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Using palaeoecology to support blanket peatland management

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Abstract

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

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

1.0 Introduction

The world's peatlands cover 3% of the Earth's land surface but contribute 30% of its soil carbon (Parish et al., 2008) and store more organic carbon per hectare than any other terrestrial store. Degraded peatland (one tenth of the peatland resource) contributes 6% of global anthropogenic CO_2 emissions (Joosten et al., 2012). Globally, peatland degradation is mainly via agriculture, forestry, peat extraction for fuel or horticulture and urbanisation. Such degradation jeopardises the ecosystem services peatlands provide (Parry et al., 2014; Maltby and Acreman, 2011; Bonn et al 2009). Blanket peatlands form over sloping landscapes under conditions of a large moisture excess and poor underlying drainage. They are typically found in temperate hyper-oceanic regions (Lindsay et al. 1988) such as eastern Russia, the South Island of New Zealand, southern Alaska and parts of the Atlantic northwest Europe (Gallego-Sala and Prentice, 2012). It is estimated that 10-15% of all blanket bog worldwide is located in the British Isles (Tallis et al., 1997). In the UK, blanket peatland covers 1.5 million hectares with around 14% (215 000 ha) in England (Jackson and McLeod, 2000). These areas are also the largest terrestrial carbon reserves in the UK acting 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., 2003).

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

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

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

A further impetus for peatland restoration schemes has been the increased dissolved organic carbon (DOC) in watercourses that has been widely reported across European and North American peatland systems. Changes in atmospheric deposition chemistry (Evans et al., 2005; Skjelkvåle et al., 2005; Stoddard et al., 2003) land management and vegetation type have been shown to be important drivers of DOC release in peatlands (Holden et al., 2012; Wilson et al 2011; Wallage et al., 2006; Armstrong et al., 2012). High levels of DOC entering raw water treatment works are very costly to deal with because complex methods of treatment are required to avoid the production of carcinogens which can be released during water disinfection when dissolved organic loads are high (Pereira et al., 1992; Chow et al., 2003). Thus a number of water companies are seeking to invest in catchment management on peatlands to reduce DOC loads to treatment works. Implementing changes in land management practice can be difficult as landowners may be doubtful of the benefits and question whether their peatland site is really ‘atypical’ in terms of its vegetation history, preferring to view the current landscape as a norm, a view based largely on living memory.

Palaeoecological techniques offer an excellent way to gain information regarding the past ecological status of a site, providing a long term perspective (Willis and Birks, 2006) from which plans for remediation devised by land managers can be well informed and supported. Despite this, palaeoecological studies have rarely been employed in peatlands with the aim of informing future land management (Davis and Wilkinson 2004; Chambers et al., 2007; 2013). As Willis and Birks (2006) suggest ‘conservation-related research largely ignores palaeoecological records’. Palaeoecological techniques have been employed on peat-based archives in the UK for over a century, but since the 1970s there has been a sharp increase in studies examining peatland development and also determining Mid-Late Holocene climate change (Blundell and Barber 2005; Charman et al., 2009). Many techniques have been employed including examination of macrofossils (Barber et al., 1994, 2003), testate amoebae (Charman et al., 2007), levels of humification (Chambers and Blackford, 2001), isotopes (Daley et al., 2010) and biomarkers (Bingham et al., 2010).

This study takes a reservoir catchment in northern England (Keighley Moor) and undertakes palaeoecological analyses in order to illustrate how they can provide important tools for informing and shaping blanket peat restoration targets. We seek to test whether the vegetation condition of the site today is unusual in the context of the site’s development over the past few thousand years. If the current vegetation condition is unusual then this would support those who seek to adopt interventions on the site to alter the vegetation cover and the data would provide some ecological indicators of restoration success.

If the vegetation cover is not unusual in the context of the site peatland development history then this would support those who wish to continue to manage it to maintain its current state.

The objectives of the study were:

1) To establish the ecological history of the site.
2) To test whether Sphagnum (as a common contemporary indicator of peatland condition) has been of historical importance at the site.
3) To test whether the present ecological status is 'atypical' based upon the derived ecological history.
4) To assess the extent to which the current vegetation is a function of contemporary management practice.

2.0 Site description

Keighley Moor Reservoir catchment (KMRC) has an area of 1.48 km^2 (Figure 1) and is 3.5 km west of Oakworth in northern England (53°85'31'' N, -02°02'13'' E). The underlying geology is predominately formed from the Millstone Grit Group of the Carboniferous period. Superficial geology recorded by the British Geological Survey is that of 'Peat' although a detailed peat depth survey has never been carried out on the site. The reservoir is fed by two main streams from the 'northern' and 'southern' catchments. These streams have a series of tributaries constituting first and second order streams with their own sub-catchments. Present day vegetation is dominated by Calluna vulgaris (Common heather) but also regularly includes E. vaginatum (hares tail cotton grass), Eriophorum angustifolium (common cotton grass) and Vaccinium myrtillus (bilberry) especially on shallow substrate. Sphagnum is rare but species include S. fallax in flushed gulleys and S. capillifolium, S. fimbriatum and S. cuspidatum. Present day vegetation at the key sampling point (master core location, see below) is dominated by Calluna vulgaris with lesser components of Eriophorum vaginatum, Eriophorum angustifolium and Campylopus pyriformis. The present day vegetation at most of the site would suggest a relatively inactive bog with regard to peat accumulation. The site is managed to promote grouse shooting, is grazed by sheep and there is no evidence of artificial drainage, especially near the area where the key detailed palaeoecological analyses have originated (master core, see below). KMRC has been managed for grouse since the 1870s (pers comm. Gamekeeper) and burning has been employed systematically with the classic ‘patch’ pattern characteristic of many of England’s uplands. Reports from the previous gamekeeper suggest that at least two wildfires occurred in the last century, one in 1918 and one in the 1940s. Evidence of wildfire, including isolated peat pedestals and isolated ‘whale back’ formations has been documented. Records of depth to water table from an automated logger (2010 - 2013) in the area where we have carried out detailed palaeoecological analyses (master core, see below), which is in a part of the catchment free of erosion features, indicates that the water table is within 0-5 cm and 5.1-10 cm of the surface for 66% and 87% of the time, respectively, with the deepest recorded water-table depth being 24.6 cm.

3.0 Methodology

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

Peat depth was measured at 122 survey points using a narrow gouge corer, allowing the substrate to be examined by hand providing confidence that the ‘entire’ depth of peat was measured (Parry et al., in press). Peat depth was then interpolated across the catchment from the 122 points using Kriging in ArcGIS 10.1. Stratigraphy and physical components of 88 of the gouge cores were logged using the Troels-Smith scheme (Troels-Smith, 1955). This scheme enables expert users to describe the substrate’s physical components in the field. After retrieval of the core it was split visually into sections in the field based on changing peat components. Physical components of each stratigraphically defined section of the cores were split into five possible parts describing the peats composition (0, 1, 2, 3, and 4) representing 0, 25, 50, 75 and 100%. Descriptive groupings in the Troels-Smith scheme are simple yet effective and here include Turfa bryophitica (mosses, Tb), Turfa herbosa (rhizomes of herbaceous plants, Th), Turfa lignosa (roots of ligneous plants, Tl), and Substantia humosa (humous substance, Sh). If a stratigraphically distinct section from 0.10-0.20 m, for example, was composed of half mosses and half sedge root remains the sample would be Tb^2 Th^2. All distinct stratigraphic sections of each core were logged.

Four specific measures were extracted for examination from each core log.

1) Maximum estimated abundance of Sphagnum remains in the top 0.3 m (Figure 2a).
2) Maximum estimated abundance of Sphagnum remains in the top 0.05 m (Figure 2b)
3) Greatest depth that Sphagnum (at least 1 part, 25%) is recorded (Figure 2c).
4) The total number of meters from each core with at least 1 part (25%) Sphagnum (Figure 2d).

The ‘master core’ for detailed laboratory analysis was sampled using a monolith tin for 0 - 0.50 m depth to maximise the volume of peat recovered. For deeper samples two overlapping 1 m long (0.09 m wide) Russian cores from 0 - 1.00 m and 0.70 - 1.70 m were recovered to minimise disturbance. The deepest samples between 1.50 and 1.90 m were obtained using and a narrow gauge 0.50 m long Russian corer which was able to be pushed through the peat to mineral boundary. Cores were placed in plastic guttering, wrapped in cling film and stored at 4°C. Monolith and cores were sub-sampled for a) spheroidal carbonaceous particles (SCPs) (2 cm^3 samples) and b) macrofossils (4 cm^3 samples). Macrofossil samples were prepared to determine the previous vegetation history of the site using standard techniques as detailed by Barber et al. (1994) and the remains were quantified using the Quadrat and Leaf Count method (Barber et al., 1994). Amesbury et al. (2010) explored the potential limits for sampling resolutions from cores obtained from raised bogs and suggested that 5 mm is the maximum meaningful potential resolution. Due to time constraints and the belief that many of the same plant remains would be re-sampled with such a high resolution, a 0.01m contiguous sampling resolution was employed from 0 - 0.50 m, with 0.04 m intervals used for deeper parts of the peat profile. Nomenclature for Sphagnum mosses follows the scheme of Daniels and Eddy (1990), whereas for other bryophytes and vascular plants we follow the schemes of Smith (1978) and Stace (1991), respectively. The resulting macrofossil diagram was split into zones based upon major changes in macrofossil components. Charcoal pieces were summed as absolute counts of charcoal >125 µm. However, at some depths charcoal was so abundant that % of quadrat was used.

To support an understanding of the timelines for the vegetation reconstructions determined by the macrofossil analysis above, radiocarbon dates were obtained at nine depths from the master core. Three were taken from the top 0.50 m of peat and six within 0.50 – 1.74 m. One basal radiocarbon date was also obtained from the deepest stratigraphy core from our chosen area (for the master core) to determine the likely date of peat initiation. Sub-sampled 1 cm^3 peat blocks were washed with deionized water in a 125 µm sieve and Sphagnum leaves, branches or stems were selected in order to minimize potential contamination. Samples were dated via Accelerator Mass Spectrometry (AMS) at the Chrono Laboratory at Queens University Belfast. Care was taken to remove ericaceous roots to prevent any possible reservoir effects as described by Kilian et al. (1995). Dates were calibrated, using the IntCal13.14C (Reimer et al., 2013), and an age-depth model (linearly interpolated) produced using the CLAM software derived by Blaauw (2010).

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

4.0 Results

4.1 Peat depth survey

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

4.2 Catchment-wide stratigraphy

The 88 points across the catchment used for detailed stratigraphic analysis are shown in Figure 1. A total of 37 of the 88 cores had evidence of Sphagnum remains. In the top 0.30 m (c. cal AD 1600 in the master core) Sphagnum remains were evident in 35 of the 88 records but these tended to be in areas of deep peat (Area 1-2). Here a transition appears to have occurred from highly decomposed peat at the base through sedge peat, and mainly within the upper metre Sphagnum peat was encountered. Cores at locations where there was <0.6 m of peat present were generally composed of highly decomposed material with some identifiable remains of sedges and Erica (Figure 2a). Within the top 0.05 m of the cores, only five sampled sites showed abundant Sphagnum remains (Figure 2b). Sphagnum remains were apparent at greatest depth and spanned the greatest depths in Areas 1 and 2 (Figure 2c & d). In Area 3 Sphagnum remains were only evident in three of the four cores and of these three Sphagnum remains existed only from 0.21 to 0.12 m from the surface.

The decline in Sphagnum occurrence from 0.30 to 0.05 m depth in most instances where Sphagnum was present, was associated with a transition to a highly decomposed amorphous black/dark brown peat containing charcoal. Charcoal was evident sporadically in all cores but in Areas 1-3 it was especially prevalent at the base of the peat and in the uppermost 0.30 m. In the uppermost 0.30 m of peat in Areas 1-3 charcoal appeared in relatively small amounts across the depth range in 58% of the cores. However, it also appeared as a distinct and concentrated band, c. 0.05 m in thickness, within the top 0.20 m.

At the base of the deepest core (Area 2, 3.70 m) there were remains of Phragmites (Common reed) suggesting standing water (Figure 3). Birch/Alder wood coincident with charcoal at the point of peat initiation is also evident in areas of deep peat demonstrating the existence of at least some tree cover before peat accumulation (Figure 3). Transition from mineral (mainly bedrock/regolith) to organic-dominated material occurs over 0.2 to 0.3 m from the base of the profile in cores from Area 1-3.

4.3 Stratigraphy around master core

Results from Transect A are examined here; those from Transects B-G are available in the Supplementary Data. The deepest accumulation (2.94 m) of peat was at the downslope end of Transect A (core 15, Figure 4-5). Across cores 76 to 16 (180 m) a relatively uniform depth of peat (2.00 m) existed. However, peat depth thinned to ~1.00 m, 150 m upslope of this transect. Highly degraded amorphous (Substansia humosa) material was dominant in the lower portion of all the cores from Transect A varying in extent from ~0.20 to 0.90 m (Figure 5). Cores 15, 76 and 82 in the deepest part of Area 1 contained remains of Birch wood close to the transition from mineral substrate to organic accumulation suggesting the previous existence of some tree cover. Charcoal was a major feature at the base of most cores from transect A and was coincident with peat initiation and the decline of arboreal macrofossils. Highly degraded basal peat was succeeded by peat often dominated by sedge remains (Turfa herbosa) together with more decomposed unidentifiable material (Figure 5). After this were substantial, yet variable, levels of Sphagnum remains in the top metre of most cores in transect A. The role of Sphagnum in the development of the upper peat across Transect A increased down slope with increased presence in cores 15, 76, 83, MASTER and 78 (Figure 5). All transect cores (A-G) displayed a shift from Sphagnum remains to degraded peat (Substansia humosa), often associated with charcoal, woody roots from ericaceous plants (Turfa lignosa) and sedge roots (Turfa herbosa) in the upper 0.15 m. A discrete band of black amorphous material with abundant levels of charcoal existed at around 0.05 – 0.10 m depth in transect A. Although concentrated in the basal layers and the uppermost 0.15 m of peat, sporadic evidence of charcoal existed throughout the cores.

4.4 Master core

4.4.1 Chronology

SCPs from the master core displayed a typical abundance curve for Northern Britain with a pronounced peak and subsequent decline up to the present day. Based on the resolution of the SCP record and the 'peaky' profile, three dating points were employed; the initiation of the record at 0.110-0.115 m, the rapid rise in SCPs at 0.040 - 0.045 m and the peak at 0.030 - 0.035 m depth which corresponds to AD 1850+/-25, 1955+/-10 and 1978+/-4 respectively (Rose and Appleby, 2005). These have been incorporated together with the radiocarbon dates to derive a chronology for the site (Table 1). Accumulation rates 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 0.42 to 0.73 m.

4.4.2 Macrofossils

The macrofossil record (Figure 6) was zoned by eye based on major shifts in vegetation composition. Fifteen zones were identified from the earliest (Zone A) to the most recent (Zone O). These zones are summarised in Table 2.

5.0 Discussion

The spatial richness of the peat depth and stratigraphy survey and the detail of the master core analysis provided an excellent basis for understanding the development of the peatland at KMRC, especially with respect to the historical presence or absence of *Sphagnum*.

5.1 Early development

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

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

5.2 Evidence of Sphagnum

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

Chambers, 1991; Blundell et al., 2005). Sphagnum taxa were an important and often dominant component of the upper peat profile at KMRC together with sedges and ericaceous plants. Evidence from the master core demonstrated that S. section Acutifolia, S. magellanicum, S. papillosum and S. section Cuspidata have all been prevalent at some point over the last 1500 years. Abundance of these species has fluctuated extensively however, often in conjunction with evidence of burning. These burning events are the likely result of man's attempts to improve grazing, a pressure that has been highly variable, at least up until the industrial revolution. Burning has been a feature throughout the history of the KMRC peatland development but crucially, however, when Sphagnum has been affected by fire it has later returned. This reflects the fact that there has likely been a diverse mosaic of plant groups that have been able to respond and adapt to these changes in burning (Ellis, 2008). Sphagnum moss especially, S. papillosum, S. magellanicum and S. rubellum, have been observed as being sensitive to burning (Pearsall, 1956; Ratcliffe, 1964).

Data from the master core showed that since the early 1900s a distinct and 'atypical' change in the vegetation at KMRC occurred. Sphagnum declined from the master core and from 30 of the 36 stratigraphic cores where Sphagnum was recorded in the upper 0.30 m of peat. The present day vegetation is dominated by Calluna vulgaris. Evidence of Sphagnum on the present day surface is generally sparse with five species of Sphagnum identified across the catchment as a whole: S. fallax, S. fimbriatum, S. palustre (very sparse), S. cuspidatum and S. capillifolium. S. fallax is largely confined to wet flushes in streams and gullies and the remaining species are extremely rare. The vegetation at the surface of the site changed from an 'active' blanket bog system within the 19th century to what might be termed an inactive state today. The term inactive is often used for peatlands when there is only very slow accumulation of peat and Sphagnum is lacking. It is typically used in the UK when National Vegetation Classification categories (Rodwell, 1991) M15, M17, M18, or M19 cannot be readily ascribed to the peatland. Coincident with the decline in Sphagnum around the start of the 20th century was the highest abundance of charcoal observed throughout the 2900yr master core history (c. AD 1920, 0.05-0.07 m). This charcoal layer contained 70, 42 and 17% charcoal at 0.05, 0.07 and 0.06 m depths respectively. Such a high level of charcoal (Figure 5 & 6) would suggest a major uncontrolled fire or fires which relates well to those suggested by the local gamekeeper to have been c. 1918 and in the 1940s. The base of the charred layer is dated to c. AD 1920 and the upper limit at c. AD 1955 putting the layer in the correct time frame matching personal accounts. Uncontrolled burns (wildfire), unlike prescribed patch burning (Holden et al., 2011), often occur in summer months, may burn for a long time attaining great intensity (Kayll, 1966) and may lead to the peat mass becoming ignited potentially causing extensive problems of erosion (Maltby, 1990; Tucker 2003). Such an event would probably impact the peat's chemical and physical properties and its vegetation cover (Mallik, 1984; Maltby et al., 1990; Doerr et al., 2006). Unlike previous burning events at the site over the last 1000 years, the last century has seen no recovery in *Sphagnum* cover from fire. There is evidence of peat loss from parts of the catchment due to erosion post fire and it is likely that the stability of the water table and mean water table levels will have been adversely affected which will have led to a reduction in *Sphagnum* and increase in vascular plants. However, although fire is likely to have burned the surface of the peat, there has been no discernable loss of peat from the master core location due to wildfire. A steady accumulation rate for the last 600 years of c. 15 yrs cm^{-1} demonstrates this. Although the decline of *Sphagnum* appears to be associated with the evidence for wildfire the continued absence thereafter is coincident with less concentrated but continued charcoal remains related to repeated and systematic burning for grouse moor management. The charcoal remains over the past century are coincident with a rise in *Calluna vulgaris* dominance in the catchment and at the master core the burning is even to the detriment of monocotyledons which had been a consistent component throughout the peat profile. The contemporary vegetation at KMRC is atypical in the context of the past thousand years and it seems clear that this is at very least in part due to land management practice as it is coincident with the initiation and continued practice of systematic burning. The timing of the decline of *Sphagnum* in the master core does not equate with the onset of elevated air pollution (SOx and NOx compounds) for the Pennine region of the mid 1800s (Yeloff, 2006) but such pollution (Ferguson and Lee, 1980) and the potential elevated nutrient source (Bragazza, 2006) is also likely to have had an impact on the abundance of Sphagnum. Excess N availability, for example, has been shown experimentally to be detrimental to many Sphagnum taxa (Gunnarsson and Rydin, 2000; Heijmans et al., 2001) and beneficial for growth rates of vascular plants (Limpens et al., 2003). Loss of Sphagnum from the site is also likely to of had a detrimental effect on potential DOC production as vegetation that produces litter that is more degradable now dominates.

5.3 Applications of palaeoecological data

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

This study has supported Yorkshire Water, the local water company whose reservoir is downstream of the site, in developing peatland management initiatives at the site and in setting a potential precedent for their work elsewhere. The ability to demonstrate that until the start of the 20^{th} century Sphagnum played an important role in the peatland at KMRC supports modern initiatives to promote a return to a more diverse mosaic of vegetation including greater Sphagnum abundance. The work has provided a more grounded 'restoration target', based on knowledge of local peatland development. Such restoration targets may also help reduce levels of DOC entering water treatment works (Armstrong et al., 2012) and may slow runoff production and reduce flood risk (Holden et al 2008; Grayson et al., 2010). Curtis et al. (2014) have raised the question as to whether potential recovery targets using a pre-industrial reference of upland water ecosystems are achievable or even desirable based on future climate projections. However, this does not detract from the value of obtaining background historical information from which informed management decisions can be made in light of all available evidence and in understanding how peatlands respond to environmental change. Similar palaeoecological studies in other peatlands could provide historical context to provide stronger support for restoration targets or changes to current management practice, for sites around the world. Minimum recommended levels of data acquisition depends entirely on the area and type of peatland being considered but an initial coarse spatial resolution stratigraphic and peat depth survey of the site would allow this to be determined. A tiered approach with stratigraphic surveys informing the position of and supporting the findings from more detailed core analyses is recommended.

6.0 Conclusions

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

At our study site it has been demonstrated that:

1) The present vegetation state is 'atypical' and is in part likely to be a result of increased human interference, including systematic burning, over the last 100 years.

2) Wildfire and later systematic burning for grouse moor management has had a detrimental effect on the presence of Sphagnum.
3) Sphagnum has played a significant role in parts of the site's development in the last 1000 years up to the early 1900s.
4) Attempting to 'restore' Sphagnum back to parts of the site is a legitimate goal in fitting with the sites past development.

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

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Figure captions.

Figure 1. Location of KMRC (inset) and location of survey points and stratigraphy cores together with interpolated peat depths and the three main areas of peat >=1.30 m in depth.

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

Figure 3. Selection of stratigraphy profiles from the deepest cores in Areas 1-3. 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 charcoal are marked with asterisks whereas evidence of birch/alder wood and Phragmites are denoted by B/A and Ph.

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

Figure 5. Stratigraphy cores from transect A. 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. Evidence of birch/alder wood and Phragmites are denoted by B/A and Ph.

Figure 6. Macrofossil diagram for KMRC master core. Peat components are derived from averaged quadrat counts under low-power magnification (×10). Leaf counts are a breakdown of the % Identifiable Sphagnum and consist of proportions based on a random selection of leaves (100 per sample interval where possible) identified at high magnification (×400). Bar graphs are absolute counts. For charcoal, Charcoal 1 represents proportion of charcoal in each quadrat count and is used only when absolute counts are not feasible due to the large level of remains. Charcoal 2 represents the absolute count of charcoal pieces over 125 µm.

Table caption

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

Table 2. Summary of main changes in macrofossils from the master core.

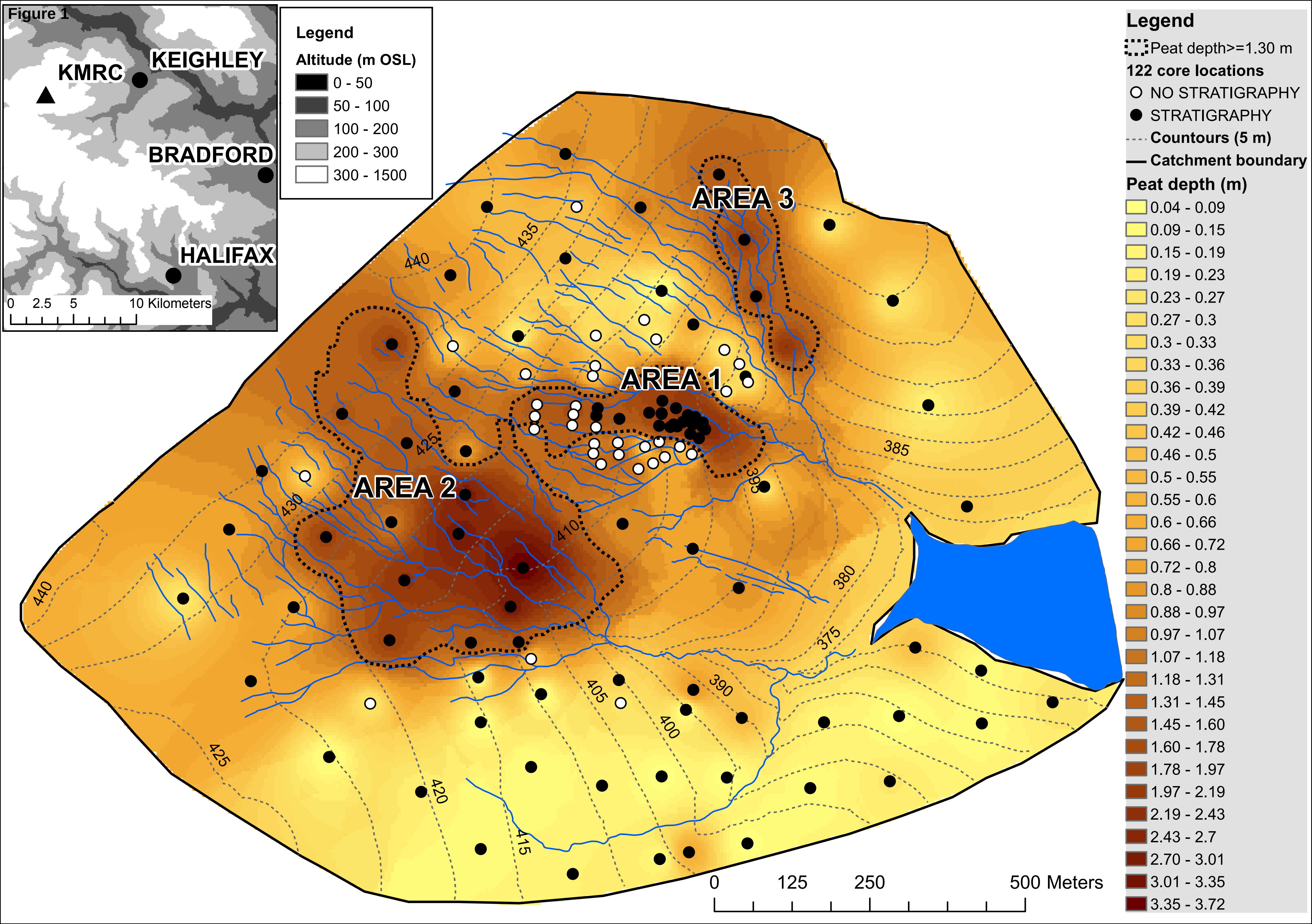


Figure 1
KMRC
KEIGHLEY
BRADFORD
HALIFAX
0 2.5 5 10 Kilometers
Legend
Altitude (m OSL)
0 - 50
50 - 100
100 - 200
200 - 300
300 - 1500
AREA 1
AREA 2
AREA 3
440
435
430
425
420
415
410
405
400
395
390
385
380
375
0 125 250 500 Meters
Legend
Peat depth>=1.30 m
122 core locations
NO STRATIGRAPHY
STRATIGRAPHY
Countours (5 m)
Catchment boundary
Peat depth (m)
0.04 - 0.09
0.09 - 0.15
0.15 - 0.19
0.19 - 0.23
0.23 - 0.27
0.27 - 0.3
0.3 - 0.33
0.33 - 0.36
0.36 - 0.39
0.39 - 0.42
0.42 - 0.46
0.46 - 0.5
0.5 - 0.55
0.55 - 0.6
0.6 - 0.66
0.66 - 0.72
0.72 - 0.8
0.8 - 0.88
0.88 - 0.97
0.97 - 1.07
1.07 - 1.18
1.18 - 1.31
1.31 - 1.45
1.45 - 1.60
1.60 - 1.78
1.78 - 1.97
1.97 - 2.19
2.19 - 2.43
2.43 - 2.7
2.70 - 3.01
3.01 - 3.35
3.35 - 3.72

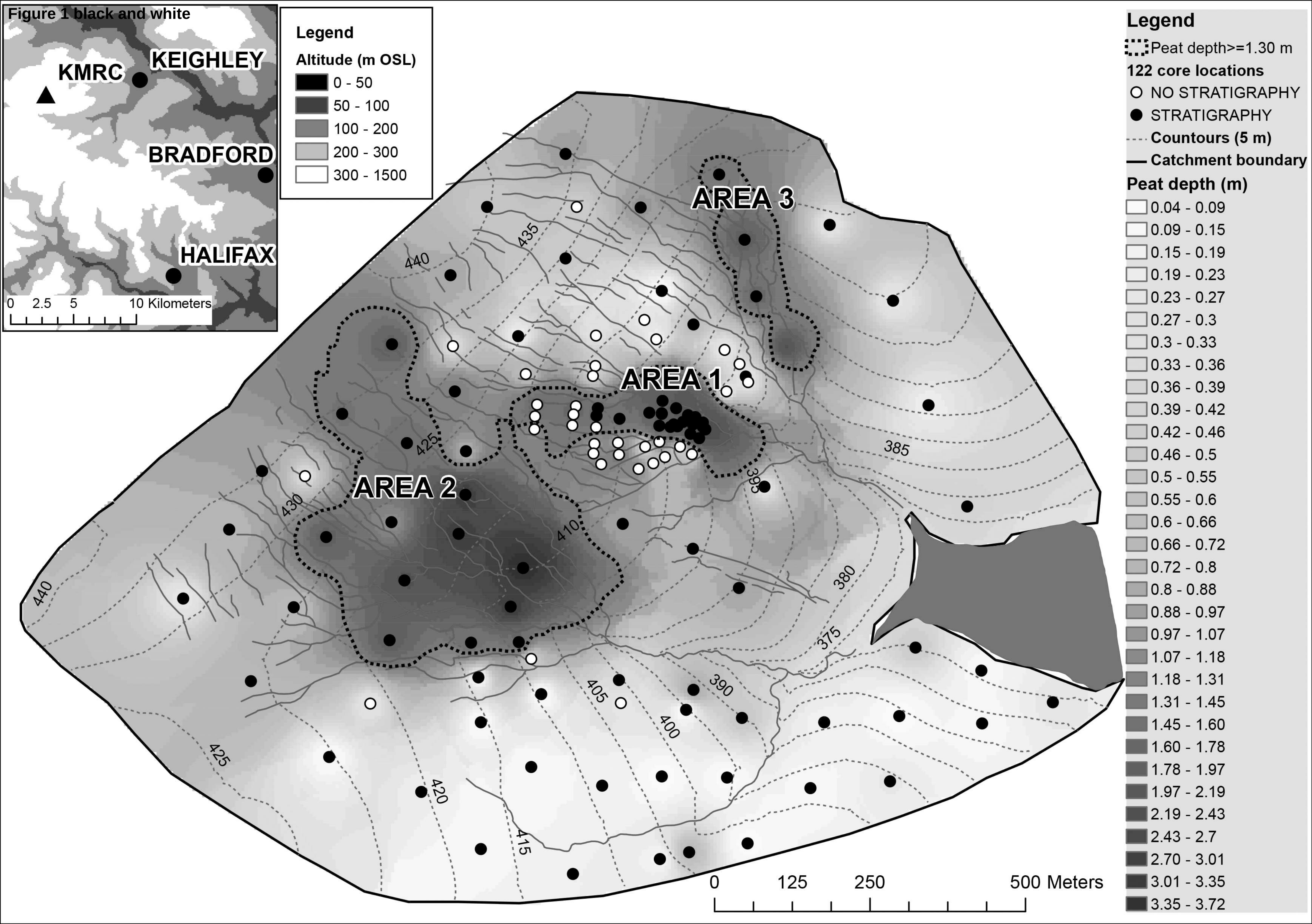


Figure 1 black and white
KMRC
KEIGHLEY
BRADFORD
HALIFAX
0 2.5 5 10 Kilometers
Legend
Altitude (m OSL)
0 - 50
50 - 100
100 - 200
200 - 300
300 - 1500
AREA 1
AREA 2
AREA 3
440
435
430
425
420
415
410
405
400
395
390
385
380
375
0 125 250 500 Meters
Legend
Peat depth>=1.30 m
122 core locations
NO STRATIGRAPHY
STRATIGRAPHY
Countours (5 m)
Catchment boundary
Peat depth (m)
0.04 - 0.09
0.09 - 0.15
0.15 - 0.19
0.19 - 0.23
0.23 - 0.27
0.27 - 0.3
0.3 - 0.33
0.33 - 0.36
0.36 - 0.39
0.39 - 0.42
0.42 - 0.46
0.46 - 0.5
0.5 - 0.55
0.55 - 0.6
0.6 - 0.66
0.66 - 0.72
0.72 - 0.8
0.8 - 0.88
0.88 - 0.97
0.97 - 1.07
1.07 - 1.18
1.18 - 1.31
1.31 - 1.45
1.45 - 1.60
1.60 - 1.78
1.78 - 1.97
1.97 - 2.19
2.19 - 2.43
2.43 - 2.7
2.70 - 3.01
3.01 - 3.35
3.35 - 3.72

Figure 2
Click here to download high resolution image

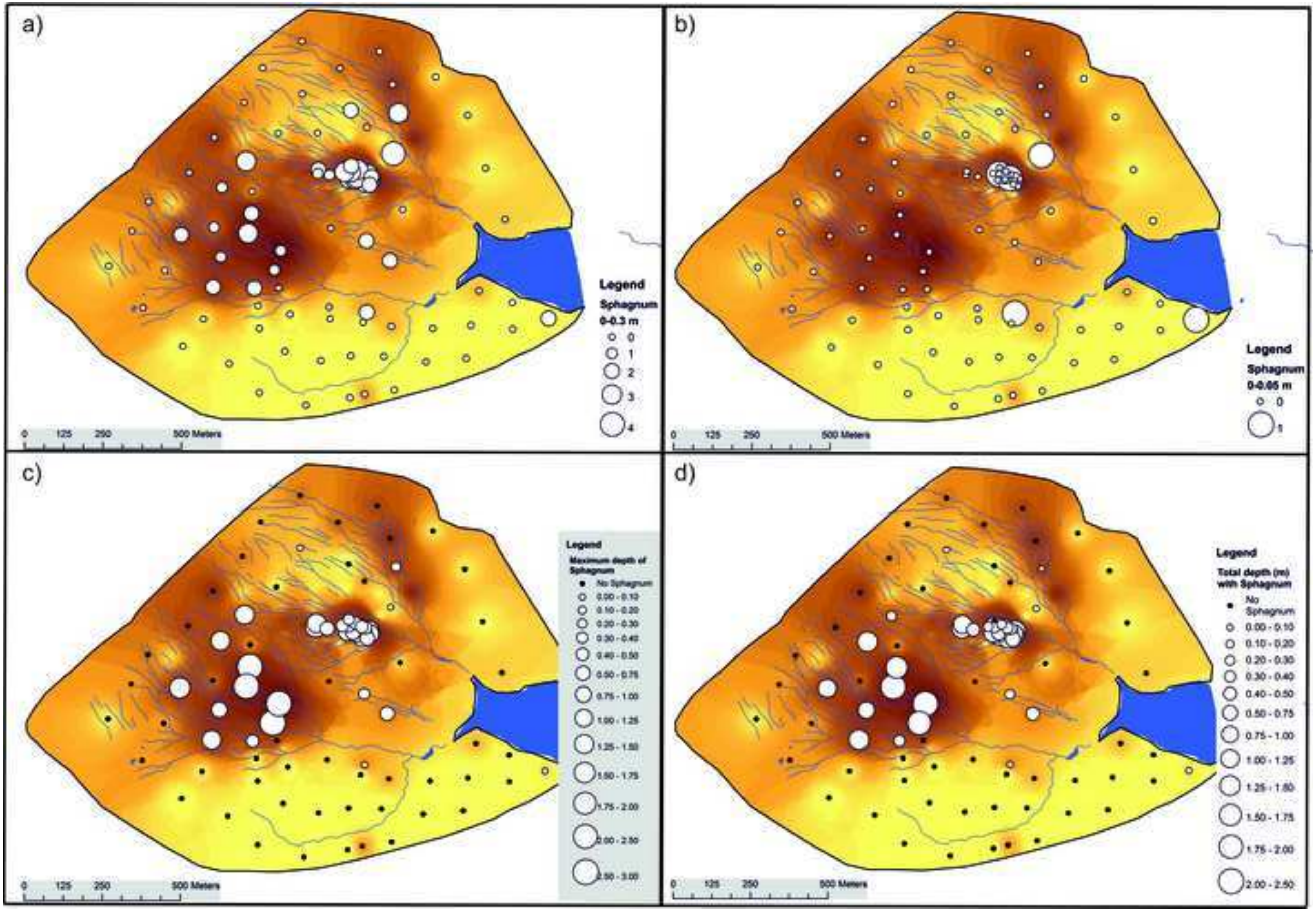


Figure 2 black and white

Click here to download high resolution image

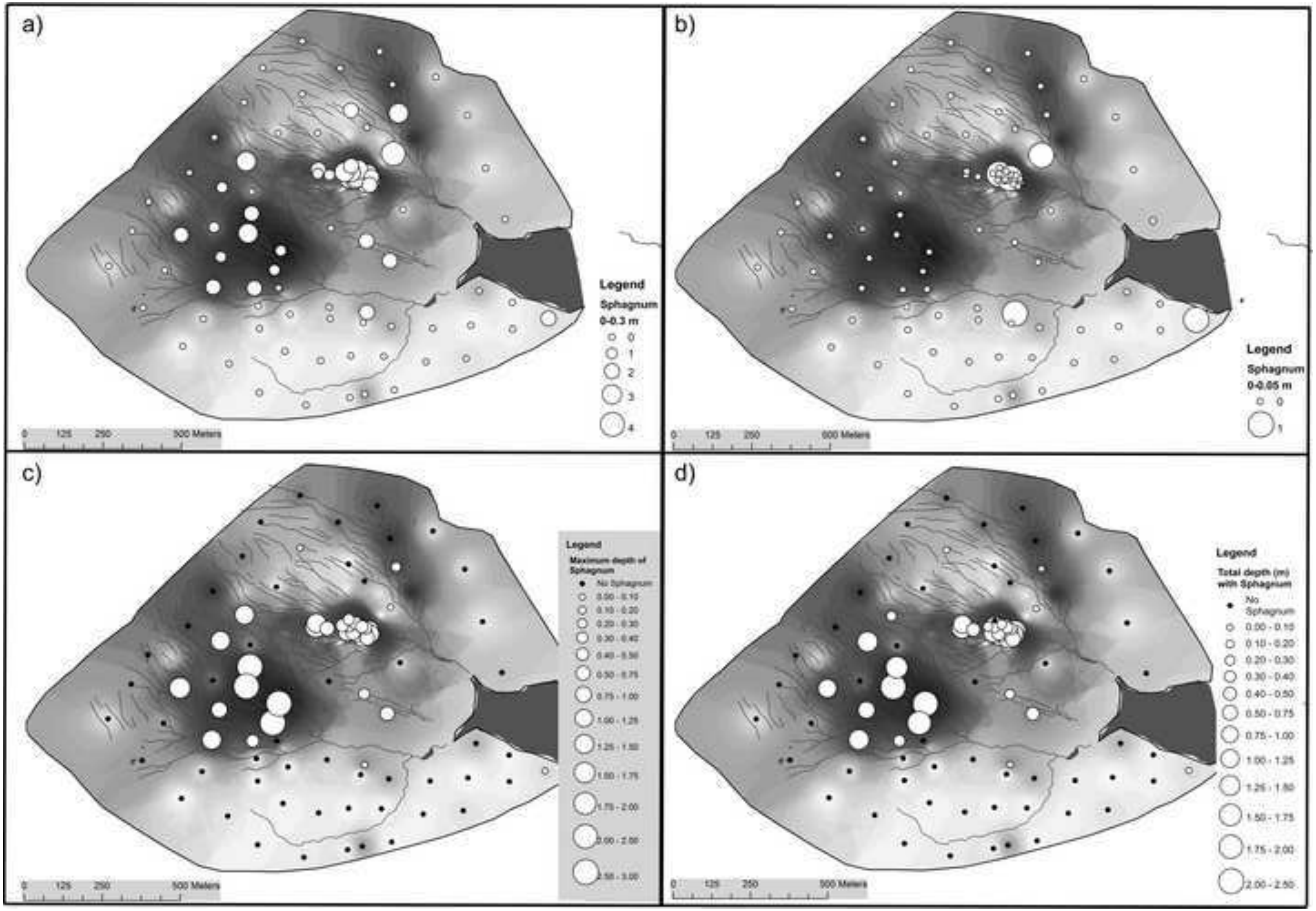


Figure 3

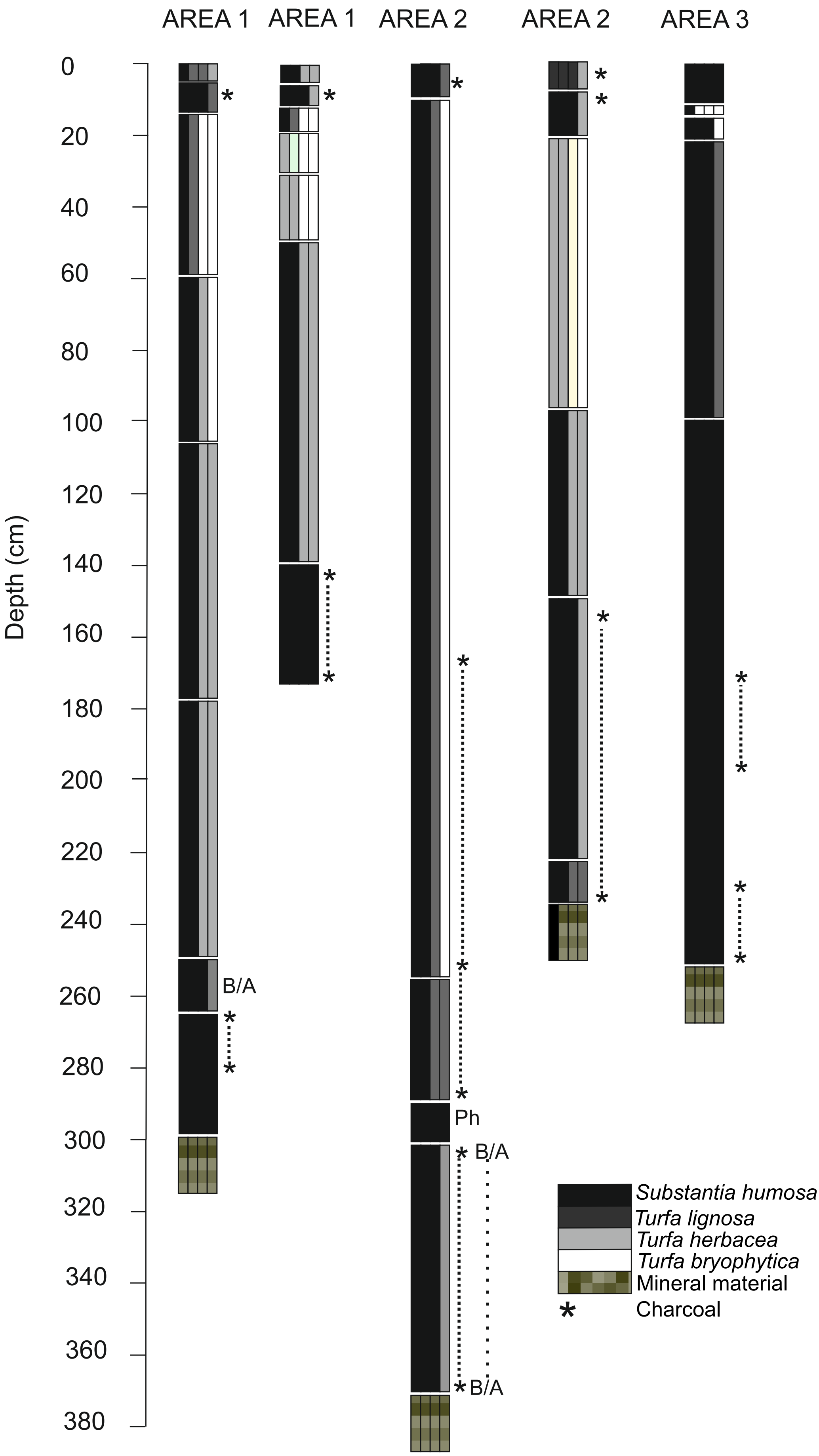
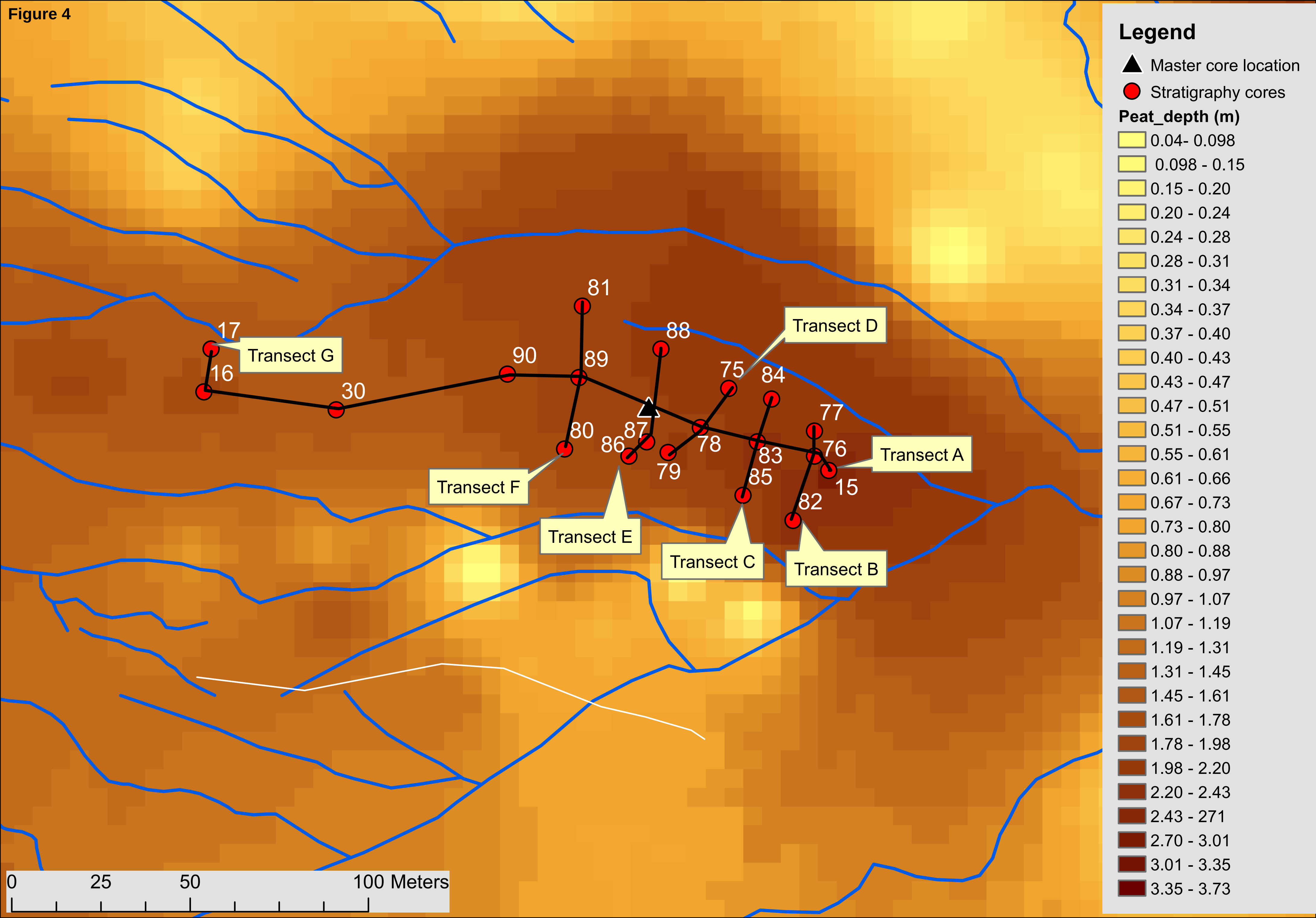

AREA 1
AREA 1
AREA 2
AREA 2
AREA 3
Depth (cm)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
B/A
Ph
B/A
B/A
Substantia humosa
Turfa lignosa
Turfa herbacea
Turfa bryophytica
Mineral material
Charcoal

Figure 4



Legend
Master core location
Stratigraphy cores
Peat_depth (m)
0.04- 0.098
0.098 - 0.15
0.15 - 0.20
0.20 - 0.24
0.24 - 0.28
0.28 - 0.31
0.31 - 0.34
0.34 - 0.37
0.37 - 0.40
0.40 - 0.43
0.43 - 0.47
0.47 - 0.51
0.51 - 0.55
0.55 - 0.61
0.61 - 0.66
0.67 - 0.73
0.73 - 0.80
0.80 - 0.88
0.88 - 0.97
0.97 - 1.07
1.07 - 1.19
1.19 - 1.31
1.31 - 1.45
1.45 - 1.61
1.61 - 1.78
1.78 - 1.98
1.98 - 2.20
2.20 - 2.43
2.43 - 271
2.70 - 3.01
3.01 - 3.35
3.35 - 3.73
Transect A
Transect B
Transect C
Transect D
Transect E
Transect F
Transect G
81
88
17
90
89
75
84
16
30
77
80
87
86
78
76
83
79
85
15
82
0
25
50
100 Meters

Figure 4 black and white

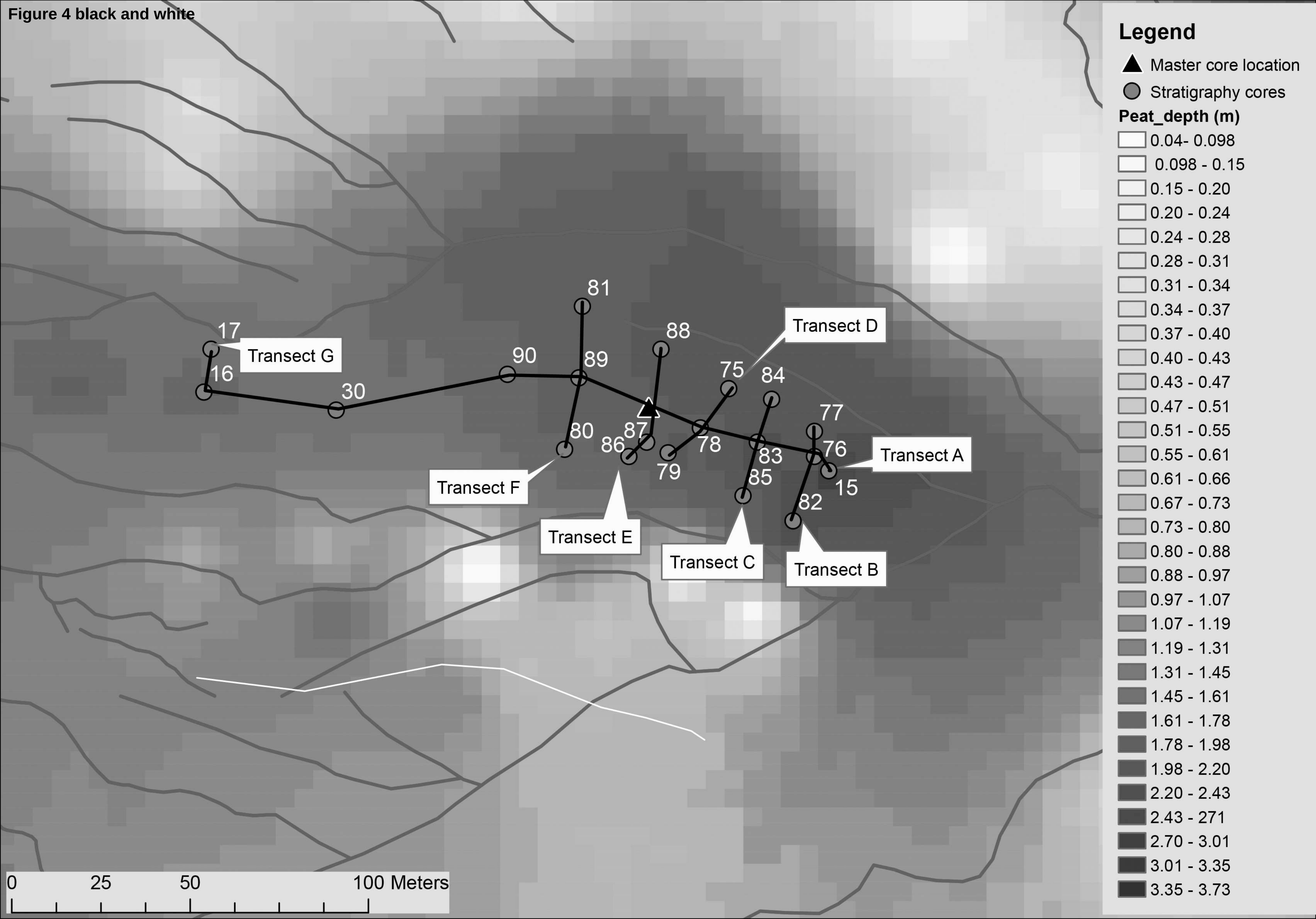
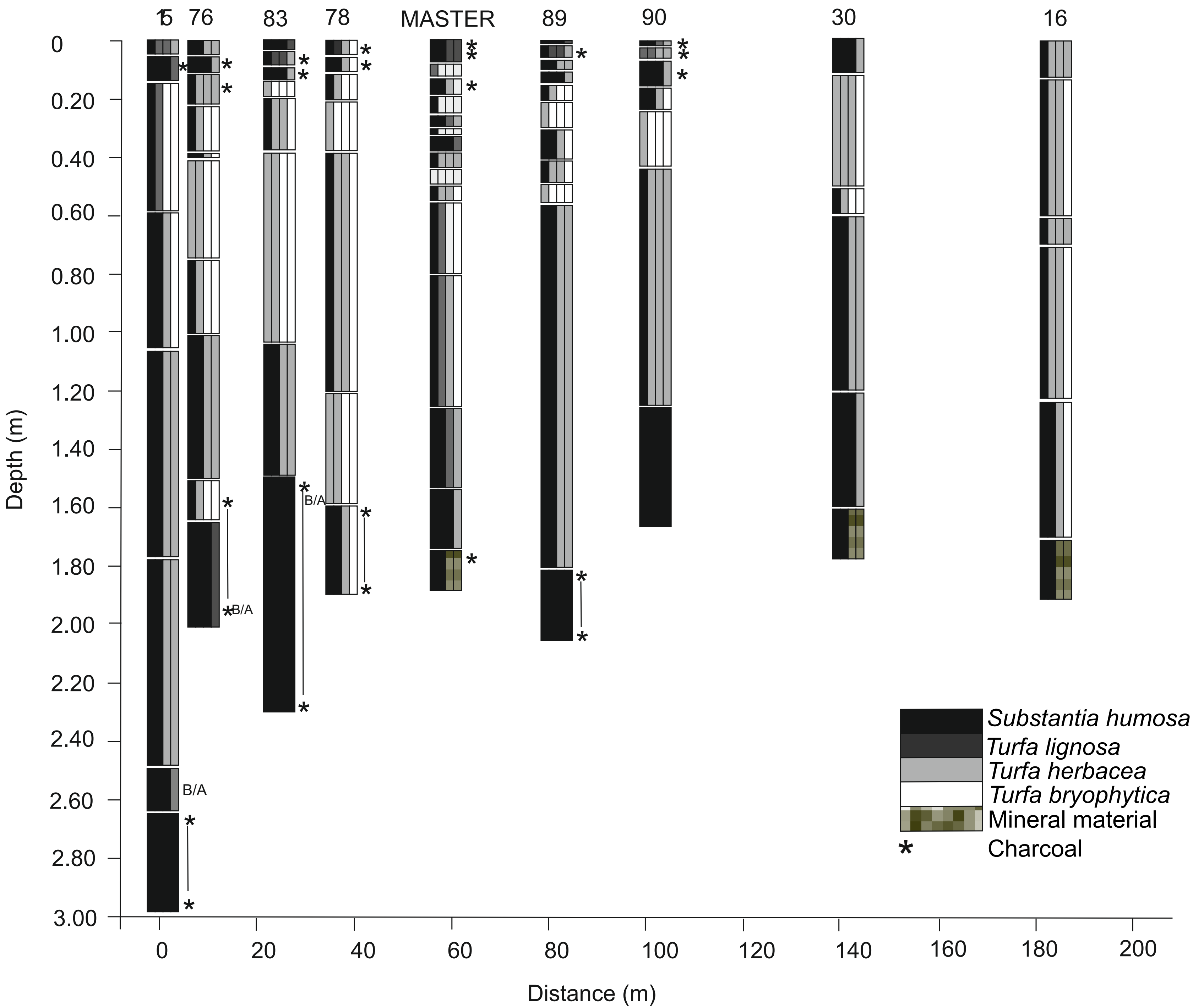


Figure 5



15
76
83
78
MASTER
89
90
30
16
Depth (m)
Distance (m)
B/A
Substantia humosa
Turfa lignosa
Turfa herbacea
Turfa bryophytica
Mineral material
Charcoal

Figure 6

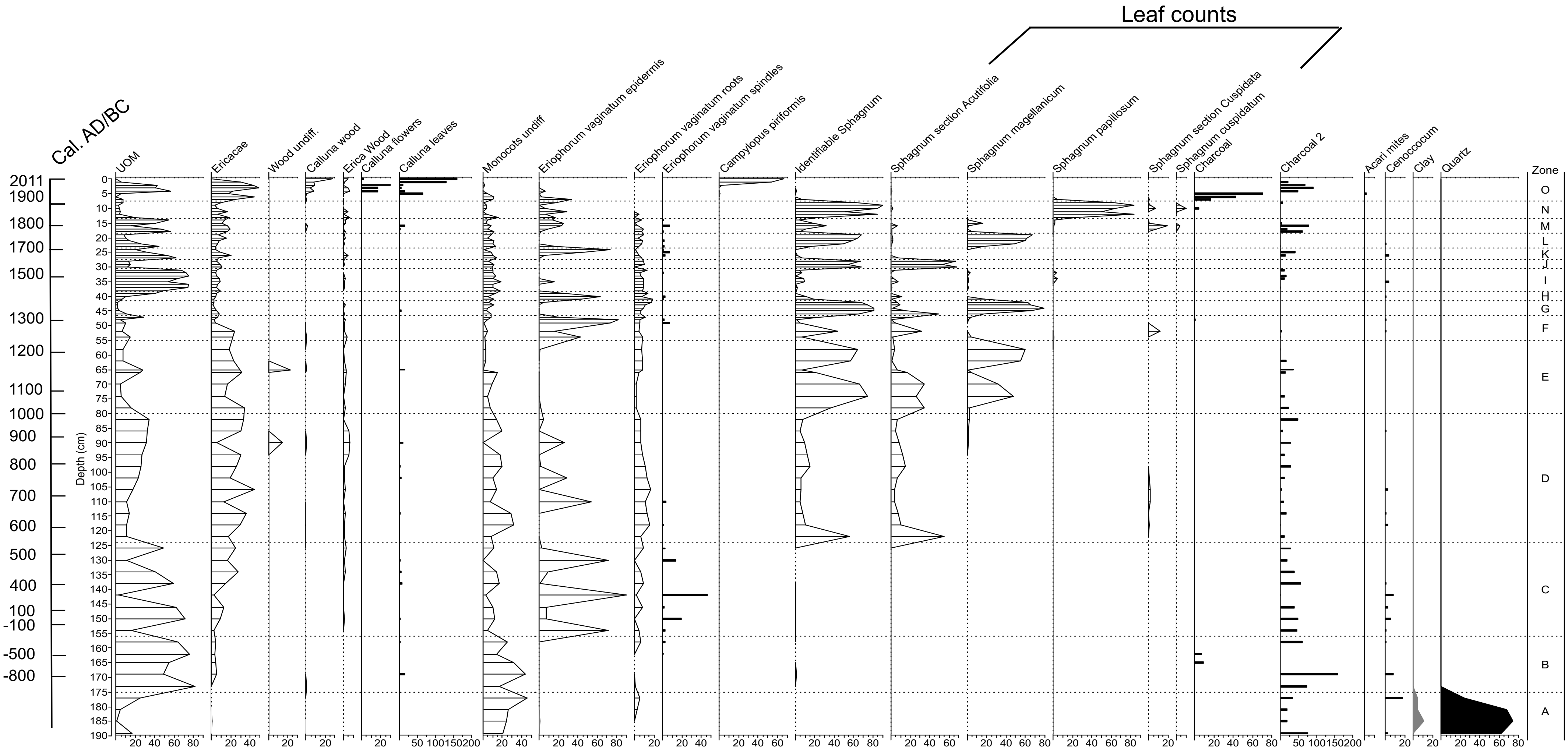

Leaf counts
Cal. AD/BC
Depth (cm)
UOM
Ericacae
Wood undiff.
Calluna wood
Erica Wood
Calluna flowers
Calluna leaves
Monocots undiff
Eriophorum vaginatum epidermis
Eriophorum vaginatum roots
Eriophorum vaginatum spindles
Campylopus piriformis
Identifiable Sphagnum
Sphagnum section Acutifolia
Sphagnum magellanicum
Sphagnum papillosum
Sphagnum section Cuspidata
Sphagnum cuspidatum
Charcoal
Charcoal 2
Acari mites
Cenococcum
Clay
Quartz
Zone
2011
1900
1800
1700
1500
1300
1200
1100
1000
900
800
700
600
500
400
100
-100
-500
-800
O
N
M
L
K
J
I
H
G
F
E
D
C
B
A

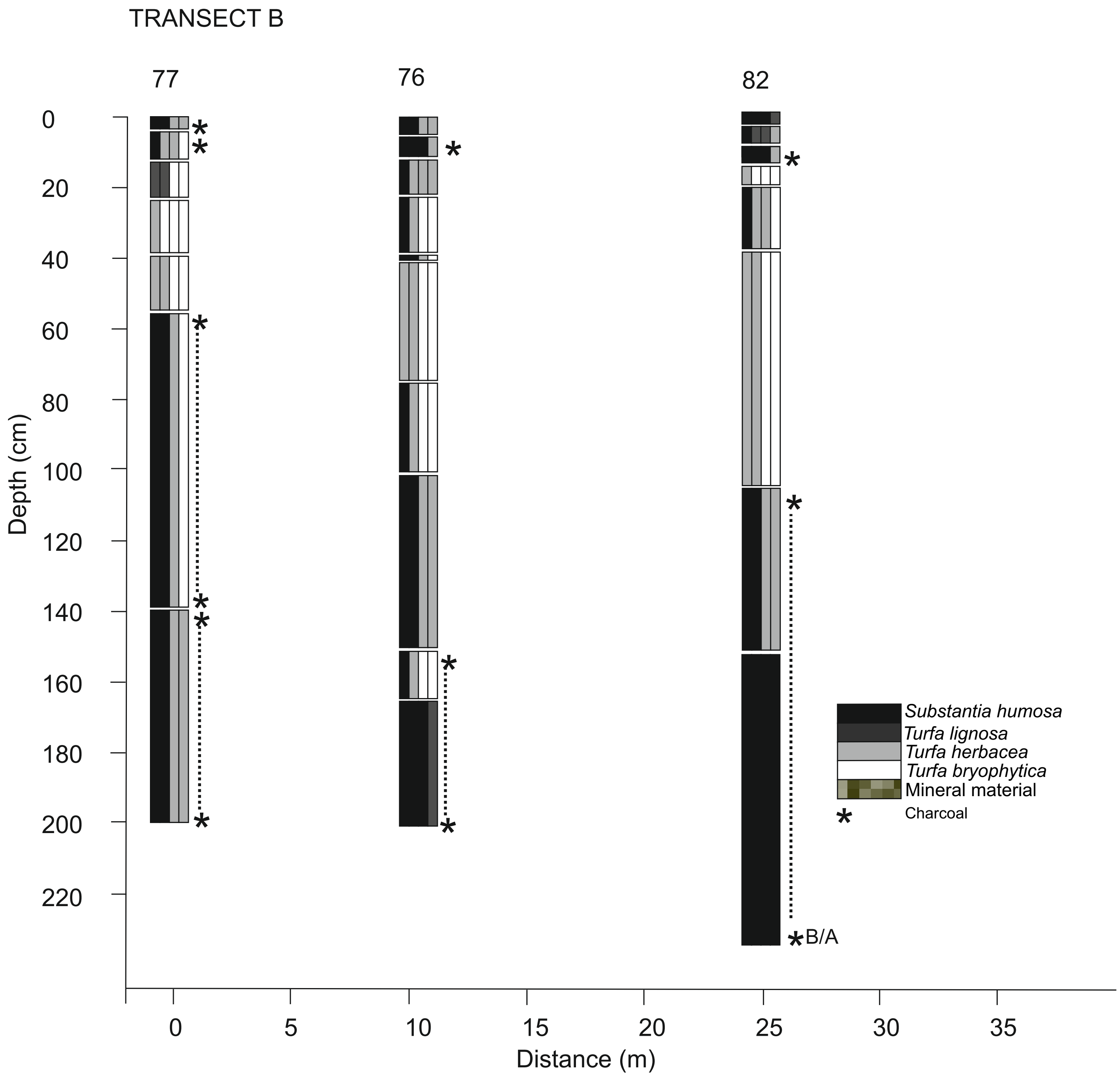
Table 1

Lab no.	Code	Depth (m)	Material	^{14}C Age	+/-	AMS $\delta^{13}C$	**Cal 2δ range BP**	**Cal 2δ range AD/BC**
UBA-18258	KM_20_BLUND	0.205	*Sphagnum* leaves/branches/stems	177	30	-26.3	- 4 - 295	1954 -1655
UBA-18259	KM_28_BLUND	0.285	*Sphagnum* leaves/branches/stems	258	32	-37.1	-3 - 432	1953 - 1518
UBA-18260	KM_42_BLUND	0.425	*Sphagnum* leaves/branches/stems	580	27	-30.5	535 - 646	1415 - 1304
UBA-18672	KM_73_BLUND	0.735	*Sphagnum* leaves/branches/stems	909	25	-32.7	744-914	1206 - 1036
UBA-18671	KM_98_BLUND	0.985	*Sphagnum* leaves/branches/stems	1227	27	-24.3	1068-1259	882 - 691
UBA-18673	KM_122_BLUND	1.225	*Sphagnum* 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

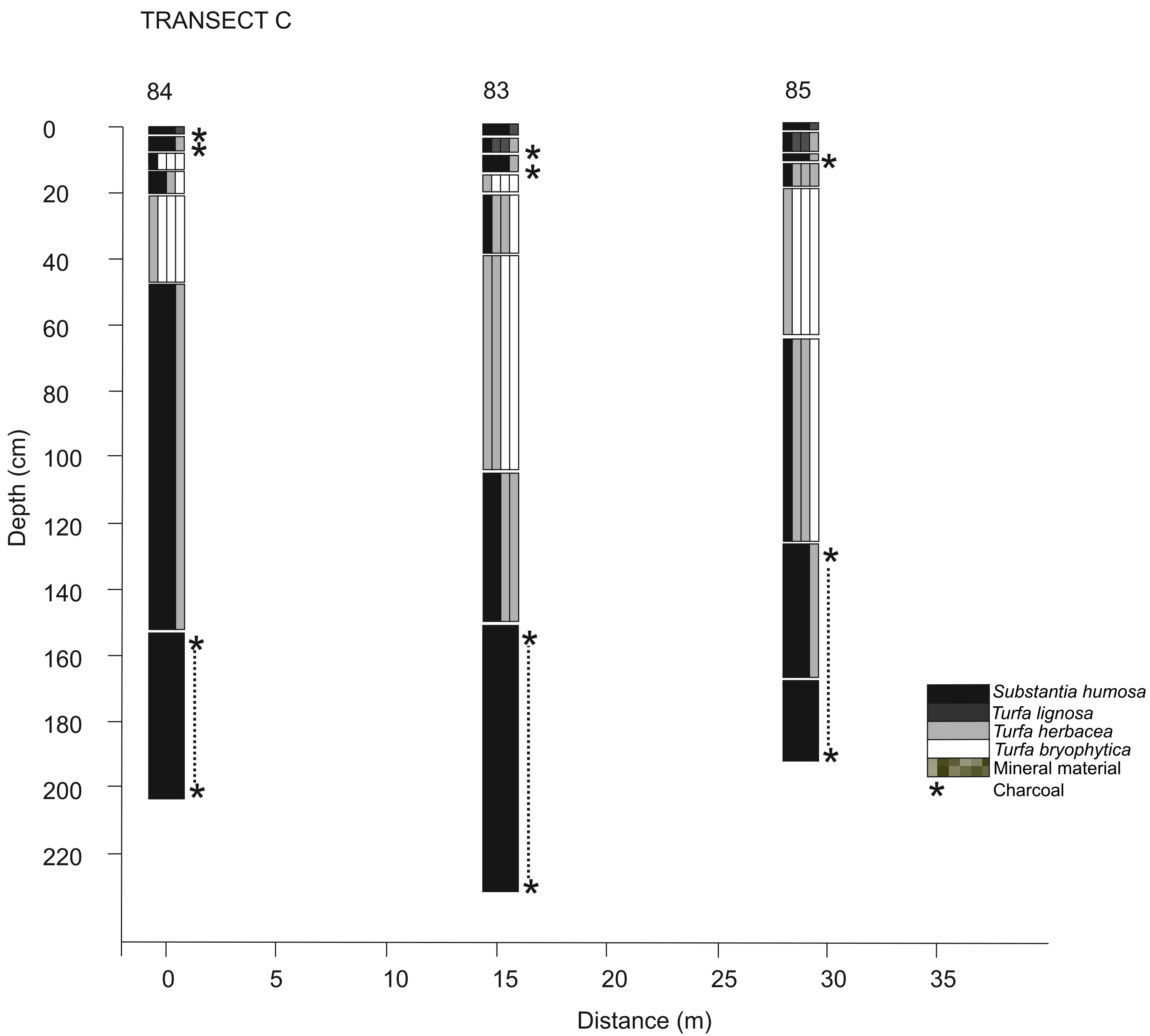
Table 2

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 *E. vaginatum* or UOM, fluctuations that are coincident with charcoal. Ericaceous plant remains are evident including *Calluna vulagris.*
D	**(1.24 –0. 80)**	**570 –1030**	*Sphagnum* (*Sphagnum* section *Acutifolia* and some evidence of *S*.s.*Cuspidata*) 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**	*S. magellanicum* and *S*. s. *Acutifolia* dominate. Ericaceous roots evident ~20% but leaves less evident.
F	**(0.56 – 0.465)**	**1250 –1320**	*Sphagnum* declines as *E. vaginatum* dominates. Little evidence of burning. Ericaceous decline roots to ~10%.
G	**(0.465 – 0.415)**	**1320 –1370**	Major reduction in *E. vaginatum* as initially *S*. s. *Acutifolia* and subsequently *S. magellanicum* increases to dominate.
H	**(0.415 – 0.385)**	**1370 –1430**	Major decline in *Sphagnum magellanicum* as *E. vaginatum* remains dominate.
I	**(0.395 – 0.305)**	**1430 –1570**	Increase in UOM (>60%) as *E. vaginatum* remains decline. *Sphagnum* evident but remains low.
J	**(0.305 – 0.275)**	**1570 –1630**	Increase in *S*. s. *Acutifolia* to > 60%
K	**(0.275 –0.235)**	**1630 –1700**	Increasing charcoal and *E. vaginatum* (>60%) remains.
L	**(0.235 – 0.185)**	**1700 –1770**	*S. magellanicum* dominates (>60%). Charcoal absent.
M	**(0.185 – 0.135)**	**1770 –1830**	UOM increases with *E. vaginatum*. Charcoal frequent.
N	**(0.135 – 0.075)**	**1830 –1910**	*S. papillosum* is dominant. *S*.s.*Cuspidata* 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. *Calluna* leaves/wood/flowers all increase. *Campylopus piriformis* is present at the surface.

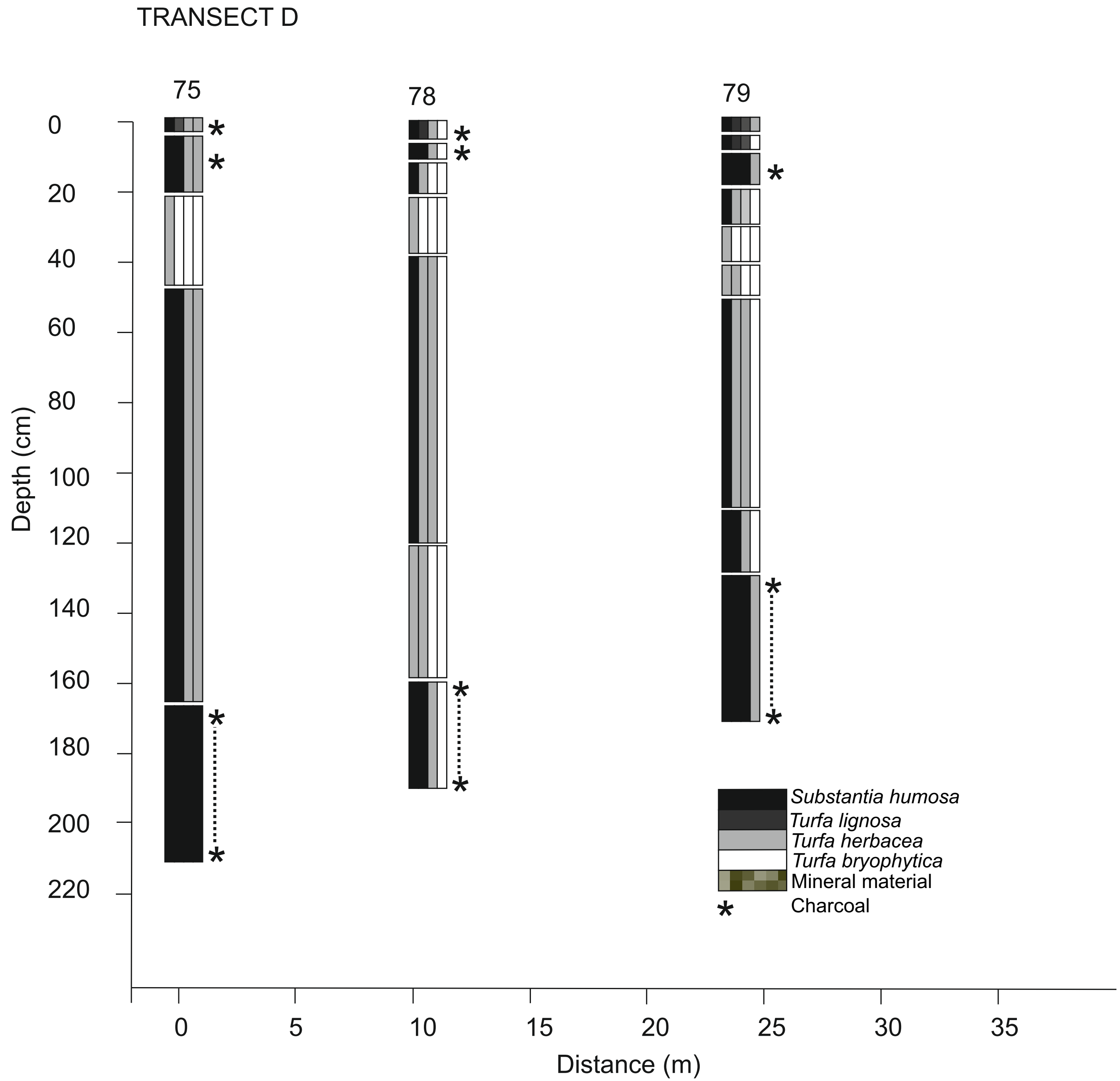
Supplementary Material 1



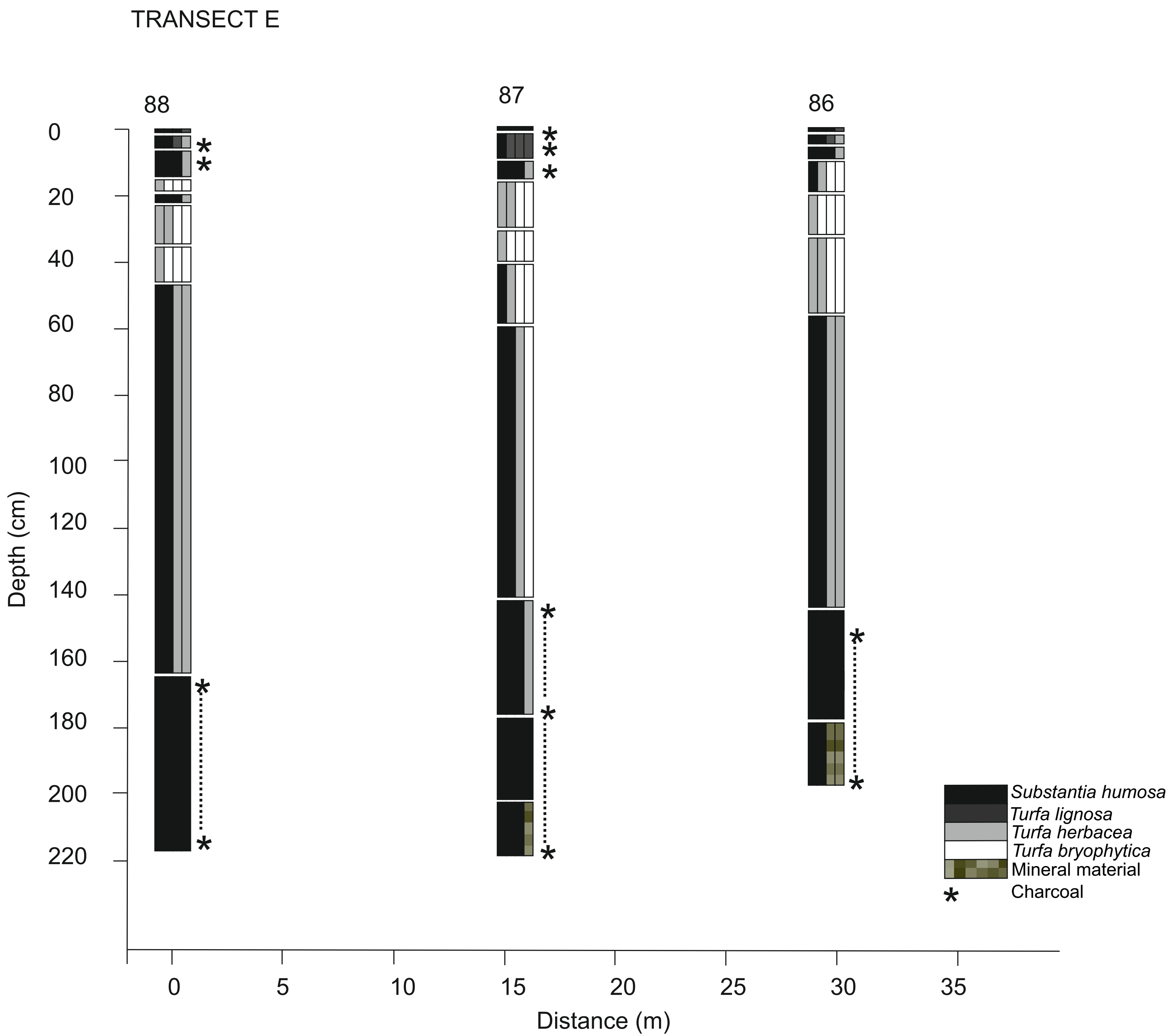
Supplementary Material 2



Supplementary Material 3



Supplementary Material 4



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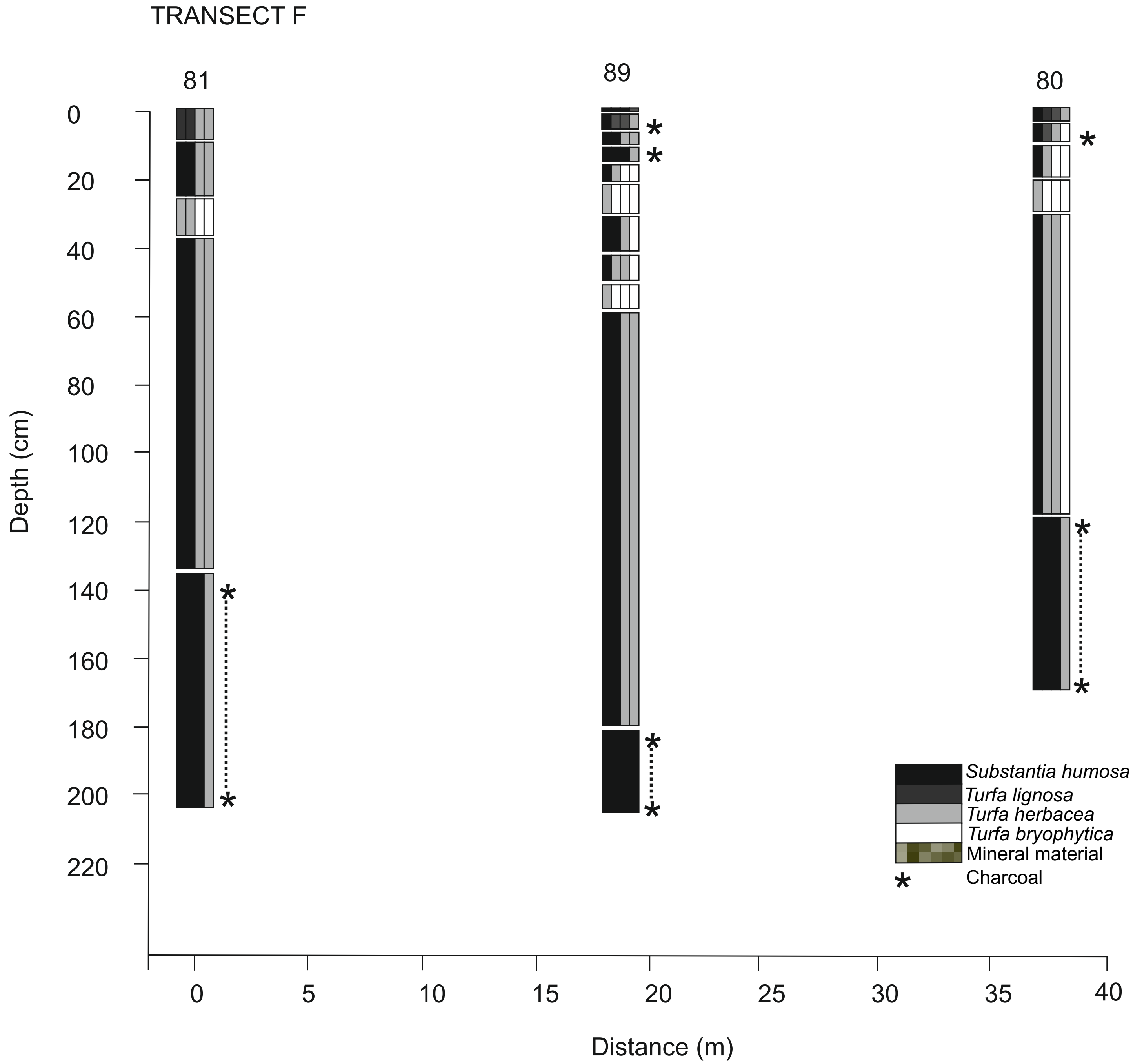
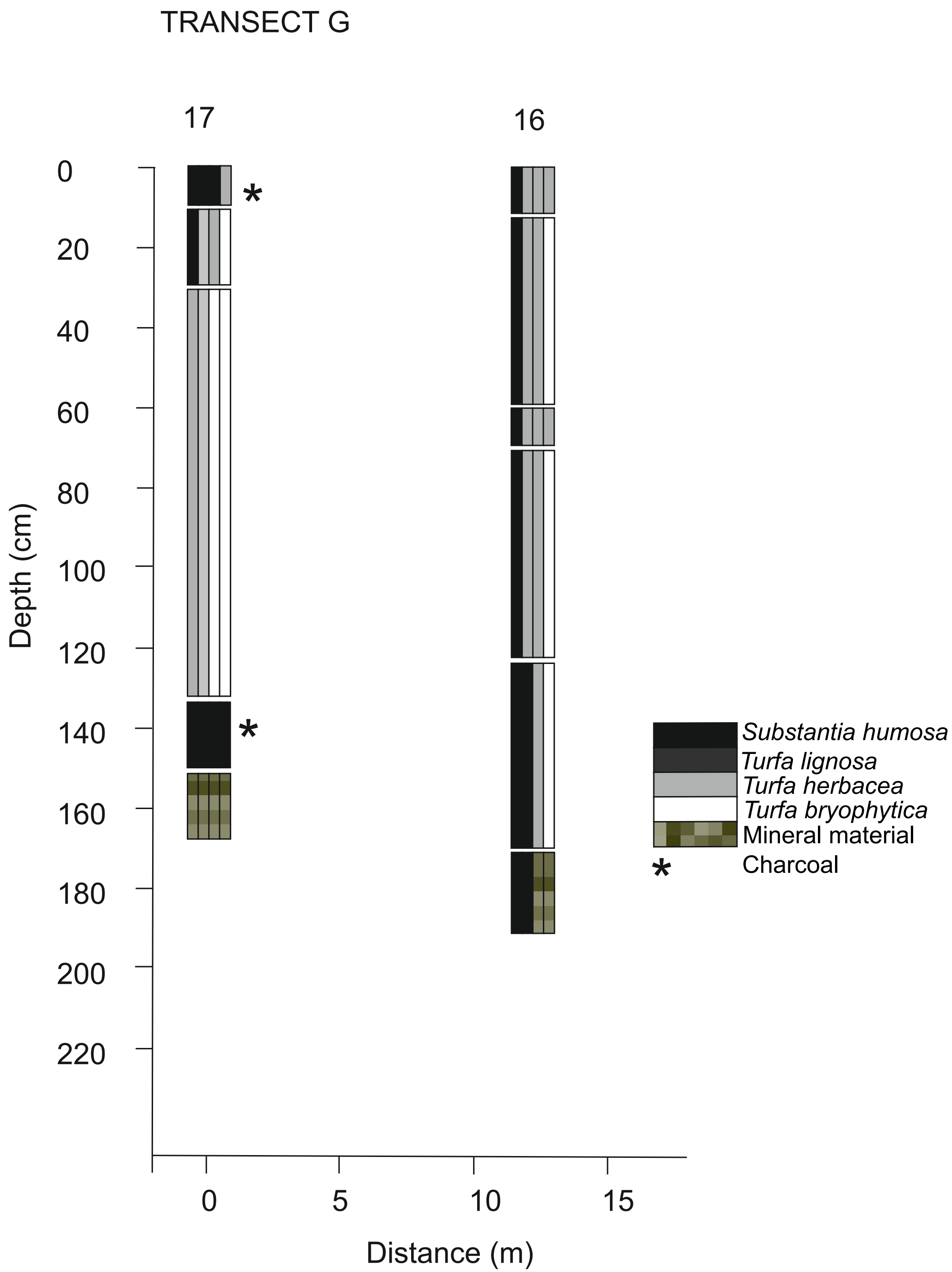


Supplementary Material 6



Supplementary Material Captions

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.