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1 Using palaeoecology to support blanket peatland management

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6 Abstract

7 Many peatlands have a recent history of being degraded by extraction, drainage, burning, overgrazing and
8 atmospheric pollution often leading to erosion and loss of peat mass. Restoration schemes have been
9 implemented aimed at rewetting peatlands, encouraging revegetation of bare peat or shifting the present
10 vegetation assemblage to an alternative. Here we demonstrate the use of palaeoecological techniques that
11 allow reconstruction of the historical development of a blanket peatland and provide a historical context
12 from which legitimate restoration targets can be determined and supported. We demonstrate the
13 applicability of simple stratigraphic techniques to provide a catchment-wide peatland development history
14 and reinforce this with a detailed macrofossil reconstruction from a central core. Analysis at Keighley
15 Moor Reservoir Catchment in northern England showed that the present vegetation state was 'atypical'
16 and has been characteristic for only the last c. 100 years. *Sphagnum* moss was an important historic
17 contributor to the vegetation cover between 1500 years ago and the early 1900s. Until the early 1900s
18 *Sphagnum* occurrence fluctuated with evidence of fire, routinely returning after fire demonstrating good
19 resilience of the ecosystem. However, from the turn of the 20th century, *Sphagnum* levels declined
20 severely, coincident initially with a wildfire event but remaining extremely diminished as the site
21 regularly underwent managed burning to support grouse moor gun sports where practitioners prefer a
22 dominant cover of heather. It is suggested that any intention to alter land management at the site to raise
23 water tables and encourage greater *Sphagnum* abundance is in line with peatland development at the site
24 over the past 1500 years. Similar palaeoecological studies providing historical context could provide
25 support for restoration targets and changes to peatland management practice for sites globally.

27 Keywords: peat, cores, stratigraphy, Holocene, *Sphagnum*, restoration

29 1.0 Introduction

30 The world's peatlands cover 3% of the Earth's land surface but contribute 30% of its soil carbon (Parish
31 et al., 2008) and store more organic carbon per hectare than any other terrestrial store. Degraded peatland
32 (one tenth of the peatland resource) contributes 6% of global anthropogenic CO₂ emissions (Joosten et al.,
33 2012). Globally, peatland degradation is mainly via agriculture, forestry, peat extraction for fuel or
34 horticulture and urbanisation. Such degradation jeopardises the ecosystem services peatlands provide
35 (Parry et al., 2014; Maltby and Acreman, 2011; Bonn et al 2009). Blanket peatlands form over sloping
36 landscapes under conditions of a large moisture excess and poor underlying drainage. They are typically
37 found in temperate hyper-oceanic regions (Lindsay et al. 1988) such as eastern Russia, the South Island of
38 New Zealand, southern Alaska and parts of the Atlantic northwest Europe (Gallego-Sala and Prentice,
39 2012). It is estimated that 10-15% of all blanket bog worldwide is located in the British Isles (Tallis et al.,
40 1997). In the UK, blanket peatland covers 1.5 million hectares with around 14% (215 000 ha) in England
41 (Jackson and McLeod, 2000). These areas are also the largest terrestrial carbon reserves in the UK acting
42 as a net carbon sink of between 0.7 Mt C/year (Cannell *et al.* 1999) and 0.3 Mt C/year (Worrall *et al.*,
43 2003).

44
45 A recent history of often interlinked factors such as drainage, burning, atmospheric pollution and
46 overgrazing is often blamed for degradation of UK peatland environments (Holden, 2007). Some
47 peatlands have suffered from severe erosion since the middle of the last century (Bower, 1961; Bower,
48 1962; Tallis, 1973; Maltby et al., 1990; Evans, 2005). Drainage of agriculturally marginal uplands
49 expanded rapidly after the Second World War in Britain (Holden et al., 2007). Since the start of the 19th
50 century systematic controlled patch burning to attain the optimum habitat for gun sport related birds has
51 been widespread in the UK uplands and this has included burning of vegetation on blanket peatlands
52 (Yallop et al., 2006). Atmospheric pollution since the industrial revolution, particularly the deposition of
53 sulphur and nitrogen, has been linked with the declining abundance of *Sphagnum* (Ferguson et al., 1978;

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54 Lee, 1998). Elevated stocking densities for sheep associated with the EU Common Agricultural Policy
55 have been linked with enhanced erosion and degradation of upland peatlands in the UK (Rawes and
56 Hobbs, 1979; Holden et al., 2007) since peatlands often have a very low carrying capacity (Simpson et al.,
57 1988).

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59 However, realization of the economic and environmental value of peatlands and the damage that has been
60 caused to them has led both public and private organizations to implement ‘restoration’ schemes (Holden
61 et al., 2007). On the whole, restoration schemes in blanket peatlands have focused on the objectives of
62 raising the water table via blocking drainage channels and gullies, re-vegetating bare areas of peat that are
63 prone to erosion (Parry et al., 2014) and attempting to replace some vegetation assemblages with
64 assemblages that are thought to be suitable for rapid peat formation (Holden et al., 2008). The word
65 ‘restore’ implies that practitioners attempt to reverse the adverse effects that have occurred and return the
66 ecosystem to a pre-disturbance state (Charman, 2002). However, rarely is the full historical developments
67 of a site investigated, and so target restoration points related to a former condition are not known with any
68 certainty (Chambers and Daniells, 2011). Information from surveys and aerial imagery regarding
69 vegetation will only span at most the last two centuries providing a limited context. In many instances
70 ‘full restoration’ is not feasible as the damage is too severe. However, restoration to conditions similar to
71 those pre-disturbance may be attainable and lead to a peatland more resilient to climate change.

72
73 A further impetus for peatland restoration schemes has been the increased dissolved organic carbon
74 (DOC) in watercourses that has been widely reported across European and North American peatland
75 systems. Changes in atmospheric deposition chemistry (Evans et al., 2005; Skjelkvåle et al., 2005;
76 Stoddard et al., 2003) land management and vegetation type have been shown to be important drivers of
77 DOC release in peatlands (Holden et al., 2012; Wilson et al 2011; Wallage et al., 2006; Armstrong et al.,
78 2012). High levels of DOC entering raw water treatment works are very costly to deal with because
79 complex methods of treatment are required to avoid the production of carcinogens which can be released

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4 80 during water disinfection when dissolved organic loads are high (Pereira et al., 1992; Chow et al., 2003).

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6 81 Thus a number of water companies are seeking to invest in catchment management on peatlands to reduce
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8 82 DOC loads to treatment works. Implementing changes in land management practice can be difficult as
9
10 83 landowners may be doubtful of the benefits and question whether their peatland site is really ‘atypical’ in
11
12 84 terms of its vegetation history, preferring to view the current landscape as a norm, a view based largely on
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14 85 living memory.
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19 87 Palaeoecological techniques offer an excellent way to gain information regarding the past ecological
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21 88 status of a site, providing a long term perspective (Willis and Birks, 2006) from which plans for
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23 89 remediation devised by land managers can be well informed and supported. Despite this, palaeoecological
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25 90 studies have rarely been employed in peatlands with the aim of informing future land management (Davis
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27 91 and Wilkinson 2004; Chambers et al., 2007; 2013). As Willis and Birks (2006) suggest ‘conservation-
28
29 92 related research largely ignores palaeoecological records’. Palaeoecological techniques have been
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31 93 employed on peat-based archives in the UK for over a century, but since the 1970s there has been a sharp
32
33 94 increase in studies examining peatland development and also determining Mid-Late Holocene climate
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35 95 change (Blundell and Barber 2005; Charman et al., 2009). Many techniques have been employed
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37 96 including examination of macrofossils (Barber et al., 1994, 2003), testate amoebae (Charman et al.,
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39 97 2007), levels of humification (Chambers and Blackford, 2001), isotopes (Daley et al., 2010) and
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41 98 biomarkers (Bingham et al., 2010).
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49 100 This study takes a reservoir catchment in northern England (Keighley Moor) and undertakes
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51 101 palaeoecological analyses in order to illustrate how they can provide important tools for informing and
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53 102 shaping blanket peat restoration targets. We seek to test whether the vegetation condition of the site today
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55 103 is unusual in the context of the site’s development over the past few thousand years. If the current
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57 104 vegetation condition is unusual then this would support those who seek to adopt interventions on the site
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59 105 to alter the vegetation cover and the data would provide some ecological indicators of restoration success.
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4 106 If the vegetation cover is not unusual in the context of the site peatland development history then this
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6 107 would support those who wish to continue to manage it to maintain its current state.

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9 108 The objectives of the study were:

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11 109 1) To establish the ecological history of the site.
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13 110 2) To test whether *Sphagnum* (as a common contemporary indicator of peatland condition) has been
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15 111 of historical importance at the site.
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17 112 3) To test whether the present ecological status is ‘atypical’ based upon the derived ecological
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19 113 history.
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21 114 4) To assess the extent to which the current vegetation is a function of contemporary management
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23 115 practice.
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29 117 **2.0 Site description**

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32 118 Keighley Moor Reservoir catchment (KMRC) has an area of 1.48 km² (Figure 1) and is 3.5 km west of
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34 119 Oakworth in northern England (53°85’31’’ N, -02°02’13’’ E). The underlying geology is predominately
35
36 120 formed from the Millstone Grit Group of the Carboniferous period. Superficial geology recorded by the
37
38 121 British Geological Survey is that of ‘Peat’ although a detailed peat depth survey has never been carried
39
40 122 out on the site. The reservoir is fed by two main streams from the ‘northern’ and ‘southern’ catchments.
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42 123 These streams have a series of tributaries constituting first and second order streams with their own sub-
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44 124 catchments. Present day vegetation is dominated by *Calluna vulgaris* (Common heather) but also
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46 125 regularly includes *E. vaginatum* (hares tail cotton grass), *Eriophorum angustifolium* (common cotton
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48 126 grass) and *Vaccinium myrtillus* (bilberry) especially on shallow substrate. *Sphagnum* is rare but species
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50 127 include *S. fallax* in flushed gulleys and *S. capillifolium*, *S. fimbriatum* and *S. cuspidatum*. Present day
51
52 128 vegetation at the key sampling point (master core location, see below) is dominated by *Calluna vulgaris*
53
54 129 with lesser components of *Eriophorum vaginatum*, *Eriophorum angustifolium* and *Campylopus*
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56 130 *pyriformis*. The present day vegetation at most of the site would suggest a relatively inactive bog with
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131 regard to peat accumulation. The site is managed to promote grouse shooting, is grazed by sheep and
132 there is no evidence of artificial drainage, especially near the area where the key detailed palaeoecological
133 analyses have originated (master core, see below). KMRC has been managed for grouse since the 1870s
134 (pers comm. Gamekeeper) and burning has been employed systematically with the classic ‘patch’ pattern
135 characteristic of many of England’s uplands. Reports from the previous gamekeeper suggest that at least
136 two wildfires occurred in the last century, one in 1918 and one in the 1940s. Evidence of wildfire,
137 including isolated peat pedestals and isolated ‘whale back’ formations has been documented. Records of
138 depth to water table from an automated logger (2010 - 2013) in the area where we have carried out
139 detailed palaeoecological analyses (master core, see below), which is in a part of the catchment free of
140 erosion features, indicates that the water table is within 0-5 cm and 5.1-10 cm of the surface for 66% and
141 87% of the time, respectively, with the deepest recorded water-table depth being 24.6 cm.

143 **3.0 Methodology**

144 Palaeoecological and field survey techniques can be time intensive and hence to achieve our aims a tiered
145 approach was employed. The site underwent an extensive peat depth survey together with detailed
146 stratigraphic logging to permit a catchment-wide assessment of the site’s development (tier 1). This also
147 allowed us to find areas suitable for a master core for detailed laboratory analysis. These areas needed to
148 be intact to ensure a long record, not extensively eroded by gullies and located close to dipwells in our
149 modern monitoring program (which was focused on hydrology and water quality for water company
150 needs) to enable future comparison between modern and palaeo data. To provide confidence that the
151 master core location would be representative of the developmental changes in that area, a higher spatial
152 resolution stratigraphic survey (tier 2) was completed before obtaining the master core for detailed
153 investigation in the final phase of work (tier 3).

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4 155 Peat depth was measured at 122 survey points using a narrow gouge corer, allowing the substrate to be
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6 156 examined by hand providing confidence that the 'entire' depth of peat was measured (Parry et al., in
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8 157 press). Peat depth was then interpolated across the catchment from the 122 points using Kriging in
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10 158 ArcGIS 10.1. Stratigraphy and physical components of 88 of the gouge cores were logged using the
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12 159 Troels-Smith scheme (Troels-Smith, 1955). This scheme enables expert users to describe the substrate's
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14 160 physical components in the field. After retrieval of the core it was split visually into sections in the field
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16 161 based on changing peat components. Physical components of each stratigraphically defined section of the
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18 162 cores were split into five possible parts describing the peats composition (0, 1, 2, 3, and 4) representing 0,
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20 163 25, 50, 75 and 100%. Descriptive groupings in the Troels-Smith scheme are simple yet effective and here
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22 164 include *Turfa bryophitica* (mosses, Tb), *Turfa herbosa* (rhizomes of herbaceous plants, Th), *Turfa lignosa*
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24 165 (roots of ligneous plants, Tl), and *Substantia humosa* (humous substance, Sh). If a stratigraphically
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26 166 distinct section from 0.10-0.20 m, for example, was composed of half mosses and half sedge root remains
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28 167 the sample would be Tb² Th². All distinct stratigraphic sections of each core were logged.
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35 169 Four specific measures were extracted for examination from each core log.
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- 37 170 1) Maximum estimated abundance of *Sphagnum* remains in the top 0.3 m (Figure 2a).
- 38 171 2) Maximum estimated abundance of *Sphagnum* remains in the top 0.05 m (Figure 2b)
- 39 172 3) Greatest depth that *Sphagnum* (at least 1 part, 25%) is recorded (Figure 2c).
- 40 173 4) The total number of meters from each core with at least 1 part (25%) *Sphagnum* (Figure 2d).

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46 176 The 'master core' for detailed laboratory analysis was sampled using a monolith tin for 0 - 0.50 m depth
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48 177 to maximise the volume of peat recovered. For deeper samples two overlapping 1 m long (0.09 m wide)
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50 178 Russian cores from 0 - 1.00 m and 0.70 - 1.70 m were recovered to minimise disturbance. The deepest
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52 179 samples between 1.50 and 1.90 m were obtained using and a narrow gauge 0.50 m long Russian corer
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54 180 which was able to be pushed through the peat to mineral boundary. Cores were placed in plastic guttering,
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4 181 wrapped in cling film and stored at 4°C. Monolith and cores were sub-sampled for a) spheroidal
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6 182 carbonaceous particles (SCPs) (2 cm³ samples) and b) macrofossils (4 cm³ samples). Macrofossil samples
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8 183 were prepared to determine the previous vegetation history of the site using standard techniques as
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10 184 detailed by Barber et al. (1994) and the remains were quantified using the Quadrat and Leaf Count
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12 185 method (Barber et al., 1994). Amesbury et al. (2010) explored the potential limits for sampling
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14 186 resolutions from cores obtained from raised bogs and suggested that 5 mm is the maximum meaningful
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16 187 potential resolution. Due to time constraints and the belief that many of the same plant remains would be
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18 188 re-sampled with such a high resolution, a 0.01m contiguous sampling resolution was employed from 0 -
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20 189 0.50 m, with 0.04 m intervals used for deeper parts of the peat profile. Nomenclature for *Sphagnum*
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22 190 mosses follows the scheme of Daniels and Eddy (1990), whereas for other bryophytes and vascular plants
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24 191 we follow the schemes of Smith (1978) and Stace (1991), respectively. The resulting macrofossil diagram
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26 192 was split into zones based upon major changes in macrofossil components. Charcoal pieces were summed
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28 193 as absolute counts of charcoal >125 µm. However, at some depths charcoal was so abundant that % of
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30 194 quadrat was used.

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37 196 To support an understanding of the timelines for the vegetation reconstructions determined by the
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39 197 macrofossil analysis above, radiocarbon dates were obtained at nine depths from the master core. Three
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41 198 were taken from the top 0.50 m of peat and six within 0.50 – 1.74 m. One basal radiocarbon date was also
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43 199 obtained from the deepest stratigraphy core from our chosen area (for the master core) to determine the
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45 200 likely date of peat initiation. Sub-sampled 1 cm³ peat blocks were washed with deionized water in a 125
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47 201 µm sieve and *Sphagnum* leaves, branches or stems were selected in order to minimize potential
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49 202 contamination. Samples were dated via Accelerator Mass Spectrometry (AMS) at the Chrono Laboratory
50
51 203 at Queens University Belfast. Care was taken to remove ericaceous roots to prevent any possible reservoir
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53 204 effects as described by Kilian et al. (1995). Dates were calibrated, using the IntCal13.14C (Reimer et al.,
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55 205 2013), and an age-depth model (linearly interpolated) produced using the CLAM software derived by
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57 206 Blaauw (2010).

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208 Radiocarbon dating is unsuitable for dating peat from the last 200 years due to dilution of ^{14}C with ^{12}C
209 from fossil fuel burning and also anthropogenic release of ^{14}C from atomic explosions. SCPs, airborne by-
210 products of fossil fuel burning, were used to date the most recent peat. Age determinations were made
211 based on comparison of the regionally observed (Rose et al., 1995; 2005) initiation (1850+/-25), ‘take off’
212 point (1955 +/- 10) and peak (1978 +/-6) to our SCP curve. SCPs were counted from 0 - 0.20 m using a
213 modified method to that detailed by Rose (1990, 1994). Samples of 0.1 g of dried peat were digested in 3
214 mL of HNO_3 for 24 h. Further HNO_3 was added and a water bath used for 2 hours to aid digestion. After
215 washing and drying, the resulting samples containing inorganic material only were weighed. A measured
216 amount of the sample was then re-wetted and mounted on a slide and the abundance of SCPs counted at
217 $\times 400$ magnifications and expressed as SCPs gDM^{-1} .

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219 **4.0 Results**

220 4.1 Peat depth survey

221 Peat depth was not uniform across the catchment (Figure 1). Based on interpolated data, 47% of the
222 catchment had peat depths ≥ 0.6 m, 15% ≥ 1.30 m and only 5% ≥ 1.80 m. Three distinct areas (Areas 1-
223 3) of ‘deep peat’ were identified where peat was deeper than 1.30 m (Figure 1). Area 2 had the greatest
224 maximum depth of 3.72 m but all three areas had similar mean values of between 1.50 and 1.85 m.

225

226 4.2 Catchment-wide stratigraphy

227 The 88 points across the catchment used for detailed stratigraphic analysis are shown in Figure 1. A total
228 of 37 of the 88 cores had evidence of *Sphagnum* remains. In the top 0.30 m (c. cal AD 1600 in the master
229 core) *Sphagnum* remains were evident in 35 of the 88 records but these tended to be in areas of deep peat
230 (Area 1-2). Here a transition appears to have occurred from highly decomposed peat at the base through
231 sedge peat, and mainly within the upper metre *Sphagnum* peat was encountered. Cores at locations where

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4 232 there was <0.6 m of peat present were generally composed of highly decomposed material with some
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6 233 identifiable remains of sedges and *Erica* (Figure 2a). Within the top 0.05 m of the cores, only five
7
8 234 sampled sites showed abundant *Sphagnum* remains (Figure 2b). *Sphagnum* remains were apparent at
9
10 235 greatest depth and spanned the greatest depths in Areas 1 and 2 (Figure 2c & d). In Area 3 *Sphagnum*
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12 236 remains were only evident in three of the four cores and of these three *Sphagnum* remains existed only
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14 237 from 0.21 to 0.12 m from the surface.
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20 239 The decline in *Sphagnum* occurrence from 0.30 to 0.05 m depth in most instances where *Sphagnum* was
21
22 240 present, was associated with a transition to a highly decomposed amorphous black/dark brown peat
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24 241 containing charcoal. Charcoal was evident sporadically in all cores but in Areas 1-3 it was especially
25
26 242 prevalent at the base of the peat and in the uppermost 0.30 m. In the uppermost 0.30 m of peat in Areas 1-
27
28 243 3 charcoal appeared in relatively small amounts across the depth range in 58% of the cores. However, it
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30 244 also appeared as a distinct and concentrated band, c. 0.05 m in thickness, within the top 0.20 m.
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35 246 At the base of the deepest core (Area 2, 3.70 m) there were remains of *Phragmites* (Common reed)
36
37 247 suggesting standing water (Figure 3). Birch/Alder wood coincident with charcoal at the point of peat
38
39 248 initiation is also evident in areas of deep peat demonstrating the existence of at least some tree cover
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41 249 before peat accumulation (Figure 3). Transition from mineral (mainly bedrock/regolith) to organic-
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43 250 dominated material occurs over 0.2 to 0.3 m from the base of the profile in cores from Area 1-3.
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48 49 252 4.3 Stratigraphy around master core

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51 253 Results from Transect A are examined here; those from Transects B-G are available in the Supplementary
52
53 254 Data. The deepest accumulation (2.94 m) of peat was at the downslope end of Transect A (core 15, Figure
54
55 255 4-5). Across cores 76 to 16 (180 m) a relatively uniform depth of peat (2.00 m) existed. However, peat
56
57 256 depth thinned to ~1.00 m, 150 m upslope of this transect. Highly degraded amorphous (*Substantia*
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59 257 *humosa*) material was dominant in the lower portion of all the cores from Transect A varying in extent
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4 258 from ~0.20 to 0.90 m (Figure 5). Cores 15, 76 and 82 in the deepest part of Area 1 contained remains of
5
6 259 Birch wood close to the transition from mineral substrate to organic accumulation suggesting the previous
7
8 260 existence of some tree cover. Charcoal was a major feature at the base of most cores from transect A and
9
10 261 was coincident with peat initiation and the decline of arboreal macrofossils. Highly degraded basal peat
11
12 262 was succeeded by peat often dominated by sedge remains (*Turfa herbosa*) together with more
13
14 263 decomposed unidentifiable material (Figure 5). After this were substantial, yet variable, levels of
15
16 264 *Sphagnum* remains in the top metre of most cores in transect A. The role of *Sphagnum* in the development
17
18 265 of the upper peat across Transect A increased down slope with increased presence in cores 15, 76, 83,
19
20 266 MASTER and 78 (Figure 5). All transect cores (A-G) displayed a shift from *Sphagnum* remains to
21
22 267 degraded peat (*Substansia humosa*), often associated with charcoal, woody roots from ericaceous plants
23
24 268 (*Turfa lignosa*) and sedge roots (*Turfa herbosa*) in the upper 0.15 m. A discrete band of black amorphous
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26 269 material with abundant levels of charcoal existed at around 0.05 – 0.10 m depth in transect A. Although
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28 270 concentrated in the basal layers and the uppermost 0.15 m of peat, sporadic evidence of charcoal existed
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30 271 throughout the cores.
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38 273 4.4 Master core

40 274 4.4.1 Chronology

42 275 SCPs from the master core displayed a typical abundance curve for Northern Britain with a pronounced
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44 276 peak and subsequent decline up to the present day. Based on the resolution of the SCP record and the
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46 277 ‘peaky’ profile, three dating points were employed; the initiation of the record at 0.110-0.115 m, the rapid
47
48 278 rise in SCPs at 0.040 - 0.045 m and the peak at 0.030 - 0.035 m depth which corresponds to AD 1850+/-
49
50 279 25, 1955+/-10 and 1978+/-4 respectively (Rose and Appleby, 2005). These have been incorporated
51
52 280 together with the radiocarbon dates to derive a chronology for the site (Table 1). Accumulation rates
53
54 281 between dating points range from 42 yrs cm⁻¹ near the base of the peat to as high as 8 yrs cm⁻¹ at depths of
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56 282 0.42 to 0.73 m.
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4 284 4.4.2 Macrofossils
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6 285 The macrofossil record (Figure 6) was zoned by eye based on major shifts in vegetation composition.
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8 286 Fifteen zones were identified from the earliest (Zone A) to the most recent (Zone O). These zones are
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10 287 summarised in Table 2.
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15 289 **5.0 Discussion**

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18 290 The spatial richness of the peat depth and stratigraphy survey and the detail of the master core analysis
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20 291 provided an excellent basis for understanding the development of the peatland at KMRC, especially with
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22 292 respect to the historical presence or absence of *Sphagnum*.
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27 294 5.1 Early development

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29 295 There were three areas (Area 1-3) of deep peat deposits at the site and these are likely to have been the
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31 296 initial foci of peat accumulation. Data from coring demonstrates that peat initiation occurred primarily
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33 297 over previously wet mineral ground via paludification (Rydin and Jeglum, 2006). However, in Area 2
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35 298 evidence of *Phragmites* remains in the deepest area of peat accumulation suggest the existence of
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37 299 intermittent standing water (Haslam, 1972) and possibly a spatially limited aquatic phase of initiation.
38
39 300 Initiation in Area 1 was radiocarbon dated to 2020-1850 BC (2 sigma range) at a depth of 2.85m but
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41 301 initiation may be considerably older in Area 2 where peat is recorded at a deeper level (3.72m). These
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43 302 areas represent nodes of peat initiation from where paludification to the immediate surroundings occurred.
44
45 303 Peat initiation has been recorded in the English Pennines across a wide range of time (Tallis, 1991) with
46
47 304 three major phases c. 7050 BC, 5550-5050 BC and 3550 BC all of which are older than the oldest date
48
49 305 found for Area 1 but may correspond to peat initiation in Area 2, although this needs corroboration. As
50
51 306 found in other records in the British Isles, and largely attributed to human activity (Charman, 1992; Tallis,
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53 307 1991), peat initiation at KMRC was associated with extensive charcoal deposits (26 of the 88 stratigraphy
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55 308 cores) indicating burning. Spatially sporadic evidence also existed for a decline in tree growth at KMRC
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309 coincident with burning. This may point to decreased inception and hence greater potential for water
310 logging.

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312 Highly degraded organic material containing some ericaceous and monocotyledon remains accumulated
313 once peat initiation began in Areas 1-3 before any sign of *Sphagnum* growth. The master core showed this
314 initial phase (800 years duration at a rate of 42yrs cm⁻¹) followed by a phase of fluctuating *E vaginatum*
315 and UOM-dominated peat lasting c. 600 years (35 yrs cm⁻¹). Burning was prevalent and, in part, appeared
316 to correlate with lower *E vaginatum* abundance. Low pH and low base saturation are required for such
317 oligotrophic vegetation to take hold (Wein 1973; Hughes et al., 2000) and it is often associated with
318 peatland environments that experience spring flooding and desiccation in the summer (Hughes et al.,
319 2000). After examining raised bog peat, Hughes et al. (2000) suggested that *Eriophorum vaginatum*
320 domination was suited to an unstable water table where insufficient peat had built up to impede drainage
321 and allow more stable water-table conditions. Evidence of the soil fungus *Cenococcum*, a fungus that
322 implies aerated surface conditions (Ferdinandson and Winge, 1925) further support an unstable water
323 table where frequent dessication occurred.

324
325 *5.2 Evidence of Sphagnum*

326 For some of the catchment (51 of the 88 stratigraphy cores), particularly where the organic-rich deposit is
327 less than 0.60 m in thickness (and hence may not be classified as 'peat'), there is little evidence of any
328 *Sphagnum* remains at all. Where peat deposits exist in the catchment *Sphagnum* was evident only after the
329 initial peatland development phase described in section 5.1 implying the need for a more elevated or
330 stable water table. *Sphagnum*, unlike *E. vaginatum*, does not tolerate long periods of water deficit (Clymo
331 and Hayward, 1982; Wein, 1973). Establishment of *Sphagnum* may be simply an on-going autogenic
332 succession. However, in the master core the first establishment of *Sphagnum* was dated to c. AD 590
333 which is coincident with the Dark Age period in Europe (Lamb (1977, 1995). Many recorded changes in
334 peatland stratigraphy are noted in this period as being related to wetter climatic conditions (Blackford and

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4 335 Chambers, 1991; Blundell et al., 2005). *Sphagnum* taxa were an important and often dominant component
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6 336 of the upper peat profile at KMRC together with sedges and ericaceous plants. Evidence from the master
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8 337 core demonstrated that *S.* section *Acutifolia*, *S. magellanicum*, *S. papillosum* and *S.* section *Cuspidata*
9
10 338 have all been prevalent at some point over the last 1500 years. Abundance of these species has fluctuated
11
12 339 extensively however, often in conjunction with evidence of burning. These burning events are the likely
13
14 340 result of man's attempts to improve grazing, a pressure that has been highly variable, at least up until the
15
16 341 industrial revolution. Burning has been a feature throughout the history of the KMRC peatland
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18 342 development but crucially, however, when *Sphagnum* has been affected by fire it has later returned. This
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20 343 reflects the fact that there has likely been a diverse mosaic of plant groups that have been able to respond
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22 344 and adapt to these changes in burning (Ellis, 2008). *Sphagnum* moss especially, *S. papillosum*, *S.*
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24 345 *magellanicum* and *S. rubellum*, have been observed as being sensitive to burning (Pearsall, 1956;
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26 346 Ratcliffe, 1964).
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31 348 Data from the master core showed that since the early 1900s a distinct and 'atypical' change in the
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33 349 vegetation at KMRC occurred. *Sphagnum* declined from the master core and from 30 of the 36
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35 350 stratigraphic cores where *Sphagnum* was recorded in the upper 0.30 m of peat. The present day vegetation
36
37 351 is dominated by *Calluna vulgaris*. Evidence of *Sphagnum* on the present day surface is generally sparse
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39 352 with five species of *Sphagnum* identified across the catchment as a whole: *S. fallax*, *S. fimbriatum*, *S.*
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41 353 *palustre* (very sparse), *S. cuspidatum* and *S. capillifolium*. *S. fallax* is largely confined to wet flushes in
42
43 354 streams and gullies and the remaining species are extremely rare. The vegetation at the surface of the site
44
45 355 changed from an 'active' blanket bog system within the 19th century to what might be termed an inactive
46
47 356 state today. The term inactive is often used for peatlands when there is only very slow accumulation of
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49 357 peat and *Sphagnum* is lacking. It is typically used in the UK when National Vegetation Classification
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51 358 categories (Rodwell, 1991) M15, M17, M18, or M19 cannot be readily ascribed to the peatland.
52
53 359 Coincident with the decline in *Sphagnum* around the start of the 20th century was the highest abundance
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55 360 of charcoal observed throughout the 2900yr master core history (c. AD 1920, 0.05-0.07 m). This charcoal
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361 layer contained 70, 42 and 17% charcoal at 0.05, 0.07 and 0.06 m depths respectively. Such a high level
362 of charcoal (Figure 5 & 6) would suggest a major uncontrolled fire or fires which relates well to those
363 suggested by the local gamekeeper to have been c. 1918 and in the 1940s. The base of the charred layer is
364 dated to c. AD 1920 and the upper limit at c. AD 1955 putting the layer in the correct time frame
365 matching personal accounts. Uncontrolled burns (wildfire), unlike prescribed patch burning (Holden et
366 al., 2011), often occur in summer months, may burn for a long time attaining great intensity (Kayll, 1966)
367 and may lead to the peat mass becoming ignited potentially causing extensive problems of erosion
368 (Maltby, 1990; Tucker 2003). Such an event would probably impact the peat's chemical and physical
369 properties and its vegetation cover (Mallik, 1984; Maltby et al., 1990; Doerr et al., 2006). Unlike previous
370 burning events at the site over the last 1000 years, the last century has seen no recovery in *Sphagnum*
371 cover from fire. There is evidence of peat loss from parts of the catchment due to erosion post fire and it
372 is likely that the stability of the water table and mean water table levels will have been adversely affected
373 which will have led to a reduction in *Sphagnum* and increase in vascular plants. However, although fire is
374 likely to have burned the surface of the peat, there has been no discernable loss of peat from the master
375 core location due to wildfire. A steady accumulation rate for the last 600 years of c. 15 yrs cm⁻¹
376 demonstrates this. Although the decline of *Sphagnum* appears to be associated with the evidence for
377 wildfire the continued absence thereafter is coincident with less concentrated but continued charcoal
378 remains related to repeated and systematic burning for grouse moor management. The charcoal remains
379 over the past century are coincident with a rise in *Calluna vulgaris* dominance in the catchment and at the
380 master core the burning is even to the detriment of monocotyledons which had been a consistent
381 component throughout the peat profile. The contemporary vegetation at KMRC is atypical in the context
382 of the past thousand years and it seems clear that this is at very least in part due to land management
383 practice as it is coincident with the initiation and continued practice of systematic burning. The timing of
384 the decline of *Sphagnum* in the master core does not equate with the onset of elevated air pollution (SOx
385 and NOx compounds) for the Pennine region of the mid 1800s (Yeloff, 2006) but such pollution
386 (Ferguson and Lee, 1980) and the potential elevated nutrient source (Bragazza, 2006) is also likely to

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387 have had an impact on the abundance of *Sphagnum*. Excess N availability, for example, has been shown
388 experimentally to be detrimental to many *Sphagnum* taxa (Gunnarsson and Rydin, 2000; Heijmans et al.,
389 2001) and beneficial for growth rates of vascular plants (Limpens et al., 2003). Loss of *Sphagnum* from
390 the site is also likely to of had a detrimental effect on potential DOC production as vegetation that
391 produces litter that is more degradable now dominates.

392

393 5.3 Applications of palaeoecological data

394 At KMRC, peat depth, stratigraphy and master core analyses have provided enlightening context
395 regarding the site's historical development demonstrating an 'atypical' present day status. Peat depth data
396 alone permits those devising restoration schemes to take into account where the greatest levels of carbon
397 storage are. The important role and spatial pattern of *Sphagnum* moss occurrence in the peatland's
398 development up until the 20th century has also been highlighted. This provides support for restoration
399 plans to revive *Sphagnum* moss in a focused way, encouraging it primarily in the areas of deeper peat
400 accumulation where it has been demonstrated historically as being relatively resilient. This study has
401 demonstrated that the decline of *Sphagnum* and prevalence of *Calluna vulgaris* at KMRC has been
402 associated with wildfire and recent prescribed burning practice. While evidence at KMRC has
403 demonstrated that burning has been a factor at the site since peat initiation, only recently does burning
404 practice appear to have contributed to a major 'atypical' shift in vegetation. Long-term stability of
405 peatland vegetation in the past has been demonstrated as a result of contrasting plant groups that can
406 respond to external pressures such as climate change and burning (Ellis, 2008). This diversity has been
407 lost over the last century at KMRC and other sites potentially depleting the resilience of many of these
408 blanket peatlands.

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410 This study has supported Yorkshire Water, the local water company whose reservoir is downstream of the
411 site, in developing peatland management initiatives at the site and in setting a potential precedent for their
412 work elsewhere. The ability to demonstrate that until the start of the 20th century *Sphagnum* played an

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4 413 important role in the peatland at KMRC supports modern initiatives to promote a return to a more diverse
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6 414 mosaic of vegetation including greater *Sphagnum* abundance. The work has provided a more grounded
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8 415 ‘restoration target’, based on knowledge of local peatland development. Such restoration targets may also
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10 416 help reduce levels of DOC entering water treatment works (Armstrong et al., 2012) and may slow runoff
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12 417 production and reduce flood risk (Holden et al 2008; Grayson et al., 2010). Curtis et al. (2014) have raised
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14 418 the question as to whether potential recovery targets using a pre-industrial reference of upland water
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16 419 ecosystems are achievable or even desirable based on future climate projections. However, this does not
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18 420 detract from the value of obtaining background historical information from which informed management
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20 421 decisions can be made in light of all available evidence and in understanding how peatlands respond to
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22 422 environmental change. Similar palaeoecological studies in other peatlands could provide historical
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24 423 context to provide stronger support for restoration targets or changes to current management practice, for
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26 424 sites around the world. Minimum recommended levels of data acquisition depends entirely on the area
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28 425 and type of peatland being considered but an initial coarse spatial resolution stratigraphic and peat depth
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30 426 survey of the site would allow this to be determined. A tiered approach with stratigraphic surveys
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32 427 informing the position of and supporting the findings from more detailed core analyses is recommended.
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43 430 **6.0 Conclusions**

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46 431 Palaeoecological studies that provide historical context and help inform restoration targets to help
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48 432 safeguard the health of blanket peatlands could act as an important link in the chain of management
49
50 433 decisions which support the long term provision of multiple ecosystem services.

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53 434 At our study site it has been demonstrated that:

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55 435 1) The present vegetation state is ‘atypical’ and is in part likely to be a result of increased human
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57 436 interference, including systematic burning, over the last 100 years.
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437 2) Wildfire and later systematic burning for grouse moor management has had a detrimental effect on
438 the presence of *Sphagnum*.

439 3) *Sphagnum* has played a significant role in parts of the site’s development in the last 1000 years up
440 to the early 1900s.

441 4) Attempting to ‘restore’ *Sphagnum* back to parts of the site is a legitimate goal in fitting with the
442 sites past development.

443 Attempting to return shrub-dominated peatland towards more sedge, grass and moss dominant sites is
444 likely to result in benefits in water quality, biodiversity and carbon sequestration. We advocate further
445 simple palaeoecological studies at a wider range of peatland sites where there is conflict over whether the
446 current vegetation assemblage is typical or atypical of the site history.

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4 **732 Figure captions.**

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7 **733** Figure 1. Location of KMRC (inset) and location of survey points and stratigraphy cores together with
8 **734** interpolated peat depths and the three main areas of peat ≥ 1.30 m in depth.

9
10 **735** Figure 2. Abundance (1-4, representing 25, 50 75 or 100%) of *Sphagnum* remains in each core from a) 0-
11 **736** 0.3 m and b) 0-0.05 m and c) the maximum depth recorded for *Sphagnum* (at least 1 part, 25%) and d) the
12 **737** greatest total number of meters with *Sphagnum* (at least 1 part, 25%).

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15 **738** Figure 3. Selection of stratigraphy profiles from the deepest cores in Areas 1-3. Each segment is split into
16 **739** four parts each representing 1 part of the Troels-Smith classification of physical components. Here black
17 **740** represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*.
18 **741** Areas of charcoal are marked with asterisks whereas evidence of birch/alder wood and *Phragmites* are
19 **742** denoted by B/A and Ph.

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22 **743** Figure 4. Location of detailed stratigraphy survey around master core location. Transect A described in
23 **744** the main text runs from right to left and includes core numbers 15, 76, 83, 78, 89, MASTER, 90, 30 and
24 **745** 16.

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27 **746** Figure 5. Stratigraphy cores from transect A. Cores are not displayed attitudinally as there is too much
28 **747** elevation change between cores. Each segment is split into four parts each representing 1 part of the
29 **748** Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey
30 **749** *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are
31 **750** marked with asterisks. Lines between asterisks denote continued frequent charcoal remains. Evidence of
32 **751** birch/alder wood and *Phragmites* are denoted by B/A and Ph.

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35 **752** Figure 6. Macrofossil diagram for KMRC master core. Peat components are derived from averaged
36 **753** quadrat counts under low-power magnification ($\times 10$). Leaf counts are a breakdown of the % Identifiable
37 **754** *Sphagnum* and consist of proportions based on a random selection of leaves (100 per sample interval
38 **755** where possible) identified at high magnification ($\times 400$). Bar graphs are absolute counts. For charcoal,
39 **756** Charcoal 1 represents proportion of charcoal in each quadrat count and is used only when absolute counts
40 **757** are not feasible due to the large level of remains. Charcoal 2 represents the absolute count of charcoal
41 **758** pieces over 125 μm .
42 **759**

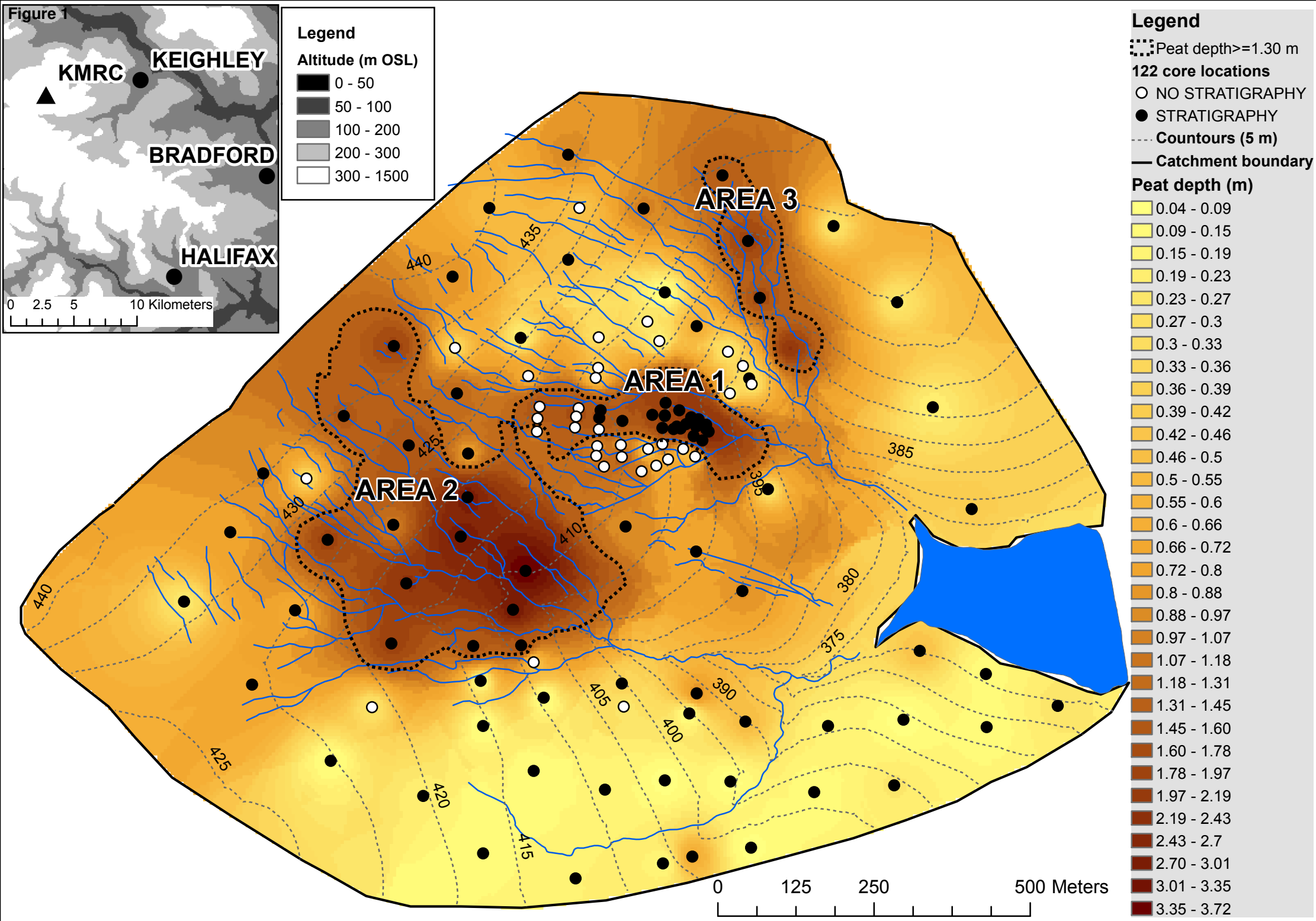
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46 **760 Table caption**

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48 **761** Table 1. AMS radiocarbon dates, calibrated (2 sigma range). Dates are from the master core apart from
49 **762** the final entry which is from a separate core at the deepest peat/mineral interface in Area 1.

50
51 **763** Table 2. Summary of main changes in macrofossils from the master core.
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Figure 1



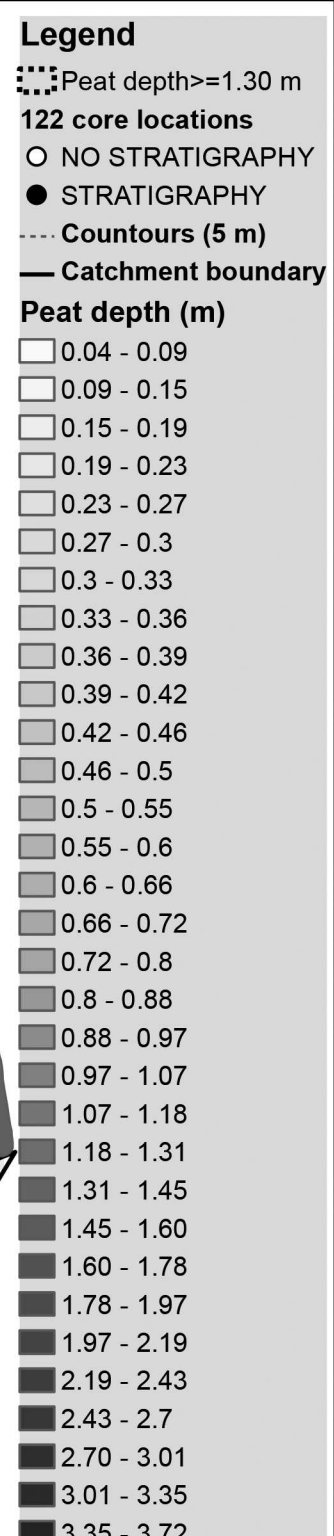
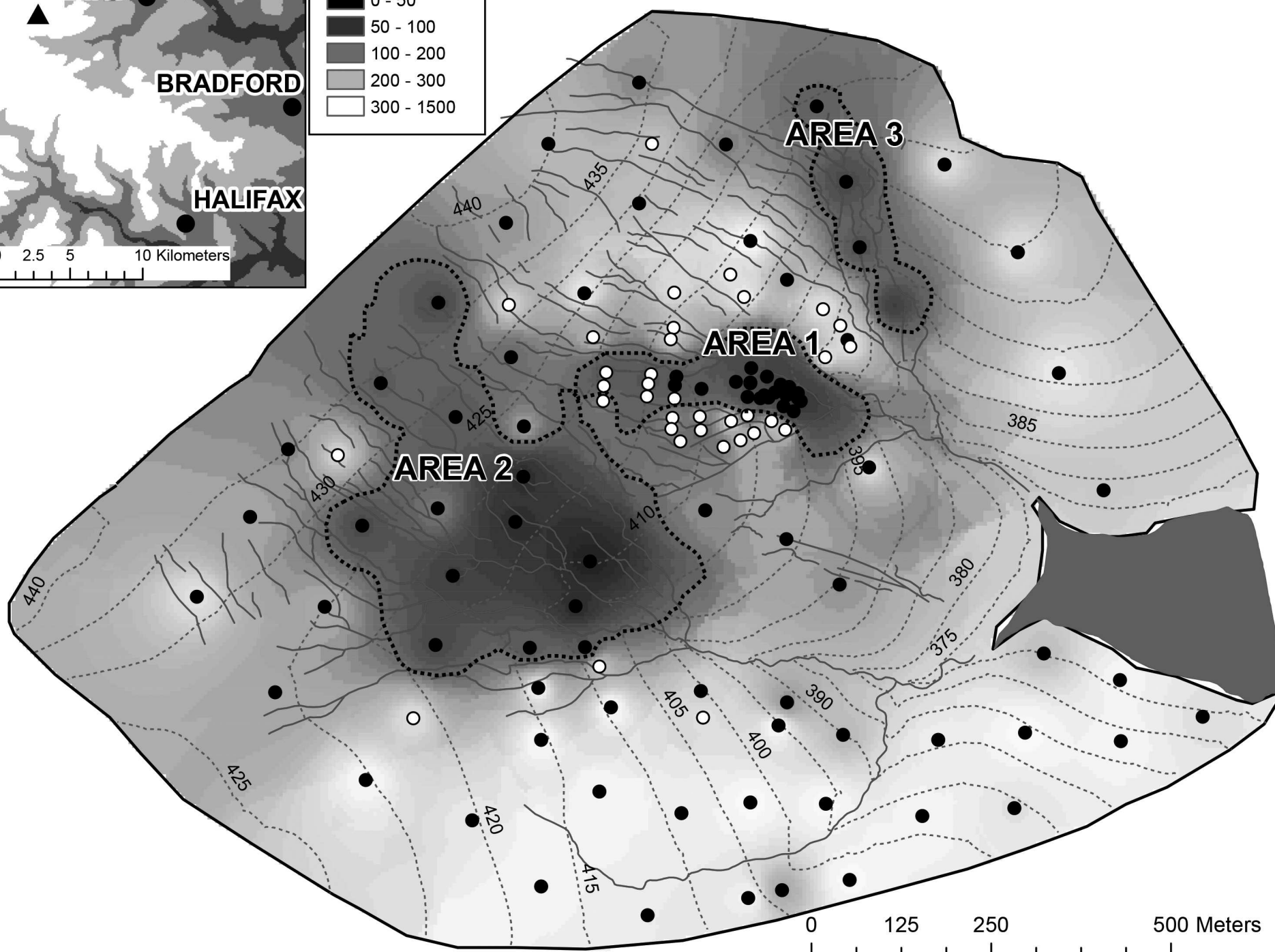
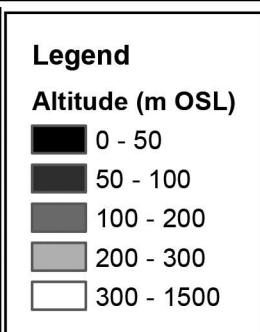
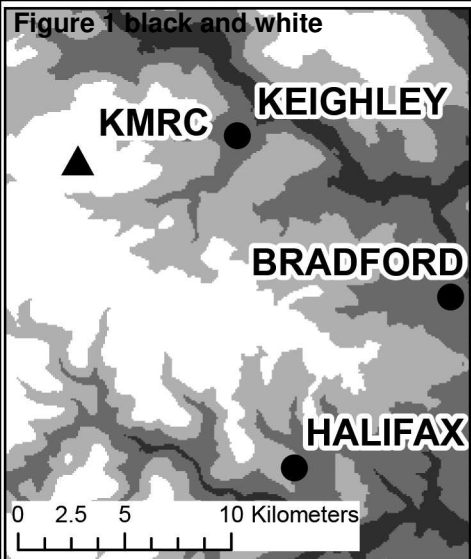


Figure 2
[Click here to download high resolution image](#)

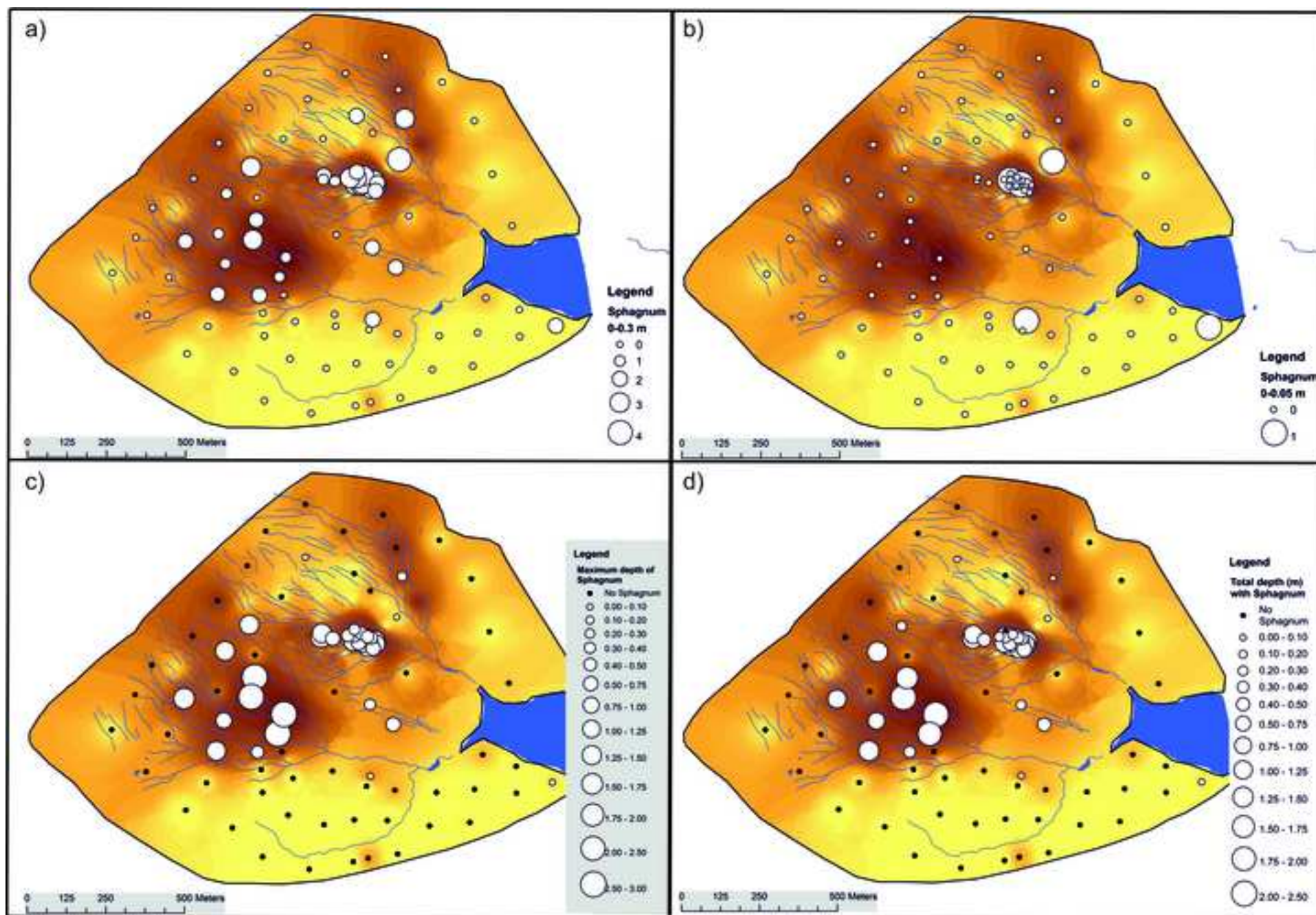


Figure 2 black and white
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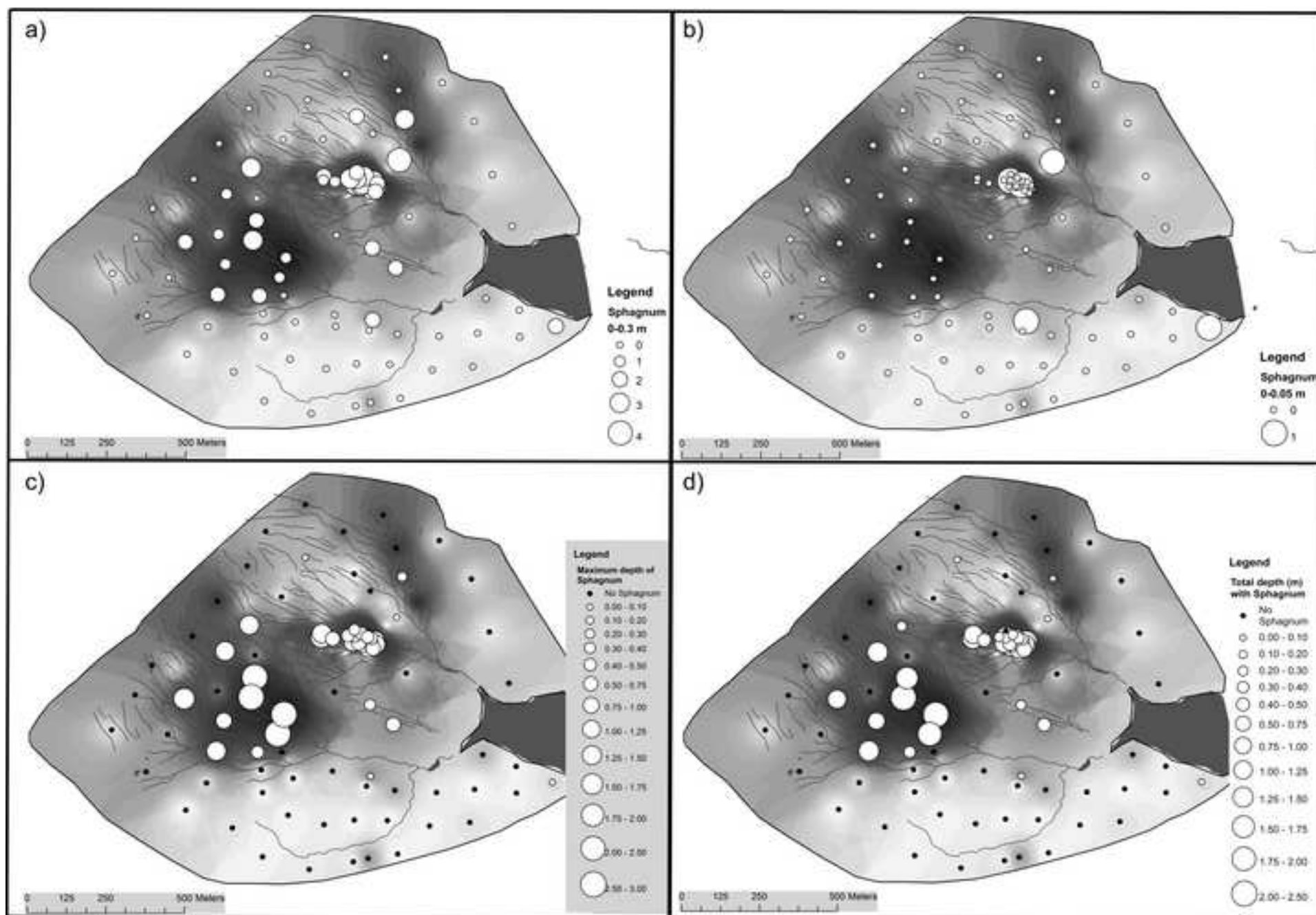


Figure 4

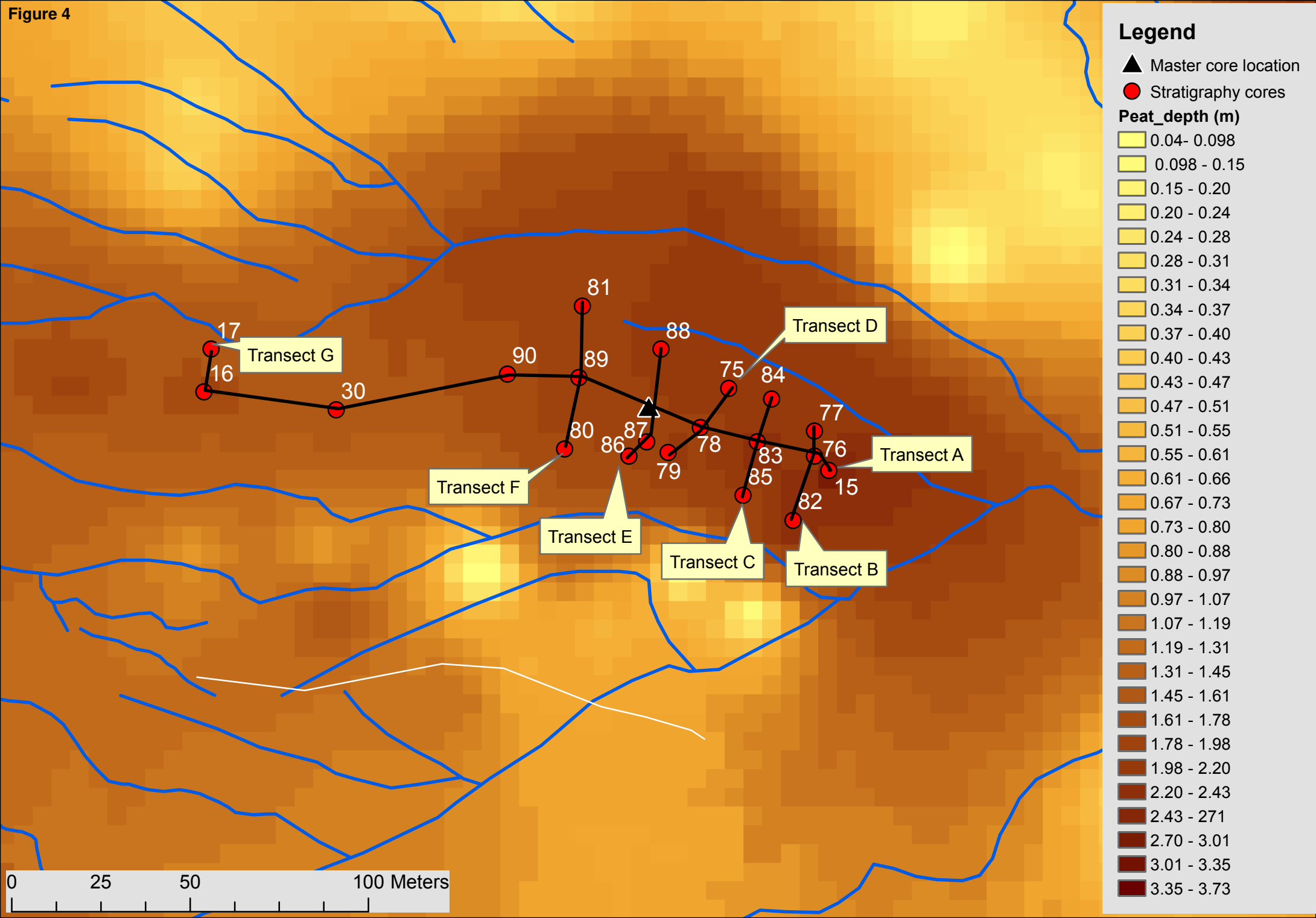


Figure 4 black and white

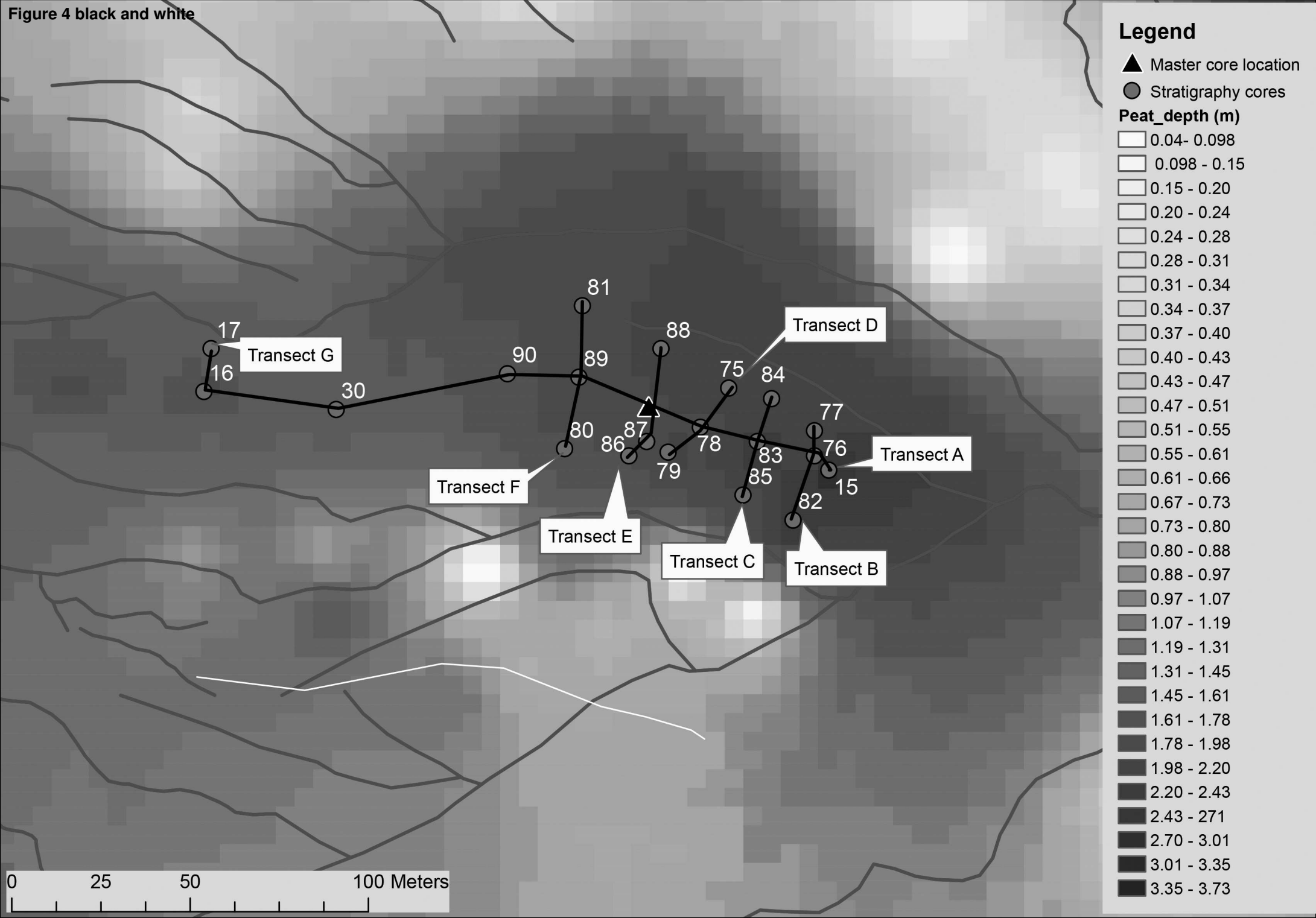


Figure 5

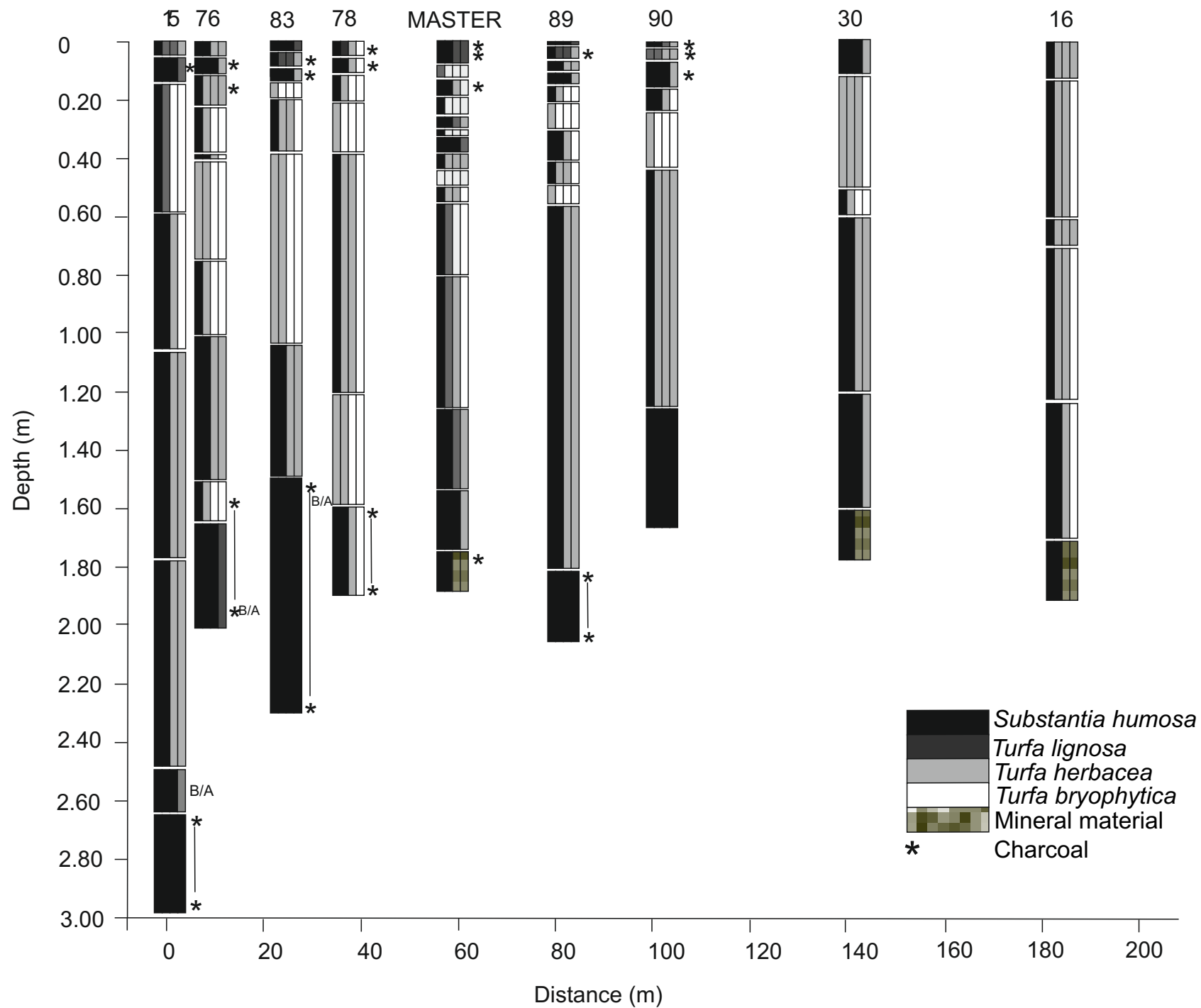


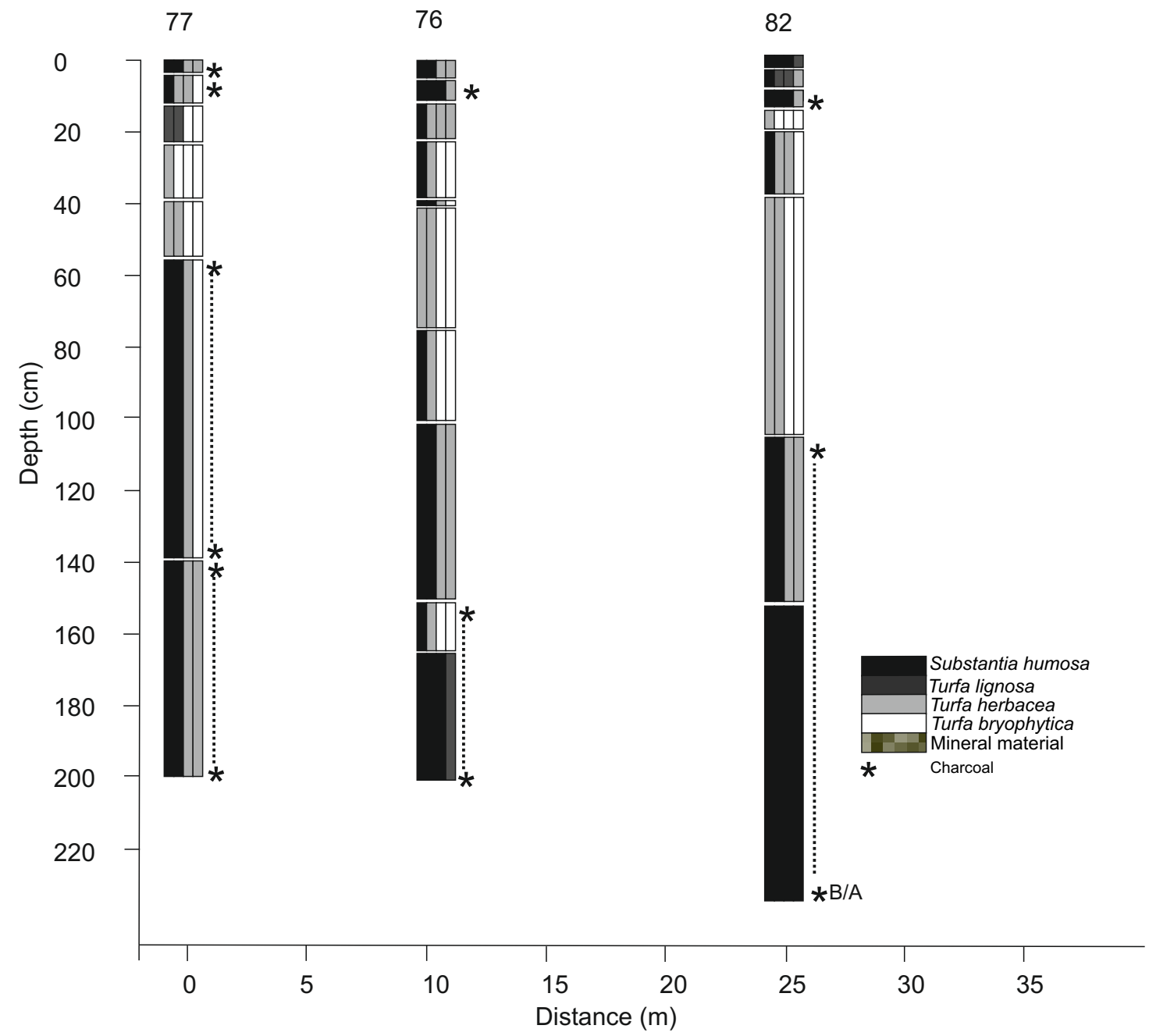
Table 1

Lab no.	Code	Depth (m)	Material	¹⁴ C Age	+/-	AMS δ ¹³ C	Cal 2σ range BP	Cal 2σ range AD/BC
UBA-18258	KM 20 BLUND	0.205	<i>Sphagnum</i> leaves/branches/stems	177	30	-26.3	- 4 - 295	1954 -1655
UBA-18259	KM 28 BLUND	0.285	<i>Sphagnum</i> leaves/branches/stems	258	32	-37.1	-3 - 432	1953 - 1518
UBA-18260	KM 42 BLUND	0.425	<i>Sphagnum</i> leaves/branches/stems	580	27	-30.5	535 - 646	1415 - 1304
UBA-18672	KM 73 BLUND	0.735	<i>Sphagnum</i> leaves/branches/stems	909	25	-32.7	744-914	1206 - 1036
UBA-18671	KM 98 BLUND	0.985	<i>Sphagnum</i> leaves/branches/stems	1227	27	-24.3	1068-1259	882 - 691
UBA-18673	KM 122 BLUND	1.225	<i>Sphagnum</i> leaves/branches/stems	1472	38	-30.6	1296-1480	654 - 470
UBA-18677	KM 140 BLUND	1.405	Bulk peat	1664	34	-29.2	1421-1693	529 - 257
UBA-18676	KM 154 BLUND	1.545	Bulk peat	2078	35	-25.6	1950-2142	1 - -192
UBA-18263	KM 174 BLUND	1.745	Bulk peat	2785	26	-29.3	2796 - 2954	-846 - -1004
UBA-20133	KM 285 BLUND	2.85	Bulk peat	5100	30	-30.4	3968 - 3800	-2018 - -1850

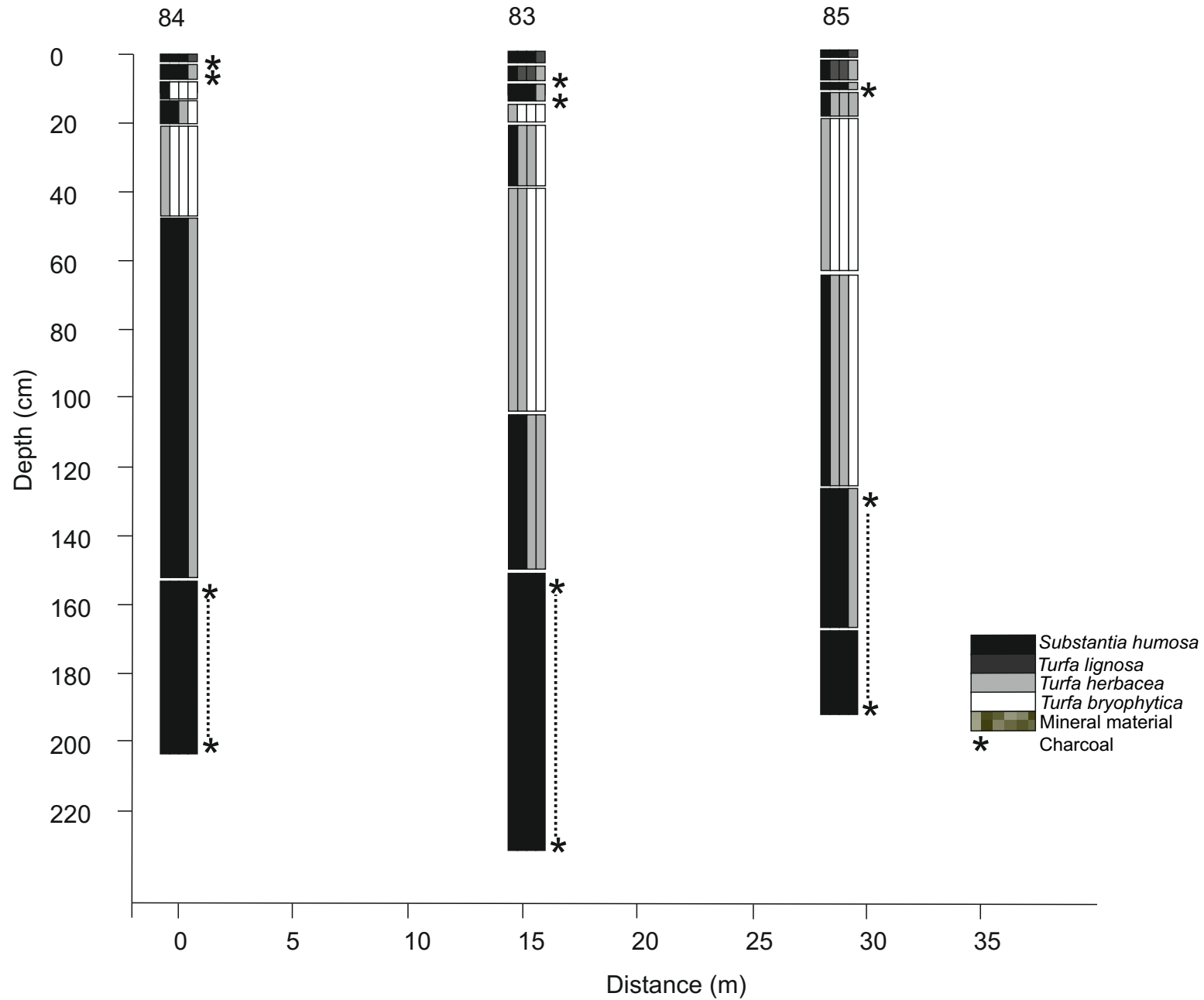
Table 2

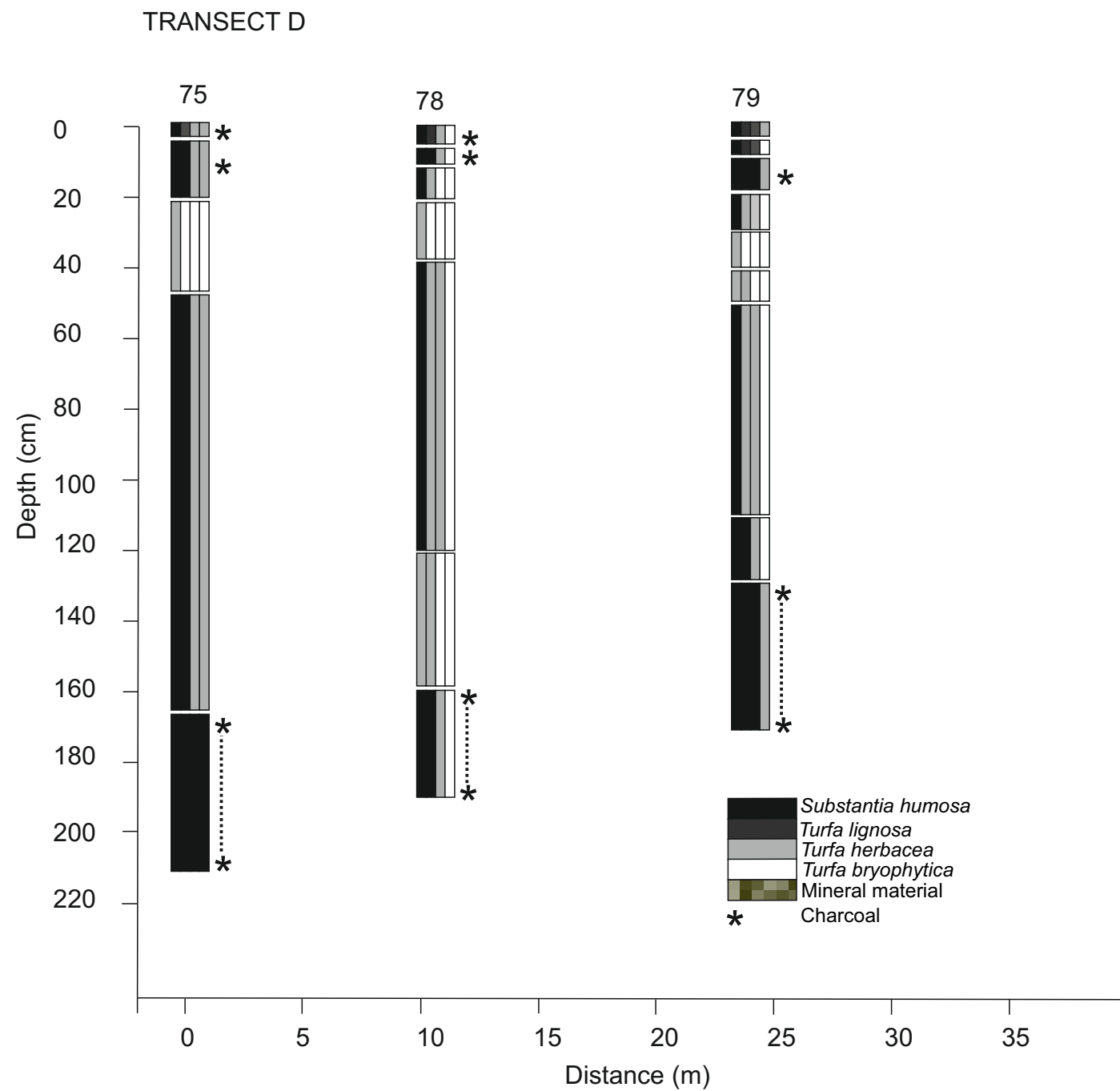
Zone	Depth (m)	Age AD/BC	Macrofossils
A	(1.89 – 1.75)	950 BC	Quartz grains and some finer mineral matter together with charcoal and monocot remains.
B	(1.75 – 1.55)	950 – 120 BC	Peat initiation. Highly decomposed material with few identifiable macrofossils. Ericaceous plants are evident with monocots. Charcoal abundant at start of zone.
C	(1.55 – 1.24)	120 BC – AD 570	Dominated by <i>E. vaginatum</i> or UOM, fluctuations that are coincident with charcoal. Ericaceous plant remains are evident including <i>Calluna vulgaris</i> .
D	(1.24 – 0.80)	570 – 1030	<i>Sphagnum</i> (<i>Sphagnum</i> section <i>Acutifolia</i> and some evidence of <i>S.s.Cuspidata</i>) is evident for the first time. Initial high abundance declines to ~10% and is associated with increased charcoal and a mix of ericaceous and monocot remains.
E	(0.80 – 0.56)	1030 – 1250	<i>S. magellanicum</i> and <i>S. s. Acutifolia</i> dominate. Ericaceous roots evident ~20% but leaves less evident.
F	(0.56 – 0.465)	1250 – 1320	<i>Sphagnum</i> declines as <i>E. vaginatum</i> dominates. Little evidence of burning. Ericaceous decline roots to ~10%.
G	(0.465 – 0.415)	1320 – 1370	Major reduction in <i>E. vaginatum</i> as initially <i>S. s. Acutifolia</i> and subsequently <i>S. magellanicum</i> increases to dominate.
H	(0.415 – 0.385)	1370 – 1430	Major decline in <i>Sphagnum magellanicum</i> as <i>E. vaginatum</i> remains dominate.
I	(0.395 – 0.305)	1430 – 1570	Increase in UOM (>60%) as <i>E. vaginatum</i> remains decline. <i>Sphagnum</i> evident but remains low.
J	(0.305 – 0.275)	1570 – 1630	Increase in <i>S. s. Acutifolia</i> to > 60%
K	(0.275 – 0.235)	1630 – 1700	Increasing charcoal and <i>E. vaginatum</i> (>60%) remains.
L	(0.235 – 0.185)	1700 – 1770	<i>S. magellanicum</i> dominates (>60%). Charcoal absent.
M	(0.185 – 0.135)	1770 – 1830	UOM increases with <i>E. vaginatum</i> . Charcoal frequent.
N	(0.135 – 0.075)	1830 – 1910	<i>S. papillosum</i> is dominant. <i>S.s.Cuspidata</i> is also evident.
O	(0.075 – 0)	1910 – 2010	Charcoal dominates (up to 70% of sample) from 0.07-0.05 m. Charcoal reduces but remains abundant until the present. Ericaceous material increases. <i>Calluna</i> leaves/wood/flowers all increase. <i>Campylopus piriformis</i> is present at the surface.

TRANSECT B

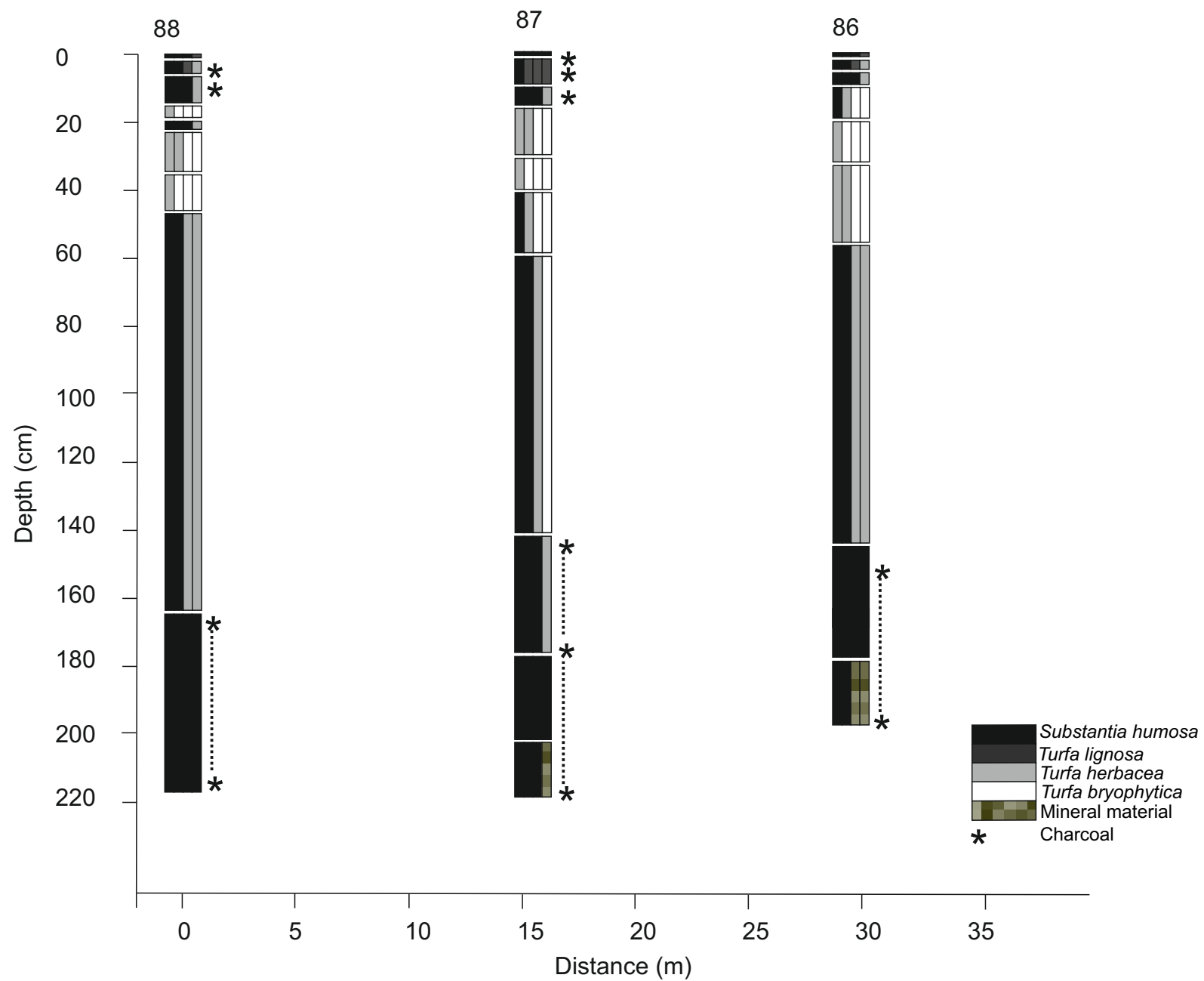


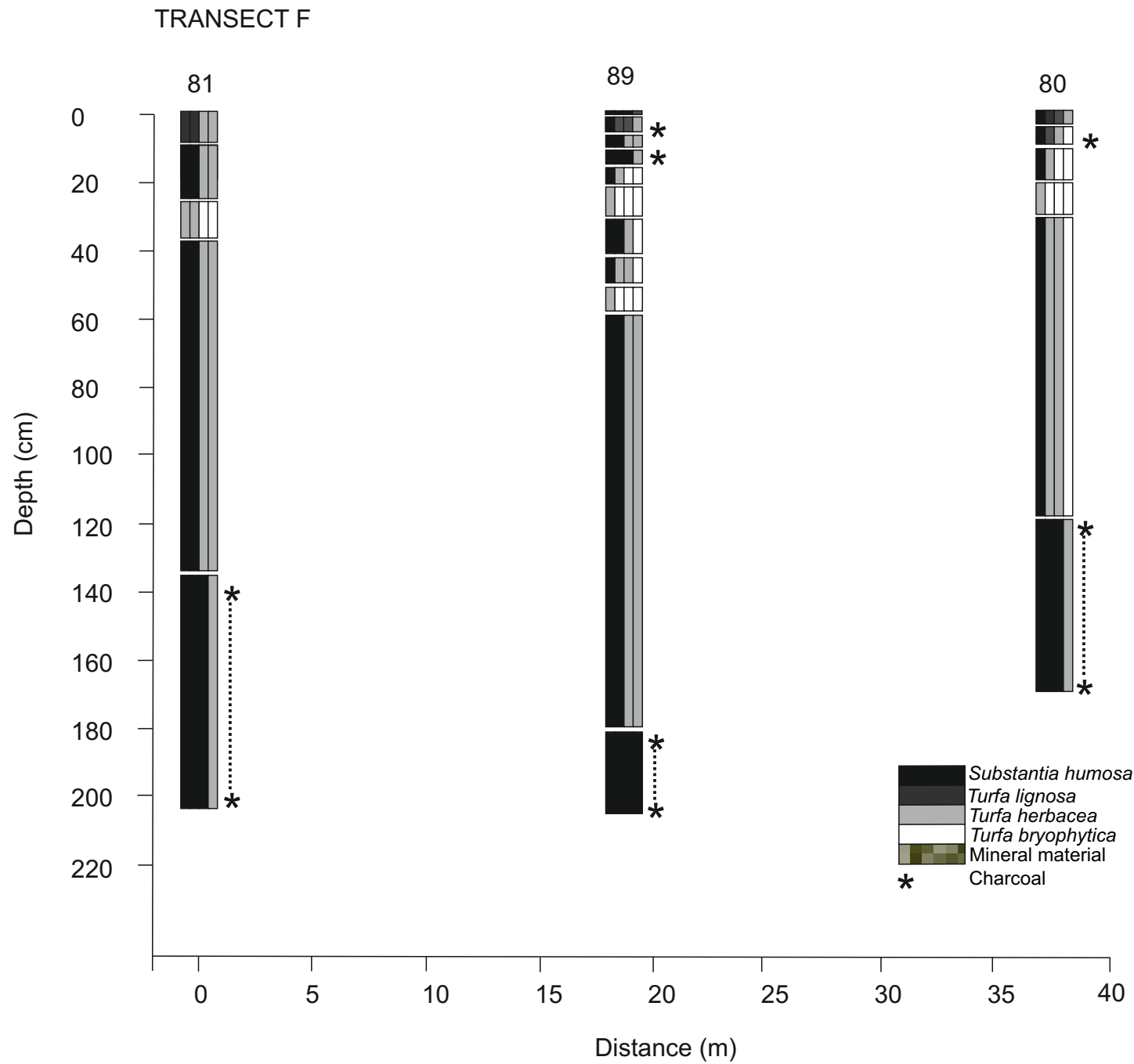
TRANSECT C



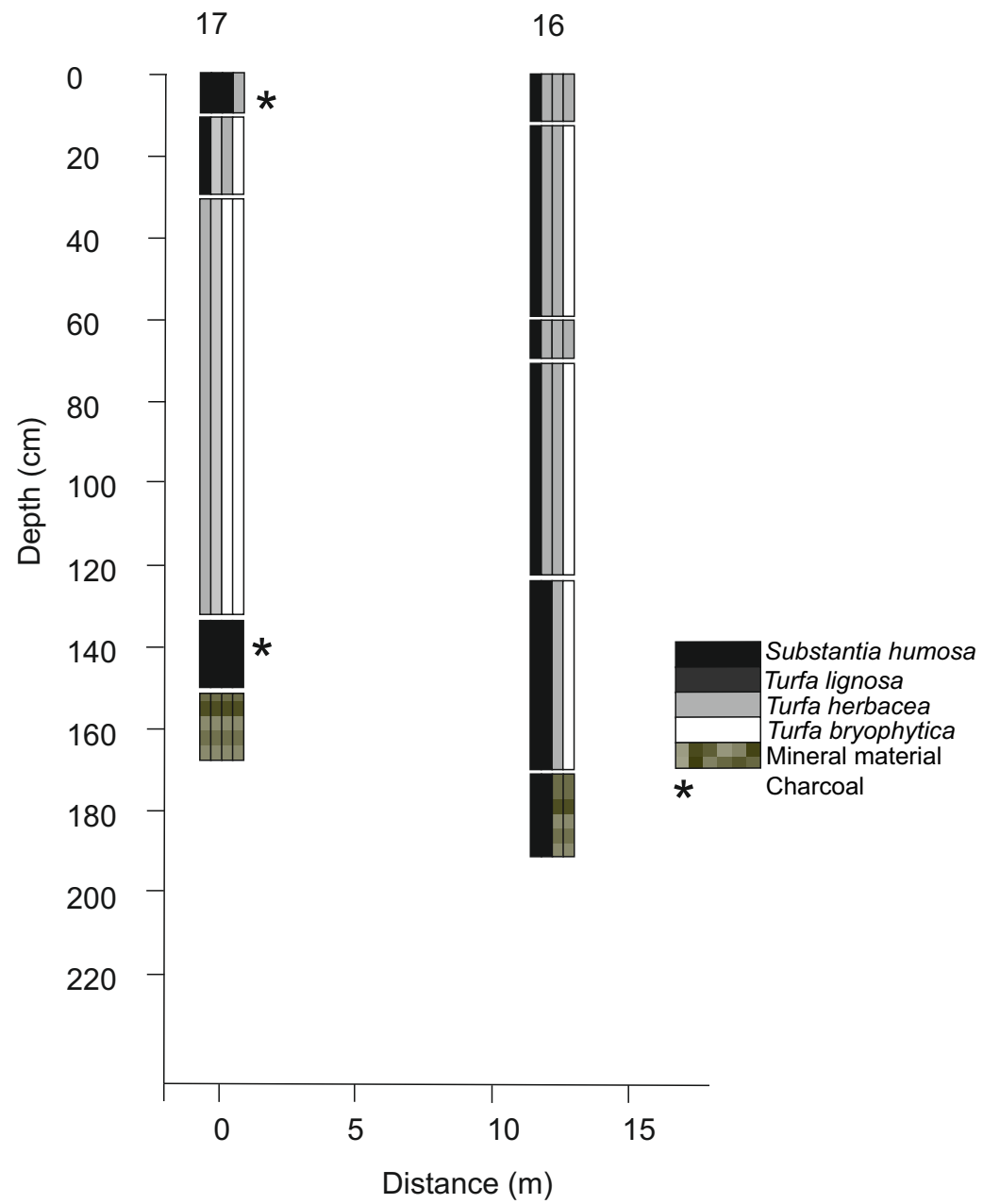


TRANSECT E





TRANSECT G



Supplementary Figure 1. Stratigraphy cores from transect B. Cores are not displayed attitudinally as there is too much elevation change between cores. Each segment is split into four parts each representing 1 part of the Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are marked with asterisks. Lines between asterisks denote continued frequent charcoal remains.

Supplementary Figure 2. Stratigraphy cores from transect C. Cores are not displayed attitudinally as there is too much elevation change between cores. Each segment is split into four parts each representing 1 part of the Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are marked with asterisks. Lines between asterisks denote continued frequent charcoal remains.

Supplementary Figure 3. Stratigraphy cores from transect D. Cores are not displayed attitudinally as there is too much elevation change between cores. Each segment is split into four parts each representing 1 part of the Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are marked with asterisks. Lines between asterisks denote continued frequent charcoal remains.

Supplementary Figure 4. Stratigraphy cores from transect E. Cores are not displayed attitudinally as there is too much elevation change between cores. Each segment is split into four parts each representing 1 part of the Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are marked with asterisks. Lines between asterisks denote continued frequent charcoal remains.

Supplementary Figure 5. Stratigraphy cores from transect F. Cores are not displayed attitudinally as there is too much elevation change between cores. Each segment is split into four parts each representing 1 part of the Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are marked with asterisks. Lines between asterisks denote continued frequent charcoal remains.

Supplementary Figure 6. Stratigraphy cores from transect G. Cores are not displayed attitudinally as there is too much elevation change between cores. Each segment is split into four parts each representing 1 part of the Troels Smith classification of physical components. Here black represents *Substantia humosa*, dark grey *Turfa lignosa*, grey *Turfa herbosa* and white *Turfa bryophitica*. Areas of concentrated charcoal are marked with asterisks. Lines between asterisks denote continued frequent charcoal remains.

