

This is a repository copy of *Microform-scale variations in peatland permeability and their ecohydrological implications*.

White Rose Research Online URL for this paper: <u>https://eprints.whiterose.ac.uk/92977/</u>

Version: Accepted Version

#### Article:

Baird, AJ orcid.org/0000-0001-8198-3229, Milner, AM, Blundell, A et al. (2 more authors) (2016) Microform-scale variations in peatland permeability and their ecohydrological implications. Journal of Ecology, 104 (2). pp. 531-544. ISSN 0022-0477

https://doi.org/10.1111/1365-2745.12530

#### Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

#### Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk https://eprints.whiterose.ac.uk/

1	Microform-scale variations in peatland permeability and their ecohydrological implications
2	
3	Andy J. Baird <sup>1</sup> *, Alice M. Milner <sup>2</sup> , Antony Blundell <sup>1</sup> , Graeme T. Swindles <sup>1</sup> , and Paul J. Morris <sup>1</sup>
4	
5	<sup>1</sup> School of Geography, University of Leeds, Leeds, LS2 9JT, United Kingdom
6	<sup>2</sup> Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX,
7	United Kingdom
8	
9	*Correspondence author. E-mail: a.j.baird@leeds.ac.uk
10	
11	Running headline: Fine-scale lateral variation in peatland permeability
12	
13	
14	Supporting information: Appendices S1-S5
15	
16	

#### 17 Summary

1. The acrotelm-catotelm model of peatland hydrological and biogeochemical processes posits that 18 the permeability of raised bogs is largely homogenous laterally but varies strongly with depth 19 20 through the soil profile; uppermost peat layers are highly permeable while deeper layers are, effectively, impermeable. 21 22 2. We measured down-core changes in peat permeability, plant macrofossil assemblages, dry bulk 23 density and degree of humification beneath two types of characteristic peatland microform – ridges and hollows – at a raised bog in Wales. Six <sup>14</sup>C dates were also collected for one hollow and an 24 25 adjacent ridge. 26 **3.** Contrary to the acrotelm-catotelm model, we found that deeper peat can be as highly permeable as near-surface peat and that its permeability can vary by more than an order of magnitude between 27 microforms over horizontal distances of 1-5 metres. 28 4. Our palaeo-ecological data paint a complicated picture of microform persistence. Some 29 microforms can remain in the same position on a bog for millennia, growing vertically upwards as 30 31 the bog grows. However, adjacent areas on the bog (< 10 m distant) show switches between 32 microform type over time, indicating a lack of persistence. 5. Synthesis. We suggest that the acrotelm-catotelm model should be used cautiously; spatial 33 34 variations in peatland permeability do not fit the simple patterns suggested by the model. To understand how peatlands as a whole function both hydrologically and ecologically it is necessary 35 to understand how patterns of peat physical properties and peatland vegetation develop and persist. 36 37 Key-words: acrotelm-catotelm model, ecological memory, microform, peatland, permeability, 38 39 persistence, plant-soil (below-ground) interactions, raised bog. 40

#### 42 Introduction

#### 43 Problem statement and research questions

Raised bogs occur commonly in the tropics and at latitudes greater than 45°, especially in the 44 Northern Hemisphere (Ingram 1983; Winston 1994). They are an important global carbon (C) store, 45 and there is interest in how they function as ecosystems and in how they will be affected by climate 46 change; as the climate warms, will they degrade and release their stored C back to the atmosphere, 47 thereby re-enforcing current warming, or will they show some degree of resilience (Swindles et al. 48 2012)? To answer such questions it is necessary to understand how these peatlands behave as 49 ecological and hydrological entities. Conceptually, raised bogs are often divided into two distinct 50 functional layers: (i) an upper acrotelm (literally 'topmost marsh' – see Ingram (1978)) which is the 51 52 zone in which most water moves and in which biogeochemical processes are most active; and (ii) a lower, poorly-permeable, and usually thicker catotelm in which water flow is slow or negligible and 53 where biogeochemical processes occur at much lower rates (Ingram 1978). While raised bogs 54 55 undoubtedly show strong vertical variations in peat properties and process rates (e.g. Morris, Baird & Belyea 2015), the usefulness of the simple acrotelm-catotelm dichotomy has been questioned. 56 Morris et al. (2011), for example, noted that the model makes the inflexible assumption that a range 57 of biogeochemical and hydrological processes vary in the same binary way with depth. In addition, 58 despite some empirical support for the model, there are quite substantial gaps in our understanding 59 60 of its applicability. In this paper, we address three questions relating to the model: (i) is so-called 'catotelm' peat poorly-permeable as assumed by the model?, 61 (ii) does the permeability of this deeper peat vary laterally between microforms?, and 62 63 (iii) how are spatial patterns in permeability related to microform persistence and explained by ecological memory? 64

65 Below, we provide a rationale for our focus on these questions.

#### 67 Background and rationale

Ingram (1978) credited Ivanov (1953) with being the first to propose the concepts of acrotelm and 68 catotelm, although Ivanov (1953, 1981) himself suggested the binary model was established by 69 70 others before him. Despite emphasising the importance of vertical variations in peat properties, 71 Ivanov (1981) also recognised that peatlands can exhibit distinct lateral variability. Horizontal 72 patterning of peatland microforms (sometimes known as microhabitats or Scale Level 1 features -73 see Baird, Belyea & Morris (2009)) is seen on many raised bogs. For example, in mid- and highlatitude raised bogs, arrays of hummocks, lawns, and hollows (sensu Belyea & Clymo 2001) are 74 75 common. Hummocks may be c. 0.05-0.6 m higher than adjacent hollows and lawns. They are typically 1-3 m in diameter, while the intervening lawns and hollows are often larger, although 76 there is considerable variation in size. These microforms have characteristic plant assemblages. 77 Hummocks tend to be dominated by ericaceous shrubs such as *Calluna vulgaris* (see Appendix S1 78 in Supporting Information for botanical authorities and common English names) and *Rhododendron* 79 groenlandicum, sedges such as Eriophorum vaginatum, and small-leaved Sphagna such as 80 81 Sphagnum fuscum and Sphagnum capillifolium. Lawns and hollows have a cover of larger-leaved Sphagna such as Sphagnum papillosum, Sphagnum pulchrum, and Sphagnum cuspidatum, with 82 sedges such as Rhynchospora alba often co-dominant. (The species listed here may be found in 83 84 peatlands in northwest Europe and parts of northeast USA and southeast Canada, and are examples only.) Because peat is the decomposing remains of plants, variations in the composition of the 85 vegetation growing on a bog can be expected to produce variations in peat type; as a bog grows, 86 different types of peat will build up under different types of vegetation. 87

Lateral variations in the peat under different vegetation types have been described using both direct observation and non-invasive geophysical methods. For example, in a palaeo-ecological study of a raised bog in northern England, Barber (1981) showed how hummocks and intervening lawns and hollows may persist over millenia as a peatland grows. He also suggested that lawns and hollows expand laterally during wet climatic phases and shrink during drier phases (when

Page | 4

hummocks expand), a suggestion made previously by Aaby (1976). Barber (1981) studied peat 93 faces produced by peat cutters from which lateral variations in peat type could be directly recorded 94 and sampled. More recently, Kettridge et al. (2008) used ground-penetrating radar (GPR) and 95 96 complex electrical conductivity surveys complemented by hand coring to reveal horizontal zonation 97 in peat geophysical properties to depths of c. 3 m along a 36-m transect in a raised bog in Maine in 98 the USA. The observations made by Barber (1981) and Kettridge et al. (2008) may easily be 99 verified by walking across a patterned bog: peat under hummocks is often firmer and safer to walk 100 on than peat in lawns and hollows. However, such variations in structural strength may not necessarily translate into differences in hydrological properties such as water-storage capacity (e.g. 101 102 specific yield or drainable porosity, s) and permeability or hydraulic conductivity (K).

Despite the recognition of lateral variability between microforms on bogs and an interest in 103 how spatial patterns form (see below), there is little information on how hydrological properties 104 vary between microforms. Some work has been done on poor fens (sensu Rydin & Jeglum 2006) 105 which have similar types of vegetation to bogs. For example, in an undrained area of poor fen in 106 107 Quebec, Canada, Whittington & Price (2006) found strong lateral variability in K of one-two orders of magnitude over distances of a few metres between a ridge (an elongated hummock or series of 108 contiguous hummocks), a lawn and a 'mat', the latter a type of hollow. They also found that K 109 110 declined by two to three orders of magnitude between depths of 0.25 and 1.25 m in these microforms, which is broadly what would be expected from the acrotelm-catotelm model. 111 Therefore, lateral variability appears to be superimposed onto vertical variability. Whittington & 112 Price's (2006) data are useful in showing that lateral variability can be substantial, but they only 113 measured K at one location in one example of each microform, so their study lacked spatial 114 115 replication. Ivanov (1981) reproduced empirical functions in which K at the same depth below the surface may vary by more than two orders of magnitude depending on microform type. However, it 116 is not clear what data sets lie behind his functions (the number of measurements and sites from 117 118 which the data behind the functions come are not listed) and they deal with shallow peat only

(upper ~ 0.4 m of peat profile). The latter issue – that of water flow in shallow vs deeper peat – is 119 particularly pertinent, because, although he stressed the importance of lateral variation, Ivanov 120 (1981) still considered shallow peat to be the main route for water flow, a key assumption of the 121 122 acrotelm-catotelm model. There is abundant evidence that uppermost layers of bogs can be highly permeable (e.g. Boelter 1965; Hoag & Price 1995; Morris, Baird & Belyea 2015), but the situation 123 124 with deeper peat is less clear. Some of the low K values reported for deeper peat may, in part, be measurement and sampling artefacts (see discussions in Koerselman (1989) and Baird, Surridge & 125 Money (2004)). Where robust measurement protocols have been used there is evidence that deeper 126 peat, on some sites at least, can be relatively permeable (e.g. Baird, Eades & Surridge 2008) and it 127 128 is important that more work is done on estimating the K of deeper peat. Where permeable deeper peat is found, its effect on overall water flow through a bog will depend on whether it occurs in 129 pockets isolated by poorly-permeable peat or whether it is connected to other higher-permeability 130 zones (Belyea & Baird 2006). In other words, it is important to know both the absolute value of K 131 and its spatial pattern – vertically and laterally – when considering the hydrological behaviour of 132 133 bogs. The hydrological functioning of a peatland, often expressed in terms of the water-table regime, is closely linked with its ecological functioning (e.g. Belyea & Baird 2006; Roulet et al. 134 2007; Frolking et al. 2010; Morris, Baird & Belyea 2012), and anything that influences the 135 behaviour of the water table will also affect key ecological processes such as litter production, 136 vegetation composition, and depth-integrated rates of peat decay (e.g. Belyea & Clymo 2001). 137 A group of theoretical studies (Swanson & Grigal 1988; Couwenberg & Joosten 2006; 138 Eppinga et al. 2009; Morris, Baird & Belyea 2013) used cellular landscape models to investigate 139 the linkages between the hydrological and ecological functioning of peatlands, in particular how 140 141 these linkages can lead to the development of hummock-hollow patterns. These models assume that the hydraulic properties of peat under different microforms are also different – they assume there is 142 lateral variability – but also that most water flow occurs in the uppermost layers of a bog. Morris, 143 144 Baird & Belyea (2013) showed that these models, despite considering horizontal variability, likely

lack some important ecohydrological feedbacks and may produce realistic patterns for the wrong 145 reasons. Specifically, Morris, Baird & Belyea (2013) raised the question of whether microforms 146 such as hummocks and hollows can be considered as features only of shallow peat, or whether their 147 148 structural and hydrological importance at both the scale of the microform and the whole bog extends into deeper peat. They proposed a hypothetical mechanism for ecological memory (sensu 149 150 Hendy & McGlade 1995) in peatlands whereby former surface vegetation patterns can leave a 3-151 dimensional imprint in the hydraulic structure of peat even after they are buried by litter from more recent plant assemblages. In a bog that possesses strong ecological memory of the type proposed by 152 Morris, Baird & Belyea (2013), differences in peat properties (e.g. K) that characterise particular 153 154 microform types would be evident not only near the surface in upper peat but also in deeper peat. Where a particular microform type had persisted for a long time, continued accretion would form a 155 3-dimensional pillar or curtain (sensu Belyea & Baird 2006) of peat that could be distinguished 156 from adjacent peat produced by different microform types. In a bog with no ecological memory, 157 deeper peat would be laterally homogenous in terms of the property of interest; i.e., even if 158 159 microforms persisted in place for long periods, characteristic differences in the peat property of interest would only be identifiable in surficial layers and would not be preserved in deeper peat. A 160 situation in which characteristic differences between microform types persist to a limited depth, or 161 perhaps diminish gradually with depth, might be thought of as a weak ecological memory. It is clear 162 that, to understand the patterning of peat hydrophysical properties in bogs, we must first understand 163 how microforms develop and persist, and how peat properties change through time. 164

165

#### 166 Materials and Methods

To address the first and second research questions on the magnitude and lateral variability of K in deeper peat, we measured K at two depths in two types of microform – ridges and hollows – in a Welsh raised bog. Measurements of the abundance of a range of plant macrofossils in cores of peat extracted from the bog were used to reconstruct the developmental history of the different 171 microforms used for the *K* measurements, thus providing data for answering the third research

172 question. The plant macrofossil and *K* data were complemented with measurements of peat dry bulk

density, degree of humification and age (from calibrated <sup>14</sup>C dates). Our combination of

174 palaeoecological techniques and detailed measurements of hydrological properties is perhaps an

unusual one, but serves as a powerful and novel tool for understanding ecohydrological memory inpeatlands.

177

#### 178 *Field site and sampling rationale*

The site chosen for study – Cors Fochno in west Wales – has been described in detail in Baird, 179 Eades & Surridge (2008) and Kettridge et al. (2012). Its margins have been disturbed or damaged 180 by drainage and peat cutting, but its central area is undamaged and contains maze-like and 181 sometimes striped patterns of ridges, hummocks, lawns, and hollows that are typical of many raised 182 bogs and northern peatlands more generally (see Eppinga et al. 2009). Four microforms in this 183 central area were investigated: a ridge-hollow-ridge-hollow sequence at 52° 30' 10.0" N and 4° 00' 184 45.5" W. These features coincided with the first c. 10 m of the northern end of a 45-m transect used 185 by Kettridge et al. (2012) for a GPR survey of the peat, and are, for convenience, named Ridge 1, 186 Hollow 1, Ridge 2, and Hollow 2 (Fig. 1). Ridge vegetation comprised mostly Calluna vulgaris, 187 Eriophorum vaginatum, and Sphagnum capillifolium, with some Eriophorum angustifolium and 188 189 Myrica gale. Hollow vegetation was dominated by Sphagnum pulchrum, Rhynchospora alba, Eriophorum angustifolium, with occasional Erica tetralix and Myrica gale plants (see Appendix 190 S1). The ground surface in the ridges was typically 0.05-0.10 m above that in the hollows (as 191 192 measured using an optical level – data not reported). The location of the ridges and their position relative to the transect line used by Kettridge et al. (2012) is shown in Fig. 1. 193 We devised and conducted the study before the GPR data reported in Kettridge et al. (2012) 194

were analysed. GPR reflections from their survey tend to dip, and appear to indicate that

196 microforms at the site have migrated in one direction over time. However, the data obtained by

Kettridge et al. (2012) do not present a consistent picture. Dip angle decreases at depths of 1 m and 197 less, suggesting that microform movement has slowed in the most recent period of bog development 198 (last c. 1300 years according to data cited by Kettridge et al. (2012)). There are also sections along 199 200 the 45-m transect (see Fig. 6c in Kettridge et al. (2012)) where the reflectors are flat, which suggests that some areas remain stable – their microforms do not move – while other areas, only a 201 few metres away, are dynamic. Finally, for a 2.1-m section of the transect (27.4 m - 29.5 m) for 202 203 which the GPR reflectors were dipping, detailed core analysis (eight cores at 0.30-m intervals) did not reveal any obvious dipping structures (Kettridge et al. 2012). As such it is unclear whether the 204 microforms along our transect have been stationary or mobile through time. This issue relates 205 206 directly to our third research question and we were able to determine if microforms had moved over time using our plant macrofossil and peat age data (see *Peat core collection and analysis* below). 207

208

#### 209 *Hydraulic conductivity* (K)

To address the first and second research questions, K was measured in the four microforms using 210 211 standpipe piezometers inserted into pre-augered holes. In each microform, five measurements were made at a nominal depth of 0.5 m and five at 0.9 m. These depths were chosen because they are 212 below both the typical and the drought-year summer water table, and, therefore, represent what 213 would usually be classified as the catotelm in the two-layer model (Ivanov 1981; Ingram 1983). 214 Unpublished data from the site show that maximum water-table depths do not exceed 0.25-0.30 m 215 in hollows and 0.40 m in ridges during summer drought. Separate locations were used for 216 measuring K at the two depths. That is, we did not measure K at 0.5 m and then deepen the hole and 217 measure K at 0.9 m; rather, we used separate holes, and these were at least 1 m distant from 218 219 neighbouring holes. Therefore, we used a total of 40 locations for the K measurements. In this way we avoided a problem of repeated measures; each of our measurements could be regarded as 220 independent at the scale of the microform. 221

Piezometer installation and K measurements followed the protocols presented by Baird, 222 Surridge & Money (2004), Surridge, Baird & Heathwaite (2005), and Kelly et al. (2014). We used 223 the same piezometer tubes as Surridge, Baird & Heathwaite (2005). These have an outside diameter 224 225 (OD) of 0.033 m, an inside diameter (ID) of 0.029 m and 0.21 m long intakes. The centre of the intake was placed at each nominal depth -0.5 m and 0.9 m. 226 227 Following installation, the piezometers were 'developed' or cleaned (Butler 1998; Baird, Surridge & Money 2004) to remove any smeared peat from around the intake. After development, a 228 self-logging pressure transducer and a slug consisting of an acrylic rod were placed below the water 229 level in each instrument. The water level was then allowed to stabilise before a head-recovery test 230 231 was conducted by removing the slug. The removal of the slug caused the water level to fall by c. 0.04 m, and the subsequent rise in water level was recorded by the pressure transducer. Two types 232 of pressure transducer were used – Mini-Diver and Micro-Diver units manufactured by 233 Schlumberger Water Services (Delft, The Netherlands) – each with a resolution or precision of 234 0.002 m. A logging interval of 2 s was used for piezometers installed in the most permeable peat, 235 236 while 4 s was used for slower-responding instruments. The shortest tests were completed within a few seconds; the longest took more than 12 hours (see below). 237

238 *K* was estimated from Hvorslev's (1951) equation:

239 
$$K = -\frac{A}{Ft} \ln\left(\frac{h}{h_0}\right)$$
(1),

/

where *A* is the inside cross-sectional area of the piezometer standpipe  $(m^2)$ , *t* is the time (s) at which the head difference, *h* (m) (see below), in the piezometer was recorded, *h*<sub>0</sub> is the initial head difference, and *F* is the shape factor (m) which is a function of the size and shape of the piezometer intake and the pattern of water flow around it (see Brand & Premchitt 1982). The head difference, *h*, is defined as the difference between the water level in the piezometer at any time during a headrecovery test and the water level prior to the withdrawal of the slug. *h*<sub>0</sub> is the difference at the moment the slug has been removed from the piezometer. Strictly, equation (1) should only be applied to rigid media; peats are compressible and *K* tests in them may not yield the log-linear recovery of the equation. However, it has been shown (Baird & Gaffney 1994) that reliable estimates of *K* in peats may be obtained using the equation if the head ratio ( $h/h_0$ ) is close to zero; here, a value of  $h/h_0 = 0.05$  and its associated time ( $t_{95}$ ) were used.

252 In some tests, the rate of water flow from the piezometer was so rapid that an initial head difference could not be satisfactorily established. For these tests, it was assumed that  $t_{95}$  was 2 s. In 253 the 0.5-m tests carried out on Ridge 1, recovery was slow and coincided with a period of falling 254 heads in the peat around the piezometer intakes, making it difficult to estimate  $t_{95}$ . An example is 255 256 given in Fig. 2 which shows an apparent stalling of the head recovery. In these cases we assumed  $t_{95}$ occurred at the turning point as shown by the arrow in the figure. This assumption will always give 257 a value of  $t_{95}$  that is too low, and therefore a value of K that is too high, compared to what would be 258 the case if background heads around the intake remained stable. Ideally, a period of stable heads 259 would have been used for the 0.5-m tests in Ridge 1. However, because recovery was so slow, it 260 would have been very difficult to find a time when heads remained stable for 12-24 hours; in most 261 bogs, heads often vary over such timescales due to gravitational water flow through the peat or 262 evaporative losses of water. Our assumed  $t_{95}$  values were, in any case, conservative because all of 263 264 the 0.5-m K estimates from Ridge 1 were lower than the lowest K recorded in any other feature at either depth. 265

Hydraulic conductivity reflects both the properties of the porous medium and the liquid flowing through it. As the viscosity of water changes with temperature so too does the hydraulic conductivity. Our pressure transducers also measured temperature and we were able to use the temperature data to convert our *K* values (as per Klute (1965)) to a standard temperature of 20°C.

#### 271 *Peat core collection and analysis*

To reconstruct the developmental history of the microforms and to establish microform persistence 272 (third research question), cores from each of the features were analysed for plant macrofossil 273 274 remains, peat humification, and dry bulk density. In total, five cores were taken from each microform and each was 2 m in length. Three cores were taken from the centre of the microform 275 276 (close to the intersection of the microform's long and short axes), each core being within 0.3 m of its two neighbours. One of these was analysed for peat decomposition or humification, one for dry 277 bulk density  $(\rho_b)$ , and one for plant macrofossils. Two additional 'humification cores', one from the 278 western end and one from the eastern end of each feature (see Fig. 1) were also analysed. Plant 279 fragments from the upper metre from two of the cores that were used for the macrofossil analysis -280 the cores from Ridge 2 and Hollow 2 – were <sup>14</sup>C dated (dates calibrated using IntCal09 – see 281 below), and six dates from three depths in each core were obtained. All of the cores were taken with 282 a Russian corer, with a semi-circular chamber with a diameter of 0.038 m. 283

Peat humification, an indicator of the degree of decomposition, was estimated visually from fresh peat in the field. The color and texture of the peat in the core were used to define peat layers, and each layer was classified using the von Post humification scale from H1 (completely undecomposed) to H10 (completely decomposed) (see Rydin & Jeglum 2006). The humification estimates were conducted by the same person (A.M.M.) for all cores, and the von Post descriptions given in Rydin & Jeglum (2006, p. 86) were used as a constant reference to ensure consistency in classification.

In the bulk density cores, samples were taken, where possible, from 0-0.02 m, 0.10-0.12 m, 0.20-0.22 m and so on below the surface. Poor recovery in parts of the cores meant that not all the required depths could be sampled. Seventeen samples were recovered from Hollow 1, six from Hollow 2, 18 from Ridge 1 and 19 from Ridge 2. The samples were placed in foil sachets in the field and then wrapped in clingfilm for later analysis. They were stored in a cold room below 4 °C upon return to the laboratory. After removal from storage, they were dried at 80 °C for 24 hours

#### Page | 12

before being cooled in a desiccator and weighed. The samples were not ashed, so the values of  $\rho_b$ that were calculated were not corrected for the presence of any non-organic material.

Each of the four macrofossil cores was divided into bulked samples for each 0.1-m depth 299 interval. Thus, samples represented depths of 0-0.1 m, 0.1-0.2 m and so on, with each sample 300 having a volume of c.  $5.7 \times 10^{-5}$  m<sup>3</sup> depending on core recovery. It is unusual to use bulked cores 301 like this for plant macrofossil analysis. More typically, samples that span a 0.01-m depth range are 302 analysed. Sometimes these are contiguous, but, because they are time-consuming to analyse, they 303 are often spaced at intervals of 0.02-0.08 m (Amesbury, Barber & Hughes 2010). The problem with 304 the latter is that critical information may be lost. For example, there may have been a switch 305 306 between vegetation types in the un-analysed zone between two 0.01-m samples; in effect, the record is incomplete, even though the information from a 0.01-m layer can be ascribed accurately to a 307 particular depth and date. There is inevitably some loss of information and resolution with our 308 309 method, but it guarantees that all plant types present within a 0.1-m length of core are recorded, including their abundance, making it possible to establish if there have been switches between 310 311 vegetation types during the time period represented by the 0.1 m.

Each macrofossil sample (i.e., the entire  $5.7 \times 10^{-5}$  m<sup>3</sup>) was prepared for examination using 312 standard techniques as detailed by Barber et al. (1994). Macrofossil examination followed the 313 Quadrat and Leaf Count Method (Barber et al. 1994) but with some modifications as described 314 below. Before examination, each prepared sample was mixed thoroughly and emptied into a large-315 diameter (0.15 m) Petri dish. A low-powered microscope fitted with a  $10 \times 10$  square grid (quadrat) 316 in the eyepiece allowed percentage coverage of different macrofossil components to be estimated. 317 318 When possible, 100 Sphagnum leaves were picked from the sample, mounted on slides, examined at  $\times$  100-400 magnification and identified to species or at least section level. Differentiation between 319 monocotyledon remains was also achieved when suitable epidermal tissue was found (Mauquoy, 320 Hughes & van Geel 2010). Five quadrat estimations were completed for each sample. Seeds, 321 322 ericaceous leaves and charcoal were counted separately.

323	We obtained six accelerator mass spectrometry (AMS) $^{14}$ C dates of the peat in the study
324	area, three from Hollow 2 and three from Ridge 2 (Fig. 1). Plant fragments for dating were obtained
325	from depths of 0.2-0.3 m, 0.5-0.6 m, and 0.9-1.0 m from the two cores used for the plant
326	macrofossil analysis (see above). The mixed samples of peat from the 0.1-m intervals (see above)
327	were washed with deionised water in a 125 $\mu$ m sieve, and, in order to minimise potential
328	contamination, Sphagnum leaves, branches, and stems were used for the dating, except for the 0.9-
329	1.0 m interval in Ridge 2 where we used Racomitrium lanuginosum leaves and stems. Care was
330	taken to remove ericaceous roots to prevent any possible reservoir effects as described by Kilian,
331	van der Plicht & van Geel (1995). The plant fragments were dated at the <sup>14</sup> CHRONO Centre at
332	Queen's University, Belfast (an acid-alkali-acid pre-treatment was used). The <sup>14</sup> C dates were
333	calibrated using IntCal09 (Reimer et al. 2009).
334	

#### 335 Data analysis

Except for those piezometers noted earlier where an initial head difference could not be established 336 or where recovery stalled, we estimated  $t_{95}$  as the first reading where  $h/h_0 \le 0.05$ . We conducted 337 repeat K tests on some piezometers to help gauge within-instrument test variability and these 338 showed similar consistency to previous studies (see Appendix S2 in Supporting Information). As 339 well as differences in K between microform type (ridge, hollow) and depth, we were interested in 340 341 all comparisons across the K data set to see whether differences between, say, ridges and hollows 342 depends on which ridge and which hollow are being considered. We used a Bayesian multiple pair wise comparison developed by Kruschke (2011; chapter 18) that allows for non-homogenous 343 344 variance between groups, a group being, for example, all the readings at 0.5 m in Hollow 1. We undertook the analysis on the log<sub>e</sub> transformed data. In the Bayesian analysis, the data as a whole 345 (combined from all groups) are standardised to have a mean of zero and a standard deviation of 1. 346 347 The model describing the standardised data is given by:

348

$$u_i = \beta_0 + \sum_j \beta_j x_{ji} \tag{2}$$

Page | 14

where  $u_i$  is the mean of the distribution of individual values  $(y_i)$ ,  $\beta_0$  is a baseline value of  $u_i$ , while  $\beta_i$ 349 is the deflection from  $\beta_0$  for group *j*. *x* may take values of 0 or 1.  $\beta_0$  is described by a normal 350 distribution with a mean of zero and a precision of 0.001 (variance of 1000).  $\beta_i$  is also described by 351 a normal distribution, which has a mean of zero and a precision specified by a folded t distribution 352 353 with a mean of zero, a precision of 0.001 and a k or shape setting of 2. These priors for the models of both  $\beta_0$  and  $\beta_i$  are highly non-committal and have a very small influence on the posterior (or 354 outcome) of the Bayesian analysis. To account for unequal variance between groups, the precision 355 of the distribution of  $y_i$  is estimated separately for each group from a gamma distribution (see 356 Kruschke 2011). 357

The Bayesian method was applied using the data and multiple random sampling from the 358 data models as specified with the non-committal priors. Sampling was performed using a Markov 359 Chain Monte Carlo (MCMC) process (Kruschke 2011) with a sample size of 100 000 after a 'burn-360 in' of 5000 steps. The pair-wise analysis was carried out using R and JAGS (R Core Team 2012) 361 and the code and its source are given in Appendix S3. The MCMC analysis yields distributions of 362 differences in  $\beta_i$  for each pair of groups. In these distributions we may define a highest density 363 interval or HDI in which 95% of the difference values lie. If the HDI does not include zero we may 364 conclude that there is a credible difference in *K* between the groups. 365

To assess whether there is evidence of the persistence of each of the microforms over the 366 period of time represented by the 2 m peat cores, we applied cluster analysis with multiple bootstrap 367 resampling to the plant macrofossil biostratigraphic data. This analysis enables the calculation of p-368 values to identify statistically significant clusters (Suzuki & Shimodaira 2006) and was used to 369 determine the similarity-dissimilarity of samples between the hollow and ridge cores. We also 370 undertook nonmetric multidimensional scaling (NMDS; Minchin 1987) using the Bray-Curtis 371 dissimilarity index to examine the main axes of variation in the plant macrofossil data. The Bray-372 Curtis dissimilarity index is a popular and effective index for ecological data and is defined as: 373

374 
$$d^{BCD}(i,j) = \frac{\sum_{k=0}^{n-1} |y_{i,k} - y_{j,k}|}{\sum_{k=0}^{n-1} (y_{i,k} - y_{j,k})}$$
(3)

where  $d^{BCD}$  is the Bray-Curtis dissimilarity between the objects *i* and *j*, *k* is the index of a variable 375 and *n* is the total number of variables *y* (e.g. Legendre & Legendre 1998). The stress was analysed 376 in several runs to ensure a robust result was achieved. Ordination 'spiders' were used to demarcate 377 378 the four microforms and assess similarity/dissimilarity. The analysis was carried out using the vegan package (v. 2.0-5) in R (v. 2.15.1) (Oksanen et al. 2012; R Core Team 2012). 379 380 It is common in plant macrofossil analysis to include Ericaceae as a class and we followed this convention when compiling our data (see **Results**; *Macrofossils*, *humification and bulk* 381 382 density). However, Ericaceae was left out of the cluster and NMDS analysis because its main 383 components - Calluna vulgaris and Erica tetralix - may, between them, occupy a range of wetness 384 conditions from hollow to ridge. Calluna vulgaris is usually a reliable dry or ridge indicator. However, although *Erica tetralix* is often used by palaeoecologists as a dry indicator (e.g. Mauquoy 385 386 et al. 2008), it is more flood-tolerant than Calluna vulgaris (e.g. Bannister 1964) and, unlike the latter, may be common in wet conditions such as the fringe of bog pools (Elkington et al. 2001). 387 Rare taxa (with maximum values of 4% or less) were also excluded from the NMDS analysis. 388

Age-depth models for Ridge 2 and Hollow 2 were constructed using the 'Bacon' piece-wise 389 390 linear accumulation model of Blaauw & Christen (2011) in R (R Core Team, 2012). In this model, 391 the accumulation rate of sections depends to a degree on that of neighbouring sections, accumulation rates are constrained by a prior distribution (a gamma distribution with parameters 392 acc.mean and acc.shape), as is the variability in accumulation rate between neighbouring depths 393 ('memory', a beta distribution with parameters mem.mean and mem.strength). In our analysis, 0.05 394 m-thick sections were used along with acc.shape = 2 and acc.mean =  $13 \text{ yr cm}^{-1}$ . The prior 395 information was combined with the radiocarbon dates and a 2011 date for the peat surface using 396 millions of MCMC iterations (Blaauw & Christen 2011). The total chronological error (difference 397

between maximum and minimum probability ages at 95 %) associated with each depth was

calculated from the model. Ages for the 0.1 m-thick dating samples were defined using the Baconmodel and expressed in histograms (see Appendix S4).

401

#### 402 **Results**

#### 403 *Hydraulic conductivity*

The hydraulic conductivity (K) data are summarised in Fig. 3, with the data separated according to 404 microform and depth. The data show that K varies by nearly four orders of magnitude across the 405 site. The highest K values were more than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values were were less than  $1 \times 10^{-3}$  m s<sup>-1</sup> while the lowest values 406  $10^{-6}$  m s<sup>-1</sup>, equivalent, respectively, to the K of a coarse sand and that of a silt (Domenico & 407 408 Schwartz 1990). The data also suggest that there are differences in *K* between microforms. For depths of 0.5 m, hollow K appears to be significantly higher than ridge K, with nine of the 10 409 hollow values exceeding the highest value from the ridges. Four of the 10 hollow values exceed the 410 411 highest ridge value by at least an order of magnitude and two of the 10 exceed the highest ridge value by a factor of c. 250. At a depth of 0.9 m, the differences between features are less clear. All 412 of the values from Hollow 1 exceed all of the values from Ridges 1 and 2. However, there is an 413 overlap between the values from Hollow 2 and both ridges. The data also suggest that there are 414 differences in the K values between microforms of the same type and the same depth. For example, 415 416 at 0.5 m depth, all of the K values from Ridge 2 are higher than those from Ridge 1. Similarly, all of the K values at a depth of 0.9 m in Hollow 1 are higher than the values at the same depth in Hollow 417 2. 418

The results from the Bayesian analysis are summarised in Table 1 and given in more detail in Appendix S3. Table 1 identifies those categories in which the highest density interval (HDI) of between-group differences in the deflections –  $\beta_j$  – does not include zero; as noted above (see **Materials and Methods**; *Data analysis*) this may be thought of as indicating a credible difference between a pair of groups based on the data that have been collected. In terms of between-groupdifferences, the most interesting features from the Bayesian analysis are as follows.

<u>Depths of 0.5 m</u>. Ridge 1 is credibly different from all other groups at this depth (Ridge 2,
and Hollows 1 and 2). Ridge 2 also differs from Hollows 1 and 2; therefore, despite the difference
between Ridge 1 and Ridge 2, there is credible evidence that the ridges at 0.5 m are different from
the hollows at the same depth.

429 <u>Depths of 0.9 m</u>. Hollow 1 is credibly different from both ridges at this depth. Hollow 2,
430 however, is not credibly different from either ridge. These results contrast with those from 0.5 m

431 where ridges and hollows show clear differences; at 0.9 m there is no such pattern in the data.

432 Notably, Ridges 1 and 2 show no credible difference at this depth, unlike at 0.5 m.

The pairwise comparisons also suggest that there is a credible difference between depths in Ridge 1, but not in the other three microforms, although in Hollow 2 the HDI in the contrast between 0.5 m and 0.9 m only just straddles zero (Table 1), so there is some suggestion of a real difference in *K* values between depths. In Ridge 1 the 0.5-m or younger peat has a lower *K* than the deeper peat, while in Hollow 2 the opposite is the case.

438

#### 439 *Peat age-depth profiles*

Radiocarbon dates of the extracted plant fragments from Hollow 2 and Ridge 2 are given in Table 2.
The age-depth models that were derived from the data are given in Appendix S4. Age-depth curves
for each feature are given in Fig. 4. These show different trajectories for each feature. For 1 m in
Ridge 2 the modelled age is 1520-1330 cal. BP (mean = 1390 cal. BP) whereas for 1 m in Hollow 2
the modelled age is 1315-1080 cal. BP (mean = 1180 cal. BP).

The peat accumulation rates for Ridge 2 and Hollow 2 show variations. For Ridge 2 the accumulation rate was higher in the lower part of the core and decreased towards the top of the core  $(c. 0.11 \text{ cm yr}^{-1} \text{ from } 0.57\text{-}1.00 \text{ m} \text{ depth}, \text{ compared with } 0.05 \text{ cm yr}^{-1} \text{ from } 0.00\text{-}0.57 \text{ m} \text{ depth}).$  For Hollow 2, the accumulation rates were more mixed, with lower and less variable rates in the lower part of the core (*c*. 0.07 cm yr<sup>-1</sup> from 0.57-1.00 m) and higher and more variable rates in the upper
part. The maximum and minimum accumulation rates were similar, with maxima of 0.14 and 0.15
cm yr<sup>-1</sup> for Ridge 2 and Hollow 2, respectively, and a minimum of 0.05 cm yr<sup>-1</sup> for both features.
These interpretations are somewhat tentative due to the relatively low number of radiocarbon dates.

454 Macrofossils, humification and bulk density

The macrofossil, humification and dry bulk density data for the three separate cores taken from the centre of each microform are shown in Figs 5a and 5b. The data from the additional humification cores (two per microform) are available in Appendix S5.

The four microforms differ in their peat profiles in terms of degree of decomposition, macrofossil composition and abundance, and dry bulk density. Taxa indicative of surface wetness (water tables close to the surface) are more abundant in the two hollow cores (Fig. 5a) than in the two ridge cores (Fig. 5b), and *vice versa*. For example, ridge cores are notably characterised by *Sphagnum austinii*, while hollow cores are dominated by *Sphagnum* section Cuspidata, *Rhynchospora alba* and *Sphagnum papillosum* with occasional abundance of monocotyledons and *Menyanthes trifoliata*. However, 'wetter' taxa are evident, and sometimes common, in the ridge

465 cores and drier taxa in the hollow cores.

Our analysis revealed a number of statistically significant clusters (p < 0.05) (Fig. 6), and 466 shows, generally, that the ridges and hollows are strongly differentiated from each other; Hollow 1 467 is most similar to Hollow 2, and Ridge 1 is most similar to Ridge 2. However, while Ridge 2 and 468 Hollow 2 are mostly distinct features, there is considerable overlap between Ridge 1 and Hollow 1. 469 The NMDS analysis of the macrofossil data shown in Fig. 7 gives a similar outcome to the cluster 470 analysis. The major gradient in the dataset (NMDS axis 1; Fig. 7) follows a ridge-hollow/bog 471 surface wetness gradient. It is apparent that Ridge 2 and Hollow 2 are separate from each other in 472 the ordination space, whereas Hollow 1 and Ridge 1 overlap; the axis 1 scores illustrate this 473 separation and overlap clearly. The analysis confirms what appears to be evident from the 474

475 macrofossil diagrams: Ridge 2 and Hollow 2 have consistently been a ridge and hollow,

respectively, throughout their developmental history as represented by their respective macrofossil
NMDS axis 1 scores. The cores from Hollow 1 and Ridge 1 have a more mixed signal in terms of
macrofossils although Hollow 1 is more hollow-like than Ridge 1, and Ridge 1 is more ridge-like
than Hollow 1.

Generally, the two ridge cores have more decomposed peat than the two hollow cores: the average humification from the Ridge 1 and 2 cores is H7 and H8, respectively (Ridge 1, n = 44; Ridge 2, n = 53), whereas the average humification for the Hollow 1 and 2 cores is H6 (Hollow 1, n = 60; Hollow 2, n = 48). However, there is considerable down-core variability in humification in all cores (see Appendix S5).

The dry bulk density ( $\rho_b$ ) for all the microforms was below 100 kg m<sup>-3</sup> and ranges from 21 to 86 kg m<sup>-3</sup> (Figs 5a and 5b). The highest  $\rho_b$  values were recorded in Ridge 2, and the lowest in Hollow 1. The average  $\rho_b$  for Hollows 1 and 2 is, respectively, 35 kg m<sup>-3</sup> (n = 17) and 33 kg m<sup>-3</sup> (n =6 due to poor core recovery); the averages for Ridge 1 and 2 are 45 kg m<sup>-3</sup> (n = 18) and 60 kg m<sup>-3</sup> (n =19). The  $\rho_b$  values for Ridge 1 and 2 show little overlap with the values of Hollow 1 and 2: the ridges have consistently higher  $\rho_b$  than the hollows.

491

#### 492 **Discussion**

493 *High* K *in deeper peat* 

From an ecohydrological perspective the first two research questions on the magnitude and lateral variability of deeper-peat *K* only assume importance if the permeability of the deeper peat is sufficiently high to allow non-trivial rates of water flow. Even if there is an order of magnitude difference in the *K* of the deeper peat between hollows and ridges, the difference may be unimportant if those *K* values are low: for example, water flow through peat with a permeability in the range of  $1-10 \times 10^{-9}$  m s<sup>-1</sup> will be negligible under natural hydraulic gradients, so it does not matter if different microform types lie at opposite ends of this range.

In the two-layer acrotelm-catotelm model, the acrotelm conducts the vast majority of water, 501 with largely stagnant conditions prevailing in the catotelm because of its low K. While we found 502 that deeper-peat (catotelm) K can be low and consistent with the model, such as in Ridge 1 at a 503 504 nominal depth of 0.5 m (Fig. 3), we also found that K in deeper peat could equal and exceed values for shallow, near-surface, peat at the site (Fig. 3) and for a range of other peatlands - see, for 505 506 example, Boelter (1965), Hoag & Price (1995), Quinton, Hayashi & Carey (2008), Lewis et al. (2012), and Morris, Baird & Belvea (2015) (Fig. 3). In each of these studies, Sphagnum was often 507 the main or an important peat-forming species, and the highest K values reported in each were 508 generally associated with the least decomposed peat. Our results show that deeper bog peat has the 509 510 potential to conduct non-trivial amounts of water; as such, our data are inconsistent with one of the principal features of the two-layer model. This finding adds weight to the growing argument 511 (Holden & Burt 2003; Morris et al. 2011) that the two-layered model is too rigid a framework to be 512 generally applicable, because the intricacies of peatland ecohydrological structures and functions do 513 not necessarily partition neatly into two catch-all layers. However, whether the K values we 514 515 observed in deeper peat layers actually lead to rapid flows will depend on the connectivity of zones of high K within the deeper peat, and more work is required on mapping subsurface structures at the 516 site. 517

518

#### 519 *Microform persistence and* K variations

Based on the age-depth model, Hollow 2 has persisted since at least *c*. 1200 cal BP and Ridge 2
since at least *c*.1400 cal BP. Because they extend to twice the depth of the deepest dated samples,
the macrofossil data show that both microforms have persisted for considerably longer than these
ages. Both features are, therefore, ancient, persisting as the bog increased markedly in vertical
extent. The other two microforms – Hollow 1 and Ridge 1 – show a mixed signal; they have
undergone switches in their status over time. Nevertheless, Hollow 1 has been more hollow-like
than ridge-like throughout its development, and Ridge 1 has been more ridge-like than hollow-like.

Therefore, there is little evidence to support the suggestion of uni-directional microform movement 527 at the site. This finding is not necessarily inconsistent with what is suggested in Kettridge et al. 528 (2012) who found that dipping reflectors indicative of microform movement were more steeply 529 530 sloping in the peat at depths of 1-2.5 m than shallower depths; in other words that the evidence of microform movement in the uppermost metre of peat is less strong than the evidence from the 531 532 deeper peat. Nevertheless, based on their GPR data, current microform spacing and an age-depth model constructed from data from Schulz (2004), Kettridge et al. (2012) suggested that a microform 533 passing a fixed point would be expected to produce layers of peat with a mean thickness of c. 0.19 534 m. When superimposed on such layers, our contiguous 0.1-m samples should consist of some in 535 536 which there is a hollow-only signal, some which are ridge-only, and some that contain a mixture of wet and dry indicators. Such a pattern of both pure and within-sample mixed signals is not evident 537 in the data from Hollow 2 and Ridge 2, which contain, respectively, hollow-like and ridge-like 538 properties throughout most of their profiles. In Hollow 1 and Ridge 1, there is evidence of switches 539 in microform type but these don't conform to the pattern expected from 0.19-m layers, regardless of 540 541 how a 0.1-m sampling interval is staggered. Therefore, the switches seen in Hollow 1 and Ridge 1 are more likely to be due to microform contraction/expansion as per the conceptual model of Aaby 542 (1976) and Barber (1981). Whether such contraction/expansion resulted from climatic changes 543 remains unclear (it may be autogenic or allogenic). 544

Multivariate statistical tools such as the cluster analysis and NMDS we apply here provide 545 an objective statistical approach for classifying microforms and assessing how distinct they have 546 been through their developmental history. NMDS enables the determination of whether plant 547 assemblages in each microform have remained consistent, or whether switches in the microform 548 549 characteristics have occurred. We contend that using robust statistical tools such as NMDS is less prone to bias than traditional approaches where stratigraphic data are zoned and classified by eye. 550 Peat formed in ridges (from ridge vegetation) is different, botanically, from that formed in 551 552 hollows (from hollow vegetation), and the plant macrofossil data suggest that Hollow 2 has been

more hollow-like than Hollow 1 throughout its history and Ridge 2 has been more ridge like than 553 Ridge 1. With this in mind, we might expect the K at 0.5 m and the K at 0.9 m  $- K_{0.5}$  and  $K_{0.9}$  – to 554 show the greatest differences between Hollow 2 and Ridge 2, but this is not the case. The difference 555 556 in  $K_{0.5}$  between Hollow 1 and Ridge 1 is much greater than that between Hollow 2 and Ridge 2, while for  $K_{0.9}$  the Bayesian analysis suggest that there is no credible difference between Hollow 2 557 558 and Ridge 2 although there is one between Hollow 1 and Ridge 1 (Fig. 3; Table 1; Appendix S3). These differences may be taken to suggest that ecological memory is relatively weak at the site; i.e., 559 although Hollow 2 and Ridge 2 have persisted over time – considerably longer than c. 1200 and 560 1400 years – this persistence is not reflected in their K values. Such a conclusion might be 561 premature because Hollow 2 and Ridge 2 are credibly different in terms of their  $K_{0.5}$  values. Also, 562 more generally, both ridges at 0.5 m separate clearly from hollows at the same depth, with higher K 563 values in the hollows. It is notable that such a clear separation does not occur at 0.9 m, which may 564 indicate a weakening of ecological memory with time. What is clear is that our data do not provide 565 a simple answer to the third research question; patterns in K are not easily attributable to microform 566 567 persistence and ecological memory.

The strong horizontal contrasts in  $K_{0.5}$  are almost as striking as those that can occur vertically within the upper *c*. 0.2-0.5 m of the peat profile ('acrotelm'). For example, median  $K_{0.5}$ varies by two orders of magnitude between Ridge 1 and the adjacent Hollow 1, and by an order of magnitude between Ridge 2 and its Hollow 2 neighbour (Fig. 3). Such strong horizontal gradients in *K* are further indication that our study site is not well described by the acrotelm-catotelm model, which is unable to account for horizontal variations.

Although there are patterns in the *K* data, it is important to recognise that deeper-peat *K* values may not fit neatly into simple categories or always correspond in a simple way to peat type (botanical composition and degree of decomposition). Care has to be taken to avoid overinterpreting the plant-macrofossil data from the central core of each of the studied microforms because the data from these cores may not apply to each piezometer location (the piezometers for

Page | 23

the *K* tests were located across each feature). Nevertheless, if incursions of the 'other' peat type 579 (hollow peat in a 'ridge' and ridge peat in a 'hollow') occur in the centre of a feature, they should 580 also occur across the rest of the feature where the piezometers were placed. Therefore, if an 581 582 incursion recorded by the centrally-located macrofossil core corresponds to the depth at which Kwas measured, we can consider more closely how peat type affects K. If we look in detail at Ridge 583 584 1, for example, at the depth interval of c. 0.4-0.6 m (the range over which  $K_{0.5}$  was measured) there is a hollow-like incursion: there are peaks in the abundance of Sphagnum section Cuspidata, 585 Sphagnum papillosum, and Menyanthes trifoliata (Fig. 5b). The von Post score over this range 586 shows a moderate degree of decomposition (H4), and  $\rho_b$  varies between c. 45 and c. 55 kg m<sup>-3</sup>. 587 Despite such conditions, the  $K_{0.5}$  values recorded for Ridge 1 were the lowest five from the 40-588 strong data set. In contrast,  $K_{0.5}$  was very high in Hollow 1 for a very similar plant macrofossil 589 signal and a higher von Post score (H4-H7), although  $\rho_b$  was lower (30-45 kg m<sup>-3</sup>) (Fig. 3 and Fig. 590 5a). Finally, and in a similar vein, the very high  $K_{0.9}$  values recorded from Hollow 1 coincide with a 591 peak in Sphagnum austinii, indicative of hummock or ridge-like conditions, relatively high von Post 592 scores (H5-H7), but low  $\rho_b$  values (below 30 kg m<sup>-3</sup>). 593

Why do such apparent anomalies occur? The K of a porous medium is very sensitive to the 594 pore size distribution, so one modest sized pore can conduct more water than multiple small pores 595 with a combined cross-sectional area many times that of the single pore. This sensitivity to pore size 596 or diameter is an outcome of the capillary bundle analogy and Poiseuille's law (Dingman 1984). A 597 soil such as peat may be considered analogous to a bundle of capillary tubes. In each tube, flow is 598 laminar and follows Poiseuille's law; it increases with the fourth power of pore diameter. Given the 599 sensitivity of water flow, and therefore permeability, to one or two macropores, it is perhaps 600 unsurprising that K does not always vary simply with peat or microform type. 601

602 Our data were collected from a small number of microforms and, arguably, stronger patterns 603 might emerge were a larger study to be done, or many similar studies were done across a range of 604 sites. We encourage other researchers to take up this challenge; if the work is extended, we will be in stronger position to understand the importance of peatland microforms to overall peatlandfunctioning and to parameterise peatland models more accurately.

While our results indicate clear patterns in *K* between adjacent hummocks and hollows at 607 608 0.5 m depth, the picture is less clear at 0.9 m; the evidence for characteristic hydraulic structures associated with hummocks and hollows extending beyond the uppermost peat is mixed and it would 609 610 be premature to assume that deeper-peat K differs in any consistent or predictable manner between microforms. As such, evidence for the mechanism for ecological memory in peatlands proposed by 611 Morris, Baird & Belyea (2013) is similarly mixed. Our results indicate that while such an effect 612 may exist, it is likely to diminish with depth and age as old peat layers become buried by younger 613 peat. 614

We find that some peatland microforms may persist over millennial timescales (Hollow 2 615 and Ridge 2), while other, proximal, microforms are characterised by switches between wet and 616 drier conditions (Hollow 1 and Ridge 1). We suggest that such switches are more likely to be 617 contraction/expansion in line with the conceptual model of Aaby (1976) and Barber (1981) rather 618 619 than the spatial migration of individual microforms. There is debate over whether such switches can be purely autogenic in nature, or if they correspond to climatic shifts. Our findings have important 620 implications for understanding the functioning of peatlands – even over short distances there can be 621 marked heterogeneity in terms of developmental history and ecohydrological dynamics. 622

623

#### 624 Acknowledgements

We thank Nikki Dodd from the James Hutton Institute, Aberdeen, Scotland, for taking the aerial
photograph of the field site used in Fig. 1. This work was funded by The University of Leeds and
the private funds of A.J.B. and A.M.M. Natural Resources Wales (formerly the Countryside
Council for Wales) and Mike Bailey are thanked for giving permission to work on the site. We are
grateful to Professor Henry Lamb from the University of Aberystwyth for the loan of his Russian

630	corer. Finally,	we thank the	reviewers – o	one anonymous	and the other	er Professor	Nigel Roulet -
	<i>, ,</i>			2			0

631 whose comments helped us greatly improve the manuscript.

632

#### 633 **Data accessibility**

- The permeability and palaeo-ecological data (including dry bulk density and degree of
- humification) are available in the Dryad Digital Repository (Baird *et al.* 2015):
- 636 http://dx.doi.org/10.5061/dryad. v5r86.
- 637 The R script for the Bayesian pair-wise analysis is available as online supporting638 information.

639

#### 640 **References**

- Aaby, B. (1976) Cyclic climatic variations in climate over the past 5,500 yr reflected in raised bogs.
   *Nature*, 263, 281-284.
- Amesbury, M.J., Barber, K.E. & Hughes, P.D.M. (2010) The methodological basis for fineresolution, multiproxy reconstructions of ombrotrophic peat bog surface wetness. *Boreas*,
- **40**, 161-174.
- Baird, A.J., Belyea, L. & Morris, P.J. (2009) Upscaling peatland-atmosphere fluxes of carbon gases:
  small-scale heterogeneity in process rates and the pitfalls of 'bucket-and-slab' models.
- 648 *Carbon Cycling in Northern Peatlands* (eds A.J. Baird, L.R. Belyea, X. Comas, A. Reeve &
- L. Slater), pp. 37-53. Geophysical Monograph Series 184, American Geophysical Union,
  Washington, DC.
- Baird, A.J. & Gaffney, S.W. (1994) Cylindrical piezometer responses in a humified fen peat.
   *Nordic Hydrology*, 25, 167-182.
- Baird, A.J., Eades, P.A. & Surridge, B.W.J. (2008) The hydraulic structure of a raised bog and its
- 654 implications for ecohydrological modelling of bog development. *Ecohydrology*, **1**, 289-298.

- Baird, A., Milner, A., Blundell, A., Swindles, G. & Morris, P. (2015) Data from: Microform-scale
  variations in peatland permeability and their ecohydrological implications. *Dryad Digital Repository*, http://dx.doi.org/10.5061/dryad. v5r86.
- Baird, A.J., Surridge, B.W.J. & Money, R.P. (2004) An assessment of the piezometer method for
  measuring the hydraulic conductivity of a *Cladium mariscus-Phragmites australis* root mat
  in a Norfolk (UK) fen. *Hydrological Processes*, 18, 275-291.
- Bannister, P. (1964) The water relations of certain heath plants with reference to their ecological
  amplitude. III. Experimental studies: General conclusions. *Journal of Ecology*, **52**, 499-509.
- Barber, K.E. (1981) *Peat Stratigraphy and Climatic Change: A Palaeoecological Test of the Theory of Cyclic Peat Bog Regeneration*. A.A. Balkema, Rotterdam.
- Barber, K.E., Chambers, F.M., Maddy, D., Stoneman, R. & Brew, J.S. (1994) A sensitive high-
- resolution record of Late Holocene climatic change from a raised bog in northern England. *The Holocene*, 4, 198-205.
- Belyea, L.R. & Baird, A.J. (2006) Beyond the "limits to peat bog growth": cross-scale feedback in
  peatland development. *Ecological Monographs*, **76**, 299-322.
- Belyea, L.R. & Clymo, R.S. (2001) Feedback control of the rate of peat formation. *Proceedings of the Royal Society of London Series B Biological Sciences*, 268, 1315-1321.
- Blaauw, M. & Christen, J.A. (2011) Flexible paleoclimate age-depth models using an
  autoregressive gamma process. *Bayesian Analysis*, 6, 457-474.
- Boelter, D.H. (1965) Hydraulic conductivity of peats. *Soil Science*, **100**, 227-230.
- Brand, E.W. & Premchitt J. (1982) Response characteristics of cylindrical piezometers. *Géotechnique*, **32**, 203-216.
- Butler, J.J. Jr. (1998) *The Design, Performance and Analysis of Slug Tests*. Lewis Publishers, Boca
  Raton, Florida.
- 679 Couwenberg, J. & Joosten, H. (2006) Self-organization in raised bog patterning: the origin of
- 680 microtope zonation and mesotope diversity. *Journal of Ecology*, **93**, 1238-1248.

- 681 Dingman, S.L. (1984) *Fluvial Hydrology*. W.H. Freeman, New York.
- Domenico, P.A. & Schwartz, F.W. (1990) *Physical and Chemical Hydrogeology*. Wiley, New
  York.
- Elkington, T., Dayton, N., Jackson, D.L. & Strachan, I.M. (2001) *National Vegetation Classification: Field Guide to Mires and Heaths*. Joint Nature Conservation Committee,
   Peterborough, UK.
- Eppinga, M.B., de Ruiter, P.C., Wassen, M.J. & Rietkerk, M. (2009) Nutrients and hydrology
  indicate the driving mechanisms of peatland surface patterning. *American Naturalist*, 173,
  803-818.
- 690 Frolking, S., Roulet, N.T., Tuittila, E., Bubier, J.L., Quillet, A., Talbot, J. & Richard, P.J.H. (2010)
- A new model of Holocene peatland net primary production, decomposition, water balance,
  and peat accumulation. *Earth System Dynamics*, 1, 1-21.
- Hendry, R.J. & McGlade, J.M. (1995) The role of memory in ecological systems. *Proceedings of the Royal Society of London Series B Biological Sciences*, 259, 153-159.
- Hoag, R.S. & Price, J.S. (1995) A field-scale, natural gradient solute transport experiment in peat at
  a Newfoundland blanket bog. *Journal of Hydrology*, **172**, 171-184.
- Holden, J. & Burt, T.P. (2003) Hydrological studies on blanket peat: the significance of the
  acrotelm-catotelm model. *Journal of Ecology*, **91**, 86-102.
- Hvorslev, M.J. 1951. *Time Lag and Soil Permeability in Groundwater Observations*. Waterways
   Experimental Station Bulletin 36, United States Army Corps of Engineers, Mississippi,
- 701 USA.
- Ingram, H.A.P. (1978) Soil layers in mires: function and terminology. *Journal of Soil Science*, 29,
   224-227.
- Ingram, H.A.P. (1983) Hydrology. *Mires: Swamp, Bog, Fen and Moor* (ed. A.J.P. Gore), pp. 67158, Elsevier, Amsterdam.
- 706 Ivanov, K.E. (1953) *Gidrologiya Bolot* [Hydrology of Mires]. Gidrometeoizdat, Leningrad.

707	Ivanov, K.E. (1981) Water Movement in Mirelands. English language edition translated by	
708	Thompson, A. & Ingram, H.A.P., Academic Press, London.	

- 709 Kelly, T.J., Baird, A.J., Roucoux, K.H., Baker, T.R., Honorio Coronado, E.N., Ríos, M. & Lawson,
- 710 I.T. (2014) The high hydraulic conductivity of three wooded tropical peat swamps in
- northeast Peru: measurements and implications for hydrological function. *Hydrological*
- 712 *Processes*, **28**, 3373-3387.
- 713 Kettridge, N., Binley, A., Comas, X, Cassidy, N.J., Baird, A.J., Harris, A., van der Kruk, J., Strack,
- M., Milner, A.M. & Waddington, J.M. (2012) Do peatland microforms move through time?
  Examining the developmental history of a patterned peatland using ground penetrating
  radar. *Journal of Geophysical Research Biogeosciences*, **117**, G03030.
- 717 Kettridge, N., Comas, X., Baird, A., Slater, L., Strack, M., Thompson, D., Jol, H. & Binley, A.
- 718 (2008) Ecohydrologically-important subsurface structures in peatlands are revealed by
- ground-penetrating radar and complex conductivity survey. *Journal of Geophysical*
- 720 *Research Biogeosciences*, **113**, G04030.
- Kilian, M.R., van der Plicht, J. & van Geel, B. (1995) Dating raised bogs: new aspects of AMS <sup>14</sup>C
   wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews*, 14, 959-966.
- Klute, A. (1965) Laboratory measurement of hydraulic conductivity of saturated soil. *Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties* (ed. C.A. Black), pp. 210-221.
   American Society of Agronomy, Madison.
- Koerselman, W. (1989) Groundwater and surface water hydrology of a small groundwater-fed fen.
   *Wetlands Ecology and Management*, 1, 31-43.
- Kruschke, J.K. (2011) *Doing Bayesian Data Analysis: A Tutorial with R and BUGS*. Elsevier,
  Amsterdam.
- 731 Legendre, P. & Legendre, L. (1998) *Numerical Ecology*. Second edition, Elsevier, Amsterdam.

732	Lewis, C., Albertson, J.D., Xu, X. & Kiely, G. (2012) Spatial variability of hydraulic conductivity
733	and bulk density along a blanket peatland hillslope. <i>Hydrological Processes</i> , <b>26</b> , 1527-1537.
734	Mauquoy, D., Hughes, P.D.M. & van Geel, B. (2010) A protocol for plant macrofossil analysis of
735	peat deposits. Mires and Peat, 7, 6.
736	Mauquoy, D., Yeloff, D., van Geel, B., Charman, D.J. & Blundell, A. (2008) Two decadally
737	resolved records from north-west European peat bogs show rapid climate changes associated
738	with solar variability during the mid-late Holocene. Journal of Quaternary Science, 23,
739	745-763.
740	Minchin, P.R. (1987) An evaluation of the relative robustness of techniques for ecological
741	ordination. Vegetatio, 69, 89-107.
742	Morris, P.J., Baird, A.J. & Belyea, L.R. (2012) The DigiBog peatland development model 2:
743	Ecohydrological simulations in 2D. Ecohydrology, 5, 256-268.
744	Morris, P.J., Baird, A.J. & Belyea, L.R. (2013) The role of hydrological transience in peatland
745	pattern formation. Earth Surface Dynamics, 1, 29-43.

- Morris, P.J., Baird, A.J. & Belyea, L.R. (2015) Bridging the gap between models and measurements
  of peat hydraulic conductivity. *Water Resources Research*, **51**, 5353-5364.
- Morris, P.J., Waddington, J.M., Benscoter, B.W. & Turetsky, M.R. (2011) Conceptual frameworks
  in peatland ecohydrology: looking beyond the two-layered (acrotelm–catotelm) model.
- 750 *Ecohydrology*, **4**, 1-11.
- Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L.,
  Solymos, P., Stevens, M.H.H. & Wagner, H. (2012) *vegan: Community Ecology Package*. R
- package version 2.0-5. URL: http://CRAN.R-project.org/package=vegan.
- Quinton, W.L., Hayashi, M., & Carey, S.K. 2008. Peat hydraulic conductivity in cold regions and
  its relation to pore size and geometry. *Hydrological Processes*, 22, 2829-2837.

- R Core Team. (2012) *R: A Language and Environment for Statistical Computing*. R Foundation for
  Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.Rproject.org/.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C.,
- 760 Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P.,
- Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac,
- F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney,
- C.S.M., van der Plicht, J. & Weyhenmeyer, C.E. (2009) IntCal09 and Marine09 radiocarbon
  age calibration curves, 0-50,000 years Cal BP. *Radiocarbon*, **51**, 1111-1150.
- Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R. & Bubier, J. (2007)
- Contemporary carbon balance and late Holocene carbon accumulation in a northern
  peatland. *Global Change Biology*, 13, 397-411, doi: 10.1111/j.1365-2486.2006.01292.x.
- 768 Rydin, H. & Jeglum, J. (2006) *The Biology of Peatlands*. Oxford University Press, Oxford.
- 769 Schulz, J. (2004) Palaeoecological Approach using High-Resolution Macrofossil Analysis, PhD
- thesis, University. of Southampton, Southampton, UK.
- Surridge, B.W.J., Baird, A.J. & Heathwaite, A.L. (2005) Evaluating the quality of hydraulic
   conductivity estimates from piezometer slug tests in peat. *Hydrological Processes*, 19, 1227-1244.
- Suzuki, R. & Shimodaira, H. (2006). Pvclust: an R package for assessing the uncertainty in
   hierarchical clustering. *Bioinformatics*, 22, 1540-1542.
- Swanson, D.K. & Grigal, D.F. (1988) A simulation model of mire patterning. *Oikos*, **53**, 309-314.
- 577 Swindles, G.T., Morris, P.J., Baird, A.J., Blaauw, M. & Plunkett, G. (2012) Ecohydrological
- feedbacks confound peat-based climate reconstructions. *Geophysical Research Letters*, **39**,
  L11401.

- Whittington, P.N. & Price, J.S. (2006) The effects of water table draw-down (as a surrogate for
  climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes*, 20,
  3589-3600.
- Winston, R.B. (1994) Models of the geomorphology, hydrology, and development of domed peat
  bodies. *Geological Society of America Bulletin*, **106**, 1594-1604.

Table 1. Summary of the Bayesian pairwise comparisons of the K data 

_	_	_
7	8	6

	R1 0.5	R2 0.5	H1 0.5	H2 0.5	R1 0.9	R2 0.9	H1 0.9	H2 0.9
R1 0.5		1.07, 3.79	2.72, 6.67	3.11, 6.87	0.69,3.53	1.29, 4.09	3.06, 5.87	1.90, 4.58
R2 0.5			0.34, 4.19	0.73, 4.38	-1.77, 1.07	-1.16, 1.6	0.65, 3.36	-0.48, 2.14
H1 0.5				-1.92, 2.46	-4.60, -0.61	-3.99, -0.09	-2.16, 1.64	-3.32, 0.44
H2 0.5					-4.84, -1.07	-4.18, -0.48	-2.32, 1.28	-3.52, 0.05
R1 0.9						-0.84, 2.06	0.92, 3.8	-0.21, 2.56
R2 0.9							0.33, 3.13	-0.75, 1.94
H1 0.9								-2.55, 0.08

Note. R1 and R2: Ridges 1 and 2; H1 and H2: Hollows 1 and 2. 0.5: 0.5 m depth. 0.9: 0.9 m depth. The numbers indicate the limits of the 95% highest density interval (HDI). If these do not include zero, there is a credible difference between the groups (which is also indicated in bold). See text for further details. Positive values suggest that a row has a lower K value than a column. 

**Table 2.** Details of the <sup>14</sup>C dates obtained from Hollow 2 and Ridge 2 

Lab. no.	Code	Depth	Material	<sup>14</sup> C age	+/-	AMS	Cal. 2 $\sigma$
		(m)				$\delta^{13}C$	range BP
UBA-	CFH2.30	0.2-0.3	Sphagnum	82	21	-30.5	1384
20982			leaves/branches/stems				
UBA-	CFH2.60	0.5-0.6	Sphagnum	477	24	-25.2	536-502
20983			leaves/branches/stems				
UBA-	CFH2.100	0.9-1.0	Sphagnum	1206	21	-24.1	1179-1062
20984			leaves/branches/stems				
UBA-	CFR2.30	0.2-0.3	Sphagnum	321	21	-25.9	460-307
20985			leaves/branches/stems				
UBA-	CFR2.60	0.5-0.6	Sphagnum	1081	22	-26.1	1054-934
20986			leaves/branches/stems				
UBA-	CFR2.100	0.9-1.0	Racomitrium moss	1425	19	-23.1	1297-1315

Note. In the Code column CFH2 refers to Cors Fochno Hollow 2 and CFR2 refers to Cors Fochno Ridge 2.

#### 802 Figure captions

803

Figure 1. Aerial photograph of the study area. The thick dashed line shows the location of the transect used by Kettridge *et al.* (2012), with the northernmost part of the line representing the start of the transect. The fine dashed lines delineate the areas from which the *K* readings were taken. The hollows were larger than the areas shown, but measurements were restricted to those parts of the hollows that contained the greatest cover of *Sphagnum pulchrum*.

809

Figure 2. Example of the apparently stalled response of some of the 0.5-m piezometers installed in Ridge 1. The piezometer water levels shown here are atmospherically-corrected. The arrow shows the assumed  $t_{95}$ . The grey dashed line indicates how background pore-water pressure may have fallen during the test (due to water flow through the bog and evaporative losses).

814

Figure 3. The values of hydraulic conductivity (K) for each microform and depth. n = 5 in each 815 case, but over-plotting of similar values hides some symbols. All values are corrected to 20°C. Also 816 shown are the ranges of K values found (i) in the uppermost 0.3 m from the central patterned area of 817 the study site (unpublished data), and (ii) in the uppermost 0.5 m from a selection of raised and 818 blanket bogs (see the named studies). The K range given for the near-surface peat at the study site is 819 based on values corrected to 20°C; the minimum of this range is  $4.8 \times 10^{-8}$  m s<sup>-1</sup>. *K* was measured at 820 a temperature of 18°C by Lewis et al. (2011), and their K values have been corrected to 20°C in the 821 figure. The K values from the other studies are not temperature-corrected. 822

823

Figure 4. Age-depth curves for Hollow 2 and Ridge 2. The curves show the maximum probabilityages from the Bayesian age-depth models.

Figures 5a and b. Macrofossil, humification, and dry bulk density data for three separate cores that were taken from the centre of each microform. In the macrofossil part of each figure the  $\bigcirc$  symbol indicates a null return (the macrofossil concerned was absent throughout the core). The pale grey bands indicate the depth intervals over which the *K* tests were done. Dry bulk densities are shown by filled circles joined by a dotted line, von Post scores by a continuous line with no symbols.

Figure 6. Cluster dendrogram of the plant macrofossil data. The initial letter and first digit of the
sample codes refer to ridge (R) or hollow (H) and replicate (R1, R2, H1, H2). The remaining digit
or digits refer(s) to sample depth in m multiplied by 10 (so a depth in the figure of 1 is 0.1 m).

836

Figure 7. NMDS ordination biplots of plant macrofossil data (sample codes are the same as in Fig.
6). Species codes are abbreviated (see Figs 5a and 5b for the full names). NMDS axis 1 follows a
ridge-hollow/bog surface wetness gradient.





846 Figure 2.









## 860 Figure 5a.

861 See separate pdf file.



862

## 864 Figure 5b.

865 See separate pdf file.



866

867





- 1 Microform-scale variations in peatland permeability and their ecohydrological implications
- 2
- **3 SUPPORTING INFORMATION**
- 4
- 5 Web-based appendices S1-S5
- 6
- 7

### 8 Appendix S1: Botanical authorities and common names for the plant species named in the

- 9 paper
- 10

Plant species	Botanical authority	Common name
Aulacomnium palustre	(Hedw.) Schwägr.	Bog Bead-moss
Calluna vulgaris	L.	Heather or Ling
Erica tetralix	L.	Cross-leaved Heath
Eriophorum angustifolium	Honck	Common Cottongrass
Eriophorum vaginatum	L.	Hare's Tail Cottongrass
Menyanthes trifoliata	L.	Bog Bean
Myrica gale	L.	Bog Myrtle
Racomitrium lanuginosum	Brid.	Woolly Fringe-moss
Rhododendron		
groenlandicum	(Oeder) Kron & Judd	Labrador Tea
[formerly Ledum		
groenlandicum]	[Oeder]	
Rhynchospora alba	(L.) Vahl.	White-beaked Sedge
Sphagnum austinii	Sull.	Austin's Bog-moss
Sphagnum capillifolium	(Ehrh.) Hedw.	Acute-leaved Bog-moss
Sphagnum cuspidatum	Ehrh. ex Hoffm.	Feathery Bog-moss
Sphagnum fuscum	(Schimp.) Klinggr.	Rusty Bog-moss
Sphagnum magellanicum	Brid.	Magellanic Bog-moss
Sphagnum papillosum	Lindb.	Papillose Bog-moss
Sphagnum pulchrum	(Lindb. ex Braithw.) Warnst.	Golden Bog-moss

- 11
- 12
- 13

#### 14 Appendix S2: The consistency of the piezometer tests

Three repeats were done on piezometers 23, 32, and 39, which were placed at a nominal depth of 15 0.5 m in Ridge 1, Ridge 2, and Hollow 2 respectively. Each repeat test was done within a day of the 16 17 first test, and the results from both tests are shown in the three figures below. In piezometers 23 and 39 head recovery in the repeat test was similar to recovery to the first test, although for instrument 18 19 39 the second test took 60 % longer to reach  $h/h_0 = 0.05$ . In piezometer 32 the second test showed a 20 much slower response than the first. It is unusual for repeat tests to be done on piezometers, especially over such short intervals, and it is difficult to put the results into a wider context. In 21 piezometer tests on fen and bog peats, Rosa & Larocque (2008) report little between-test variability. 22 23 They reproduce results from one piezometer installed in a fen peat that show very similar recoveries for the first and the repeat tests. Some tests done by Baird, Eades & Surridge (2008) in an earlier 24 study of the permeability of the bog peat at Cors Fochno show variation between first and second 25 tests that is similar to that found in the current study. However, most of the repeat tests carried out 26 by Baird, Eades & Surridge (2008), from a total of 12 piezometers, tended to give similar responses 27 to the first test, as with piezometer 23. Where Baird, Eades & Surridge (2008) found larger 28 deviations, like that with piezometer 32 here, there was not a consistent pattern in terms of 29 responses becoming progressively slower or faster. For example, in one of their piezometers, they 30 31 found that the second test took more than twice as long as the first; however, a third test was much closer in duration to the first. It is difficult to explain the difference in response between second and 32 first tests that occurs in some instruments, but it may be due to bubble migration and coalescence in 33 the peat around the intake as discussed by Surridge, Baird & Heathwaite (2005). The same 34 cautionary note as given by Baird, Eades & Surridge (2008) applies here: our results should be 35 36 interpreted with an appreciation that substantial between-test variability is possible in individual instruments, although it seems that most instruments (piezometer 23 and the majority of the 12 37 piezometers that Baird, Eades & Surridge (2008) conducted repeat tests on) show little such 38 39 variability.

- 40 Figures: Results from the replicate head-recovery tests conducted on piezometers 23 (upper: 0.5 m,
- 41 Hollow 2), 32 (middle: 0.5 m, Ridge 2) and 39 (lower: 0.5 cm, Ridge 1) (lower). In each case the





46	Baird, A.J., Eades, P.A. & Surridge, B.W.J. (2008) The hydraulic structure of a raised bog and its
47	implications for ecohydrological modelling of bog development. <i>Ecohydrology</i> , <b>1</b> , 289-298.
48	Rosa, E. & Larocque, M. (2008) Investigating peat hydrological properties using field and
49	laboratory methods: application to the Lanoraie peatland complex (southern Quebec,
50	Canada). <i>Hydrological Processes</i> , <b>22</b> , 1866-1875.
51	Surridge, B.W.J., Baird, A.J. & Heathwaite, A.L. (2005) Evaluating the quality of hydraulic
52	conductivity estimates from piezometer slug tests in peat. Hydrological Processes, 19,
53	1227-1244.
54	
55	
56	

59	Appendix S3: The Bayesian pair-wise comparison analysis
60	The JAGS (Just Another Gibbs Sampler) and R code used to undertake the Bayesian pairwise
61	comparison of the permeability data is modified from the original
62	(ANOVAonewayNonhomogvarJagsSTZ) available at:
63	http://www.indiana.edu/~kruschke/DoingBayesianDataAnalysis/Programs/ANOVAonewayNonho
64	mogvarJagsSTZ.R
65	and at
66	https://github.com/pommedeterresautee/doingBayesianDataAnalysis/blob/master/ANOVAoneway
67	NonhomogvarJagsSTZ.R
68	Both were last accessed on 2 <sup>nd</sup> July 2015.
69	
70	The code used is reproduced below.
71	
72 73 74	<pre>rm(list=ls()) # Careful! This clears all of R's memory! graphics.off() # This closes all of R's graphics windows.</pre>
75 76 77	<pre>graphics.off() rm(list=ls(all=TRUE))</pre>
78 79 80 81	<pre>source("openGraphSaveGraph.R") source("plotPost.R") fileNameRoot="ANOVAonewayNonhomogvarJagsSTZ" # for constructing output filenames require(riags)</pre>
82	# A Tutorial with R and BUGS. Academic Press / Elsevier.
83 84	## THE MODEL.
85 86 87 88 89 90 91 92 93 94 95	<pre>modelstring = " model {   for ( i in 1:Ntotal ) {     y[i] ~ dnorm( mu[i] , tau[x[i]] )     mu[i] &lt;- a0 + a[x[i]]   }   a0 ~ dnorm(0,0.001)   for ( j in 1:NxLvl ) {       a[j] ~ dnorm( 0.0 , atau )       tau[j] ~ dgamma( sG , rG ) </pre>
96 97	g <-pow(m,2)/pow(d,2)
98 99 100	rG <- m/pow(d,2) m ~ dgamma(1,1) d ~ dgamma(1,1)

```
101
        atau <- 1 / pow( aSD , 2 )
102
        aSD <- abs( aSDunabs ) + .1
103
        aSDunabs ~ dt( 0 , 0.001 , 2 )
104
        # Convert a0,a[] to sum-to-zero b0,b[] :
105
        for ( j in 1:NxLvl ) { mpred[j] <- a0 + a[j] }</pre>
106
       b0 <- mean( mpred[1:NxLvl] )</pre>
107
        for ( j in 1:NxLvl ) { b[j] <- mpred[j] - b0 }</pre>
108
      ł
109
      " # close quote for modelstring
110
      # Write model to a file, and send to BUGS:
111
      writeLines(modelstring,con="model.txt")
112
113
      #_____
114
      # THE DATA.
115
116
      # Specify data source:
117
      dataSource = c( "lncorsfochno" )[1]
118
119
      #meta-data
120
      #A = Ridge 1 (0.5 m)
121
      #B = Ridge 2 (0.5 m)
122
      #C = Hollow 1 (0.5 m)
123
      #D = Hollow 2 (0.5 cm)
124
      #E = Ridge 1 (0.9 cm)
125
      #F = Ridge 2 (0.9 cm)
126
      #G = Hollow 1 (0.9 cm)
127
      #H = Hollow 2 (0.9 cm)
128
129
      # Load the data:
130
131
      if ( dataSource == "lncorsfochno" ) {
132
        fileNameRoot = paste( fileNameRoot , dataSource , sep="" )
133
        datarecord = read.csv( "lncorsfochno.csv" )
134
        y = datarecord
135
       Ntotal = length(y)
136
        x = as.numeric(datarecord$Group)
137
        xnames = levels(datarecord$Group)
138
        NxLvl = length(levels(datarecord$Group))
139
        normalize = function( v ) { return( v / sum(v) ) }
140
        contrastList = list(
141
          BvA = (xnames == "B") - (xnames == "A")
142
          CvA = (xnames=="C") - (xnames=="A")
143
          DvA = (xnames=="D") - (xnames=="A")
144
          EvA = (xnames=="E") - (xnames=="A")
145
          FvA = (xnames == "F") - (xnames == "A")
146
          GvA = (xnames=="G") - (xnames=="A")
147
          HvA = (xnames=="H") - (xnames=="A")
148
          CvB = (xnames=="C") - (xnames=="B")
149
          DvB = (xnames=="D") - (xnames=="B")
150
          EvB = (xnames=="E") - (xnames=="B")
151
          FvB = (xnames=="F") - (xnames=="B")
152
          GvB = (xnames=="G") - (xnames=="B")
153
          HvB = (xnames=="H") - (xnames=="B")
154
          DvC = (xnames=="D") - (xnames=="C")
155
          EvC = (xnames=="E") - (xnames=="C")
156
          FvC = (xnames = "F") - (xnames = "C")
157
          GvC = (xnames=="G") - (xnames=="C")
158
          HvC = (xnames=="H") - (xnames=="C")
159
          EvD = (xnames=="E") - (xnames=="D")
160
          FvD = (xnames=="F") - (xnames=="D")
161
          GvD = (xnames=="G") - (xnames=="D")
162
          HvD = (xnames=="H") - (xnames=="D")
163
          FvE = (xnames == "F") - (xnames == "E"),
```

```
164
         GvE = (xnames=="G") - (xnames=="E") ,
         HvE = (xnames=="H") - (xnames=="E") ,
165
         GvF = (xnames=="G") - (xnames=="F") ,
166
167
         HvF = (xnames=="H") - (xnames=="F") ,
168
         HvG = (xnames=="H") - (xnames=="G")
169
         )
170
171
     # Specify the data in a form that is compatible with BRugs model, as a list:
172
     ySDorig = sd(y)
173
     yMorig = mean(y)
174
     z = ( y - yMorig ) / ySDorig
175
     dataList = list(
176
      y = z,
177
      \mathbf{x} = \mathbf{x},
178
      Ntotal = Ntotal ,
179
       NxLvl = NxLvl
180
     )
181
182
     183
     # INTIALIZE THE CHAINS.
184
185
     theData = data.frame( y=dataList$y , x=factor(x,labels=xnames) )
186
     a0 = mean( theData$y )
187
     a = aggregate( theData$y , list( theData$x ) , mean )[,2] - a0
188
     tau = 1/(aggregate(theData$y, list(theData$x), sd)[,2])^2
189
     initsList = list( a0 = a0 , a = a , tau = tau , m = mean( tau ) ,
190
                      d = sd(tau), aSDunabs = sd(a))
191
192
     193
     # RUN THE CHAINS
194
     parameters = c( "a0" , "a" , "b0" , "b" , "tau", "m", "d", "aSD" )
195
196
                                 # Number of steps to "tune" the samplers.
     adaptSteps = 1000
197
                                 # Number of steps to "burn-in" the samplers.
     burnInSteps = 5000
198
     nChains = 3
                                 # Number of chains to run.
     numSavedSteps=100000
199
                                 # Total number of steps in chains to save.
200
                                 # Number of steps to "thin" (1=keep every step).
     thinSteps=1
201
     nPerChain = ceiling( ( numSavedSteps * thinSteps ) / nChains ) # Steps per
202
     chain.
203
     # Create, initialize, and adapt the model:
204
     jagsModel = jags.model( "model.txt" , data=dataList , inits=initsList ,
205
                           n.chains=nChains , n.adapt=adaptSteps )
206
     # Burn-in:
207
     cat( "Burning in the MCMC chain... \n" )
208
     update( jagsModel , n.iter=burnInSteps )
209
     # The saved MCMC chain:
210
     cat( "Sampling final MCMC chain...\n" )
211
     codaSamples = coda.samples( jagsModel , variable.names=parameters ,
212
                               n.iter=nPerChain , thin=thinSteps )
213
     # resulting codaSamples object has these indices:
214
     #
       codaSamples[[ chainIdx ]][ stepIdx , paramIdx ]
215
216
     217
     # EXAMINE THE RESULTS
218
219
     checkConvergence = FALSE
220
     if ( checkConvergence ) {
221
      openGraph(width=7,height=7)
       autocorr.plot( codaSamples[[1]] , ask=FALSE )
222
223
       show( gelman.diag( codaSamples ) )
224
       effectiveChainLength = effectiveSize( codaSamples )
225
       show( effectiveChainLength )
226
     }
```

```
227
228
      # Convert coda-object codaSamples to matrix object for easier handling.
229
      # But note that this concatenates the different chains into one long chain.
230
      # Result is mcmcChain[ stepIdx , paramIdx ]
231
     mcmcChain = as.matrix( codaSamples )
232
      chainLength = NROW (mcmcChain)
233
234
      # Extract parameters:
235
     aSDSample = mcmcChain[,"aSD"]
236
      tauSample = array( 0 , dim=c( dataList$NxLvl , chainLength ) )
237
      for ( xidx in 1:dataList$NxLvl ) {
238
         tauSample[xidx,] = mcmcChain[, paste("tau[",xidx,"]",sep="") ]
239
      ł
240
     a0Sample = mcmcChain[, "a0" ]
241
      aSample = array( 0 , dim=c( dataList$NxLvl , chainLength ) )
242
      for ( xidx in 1:dataList$NxLvl ) {
243
         aSample[xidx,] = mcmcChain[, paste("a[",xidx,"]",sep="") ]
244
      }
245
     b0Sample = mcmcChain[, "b0" ]
246
     bSample = array( 0 , dim=c( dataList$NxLvl , chainLength ) )
247
      for ( xidx in 1:dataList$NxLvl ) {
248
         bSample[xidx,] = mcmcChain[, paste("b[",xidx,"]",sep="") ]
249
      }
250
251
      # Convert from standardized b values to original scale b values:
252
     b0Sample = b0Sample * ySDorig + yMorig
253
     bSample = bSample * ySDorig
254
      sigmaSample = 1/sqrt(tauSample) * ySDorig
255
256
      # Plot aSD
257
     openGraph(width=7,height=7)
258
     layout( matrix(1:2,nrow=2) )
259
     par(mar=c(3,1,2.5,0), mgp=c(2,0.7,0))
260
     plotPost( aSDSample , xlab="aSD" , main="a SD" , showMode=T )
261
      saveGraph(file=paste(fileNameRoot,"SD",sep=""),type="eps")
262
263
      # Plot b values:
264
     openGraph(width=dataList$NxLvl*2.75,height=2.5)
265
      layout( matrix( 1:dataList$NxLvl , nrow=1 ) )
266
     par(mar=c(3,1,2.5,0), mgp=c(2,0.7,0))
267
      for ( xidx in 1:dataList$NxLvl ) {
268
          plotPost( bSample[xidx,]
269
                    xlab=bquote(beta*1[.(xidx)])
270
                    main=paste("x:",xnames[xidx]) )
271
      }
272
      saveGraph(file=paste(fileNameRoot,"b",sep=""),type="eps")
273
274
      # Plot tau values:
275
      openGraph(width=dataList$NxLv1*2.75,height=2.5)
276
      layout( matrix( 1:dataList$NxLvl , nrow=1 ) )
277
     par( mar=c(3,1,2.5,0) , mgp=c(2,0.7,0) )
278
      for ( xidx in 1:dataList$NxLvl ) {
279
          plotPost( tauSample[xidx,]
280
                    xlab=bquote(tau[.(xidx)])
281
                    main=paste("x:",xnames[xidx]) , showMode=T )
282
      ł
283
      saveGraph(file=paste(fileNameRoot,"tau",sep=""),type="eps")
284
285
      # Display contrast analyses
286
     nContrasts = length( contrastList )
287
     if ( nContrasts > 0 ) {
288
         nPlotPerRow = 5
289
         nPlotRow = ceiling(nContrasts/nPlotPerRow)
```

```
290
         nPlotCol = ceiling(nContrasts/nPlotRow)
291
         openGraph(width=3.75*nPlotCol,height=2.5*nPlotRow)
292
         layout( matrix(1:(nPlotRow*nPlotCol), nrow=nPlotRow, ncol=nPlotCol, byrow=T) )
293
         par( mar=c(4, 0.5, 2.5, 0.5) , mgp=c(2, 0.7, 0) )
294
         for ( cIdx in 1:nContrasts ) {
295
             contrast = matrix( contrastList[[cIdx]],nrow=1) # make it a row matrix
296
             incIdx = contrast!=0
297
             histInfo = plotPost( contrast %*% bSample , compVal=0
298
                      xlab=paste( round(contrast[incIdx],2) , xnames[incIdx] ,
299
                                   c(rep("+",sum(incIdx)-1),"") , collapse=" " ) ,
300
                       cex.lab = 1.0
301
                      main=paste( "X Contrast:", names(contrastList)[cIdx] ) )
302
         }
303
         saveGraph(file=paste(fileNameRoot,"xContrasts",sep=""),type="eps")
304
      }
305
306
      # Display data with posterior predictive distributions
307
      openGraph(width=1.5*NxLvl,height=5)
308
     plot(0,0,
309
           xlim=c(0.2,NxLvl+0.1) , xlab="X" ,
310
           xaxt="n"
311
           y = c (min(y) - 0.2*(max(y) - min(y)), max(y) + 0.2*(max(y) - min(y))), y = y = y'',
312
           main="Data with Posterior Predictive Distrib.")
313
      axis( 1 , at=1:NxLvl , lab=xnames )
314
      for ( j in 1:NxLvl ) {
315
        yVals = y[x==j]
316
        points( rep(j,length(yVals))+runif(length(yVals),-0.03,0.03) ,
317
                yVals , pch=20 , cex=1.5 , col="red" )
318
        chainSub = round(seq(1, chainLength, length=20))
        for ( chnIdx in chainSub ) {
319
320
          m = b0Sample[chnIdx] + bSample[j,chnIdx]
321
          s = sigmaSample[j,chnIdx]
          yl = m - 1.96 * s
322
          yh = m+1.96*s
323
324
          ycomb=seq(yl,yh,length=201)
325
          ynorm = dnorm(ycomb,mean=m,sd=s)
326
          ynorm = 0.75*ynorm/max(ynorm)
327
          lines( j-ynorm , ycomb , col="skyblue" ) # col=chnIdx )
328
        }
329
      }
330
      saveGraph(file=paste(fileNameRoot,"PostPred",sep=""),type="eps")
331
332
     The principal results from the analysis are reproduced below. These show pair-wise comparisons of
333
```

```
the \beta_j values (see explanation in main paper). Labels are as follows: A - Ridge 1 (0.5 m), B - Ridge
```

```
335 2 (0.5 m), C - Hollow 1 (0.5 m), D - Hollow 2 (0.5 cm), E - Ridge 1 (0.9 cm), F - Ridge 2 (0.9 cm),
```

```
336 G - Hollow 1 (0.9 cm), H - Hollow 2 (0.9 cm).
```



#### Appendix S4: The Bayesian age-depth models for Hollow 2 and Ridge 2 341

The R code used to derive the age-depth models is as follows. 342

```
343
     setdir("C:\Bacon").
344
     source('Bacon.R')
345
     Bacon("CF", acc.shape=2, acc.mean=13) # load CF data, define accumulation shape
346
     and accumulation mean priors
347
     ds <- seq(15, 20, length=10) # define the ages that describe the interval of
348
     interest at a 'reasonable' resolution
349
     ages <- c() # define a variable to contain the ages of said interval of depths
350
     for(i in ds)# determine them from model
351
     ages <- c(ages, Bacon.Age.d(i)) # assign them
352
     hist(ages) # plot histogram of resulting ages of this depth interval
```

```
354
       The graphs showing the analysis and the resulting models are given below. On the top panels of
       both graphs, leftmost plots show that both MCMC runs were stable (> 2000 iterations), middle plots
355
       show the prior (curves) and posterior (filled histograms) distributions for the accumulation rate (yr
356
       cm<sup>-1</sup>), and the rightmost plots show the prior (curves) and posterior (filled histograms) for the
357
       dependence of accumulation rate between sections. The large plots show age distributions of
358
       calibrated <sup>14</sup>C dates and the age-depth model (grey-scale). Dark grey areas indicate precisely dated
359
       sections of the chronology, while lighter grey areas indicate less chronologically secure sections.
360
361
362
```





# 367 Appendix S5: The von Post humification data from all three humification cores in each

microform (the data from the central cores are also shown in Figs 5a and 5b in the main

369 **paper**).

370 The western, central and eastern cores for each microform are shown from left to right.

