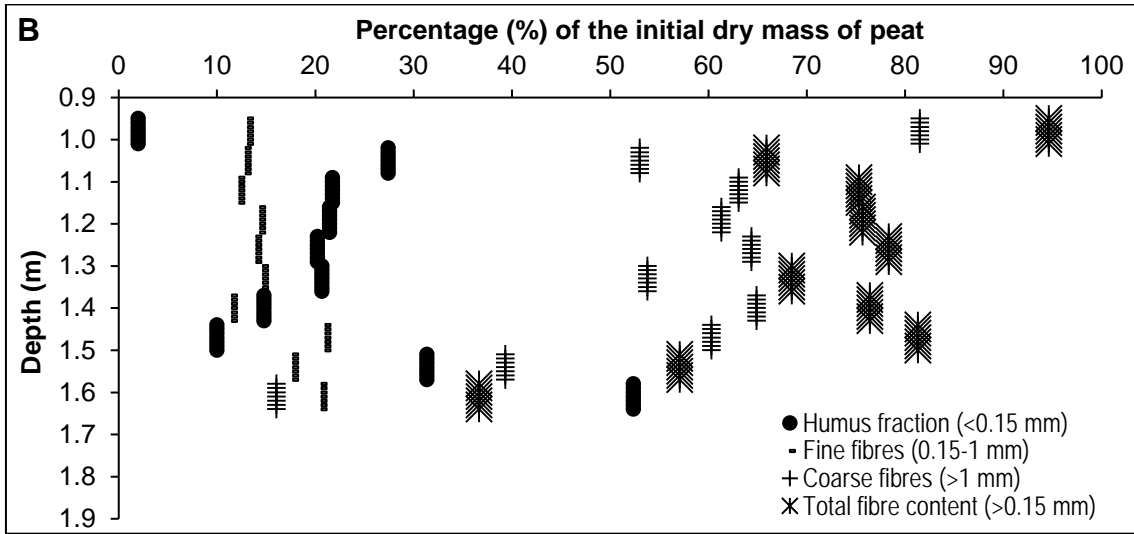
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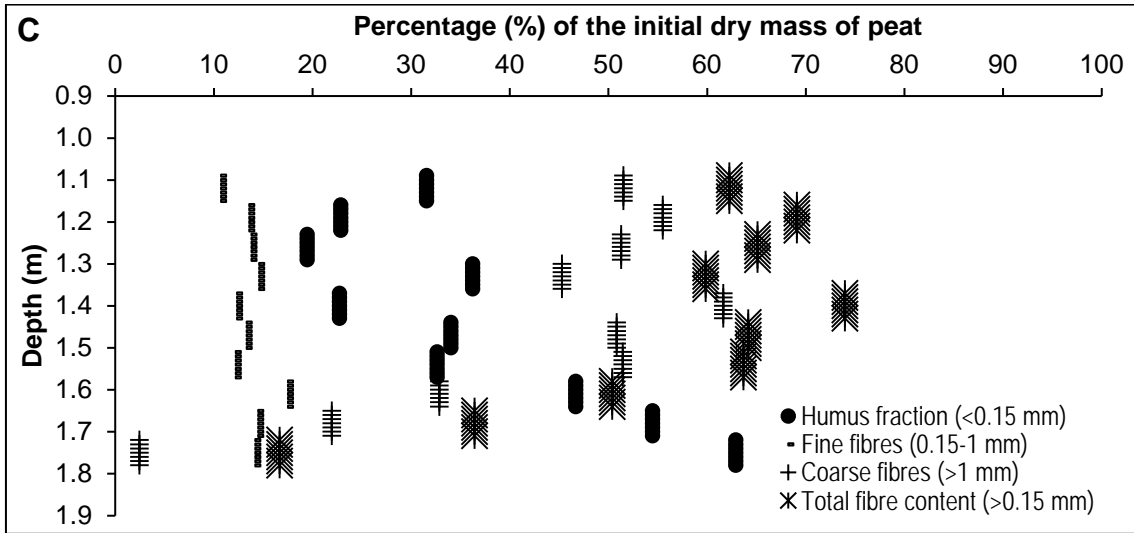
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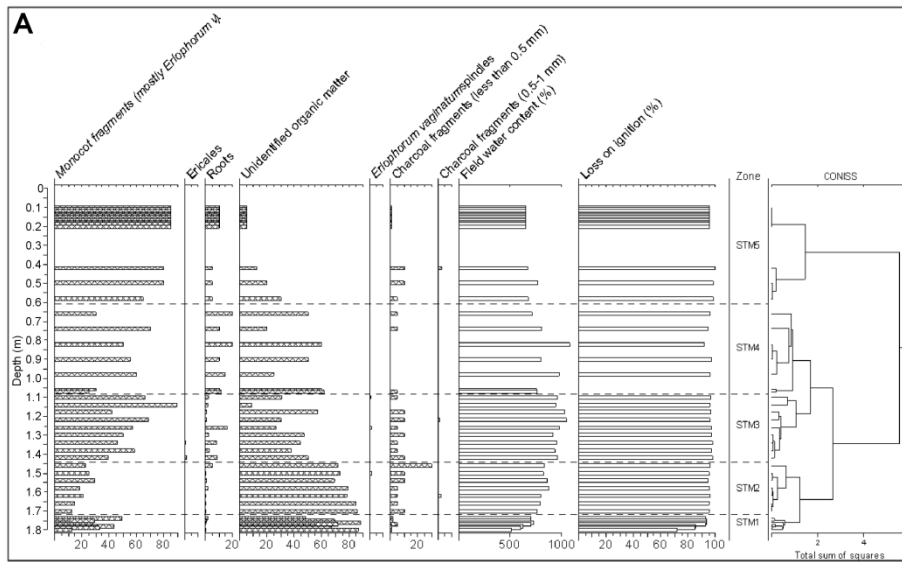
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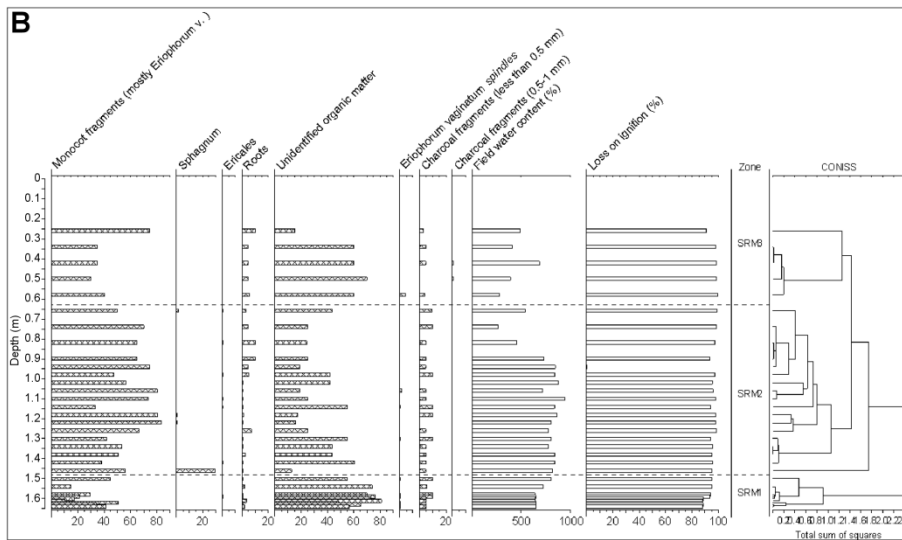
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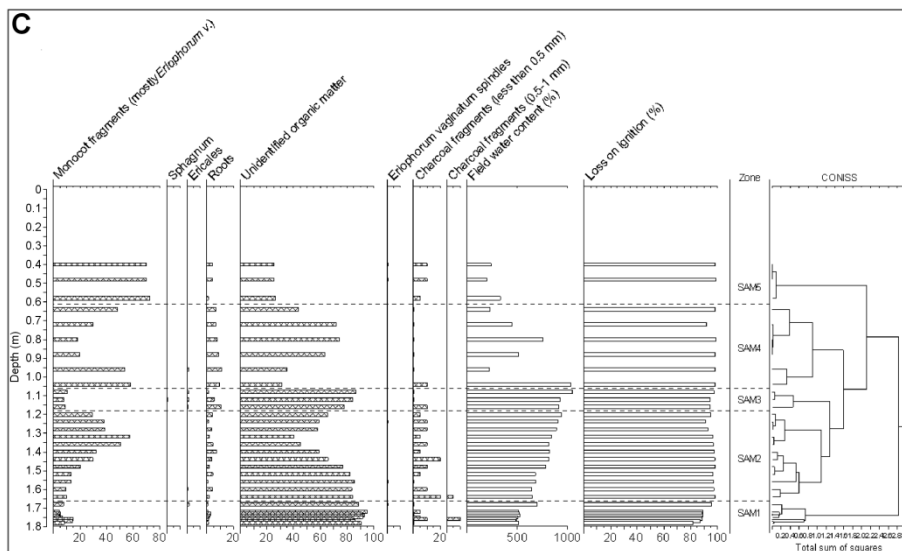
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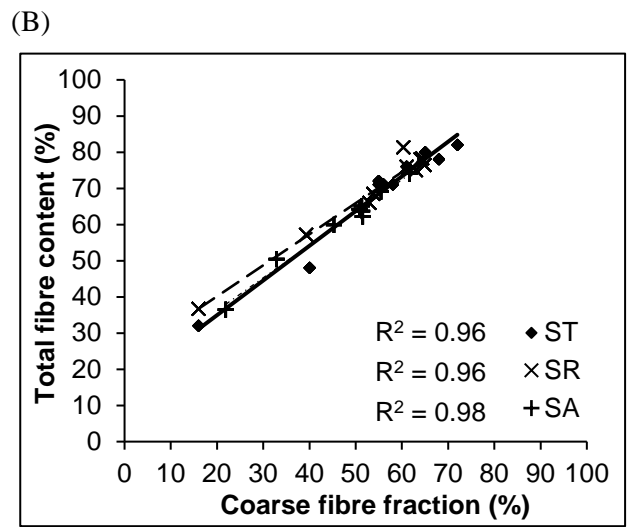
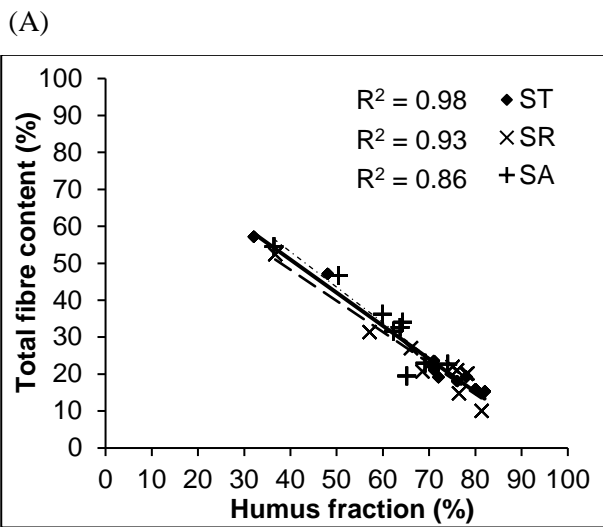
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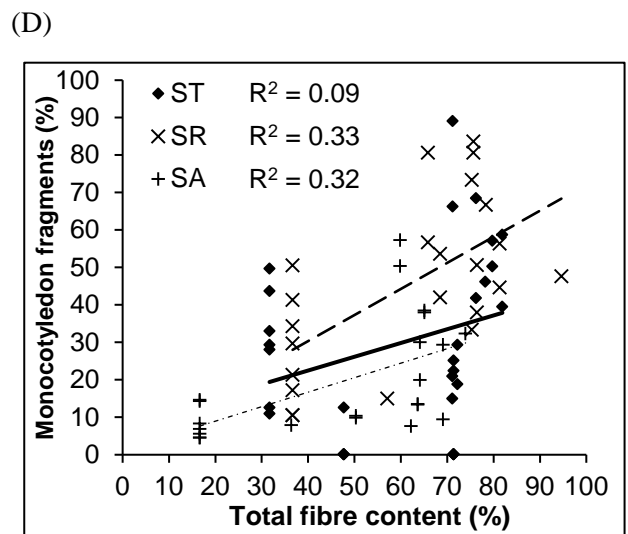
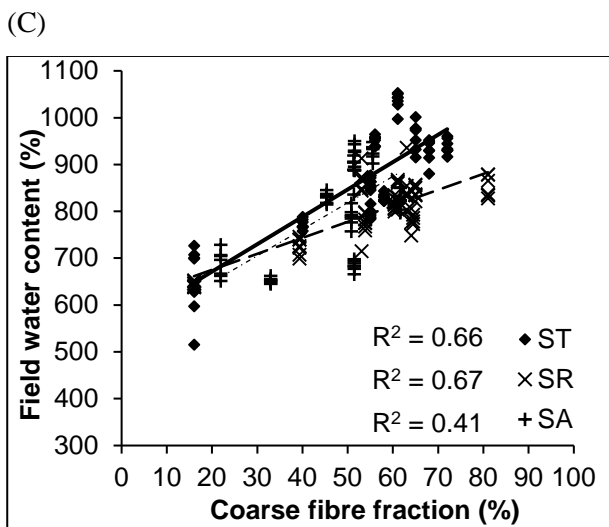
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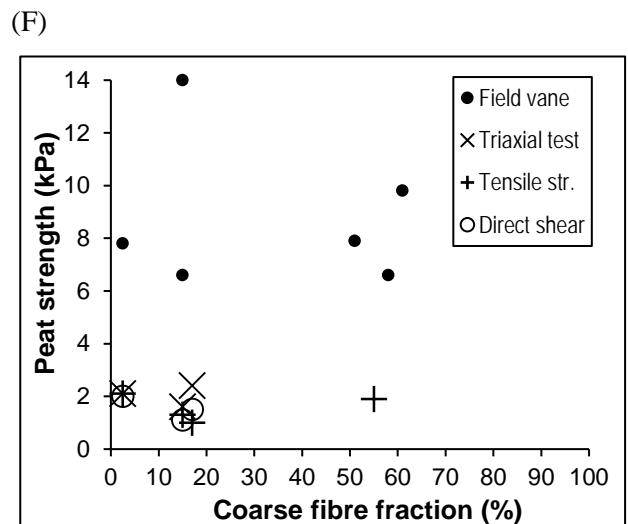
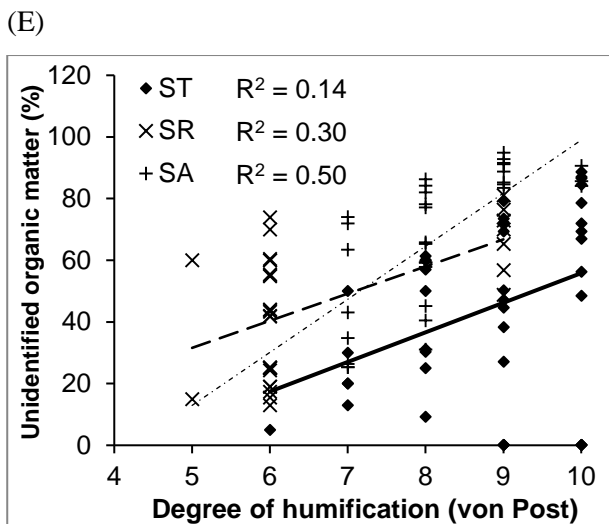
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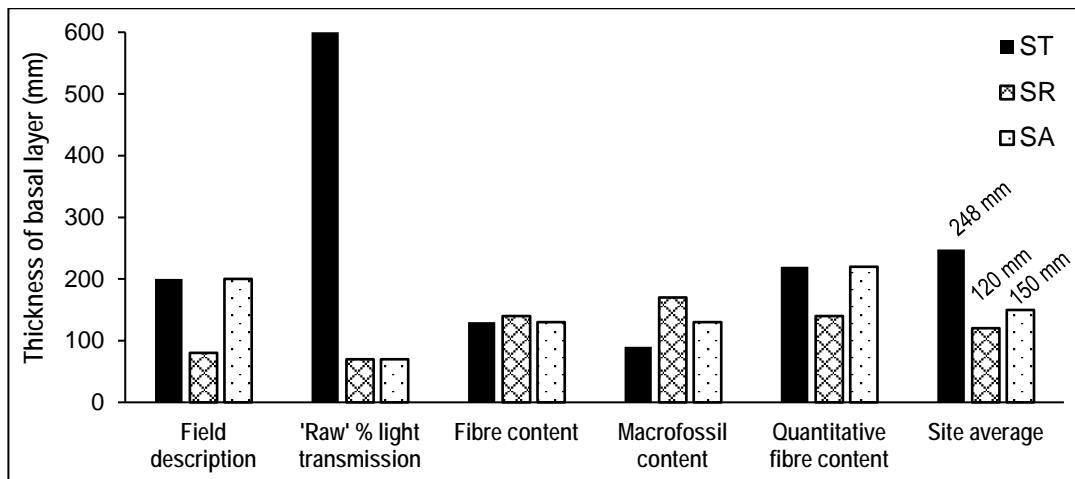
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