# A morphological analysis of Holocene charcoal particles from a peatland in southwest England

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## SUMMARY

Peat deposits that preserve charcoal particles can provide valuable archives for reconstructing fire histories. Palaeofire studies using lake sediments often use morphometric data or morphotype classifications of charcoal particles, from which information on fuel types and taphonomic processes may be derived. We present a preliminary assessment of whether such methods may be useful for peat charcoal studies, using a single Holocene peat core from an upland area in southwest England. Diverse charcoal morphotypes were preserved in the peat, some displaying plant anatomy and others amorphous, and with a variety of structures and textures. Quantitative measures of shape also varied widely, and aspect ratios appear to reflect shifts in dominance between grasses and woody taxa as is seen in lake sediments. Some of the morphotypes found could not be meaningfully described using only the categories established for lake sediment charcoal, indicating that peatlands may preserve distinctive charcoal morphologies. Detailed research on peatland charcoal morphotypes and their origins would enable greater understanding of the fire histories that peat archives can reveal.

**KEY WORDS:** charcoal morphology, charcoal morphometry, fire history, image analysis, palaeofire

## INTRODUCTION

Charcoal preserved in various types of sedimentary archives provides the principal method of interpreting fire histories in palaeoecological studies. Although most of these studies are conducted on lake sediments, peatlands can provide equally valuable archives (Mooney & Tinner 2011, Remy *et al.* 2018). In both cases, charcoal may have been deposited after hydrological or aeolian transport (Scott 2010), and in peats it may also be autochthonous (New *et al.* 2016). While lake sediments are protected from the burning of the archive itself (Remy *et al.* 2018), they are subject to sediment mixing and redeposition which can distort the record obtained (Wein *et al.* 1987, Patterson *et al.* 1987), and they incorporate material that may have been significantly altered by catchment processes prior to deposition. Peat archives can also be subject to considerable hydrological, biotic and anthropogenic disturbance (e.g. Bartolome *et al.* 1990), but it has been argued that they tend to have simpler taphonomic processes and lower susceptibility to redeposition than lake sediments (Rhodes 1996, Chambers & Charman 2004), and that this may allow for more spatially precise reconstructions of burning (Innes *et al.* 2004).

As most palaeocharcoal studies use lake sediments, understanding of peatland charcoal is less developed in some respects. One area in which it is lacking is particle morphology. Morphologies of charcoal particles in lake sediments have been the subject of a number of studies (Umbanhowar *et al.* 2006, Enache & Cumming 2006, 2007, 2009; Jensen *et al.* 2007, Thevenon & Anselmetti 2007, Moos & Cumming 2012, Aleman *et al.* 2013, Lim *et al.* 2014, Courtney Mustaphi & Pisaric 2014, Leys *et al.* 2017), which can be divided into two broad approaches: particles can be assessed and classified by eye (Jensen *et al.* 2007, Courtney Mustaphi & Pisaric 2014), or computerised image analysis can be used to calculate quantitative morphometric parameters (Umbanhowar *et al.* 2006, Thevenon & Anselmetti 2007). Qualitative analysis of charcoal particle morphology has multiple interpretive uses. Charcoalification preserves the anatomy of the parent material, allowing identification of both taxa and plant organs burned from sufficiently large fragments. Published classifications of morphotypes and their origins aim to facilitate such interpretations (Enache & Cumming 2006, Jensen *et al.* 2007, Courtney Mustaphi & Pisaric 2014). Charcoal morphotypes may also be indicative of transportation regimes (Enache & Cumming 2007); for example, fragile morphotypes indicate the absence of high-energy transportation (Courtney Mustaphi & Pisaric 2014). Quantitative image analysis methods can enhance information recovery by permitting analysis of large numbers of particles quickly and by reducing features of shape to numeric values that can be analysed and interpreted statistically. In particular, differences in aspect ratio (i.e. the ratio of length to width) have become a commonly used method of differentiating grassland from woodland fire (e.g. Umbanhowar *et al.* 2006, Aleman *et al.* 2013, Lim *et al.* 2014). Understanding the distributions of these simple morphometrics, and their relationships to fuel types and other factors, has additional importance because particle elongation may affect both transportation, since modelling of aeolian transport indicates a substantial effect on dispersal range (Vachula & Richter 2018), and quantification of charcoal abundance, since area-based measures are subject to bias from morphometric variation (Crawford & Belcher 2016, 2020).

Morphological studies on peatland charcoal are extremely limited. New *et al.* (2016) have presented a qualitative morphological analysis of peat core charcoal, demonstrating the existence of a distinct morphotype deriving from charcoalification of the peat matrix itself, rather than aboveground vegetation. However, no quantitative (morphometric) studies have previously been published, and no detailed qualitative classification of morphotypes has been attempted for peat charcoal. Differences in transportation (Innes *et al.* 2004), and the possibility of *in situ* burning (New *et al.* 2016), suggest that peat archives can be expected to incorporate charcoal morphologies which differ from those incorporated in lake sediments, and it is also possible that post-depositional changes could vary between these different sedimentary environments; for example, differences in likelihood of fragmentation would result in differing particle morphologies and sizes. Therefore, methods and classifications based on charcoal studies in lake sediments are not necessarily applicable to peat archives. With generally simpler taphonomic histories that often exclude hydrological transport, we suggest that peatland charcoals may have greater potential for preservation of the morphotypes initially produced by fire.

This study investigates the morphologies of mesocharcoal (*sensu* Scott & Damblon 2010) or macrocharcoal (*sensu* Mooney & Tinner 2011) particles (> 125 µm) from a Holocene peat core from an upland site in southwest England. It is believed to be the first morphometric study of peatland charcoal particles, and the first attempt to test an existing morphotype classification on peatland charcoal. The aims were: (1) to assess the range of morphological variation within a temperate peatland core; (2) to investigate whether this morphological information is preserved in the peat profile (i.e. persists over time); (3) to look for evidence of changes in aspect ratio in relation to the known environmental history of the site; and (4) to compare the range of morphotypes with those reported from studies of lake sediment charcoal.

## METHODS

Shovel Down is an upland area of acid grassland, around 400 m above sea level (a.s.l.), on eastern Dartmoor, southwest England. The area contains numerous exposed archaeological features, mainly dating from the Bronze Age, and is of interest to archaeologists seeking to understand prehistoric land enclosure (Bruck *et al.* 2003, Fyfe *et al.* 2008). A small valley mire of approximately 1 ha partly overlies important elements of the archaeological remains. Radiocarbon age determinations of the oldest basal peat indicate that the mire began accumulating peat ca. 8500–9000 CalBP (Fyfe *et al.* 2008). Pollen and microcharcoal preserved in the peat have been studied in order to reconstruct the palaeoenvironment (Fyfe *et al.* 2008).

Peat initiation took place amid a local Cyperaceae-dominated herbaceous vegetation, within a wider landscape of ericaceous heath and *Pinus*, *Corylus* and *Quercus* woodland. From ca. 7000 CalBP, the wider landscape was dominated by *Quercus* and *Corylus* woodland. A shift to *Calluna*-dominated heathland vegetation occurred ca. 5500 CalBP and does not appear to have been anthropogenic or associated with burning. However, later changes in pollen ratios are attributed to distinct land-use phases. At ca. 3400 CalBP, a shift to grassland vegetation occurred, probably associated with grazing, followed by reversion to *Calluna*-dominated heath and scrub after ca. 3000 CalBP, with Poaceae increasing again from ca. 1600 CalBP. While Fyfe *et al.* (2008) found charcoal throughout their record, it was not obviously correlated with heathland expansion, even though such correlations are often seen in Holocene sequences from temperate Europe (Bradshaw *et al.* 1997).

The samples used by Fyfe *et al.* (2008) for $^{14}C$ dating were taken at the location of a stone reave (a prehistoric land boundary) which crosses and is submerged by the mire. The core extracted for the present study was taken less than 5 m from that location, at 50° 39′ 20.10″ N, 3° 54′ 34.91″ W (± 3 m), and at 400 m a.s.l. The vegetation at the sampling point was predominantly *Sphagnum* moss, and the ground was sufficiently saturated that water rose above the surface by compression of the peat as the corer was driven in. Figure 1 shows the location of the sampling point as recorded by GPS.

The peat core was extracted from the mire using a Russian corer. It was extracted in three sections from

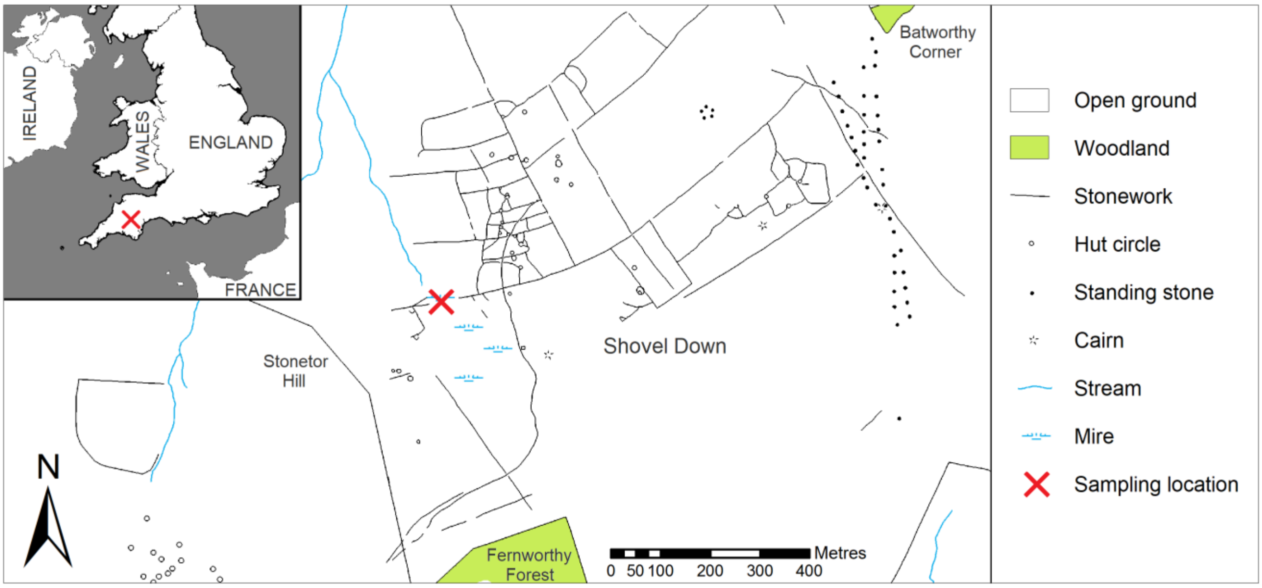


Figure 1. Location of the peat coring site in relation to exposed archaeology at Shovel Down, and (inset) location of the site in southwest England (red 'X'). Ordnance Survey data © Crown copyright and database right 2011.

two adjacent points, reaching a depth of 102 cm. Although the corer penetrated to the base of the peat (reaching impenetrable ground), the lowest 10 cm could not be retrieved, as this is the length of the corer's nose, while the upper 30 cm was too insubstantial to be recovered intact. Sections were transferred to plastic troughs, sealed with cling film, and refrigerated at 4°C.

21 samples of approximately 2 cm³ were removed from the core at intervals of 5 cm, each within a thickness (depth) of approximately 1 cm. The resolution is coarse due to the preliminary nature of this study into charcoal morphology, the site having previously been the subject of a detailed palaeoecological reconstruction (Fyfe *et al.* 2008). The resolution was chosen to provide a sufficient number of particles to characterise the range of morphologies, and sufficient depth categories to allow testing of their variability with depth. Samples were left in sodium hypochlorite (NaOCl) solution (~8 % Cl) for approximately 20 hours. Clumps of material that were not becoming disaggregated during this process were gently compressed with a paintbrush and the samples given a light swirling motion. Samples were sieved at 125 µm and the larger fraction retained for examination. This restricts the particles to the mesoscopic fraction (125–1000 µm; Scott & Damblon 2010) to allow comparison with studies on lake sediment charcoal morphology (e.g. Jensen *et al.* 2007, Moos & Cumming 2012).

All apparently black particles, excluding those which were clearly < 125 µm in diameter, were removed from each sample, using a stereo microscope at ×10 magnification under reflected light. These particles were then further examined at ×50 magnification. Those identified as charcoal (based on colour, opacity, reflective quality, texture, and absence of pliability) were temporarily mounted (in water beneath glass cover slips) and photographed. Where the number of particles in a sample was high, this process was stopped after approximately 50 images had been taken.

Images were saved in TIFF format and analysed using ImageJ 1.47t (Rasband 2013). Images were cropped to remove extraneous detail, and in rare cases details adjacent to charcoal particles were manually masked using a graphics programme. Images were converted to 8-bit greyscale, then binarised using the Auto Threshold function and IsoData algorithm. Size and shape descriptors (Pirard 2004, Zhang 2019) for the particle images were then generated. Size descriptors consisted of perimeter length, maximum and minimum diameters (the maximum and minimum distances between any two points on the perimeter), and area. Particles of maximum diameter <100 µm were excluded from the data set to restrict it to the mesocharcoal/ macrocharcoal fraction. Shape descriptors consisted of aspect ratio, circularity, roundness and solidity; formulae (Ferreira & Rasband 2012) are given in Table 1. Aspect ratio is calculated as the ratio of the major and minor axes of the best fitting ellipse,

Table 1. Formulae for shape descriptors calculated using ImageJ (Ferreira & Rasband 2012). Major and minor axes are for the best fit ellipse. Convex area is the area of the smallest convex shape that would contain the target shape.

| | |
|---|---|
| Aspect ratio | $aspect\ ratio = \frac{major\ axis}{minor\ axis}$ |
| Circularity | $circularity = 4\pi \times \frac{area}{(perimeter)^2}$ |
| Roundness | $roundness = 4 \times \frac{area}{\pi \times (major\ axis)^2}$ |
| Solidity | $solidity = \frac{area}{convex\ area}$ |

producing values ≥1. Circularity, roundness and solidity all return a value of 1 only for a perfect circle, while departures from circularity progress toward 0. They can be considered as measures of complexity, as they quantify the degree of departure from the simplest two-dimensional shape.

A subset of 100 particles was selected, using random number generation, for detailed qualitative analysis, and each was categorised according to the criteria given by Enache & Cumming (2006) and Courtney Mustaphi & Pisaric (2014).

The core was not dated, but $^{14}C$ dates given by Fyfe *et al.* (2008) were used to estimate the approximate age-depth relationship (Figure 2). The core was taken within 5 m of the dated sequence. Using the mid-points of depth and age ranges reported for 11 depths by Fyfe *et al.* (2008) in their section SBE3 (and taking the mean value where > 1 sample at the same depth) we obtained a model of age to relative (%) depth of $y = 0.0181 \times x^{2.8446}$ ($r^2 = 0.91$). Relative depth was used to account for the difference in peat depth between the dated peat sequence (102 cm) and our core (112 cm, including the 10 cm of basal peat not recovered). This approach will have greater error than would result from direct $^{14}C$ dating of the core but, given the proximity of the two locations and the apparent homogeneity of the mire, we expected that the dates would be sufficiently accurate for the purpose of relating charcoal morphology to broad changes in vegetation.

A series of one-sample Kolmogorov-Smirnov tests was run to assess whether size and shape descriptors, and age and depth values, conformed to normal distributions. Due to non-normality, correlations between depth or estimated age and all shape descriptors were assessed using Spearman's rank-order correlation coefficient (ρ). For each shape descriptor, a Kruskal-Wallis one-way analysis of variance (ANOVA) by ranks was run to test the hypothesis that the values did not differ (i.e. that they represented populations without different median values) across depth categories. All statistical analyses were done using SPSS Statistics 21 (IBM Corp. 2012).

## RESULTS

Inspection of the peat core prior to sampling showed it to be composed primarily of partially humified *Sphagnum* moss, and generally homogenous throughout, with little variation in colour or texture and no horizons evident. Images were obtained of a total of 636 mesocharcoal particles (100–696 μm), with the number from each sample ranging from 4 to 99. Based on visual assessment, a wide range of morphologies were represented. There were wide variations in elongation, texture, and complexity of structure, with some forms showing similarities to particular plant anatomical features such as leaf venation or xylem, and others which were more ambiguous or distinctly amorphous. Aspect ratios ranged from 1.0 to 15.5 but were heavily skewed toward the lower end (Figure 3), with a mean of 3.4 and a median of 2.7, and values over 9.0 accounting for only 2.2 % of the particles. Circularity ranged from 0.05 to 0.68, with a mean of 0.35 and an apparently normal distribution. Roundness ranged from 0.07 to 0.97, with a more irregular distribution somewhat skewed toward the lower values, and a mean of 0.41. Solidity ranged from 0.39 to 0.96, skewed toward the higher values, with a mean of

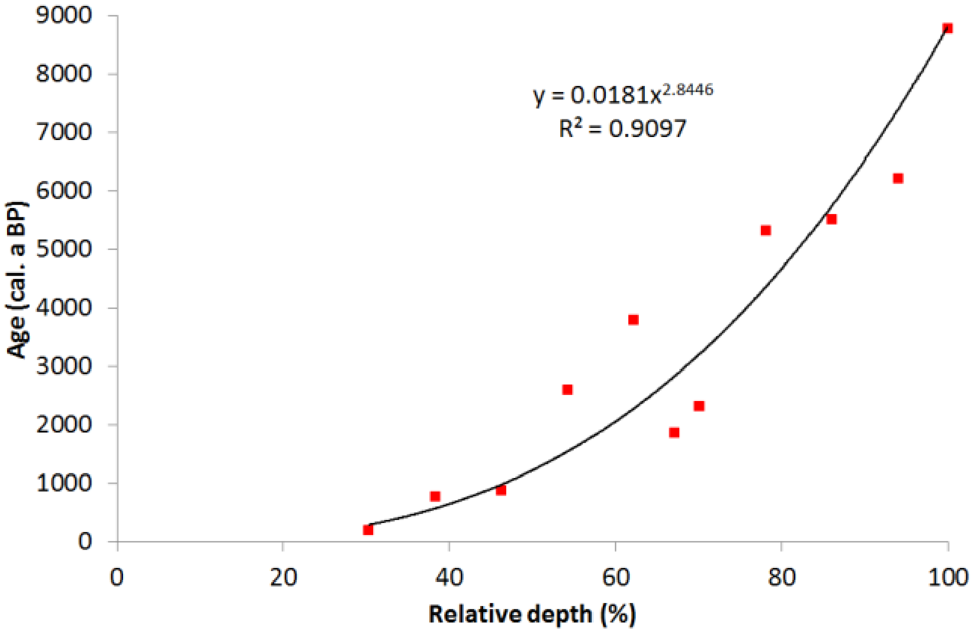


Figure 2. Age-depth model based on $^{14}C$ dates from Fyfe *et al*. (2008), showing calibrated $^{14}C$ age as a function of relative depth.

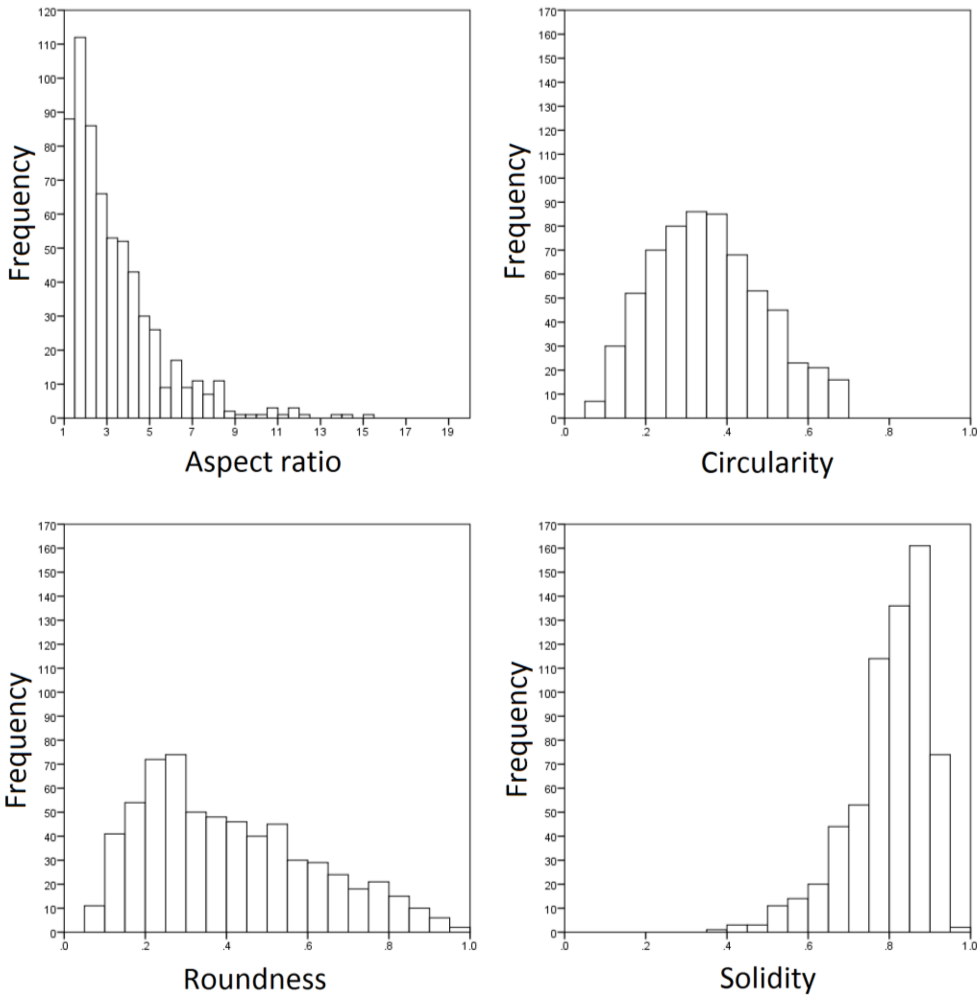


Figure 3. Frequency distributions of shape descriptors.

0.80. Descriptive statistics for shape descriptors are given in Table 2, and frequency distributions are shown in Figure 3.

Kolmogorov-Smirnov tests to assess normality of size and shape descriptors, and age and depth values, returned (two-tailed) P-values < 0.001, indicating that the hypothesis of normality should be rejected in each case, with the exception of circularity (P = 0.373). Non-parametric statistical methods were therefore employed.

To assess whether the morphological information (Glasbey & Horgan 1995, Pirard 2004) persists over time and is preserved in the peat profile, correlations between depth or estimated age and all shape descriptors were assessed using Spearman's rank-order correlation coefficient (ρ). Results are given in Table 3. Since the test is conducted on the ordinals, and depth and estimated age are monotonically related, each shape descriptor produces a single value for ρ whether tested for correlation with depth or age. Of the four shape descriptors, only solidity results in a sufficiently low P-value (P = 0.018) to indicate a genuine correlation with depth and age. Applying a Bonferroni correction for the fact that four tests were conducted, this is adjusted to P = 0.072. The correlation is in any case extremely weak at 0.094. Kruskal-Wallis tests for each shape descriptor, to test the hypothesis that the values did not differ across depth categories, led to the hypothesis being rejected for circularity (P < 0.001) and solidity (P < 0.001), but retained for aspect ratio (P = 0.108) and roundness (P = 0.108). Some shape descriptors therefore vary between depths, but there is no evidence of directional change with depth. Variations of mean shape descriptors with depth are shown in Figure 4.

Table 3. Correlation coefficients for age or depth and shape descriptors.

| | Spearman's ρ | P |
|---|---|---|
| Aspect ratio | -0.008 | 0.850 |
| Circularity | 0.043 | 0.277 |
| Roundness | 0.007 | 0.851 |
| Solidity | 0.094 | 0.018 |

Table 2. Descriptive statistics for shape descriptors.

| | Aspect ratio | Circularity | Roundness | Solidity |
|---|---|---|---|---|
| Minimum | 1.030 | 0.054 | 0.065 | 0.388 |
| Maximum | 15.459 | 0.679 | 0.970 | 0.957 |
| Mean | 3.359 | 0.355 | 0.406 | 0.801 |
| Median | 2.709 | 0.344 | 0.369 | 0.822 |
| Standard deviation | 2.140 | 0.138 | 0.210 | 0.098 |

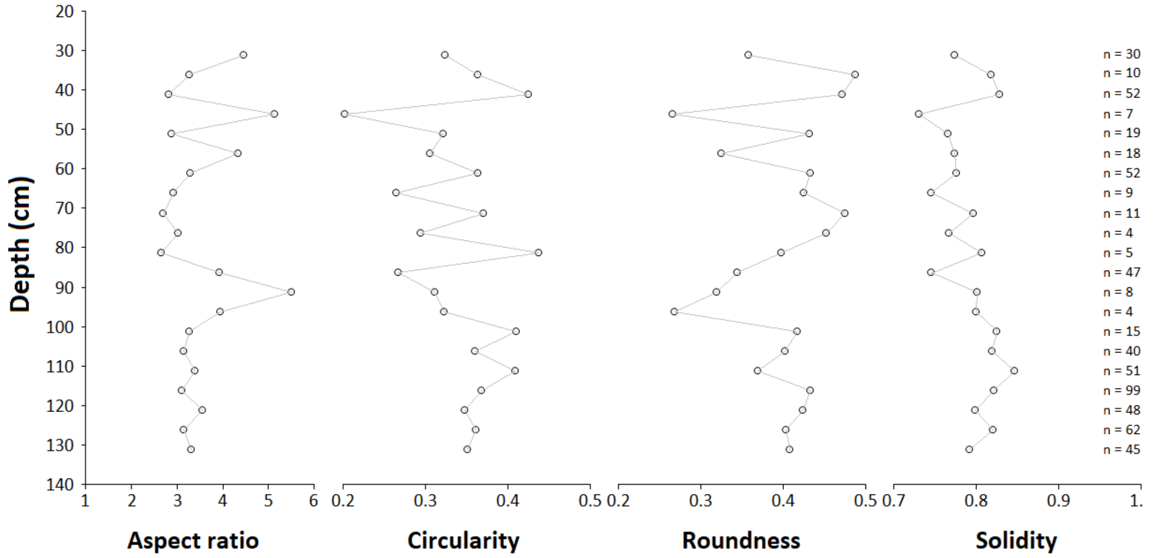


Figure 4. Variation of mean shape descriptors with depth.

## DISCUSSION

*Anthropogenic influence on the charcoal record*

The charcoal record at Shovel Down is likely to contain both anthropogenic and wildfire charcoal, and while these components cannot be separated, variations in their relative proportions may affect the morphological data considered here. The archaeology of Shovel Down and the adjacent Kestor field system, including 'round houses', indicates a settlement of some kind (Johnston 2001). However, the function of the round houses, and the way in which the site was inhabited, are unclear (Johnston 2001), and the dates at which it was occupied are poorly constrained. Evidence of flint working indicates human presence at Shovel Down from the late Mesolithic to early Bronze Age (Fyfe *et al.* 2008), while the earliest palynological evidence is cereal pollen from the early Neolithic (ca. 5000 CalBP) (Fyfe *et al.* 2008). The archaeological remains themselves are Bronze Age. While Dartmoor generally had minimal human settlement 3000–2000 CalBP (Caseldine 1999), this site may be an exception; pottery from the adjacent Kestor field system (which begins approximately 300 m to the east of the archaeology shown in Fig. 1) dates to ca. 3000–2500 CalBP (Caseldine 1999). The latest evidence of prehistoric occupation is an iron age (ca. 2800–1900 CalBP) structure at Kestor (Johnston 2001). Habitation of the area in some form therefore occurred (not necessarily continuously) from the 5$^{th}$ to 1$^{st}$ millennium BC; thus fire would have been used in the region for domestic purposes during this period. In the wider landscape, it is likely that fire was used for vegetation management; for example, late Mesolithic burning on Dartmoor has been interpreted as a means of maintaining grazing habitats for hunting (Caseldine 1999), and Fyfe *et al.* (2008) considered that both domestic fires and periodic burning of the moorland were likely to be represented in the charcoal record. From the Roman to Mediaeval periods, there is little direct evidence for human activity on Dartmoor (Caseldine 1999) with perhaps only a sparse population of herders present until the moorland was resettled after 1200 AD (Caseldine 1999). Contributions to the charcoal record from anthropogenic burning are therefore possible throughout the record, while a period of more minor human influence may have occurred around the 1$^{st}$ millennium AD. Temporal variations in the proportions of anthropogenic charcoal have the potential to influence the morphometric data, primarily by influencing the types or proportions of source material represented (i.e. through selection of fuel woods, or selective burning of unwanted vegetation types), and secondarily by determining the burning conditions (e.g. the temperature at which burned). Changes in morphological parameters are therefore not assumed to relate only to differences in fuels burned by wildfire.

*Relationship of mesocharcoal shape complexity to peat depth and age*

Measurements of shape complexity (i.e. circularity, roundness, solidity) are of interest as they are potential indicators of taphonomic change. Charcoal particles can have initially complex structures (Jensen *et al.* 2007, Courtney Mustaphi & Pisaric 2014) that are then degraded by taphonomic processes (Crawford & Belcher 2014), and this breakage may occur after burial (Scott 2010), due to pressure or movement within the sediment. It is plausible that the likelihood of this will vary according to the deformation characteristics of the sediment, and that the high compressibility of peat could make it unusual in this respect. In this study, the correlation tests show no evidence that any of the four shape descriptors vary as a function of depth, indicating that once incorporated in the peat the morphologies do not change over time. However, the ANOVA shows that circularity and solidity do vary between depth categories. As there is evidence of differences between depths, but not as functions of depth, assemblages of differing morphologies appear to have been incorporated into the peat at different times, then remained unchanged. The absence of post-depositional alteration supports the idea that peat deposits will make useful archives for charcoal morphology studies.

*Relationship of mesocharcoal aspect ratio to vegetation history*

Fyfe *et al.* (2008) established that the proportion of Poaceae in the pollen record from the mire fluctuates considerably (from < 10 % to > 50 %). According to the methods applied to lake sediment charcoal (Umbanhowar *et al.* 2006), mesocharcoal aspect ratios would be expected to reflect these changes because of the distinctive morphology of Poaceae charcoal. Experiments by Umbanhowar & McGrath (1998) demonstrated the elongate nature of Poaceae (grass) charcoal particles, with mean aspect ratios of 3.62 or 4.83 (depending on method), compared to values of 1.91–2.23 for deciduous leaf and wood charcoal. Umbanhowar *et al.* (2006) gave 2–3 as the typical range expected of charcoal from deciduous trees, and $\geq$ 3.5 for grasses. Experiments with lab-produced charcoal by Crawford & Belcher (2014), focusing on coniferous species, also found mean aspect ratios for tree-derived mesocharcoal (leaves:

2.23, wood: 1.97) to be significantly lower than grass mesocharcoal (3.70).

In this study, mean aspect ratios ranged from 2.63 to 5.48, a range which includes those characteristic of both wood and grass fires (Umbanhowar *et al.* 2006), but toward the higher end of both ranges. In the absence of paired values for aspect ratios and % Poaceae to assess their correlation, we compared the broad pattern of changes in aspect ratio with the published record of vegetation change (Fyfe *et al.* 2008) (Figure 5). While the overall down-core trends in mean aspect ratio and % Poaceae are similar, individual peaks are not well aligned, which could indicate that the assumption of comparable age-depth relationships between the two cores was mistaken. There is little variation in mean aspect ratio before 3000 CalBP, with values between 3.1 and 3.5. Higher mean aspect ratios only occur after the shift to improved grassland (phase v in Fyfe *et al.* 2008) that begins ca. 4000 CalBP. However, while grass pollen peaks at > 50 % ca. 3500 CalBP, the shift is not reflected in the mean aspect ratios until ca. 3000–2200 CalBP, during the subsequent period in which heathland returned under reduced grazing pressure, with sequential values of 3.9, 5.5 and 3.9. Confidence in the highest value is low due to the very low particle count in this sample ($n$ = 8). Aspect ratios subsequently fall, with lower values from 2000–1000 CalBP. There is then a trend toward higher aspect ratios, in keeping with the increase in Poaceae as the vegetation moves to its current mix of grassland and *Calluna* heath. During the last 700 years there are sharp fluctuations between higher (> 4) and lower (~3) mean aspect ratios. These are reflected by similarly large fluctuations in the pollen data, and do not have any obvious cause, but could represent variations in fire regime or charcoal source area as well as vegetation composition. One possibility is that anthropogenic charcoal sources become more dominant in this portion of the record, which immediately follows the resettlement of Dartmoor in the 13th century (Caseldine 1999), thus breaking the link between the vegetation types represented in the charcoal and pollen records. However, confidence in the highest of these values is low (Figure 5) due to the very low mesocharcoal count ($n$ = 7) in that sample, and it should be noted that if such decadal to centennial fluctuations were present in the lower part

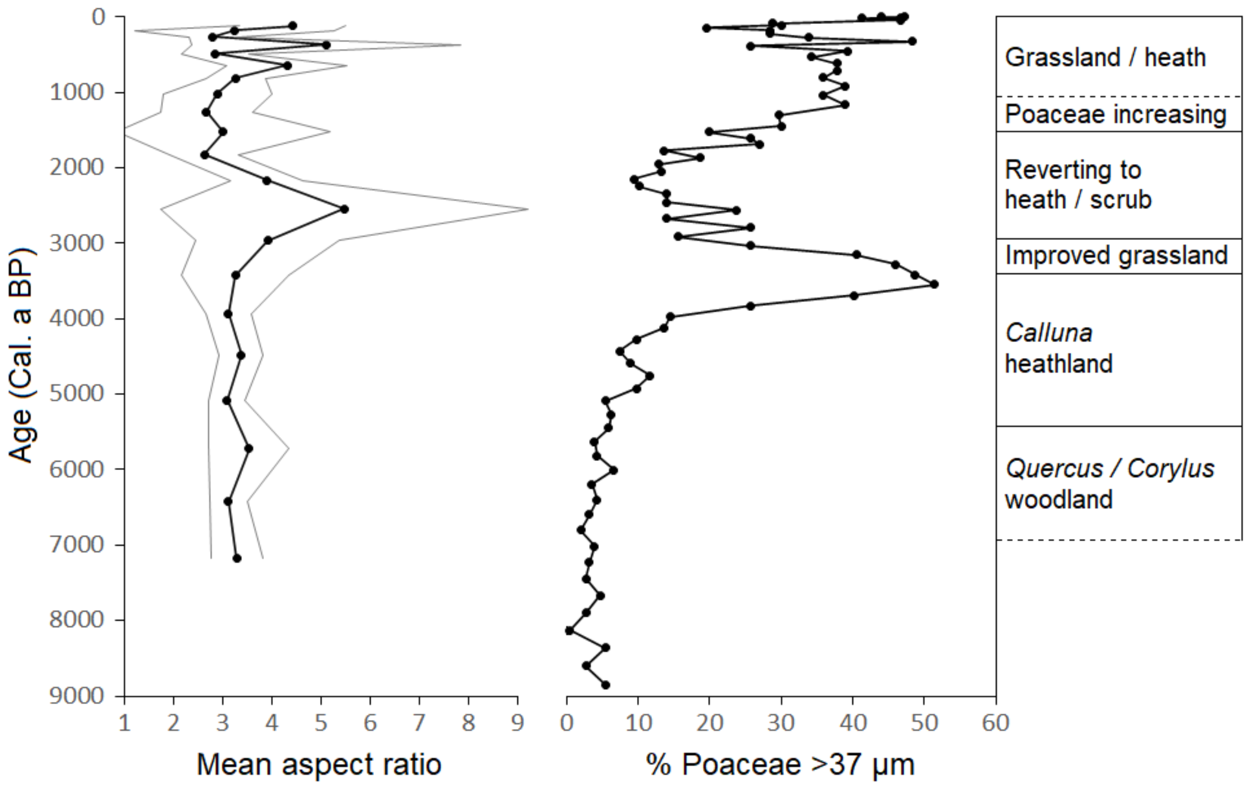


Figure 5. Variation of mean mesocharcoal aspect ratio with age, compared to variation in Poaceae as a percentage of total pollen > 37 µm (Fyfe *et al.* 2008), and major changes in vegetation as inferred from pollen records by Fyfe *et al.* (2008). All data are displayed according to the age-depth model described in this study, which differs from that of Fyfe *et al.* (2008). Grey lines indicate the 95 % confidence intervals for the population means of the aspect ratios.

of the core they would be obscured by the lower temporal resolution. Although the influence of anthropogenic charcoal sources is an unknown factor, we note that wood charcoal from settlement or campfires would be expected to decrease the aspect ratio, and variations in the proportion of the total originating from such fires would therefore tend to obscure the relation between aspect ratio and the vegetation history revealed through palynology. Burning for land management would potentially affect the proportionality between the species represented in the pollen record and in the charcoal record. This would also tend to obscure the relationship that we suggest is seen here.

Considering the coarse sampling resolution and the approximate nature of the age-depth model, changes in aspect ratio are unlikely to align precisely with published records of vegetation change (Fyfe *et al.* 2008). However, the mean aspect ratio does appear to correspond broadly to the prevalence of grassland: no high values occur prior to the establishment of a substantial grass component to the vegetation, and the subsequent fluctuations appear to be broadly reflective of changes in the proportion of Poaceae pollen, though a dated sequence would be necessary to confirm this. This suggests that the use of charcoal aspect ratio to indicate prevalence of grasses (Umbanhowar & McGrath 1998) is a viable method in peatland as well as lake sediment studies.

The generally high mean values (compared to the guidelines of Umbanhowar *et al.* 2006) may indicate that peats have greater potential for preservation of more fragile, elongate forms; if so, this may be due to the lower energy transportation associated with peatland charcoal. Aspect ratio decreases with intensity and duration of fluvial transport (Crawford & Belcher 2014), which will be less prevalent where charcoal is deposited in peats. In particular, charcoal in upland peats will not have undergone vigorous or prolonged fluvial transport, and aerial transport is more likely. Charcoal particles have a low probability of being re-transported after settling on a peat surface (Rhodes 1996) and undergo minimal movement within the peat matrix after burial (Rhodes 1996). This suggests that peatland charcoal particles could have a tendency to be more elongate, and this should be taken into account when interpreting aspect ratios as evidence of vegetation type.

### *Qualitative visual analysis, and classification using lake sediment based schemes*

The question of how peatland charcoal differs from that preserved in lake sediments was addressed by comparing the particles with previous categorisations based on lake sediment charcoal. Courtney Mustaphi & Pisaric (2014) presented the most recent and complex classification of charcoal morphotypes, with 27 morphotypes defined by a key that uses up to five levels of categorisation. This was the first charcoal morphotype study to comprehensively classify its own data set, and to aim to be adaptable to any other morphologies. Fifteen of these categories were represented in our sample; an example of each is shown in Figure 6.

The 'irregular polygons' category (A) accounted for 60 % of the particles, including 5 % categorised as A4 or A5 on account of lattice-like structure. The remaining 55 % displayed no such distinctive structure and were subdivided according to the presence of variable surface texture (A1), holes (A2), or neither (A3). Courtney Mustaphi & Pisaric (2014) suggest that Type A1 is derived from wood, on the basis of the study by Enache & Cumming (2006). As it is of irregular shape but shows some structure, it can only be Type M by Enache & Cumming's (2006) criteria. Enache & Cumming (2006) cite Umbanhowar & McGrath (1998) for evidence that Type M "likely originated at high temperatures or from the burning [of] branches and leaves", but it is not clear how the findings of Umbanhowar & McGrath (1998) support this conclusion. Courtney Mustaphi & Pisaric (2014) observe that they could produce Type A3 by burning "a wide range of materials" including fresh or decomposing wood, leaves, and other herbaceous material. Courtney Mustaphi & Pisaric (2014) suggest that Type A2 derives from herbaceous material, citing Walsh *et al.* (2010), though Walsh *et al.* (2010) identify herbaceous charcoal by the presence of stomata, which were not evident in those particles classified as A2 from the Shovel Down core.

The remaining 40 % of the sample, which did not fall into the polygonal (A) category, consisted primarily of linear forms (Type D; 21 % of total) and blocky or rectangular forms (Type B; 16 % of total). Type D (linear) particles are divided into the highly elongate D1 (2 %), and the flat D2 (9 %) and D3 (10 %). While D1 and D2 may have multiple sources (including grasses, needles and, in the case of D1, wood), Courtney Mustaphi & Pisaric (2014) identify D3, which is distinguished from D2 by the presence of oval voids, as originating from Poaceae leaves (cf. Jensen *et al.* 2007). Type B (rectilinear) particles are divided between five subcategories. While B1 (1 %) are identified unambiguously as wood charcoal, the other four subcategories (15 %) each have more than one possible source.

While the A1 and A3 morphotypes may commonly be derived from wood, there is no clear reason for supposing that this is always the case; and

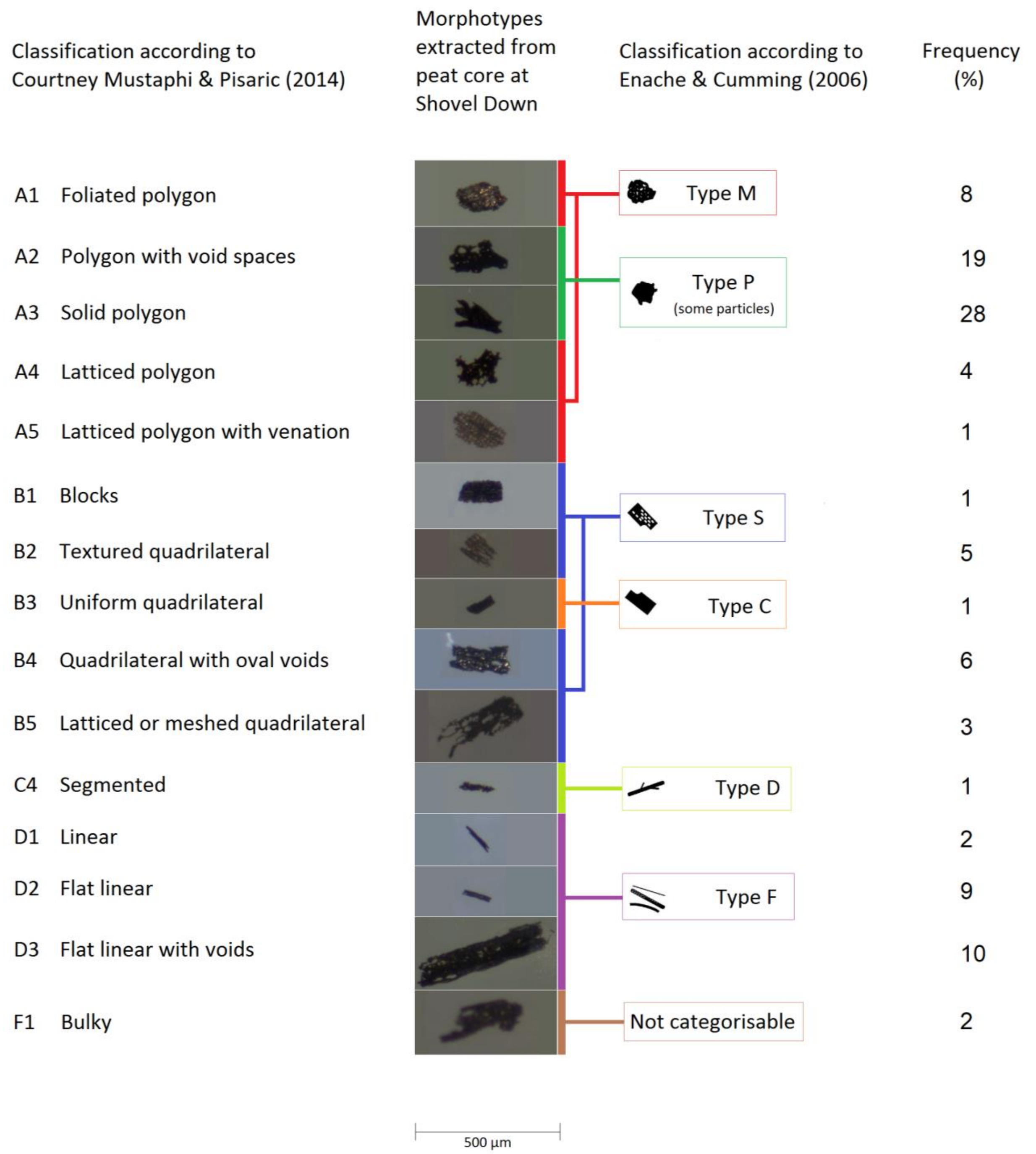


Figure 6. Charcoal morphotypes from the Shovel Down peat core categorised according to published classification schemes, including comparative images from Enache & Cumming (2006). For copyright reasons, readers are referred to Courtney Mustaphi & Pisaric (2014) for comparative images from that classification scheme.

while the A2 particles were evidently herbaceous in the samples assessed by Courtney Mustaphi & Pisaric (2014), those that fall into that category as they define it are not so in the Shovel Down assemblage. The categorisation of A1, A2 or A3 results from the particles being relatively flat, and the absence of rectangularity, ‘complex features’ (such as branching, segmentation etc.), elongation, complexity of structure, or glassy appearance. Particles therefore fall into these categories largely due to the absence of features rather than the presence of them. This applies most of all to Types A2 and A3, whose only positive attribute is that they are flat, and which account for almost half of the particles in our sample. These two types are essentially amorphous, and likely classifiable as Enache & Cumming's (2006) Type P. This is similarly a negative categorisation, based on the absence of apparent structure or geometric regularity, though it is also described as having a powdery texture, which was not always evident. This morphotype was rare in the lake sediments studied by Enache & Cumming (2006), not present at two further lakes studied by Enache & Cumming (2007), and rare in a fourth lake studied by Moos & Cumming (2012). However, amorphous charcoal was common in the Shovel Down mesocharcoal.

As amorphous charcoal forms are evidently rare in lake sediments, their abundance here is probably related to the peatland environment itself. Peat may be more likely to preserve forms that are inherently fragile, though we note that Enache & Cumming (2006, 2007) found other fragile morphotypes present. It is also possible that these morphotypes originate in the charring of the peat itself. Cohen (2009) reported "lenses of fine-grained amorphous charcoal" resulting from peatland fire, and Hudspith *et al.* (2014) found that peatland fire produced charcoalified peat clasts composed of degraded *Sphagnum* and other plant tissues within "a matrix of undifferentiated, humified plant tissue". New *et al.* (2016) found charred aggregates of partially decomposed material in a peat core from All Saints Bog, Ireland, demonstrating the incorporation of such forms into the peat column. Amorphous particles in the present study are also likely to originate in charcoalification of the peat itself, though as New *et al.* (2016) note, it is not evident from such particles whether they originate from burning of the peat itself, or pyrolysis of near-surface peat by radiative heating from surface fire.

The charcoal assemblage from Shovel Down shows wide variations in morphology, with a comparable diversity of geometry, structure and texture to that found in lake sediment charcoals. The notable difference between charcoal preserved in peat and that preserved in lake sediments appears, on the basis of our study and consistent with previous studies, to be the prevalence of amorphous charcoal particles, i.e. particles which lack defined external morphological features, geometric regularity, or evident internal structure. These particles (i.e. Types A2 and A3) account for 47 % in the present study. In keeping with the findings of New *et al.* (2016), it appears that amorphous charcoal may be a particular feature of peatland assemblages, related to charring of the peat itself in addition to the surface vegetation. This contributes to the potential for error if inferences about charcoal sources associated with existing classifications are assumed to be applicable to peatland charcoal. Jensen *et al.* (2007) noted that most of the particles in their lake sediment sequences lacked distinctive morphological features indicative of their origin and did not seek to classify these. By contrast, Courtney Mustaphi & Pisaric (2014) produced a classification which, by containing categories based on the absence of features, can accommodate all particles. However, this can result in categories containing quite dissimilar particles, and this increases the probability of error if it is assumed that the category is associated with a particular source material. This suggests that, while the classification system of Courtney Mustaphi & Pisaric (2014) is intended to be modified for use in different environments, applying it to peatland charcoal would require additional attention to account for the differences in morphotypes between lake and peat charcoal. A large-scale study of peatland charcoal morphotypes would be valuable as it would provide a sound empirical basis for peatland charcoal to undergo the detailed morphological analysis that is now possible for lake sediment charcoal.

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## AUTHOR CONTRIBUTIONS

AJC designed the study under supervision from CMB. AJC conducted the field and lab work and analysed the data under supervision from CMB. AJC wrote the first draft of the manuscript, and both authors contributed to the final version.

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