The analysis of charcoal in peat and organic sediments

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SUMMARY

The abundance of charcoal in sediments has been interpreted as a 'fire history' at about 1,000 sites across the globe. This research effort reflects the importance of fire in many ecosystems, and the diversity of processes that can be affected by fire in many landscapes. Fire appears to reflect climate through the intermediary of vegetation, but arguably responds faster than vegetation to climate change or variability. Fire and humans are also intricately linked, meaning that the activity of fire in the past is also of relevance to prehistoric and historic human transitions and to contemporary natural resource management. This article describes recent advances in the analysis of charcoal in peat and other sediments, and offers a simple method for the quantification of larger charcoal fragments (>100 μm) and a standardised method for the quantification of microscopic charcoal on pollen slides. We also comment on the challenges that the discipline still faces.

KEY WORDS: fire history, image processing, macroscopic charcoal, microscopic charcoal.

1. INTRODUCTION

Fire can be an important event affecting numerous biophysical processes in many landscapes (e.g. Clark & Robinson 1993, Carcaillet *et al*. 2002, Lynch *et al*. 2007, Pausas & Keeley 2009). The abundance of charcoal in sediments has been interpreted as a 'fire history' at about 1000 sites across the globe (Global Palaeofires Database, 2009). Changes in fire activity are attributed to climate change or variability, anthropogenic activity, fuels and/or to complex interactions among these variables.

Charcoal is an inorganic carbon compound produced from the incomplete combustion of organic material at temperatures ranging from 280 to 500°C (Clark 1984, Patterson *et al.* 1987, Braadbaart & Poole 2008). If oxygen is abundant and combustion is unimpeded, ash is the end product; however if oxygen is restricted or combustion incomplete then charring and carbonisation produces charcoal. Charcoal is resistant to oxidation and microbial activity and so is persistent on a geological timescale (Herring 1985). In (waterlogged) peat and sediments charcoal effectively sequesters carbon into the 'geological' reservoir.

Charcoal is quantified in sediments using chemical digestion (e.g. Tallis 1975, White & Hannus 1981, Griffin & Goldberg 1983, Winkler 1985, Bird & Cali 1998, Kurth *et al*. 2006) or, more commonly, using various optical techniques. The optical identification and quantification of charcoal in sediments, which dates back to Iversen (1941), is not particularly difficult and so is widely used as an indicator of past fire activity (e.g. Clark 1982, 1983, Patterson *et al.* 1987, MacDonald *et al*. 1991, Clark *et al.* 1998.

Generally, charcoal derived from plant material is black, opaque, brittle and angular, with an elongate-prismatic appearance possibly displaying some cellular structure (Swain 1973, Clark 1982, Griffin & Goldberg 1983, Patterson *et al.* 1987, Enache & Cumming 2006, Scott 2010). Despite these generalisations, charcoal morphology is often surprisingly variable and irregular.

The size of charcoal quantified optically falls into two broad categories. Smaller particles are usually quantified in conjunction with palynology using microscopy and so are referred to as microscopic charcoal. Larger charcoal particles (typically >100 μm in length) are predominantly isolated using wet sieving, and so are sometimes referred to as 'sieved' or 'macroscopic' charcoal. Conedera *et al*. (2009) provide a useful summary of the temporal and spatial resolution of the various approaches to reconstructing past fire activity.

Pollen-slide charcoal, popular since the pioneering work of Iversen (1941), probably reflects fire at all scales up to and including a regional or

extra-regional source area (Clark 1988a). Tinner *et al.* (1998) used ^{210}Pb dating and both thin section and pollen-slide charcoal quantified with image analysis, and compared the results with historical records of fires at various spatial scales around Lago di Origlio in southern Switzerland. They found that the influx of charcoal >75 μm^2 (or 10 μm length) on pollen slides compared well with fire 20–50 km from the core site. This result, in a warm-temperate climate, is in agreement with studies from the boreal biome (MacDonald *et al*. 1991).

The quantification of larger charcoal pieces started, arguably, in the late 1980s with petrographic thin sections (Clark 1988b) although this technique has not been popular due to demanding sample preparation. Since the early 1990s, macroscopic charcoal has been most commonly quantified after being wet sieved from sediments (e.g. Clark 1990, MacDonald *et al.* 1991, Clark & Royall 1995, Millspaugh & Whitlock 1995, Whitlock & Millspaugh 1996, Long *et al*. 1998, Laird & Campbell 2000, Carcaillet *et al*. 2001, Gardner & Whitlock 2001, Brunelle & Whitlock 2003, Black & Mooney 2006, Stähli *et al*. 2006, Tinner *et al*. 2006, Black & Mooney 2007, Mooney *et al*. 2007, Vannière *et al*. 2008).

Several benchmark charcoal taphonomy studies have demonstrated that macroscopic charcoal travels much shorter distances than charcoal typically encountered on a pollen slide and so reflects fire at a local scale (e.g. Whitlock & Millspaugh 1996, Clark *et al.* 1998, Blackford 2000, Ohlson & Tryterud 2000, Gardner & Whitlock 2001, Higuera *et al.* in press). Quantifying this 'local' scale is difficult; theoretical work by Clark (1988a) indicates that >100 μm charcoal particles travel only 10^1–10^3 m from the source; but charcoal >1 cm can be transported many kilometres (Garstang *et al*. 1997, Pisaric 2002, Tinner *et al*. 2006, Peters & Higuera 2007), especially as fall-out from large plumes resulting from intense fires. Duffin *et al.* (2008) defined a 'relevant source area of charcoal' based on the relationship between charcoal concentration and the fire area and intensity in Kruger National Park, South Africa.

Pollen-slide charcoal and macroscopic charcoal provide information on fire history at different but complementary spatial scales (MacDonald *et al*. 1991, Tinner *et al*. 1998, Carcaillet *et al*. 2001, Olsson *et al.* 2009). In some regions of the world (e.g. northern and southern America, Australia) there has been a move away from the reconstruction of fire history at larger spatial scales, using microscopic charcoal, to "more spatially specific reconstructions" using macroscopic charcoal (Whitlock & Bartlein 2004, p. 480). This means, of course, that regional summaries of fire history then have to be derived *via* compilation of local (macroscopic) charcoal records as described, for example, by Power *et al*. (2010). In Europe, but also in other regions of the world, paired contiguous high-resolution microscopic charcoal and pollen records have been used as sources of ecological information for environmental management and conservation purposes and for testing dynamic vegetation models (e.g. Green 1981, 1982; Odgarrd 1992, Tinner *et al.* 1999, Keller *et al*. 2002, Wick & Möhl 2006, Colombaroli *et al*. 2007, 2008). On the other hand, the application of dynamic vegetation models to resolve long-term fire ecology issues has recently been extended from microscopic charcoal and pollen analyses to tandem macroscopic charcoal and plant macrofossil analyses (Colombaroli *et al*. 2010).

The resistant chemical nature of charcoal means that it is relatively easy to isolate from sediments using a plethora of methods. Quantitative estimates of charcoal in peat and sediments may be based on a count (number of particles), area, mass or proportion, normally within a gravimetric or volumetric sample of peat or sediment. Comparison between sites is best accomplished if units are standardised (Clark & Hussey 1996), but this has been lacking in charcoal studies (Carcaillet *et al.* 2001, Whitlock & Larsen 2001, Kershaw *et al.* 2002, Tinner & Hu 2003, Turner *et al*. 2008, Conedera *et al*. 2009) leading to problems when databases are complied and regional or global summaries are attempted.

Power *et al.* (2008, 2010) and subsequent studies using the Global Palaeofire Database (2009) overcame this limitation by standardising all 'raw' data (microscopic and macroscopic charcoal) in terms of a 'charcoal index'. There are a number of important observations resulting from such inter-site comparisons (Marlon *et al*. 2008, Power *et al*. 2008, Marlon *et al*. 2009, Mooney *et al.* 2011); however, standardisation of data requires decisions which can arguably result in eccentric results. For example, standardisation techniques do not often cope well with the zero values (i.e. the absence of charcoal) obtained for ecosystems where productivity or flammability is limited (e.g. arctic environments and tropical or otherwise moist ecosystems in the absence of ignition by humans). Moreover, ecologically meaningful variability of the original data may be reduced by transformation.

Good reviews of the charcoal literature can be found in Tolonen (1986), Patterson *et al.* (1987), Whitlock & Larsen (2001), Whitlock & Bartlein (2004) and most recently in Conedera *et al*. (2009). It is not the intention to comprehensively review the

voluminous literature on charcoal here. Instead, we review recent advances in the analysis of charcoal in peat and other sediments, offer our views on methods with potential, and describe challenges that the discipline still faces. We conclude with a simple and fast method for the quantification of larger charcoal fragments (>100–200 µm) washed from volumetric sub-samples of sediment, and a standardised method for the quantification of microscopic charcoal on pollen slides.

2. METHODS FOR QUANTIFYING CHARCOAL IN PEAT AND OTHER SEDIMENTS

2.1 Chemical digestion methods

Digestion methods rely on the resistance of charcoal to various chemical processes. Charcoal-containing sediments are treated in a series of steps to remove the matrix and so determine the mass of elemental carbon (e.g. Tallis 1975, White & Hannus 1981, Griffin & Goldberg 1983, Winkler 1985, Bird & Cali 1998, Laird & Campbell 2000, Kurth *et al*. 2006). The most widely used method in palaeoenvironmental studies is that of Winkler (1985), in which treatment with concentrated HNO_3 (which digests organic carbon but not charcoal) is followed by ignition at 550 °C (when charcoal is combusted). Elemental carbon is quantified as the difference in mass before and after ignition, expressed as a percentage of the oven-dry mass of the sediment sample.

When compared, 'Winkler charcoal' differs distinctly from other measures of charcoal (Winkler 1985, Burney 1987). Few authors have related 'Winkler charcoal' to an independently derived history of fire, although two studies from Alberta (Canada) are notable exceptions. In these, MacDonald *et al.* (1991) found that no measure of charcoal abundance, including Winkler charcoal, correlated perfectly with the recent fire history, reconstructed using dendrochronology; whereas Laird & Campbell (2000) found that a modified version of Winkler charcoal did reflect fire history in the catchment but the response sometimes lagged behind fire events by several years.

Rhodes (1998) noted that chemical digestion methods are not always capable of digesting fibrous peats. Experimental error may also present problems for samples with small elemental carbon contents (<1%), although Laird & Campbell (2000) and Kurth *et al*. (2006) describe effective methods for estimating low charcoal contents. Notably, digestion techniques cannot discriminate between the products of biomass burning and fossil fuel combustion, which can be a problem when dealing with recent sediments (Patterson *et al*. 1987).

Chemical digestion methods for quantifying charcoal do not feature in much contemporary published research, although they appear to offer significant unfulfilled potential for the reconstruction of fire history. Such work requires careful consideration of the charcoal fraction quantified and hence the spatial scales represented.

2.2 Physical, chemical and biomolecular fingerprinting of charcoal: fuel and fire regimes

Charcoal formation occurs either by charring or by carbonisation of biomass in a limited supply of oxygen (Braadbaart & Poole 2008). Although often described as an inert material, charcoal produced from the same fuel source may have different physical, morphological and chemical properties depending on the temperature, time of exposure and heating rate during the combustion process. The physical and molecular composition of charcoal presents exciting but largely unexplored potential for deriving information on fire history.

Umbanhowar & McGrath (1998) investigated microscopic charcoal morphology as an indicator of the fuel (vegetation) burnt using materials from an open burn and by combusting grass samples, and leaf and twigs from tree species, in a muffle furnace. This confirmed previous observations that charcoal morphology reflected, in part, the shape of the original fuel. These authors also confirmed that grass charcoal is longer and narrower than charcoal from other biomass. The *absence* of grass charcoal might, however, reflect high fire intensity or another aspect of fire behaviour and so cannot be confidently related to the vegetation/fuel source.

In laboratory experiments, higher temperatures result in less charcoal and the charcoal produced is generally smaller (Umbanhowar & McGrath 1998); although in the case of a wildfire, particle size may be modified by exposure time, which itself may be influenced by turbulence and fire intensity (Ward & Hardy 1991). Vaughan & Nichols (1995) found that higher temperatures produce charcoal which is strongly fractured, less dense and with increased porosity in comparison to charcoal formed at lower temperatures.

A useful summary of the properties of a 'combustion continuum' ranging from unburnt materials through slightly charred materials, charcoal, soot and graphitic black carbon to the endpoint graphite is provided by Conedera *et al*. (2009). Braadbaart & Poole (2008) undertook a series of experiments to show that the carbon content of charcoal is linearly related to the temperature of formation up to ~650 °C. Scott &

Glasspool (2007) have demonstrated that reflective properties of charcoal can be related to the temperature at which it formed. Reflectance is a technique used in coal petrology but it has not been applied to palaeoenvironmental studies of past fire intensity. Braadbaart & Poole (2008) demonstrated that reflectance not only increases with temperature but also as a function of exposure time, but this was temperature dependent for their experimental materials, with the influence of time strongest at temperatures 500–800 °C.

The combustion of organic matter and particularly the structural components of wood such as cellulose, hemicellulose and lignin results in a multitude of molecular products which may be used as fire proxies (e.g. see Conedera *et al*. 2009, p. 448). At temperatures above 250 °C polysaccharide and lignin markers are gradually replaced by thermal degradation products, and above ~300 °C aromatic compounds are produced (Braadbaart & Poole 2008).

Conedera *et al*. (2009) suggests that the monosaccharide anhydride levoglucosan is the most promising marker, as it results from the combustion (>300 °C) of cellulose. Levoglucosan is stable in the atmosphere and so is often used in atmospheric sciences as a tracer for the products of biomass burning (Schkolnik & Rudich 2006). There is some uncertainty about molecular degradation (e.g. by hydrolysis or fungi) of levoglucosan but it has been found in marine sediments (Deshmukh *et al.* 2001). This uncertainty should be clarified; if levoglucosan is stable in sediments it would be an excellent independent tool for examining woody biomass burning at large spatial scales.

Such molecular characterisation uses relatively complex instrumentation which is perhaps beyond the capabilities of many palaeoenvironmental laboratories. For example, Kaal *et al*. (2008) used pyrolysis gas chromatography and mass spectrometry to observe the degree of thermal modification of pyrolysis products as an indicator of changes in fuel types. Such biomolecular fingerprinting is increasingly common in the analysis of 'black carbon' (BC). Few studies examining BC have an overt focus on fire history (Kaal *et al*. 2008 is one exception) but rather address pedological processes or carbon sequestration and the global carbon cycle (Forbes *et al*. 2006, Preston & Schmidt 2006). Nonetheless, interest in the history of the global carbon cycle progressively results in the application of advanced chemical methods to BC in palaeoenvironmental archives such as soils, deep sea sediments and ice cores. It is perhaps only a matter of time for improving analytical techniques before the chemical fingerprinting of fire products like benzene, toluene, PAHs, benzonitrile and isoquinoline can be applied to peat and lake sediments to investigate Quaternary fire histories.

2.3 Macroscopic charcoal

Although a feature of many earlier studies (e.g. Swain 1973, Clark 1982, Tolonen 1986), there has been a move away from the quantification of charcoal (both microscopic and macroscopic) in distinct size classes. This has resulted from studies which have questioned the utility of the information gained versus the time required for the analysis (e.g. Tinner *et al.* 1998). Carcaillet *et al*. (2001) found that all size classes of macroscopic charcoal were significantly correlated with total charcoal concentration and other studies have reported a high correlation between various fractions of macroscopic charcoal (e.g. Whitlock & Millspaugh 1996, Thevenon *et al*. 2003, Higuera *et al*. 2005).

The time spent on quantification of different size fractions of macroscopic charcoal is perhaps more efficiently used on high resolution, contiguous analyses and spatial replication. The easiest size fraction above about 100 µm should be used; "easiest" should take into account materials (e.g. sieve mesh available, magnification, capability of image processing *etc*.) and the likely concentration of charcoal (such that you get enough particles for meaningful records but not so many that quantification is onerous). Quantifying charcoal of only one size can, however, lead to oversight of potentially important chronological markers arising from pollution (e.g. Thevenon & Anselmetti 2007).

Enache & Cumming (2006) examined the accumulation of different morphologies (shape, major : minor axis ratio, porosity) in wet sieved charcoal >150 µm from Prosser Lake, British Columbia (Canada). They compared the accumulation of total charcoal and different morphotypes to historic fires of the Twentieth Century within a radius of 20 km around the lake. Notably, the area burned and total charcoal accumulation were not correlated (neither directly nor with any lag or lead in cross-correlograms) at 5, 10 or 20 km radius of the lake, which Enache and Cumming (2006) attributed to changes in rainfall and hence charcoal taphonomy. Some charcoal morphologies (e.g. 'irregular with structure', 'fragile and highly porous') gave a better fire history (*viz*. recorded most fires and did not give any false positives), whereas others (notably 'elongated with no ramifications') were negatively associated with fire! This is perhaps dependent on the vegetation, making generalisations difficult, but it clearly suggests some complexity.

2.4 Microscopic charcoal

In the period between Iversen's (1941) pioneering work and the mid-1990s the fire history of an area was most commonly reconstructed using sediment-based archives *via* quantification of charcoal on pollen slides. Various techniques are evident in the literature, ranging from subjective estimates on an ordinal scale, through to absolute abundance counts, size class methods and point count methods. The main attraction of these methods is that they can be applied to slides prepared for palynology and so require no further processing, and they can be paired with pollen analysis. They have thus been commonly associated with studies of vegetation history or long-term fire ecology. Conversely, the preparation of pollen slides is laborious and hence they are not often used for contiguous, high resolution analyses.

In the mid-1990s Rhodes (1998) reported that the point count method (PCM) of Clark (1982) was becoming increasingly popular. Point counting suggests that the ratio of the number of points intersecting a phase to the total number of points applied is proportional to the area of that phase (Clark 1982). The relative simplicity and speed, as well as the perception that it is a more quantitative approach, all added to the popularity of the PCM.

The concentration of charcoal on a palynological slide can be expressed as a count or as an area. Quantitative comparisons spanning different biomes (Tinner & Hu 2003) suggest that area estimates (including PCM) of pollen-slide charcoal, which are often time consuming, are not necessary for the reconstruction of fire history (Conedera *et al*. 2009). For comparison of charcoal numbers with studies reporting estimated or measured charcoal areas, regression equations which have been tested in both boreal and temperate biomes might be used (Tinner & Hu 2003 but see Ali *et al*. 2009).

Some problems with microscopic charcoal have been described in the literature (e.g. Patterson *et al.* 1987, Rhodes 1998). Most relate to the relatively small size of the charcoal particles, which are typically less than 50µm in diameter (Clark & Royall 1995), but may range up to the size of the sieve used in the pollen preparation (typically 0.2–0.5 mm). This can result in problems with identification and separation of charcoal from other dark material (Patterson *et al.* 1987). Typically, only charcoal particles greater than 10µm in length are quantified.

Charcoal of the size typically encountered on a pollen slide can also be carried long distances, both theoretically (Clark 1988a), and especially in association with convection currents during wildfires (Patterson *et al*. 1987). Despite this it is apparent that pollen-slide microscopic charcoal may also reflect fire in the local environment. As an example, Pitkanen *et al*. (1999) compared dendro-chronological data with microscopic charcoal in an annually laminated lake record from eastern Finland covering the past 520 years and concluded that charcoal of this size reflected the occurrence of local low-intensity fires. However, in this study standard pollen procedures were altered (sieving was omitted) to permit the analysis of large charcoal particles. Calibration studies, physical considerations and modelling efforts (see review in Conedera *et al*. 2009) suggest that microscopic charcoal derives from sources within 20–100 km around a site. This spatial scale should be considered in any research investigating fire that adopts this approach.

2.5 Sampling sediment for charcoal analyses

The recent, uppermost portion of a peat sequence needs special consideration for sampling. It can be an important part of any fire history, potentially overlapping independent records (historic archives or dendrochronological fire-scar history) allowing testing of methods, and may include important chronological markers.

In the uppermost portion of the peat profile, living or dead but not humified plant materials occupy a greater fraction of any sample, meaning that charcoal could be found to be less concentrated. Human activity during the recent past could also potentially result in the enhanced delivery of allochthonous materials or the remobilisation of charcoal stored in the catchment. This problem could be overcome with better chronological control, but recent sediments are often poorly dated (Gale 2009). As an example of this potential problem, Marlon *et al.* (2009) describe a decrease in charcoal in recent (*viz*. Twentieth Century) sediments. This could arguably be real, for example result from fire suppression (Marlon *et al*. 2009), and hence is an important observation. Alternatively, it could reflect problems with sampling recent sediments and/or the under-estimation of recent sedimentation rates in the absence of reliable physical dating (e.g. ^{210}Pb).

Sampling should always be at a resolution that is likely to capture the probable fire-return interval. Clark *et al*. (1998) and Higuera *et al*. (2007) recommend a sampling resolution of less than about 0.12 times the mean fire-return interval. Continuous sampling is highly recommended for reconstructing fire history. If fire-ecological issues are studied (e.g. impacts of fire on vegetation) all proxies should be sampled continuously at very high resolutions, usually <10–20 years (Birks 1997, Conedera *et al*.

2009). In peat and sediment sequences this is usually achieved by sampling each centimetre or half-centimetre.

Determining volumes for any series of samples warrants care. For peat which is fibrous, or where it is possible to squeeze in more sample (by increasing the bulk density), volume measurements are best achieved by volumetric displacement. For compacted sediments, packing or cutting a known volume is less time-consuming and as reliable as volumetric displacement. Carcaillet *et al*. (2001) examined the volume of sediment required for macroscopic charcoal determination and found that one cubic centimetre gave a representative sample, but this obviously depends on how much charcoal has been produced and deposited in the particular system studied. A sampling volume of 1–2 cm^3 is usually sufficient for most techniques (e.g. pollen-slide, wet sieving), but volumes may reach 20–50 cm^3 if plant macrofossils are quantified together with charcoal (e.g. Tinner *et al*. 2006, Colombaroli *et al.* 2010).

2.6 Expression of charcoal data

As noted, the concentration of charcoal in sediments can be quantified either as an abundance (i.e. a count of the number of particles) of charcoal per unit volume of sediment (e.g. cm^{-3}), or as an area of charcoal per unit volume of sediment (mm^2 cm^{-3}). Percentages or ratios (e.g. charcoal : pollen types) are not frequently used in modern literature because of potential autocorrelations (e.g. fire that disrupts vegetation may affect pollen sums).

Given that charcoal is generally brittle, handling and processing could result in a higher charcoal count (Clark 1984). This concern initially contributed to a trend towards reporting charcoal area; however, many studies have revealed that the number of charcoal particles is highly correlated with charcoal area (e.g. Tinner *et al.* 1998, Tinner & Hu 2003, Ali *et al*., 2009, Olsson *et al.* 2009). This has meant that most research during the last decade has concentrated on the quantification of charcoal as a number because it is faster.

The use of image analysis software allows macroscopic charcoal concentration to be quantified as abundance or as an area with relatively little effort (e.g. NIH Image, see method described herein). Quantification of the area of charcoal might be of greater relevance for macroscopic charcoal as it gives more weight to big pieces, which probably originated from closer sources (Conedera *et al.* 2009).

Weng (2005) acknowledged the problems with charcoal fragmentation and so suggested that total charcoal volume is the best measure. As volume is difficult to measure, he proposed a statistical calibration that estimates the total volume of charcoal (V) as the product of a coefficient (C) and the sum of the area of individual charcoal pieces (A_i) to the power of $^3/_2$

$$V = C\sum A_i^{(3/2)} \qquad [1]$$

Even when the coefficient C is unknown Weng (2005) suggested that that the total volume of charcoal in a sample can be realistically estimated from the sum of the individual charcoal pieces, i.e.

$$V \approx \sum A_i^{(3/2)} \qquad [2]$$

The power function of this algorithm means that the total volume is less sensitive to small particles which may be produced or lost during sample processing (Weng 2005). However, Ali *et al*. (2009) concluded that charcoal number, area and estimates of charcoal volume provide comparable fire-history reconstructions, suggesting that volume estimates are superfluous.

If sufficient chronological control is available, the charcoal concentration should be converted to charcoal accumulation rate or influx by dividing the data by the deposition time (years cm^{-1}) of the sediment sample (giving either number of particles cm^{-2} $year^{-1}$ or mm^2 cm^{-2} yr^{-1}). This is necessary in deposits where the rate of sediment accumulation varies; slow sedimentation means that a unit depth of sediment represents more time, with the potential for more charcoal to accumulate. Expressing results as influx also has the advantage of making charcoal values comparable across sites.

2.7 Statistical approaches for macroscopic charcoal data

It is increasingly common for high-resolution contiguous macroscopic charcoal influx (often referred to as CHAR, i.e. CHarcoal Accumulation Rates) to be statistically manipulated to determine the frequency of fire episodes (or the inverse, fire interval) through time. Taphonomic and sedimentological processes operating within lakes mean that charcoal is introduced into sediments over a number of years after a fire event, such that there is a 'background' component (Sarmaja-Korjonen 1992, Bradbury 1996, Clark & Royall 1996, Whitlock & Millspaugh 1996, Long *et al.* 1998, Tinner *et al*. 1998). These methods, summarised in Long *et al.* (1998), Whitlock and Larsen (2001), Whitlock *et al*. (2003), Whitlock & Bartlein (2004) and Higuera *et al*. (2005, 2007, 2009, 2010, in press), statistically decompose a charcoal time series

(usually interpolated to constant time steps) into this background component with superimposed 'peaks'; peaks above some threshold represent fire episodes within the charcoal catchment.

The background component is usually defined using a locally weighted (moving) average calculated along the charcoal data in a temporal 'window'. The width of the window needs to be carefully considered—too wide results in overly smoothed data, while an overly narrow window results in data that mirrors the peaks component. The 'background' component includes charcoal from distant fires and 'secondary' charcoal introduced into the sediments over a number of years after a fire event due to the delayed delivery of charcoal stored within the catchment or lake (erosion, remobilisation, sediment focusing). Whitlock & Millspaugh (1996) considered that secondary charcoal was a relatively minor component of CHAR, but the universality of this generalisation is questionable. The simulation studies of Higuera *et al*. (2007) support the use of wider smoothing windows to define the background component, as charcoal accumulation is better related to fire occurrence (burnt area within the source area) over longer timeframes.

Whitlock *et al*. (2003) and Marlon *et al*. (2006) superposed the background components for a number of sites in north-western USA to reveal an upward trend after the late glacial period which arguably continues throughout much of the Holocene. They associated this with biomass increases as forests developed after glacial retreat (Whitlock *et al*. 2003, Marlon *et al*. 2006). The size of the background component at any time is thus a function of the delivery of secondary charcoal, site characteristics, the vegetation/fuel available (Whitlock & Bartlein 2004, Marlon *et al*. 2006) and the characteristics of the fires during that time.

Determining the threshold above which peaks are considered to reflect fire events is a critical step (Higuera *et al*. 2005, 2009, 2010, in press; Kelly *et al.* 2011). Few studies have used independent evidence to justify this choice although Clark (1990), Gavin *et al*. (2003), Higuera *et al*. (2005) and Mooney *et al*. (2007) are exceptions. Higuera *et al*. (2005), for example, used an independent record of fire to determine the most favourable threshold value. More recently, Higuera *et al*. (2009, 2010) and Kelly *et al*. (2011) have introduced quantitative methods for peak detection based on a 'signal-to-noise index'.

In their study of charcoal accumulation in Yellowstone National Park, Whitlock & Millspaugh (1996, p. 14) concluded that the magnitude of any charcoal peak "reveals more about the taphonomic history of charcoal within the lake and watershed following a fire" than about the characteristics of the fire. Higuera *et al*. (2005) also found no relationship between the magnitude of charcoal peaks and fire intensity. The size of charcoal peaks might thus be controlled by charcoal taphonomy and the distance between the fire and a site.

However, in a recent study in southern Europe, Kaltenrieder *et al*. (2010) identified three populations of residual (referring to the amount of CHAR after the background component has been subtracted) peaks with the aid of a Gaussian mixture model. The three populations were divided by two threshold values. The lower threshold value was used to separate analytical noise from local fire events, while the upper threshold value was used to distinguish moderate natural from devastating anthropogenic fires. These results were corroborated by palynology, which provided independent evidence of land use when macroscopic charcoal peaked.

Using charcoal quantified in size classes from lakes in southern Finland, Sarmaja-Korjonen (1992) found that there were two types of charcoal peaks; one in which all size classes increased, and one where only the larger particles increased. The work of Enache & Cumming (2006) also suggests that different charcoal morphologies contribute more to the background component of charcoal accumulation. Hence, it is possible that image analysis and morphological classification could further aid in peak detection.

These statistical methods, applied to macroscopic charcoal, have resulted in more quantitative analyses and the extended fire histories have allowed new questions to be addressed. In contrast, the available calibration studies suggest that the magnitude of the peaks in microscopic charcoal provides important information about fire-regime parameters, e.g. fire frequency or fire size (see next section). This explains why the derivation of background and peak components is not applicable to microscopic charcoal data (Conedera *et al*. 2009).

3. TAPHONOMIC AND SPATIAL CONSIDERATIONS

3.1 Reproducibility in space and time

Questions regarding spatial scales are central to the taphonomy and interpretation of sedimentary charcoal records, and thus to the reconstruction of fire history. These include not only persistent questions about the spatial scales that charcoal size fractions represent, but also questions such as: Is it possible to derive meaningful records of fire at

landscape scale from a single site? And using a single core? Reproducibility is often the first issue raised by (neo-) ecologists and those responsible for natural resource management when presented with a fire history from a single core at a single site.

Reproducibility was addressed by Clark (1990), who investigated the annual influx of large charcoal particles to three lakes in Minnesota, USA over about 400 years. While some trends were consistent across the three sites, including Twentieth Century decreases in charcoal resulting from fire suppression, there were notable differences between the three cores. In the study of four small lakes in southern Finland by Sarmaja-Korjonen (1992) already mentioned in Section 2.7 above, the charcoal profiles also presented differently.

Some of these differences can apparently be explained by the physical characteristics of the sites (Gardner & Whitlock 2001, Marlon *et al*. 2006) and other spatial relationships (e.g. Higuera *et al*. 2007). Some spatial variability is perhaps to be expected due to the patchy nature of fire in a landscape. Blackford (2000), for example, found that the charcoal content of surface samples after a fire was extremely variable.

In other cases such explanations cannot be easily invoked. Innes *et al*. (2004) examined the mid-Holocene microscopic charcoal record from two near-duplicate peat profiles located close together in the North York Moors. The major trends of the two charcoal curves were found to correspond well but details differed between the profiles. Edwards & Whittington (2000) also quantified the area of microscopic charcoal in three littoral and one central location in Black Loch, Scotland. The influx of charcoal was notably different from that of pollen, suggesting differences in focusing. Edwards & Whittington (2000 p. 79) concluded that "the charcoal records from each of the profiles would have yielded a similar interpretation of fire history" but that differences in influx values "would discourage" (*op cit*. p. 84) attempts to calculate fire frequency. Rather than *discourage* this enquiry, further investigation is warranted, as it may allow the quantification of error terms around calculated fire frequencies.

Recently, Lynch *et al*. (2011) described charcoal influx and fire events per 500-year window (from peak frequencies) from ten small lakes across a relatively uniform landscape in north-western Wisconsin. They found that the background component varied by an order of magnitude across this landscape, and despite some spatial patterning, peak frequencies were also variable. They were, however, able to derive a fire history consistent with regional climate and vegetation reconstructions with the use of charcoal signatures derived from cluster analysis (using grass charcoal, peak frequency and background component). This allowed Lynch *et al*. (2011) to identify spatial patterns that were not otherwise obvious. Furthermore, their cluster types potentially illuminate aspects of the fire regimes through time.

Rius *et al*. (in press) examined CHAR and fire return intervals derived from one lake and three peat bogs within a relatively small geographical area in the Lourdes Basin of the Pyrenees of southern France. Although CHAR differed between the bog and lake site types, the inferred fire frequency revealed considerable consistency. Notably, Rius *et al*. (in press) also derived a composite (with 95% confidence intervals) of the inferred fire frequencies from the four records using compositing methods as described by Power *et al*. (2010). Other similar composites of fire frequencies across homogenous regions offer significant potential (Vannière *et al*. 2011). Existing global and regional syntheses (e.g. Power *et al*. 2008, Mooney *et al*. 2011) use smoothing functions that approximate the background component of 'decomposed' charcoal sequences. Composites of inferred fire frequencies from high-resolution studies could significantly supplement our views on past fire activity.

Calibration studies (relating fires to the fossil record, see e.g. Conedera *et al.* (2009) for a recent review) suggest that meaningful fire histories can be derived from single sites and single cores when charcoal counts are high enough to be statistically robust (e.g. see Finsinger & Tinner 2005). The same conclusion can be drawn from reconstructions at a landscape level, where similar fire signals are captured at different sites with independent chronologies. Nonetheless, studies by Whitlock *et al*. (2003) and Tinner *et al*. (2005), for example, demonstrate some variability across different spatial scales, indicating that the grouping of sites into regions needs to be carefully considered.

3.2 Is the size, severity or spatial configuration of a fire important for charcoal records?

Sugita *et al.* (1997) used simulation models to examine how a fire is represented in pollen records, and although concerned with questions about the spatial resolution of lacustrine pollen records, the work has wider implications. They argued that the size of the fire, proximity to the lake and size of the lake all affect the way a fire is reflected in pollen records. Their simulation models suggested that pollen records are most likely to reflect a disturbance like fire when it is close (within a few hundred metres) and significantly larger (>8×) than the lake itself. They also argued that patchy,

episodic disturbances can only be detected if the signal (in their case a change in pollen deposition) can be separated from the background, extra-local pollen arriving at the site. This is an important issue for the reconstruction of fire. Are fires that burn only a portion of a catchment reflected in our records? Is there any relationship between CHAR and the size of the fire, and the distance and size of the deposit?

These considerations might explain why, in some cases, there is a mismatch between charcoal and an independent record of fire. Laird & Campbell (2000), for example, found that macroscopic charcoal best reflected historical fire events when they burnt near the shores of their sampled site, Christina Lake in Alberta (Canada). Fires occurring elsewhere in the catchment were not always represented. Olsson *et al.* (2009) undertook a high-resolution analysis of a peat and lake sediment deposit at Storasjö in southern Sweden covering the Holocene, and also used pyrophilous beetles which are dependent on or favoured by habitats created by fire. During some time periods they found a mismatch between information from pyrophilous beetles and charcoal, suggesting that fire was a feature of the landscape but probably occurred such that it was invisible in the charcoal record.

In parallel with the application of palynology to small hollows (e.g. Calcote 1998) there has been a recent move towards the analysis of charcoal in small deposits. Such studies are often overtly focused on century- and millennial-scale forest dynamics and the role of fire as a source of disturbance (see Higuera *et al*. 2005 for references). In contrast, Higuera *et al*. (2005) were interested in the calibration of charcoal in small hollows for the reconstruction of fire history. They examined twelve small hollows on Orcas Island, north-western Washington (USA), located within an area of about 10 km^2. Macroscopic charcoal detected, on average, 60% of the fires determined from tree stand and fire scar information. Notably, the rate of detection was dependent upon fire severity, with all severe fires and 20–67% of moderate or low severity fires identified.

Using a simulation model, Higuera *et al*. (2007) suggest that charcoal accumulation is a function of the area subject to fire within the charcoal source area, especially over long timeframes. Their work also explains that the variability in height of the peaks in decomposed macroscopic charcoal records results from the source-area to fire-size ratio, and that taphonomic processes and the physical techniques of sediment sampling work against the identification of small and/or distant fires in charcoal records. Moreover, they suggest that statistical decomposition techniques place further emphasis on fires that occur closer to the sampling site.

Higuera *et al*. (in press) re-examined the Yellowstone National Park charcoal data of Millspaugh & Whitlock (1995) using 'state-of-the-art' statistical decomposition of CHAR, and compared the outcome with dendrochronological records of fire across various spatial scales. Notably, they found that in this landscape charcoal peaks best reflected fire occurrence at a smaller spatial scale (within 1–3 km radius) than total charcoal accumulation, which was significantly correlated with area burned at distances up to 10 km.

This section began with the question "is the size, severity or spatial configuration of a fire important for charcoal records?" Charcoal accumulation results from taphonomic processes which are influenced by spatial patterns involving the area burnt within the source area of the charcoal. Microscopic charcoal has been used to infer quantitative estimates of burned areas over long timescales (Tinner *et al*. 1998, 1999) but this requires a local calibration set (Conedera *et al*. 2009). Recent research strongly implies that macroscopic charcoal in palaeoenvironmental records best reflects particular types and/or spatial arrangements of fire; that fire of lower severity leaves inconsistent records; and that large, severe fires close to the sampling site create big peaks which are most suitable for analysis using decomposition methods (Higuera *et al*. 2005 in press).

4. A METHOD FOR QUANTIFYING MACROSCOPIC CHARCOAL (PARTICLES >100 µm)

This method is only slightly modified from what was once colloquially known as the 'Oregon sieving method', as described in Millspaugh & Whitlock (1995), Long *et al*. (1998) and Gardner & Whitlock (2001). It involves dispersing a volumetric sample of sediment and then washing it through a sieve. Charcoal of a particular size fraction (determined by the sieve size) can then be tallied or areas quantified manually under a dissecting microscope or using image processing. The method uses readily available materials and is designed to be fast, allowing either a finer temporal resolution or a better spatial resolution of study sites to be achieved. The quantification of macroscopic charcoal should reflect fire at a spatial scale that is relevant to ecological and natural resource management.

4.1 Sample preparation

Step 1. Sediment sub-samples of a known volume are placed in dilute bleach for 24 hours.
It is recommended that a few test samples be completed first to refine the method for the particular sediment to be analysed. In most sediments, as little as 1.0 cm^3 may be sufficient; however, in sediment with a low concentration of charcoal, 2–3 cm^3 may be necessary.

The volumetric sample of peat or sediment is placed in bleach (at room temperature or a low-temperature oven in colder climates) for 24 hours. This removes or bleaches darker, non-charcoal organic materials. In the case of highly organic sediments, bleaching leaves a very charcoal-rich sample. White & Hannus (1981) and Rhodes (1998) recommend a 6% solution of hydrogen peroxide (H_2O_2) because the solution at this concentration does not affect charcoal. Schlachter & Horn (2009) also test the efficiency and impact of various H_2O_2 solution strengths.

A simpler (and safer) method is to use household 'chlorine bleach' which typically contains 3–6 % sodium hypochlorite (NaOCl). The active ingredient of sodium hypochlorite is the free chlorine which 'runs off' slowly such that the strength of the bleach will gradually lessen. Therefore, if the same concentration is required for every analysis, it may be better to make a fresh solution each time, e.g. by dissolving 5 g of NaOCl powder in 100 mL water, which gives 4.76 % available chlorine by weight. An alternative is 'oxygen bleach', which uses hydrogen peroxide as the active ingredient and is widely available as a powder which can be made into a solution as needed.

Placing volumetric samples of sediment in freshly procured 'supermarket' domestic bleach for 24 hours is certainly simple and effective. Volumetric sampling is most easily achieved using displacement (directly) into the bleach, although this takes some practice because it needs to be done quickly; the bleach oxidises organic matter (generating CO_2) such that the original volume of sediment decreases.

For sediments containing materials that could be mistaken for charcoal particles, it might be tempting to include additional processing steps (as reviewed by Patterson *et al*. 1988), but this should be avoided to minimise the breakage of charcoal as most steps require centrifuging (see Clark 1984). Instead, manual sorting at Step 3 is recommended (see below). In the case of clay-rich sediments it may be necessary to use a dispersant first in order to ensure that the bleach will be fully effective (e.g. a 5 % or 10 % solution of sodium hexametaphosphate).

Step 2. The sediment is then washed gently through a sieve (e.g. 125 or 250 μm).
After 24 hours in the bleach, the sample is washed through a sieve with a gentle flow of water (a flexible hose and a fine brush may be helpful). Caution should be used to minimise breakage of charcoal particles.

Step 3. All material within the sieve is then carefully transferred to a labelled Petri dish and quantified.
If an appropriate volume of sediment is used, all charcoal particles can be tallied under a dissecting microscope at something like 400× magnification, most easily with the use of a numbered grid beneath the Petri dish. We have quantified charcoal in Petri dishes both after drying and in aqueous solution, and find the latter simpler.

In some samples there may be extraneous material which makes quantification of charcoal difficult, particularly if following the image processing technique outlined below, which cannot distinguish between charcoal and other dark materials. This may necessitate some manual sorting. Plant materials should have been removed by the bleach, but if present are pliable in the aqueous solution, compared to the more brittle charcoal. Dark mineral material can often be concentrated and separated from charcoal using a swirling motion of the Petri dish (similar to gold panning!), and a bulb pipette can then be used to remove it.

As an alternative to manual counting of the charcoal, which delivers the number of charcoal particles of a known size fraction sieved from a known volume of sediment, it is possible to use image processing for quantification. The method described below uses *Scion Image*, which is free software available at www.scioncorp.com. Before downloading the software it is necessary to register, but this is a simple and fast procedure. *Scion Image* for Windows is based on NIH Image, which runs on a Macintosh platform. The method also requires a digital camera to capture images and image processing software (we use *Adobe Photoshop* but the freeware *Erfan View* can also be used) to save the images in the required format.

4.2 Acquiring a digital image

Take a fine-resolution image of the Petri dish with the collected material using a digital camera. The method works best if the charcoal fragments are positioned towards the centre of the Petri dish. The use of a tripod to support the camera keeps the images at a set size and minimises movement. A scale (such as a ruler) and a label (e.g. site name, depth of sample) should be placed next to the Petri

dish. Adjust the zoom of the camera and/or the height of the tripod so that the entire Petri dish, scale and label are included in the image. Using a lightbox (e.g. Geppe Slimline) such that the sample is backlit minimises shadows. Keep the Petri dish (with collected material) for further use (see below). Repeat this step until a good image of all samples has been obtained. Download the images from the camera to the PC with *Adobe Photoshop* (or *Erfan View*) and *Scion Image* already installed.

4.3 Formatting the image for processing

Open one of the images using *Adobe Photoshop*. First re-size the image, adjust the contrast and brightness and then save the image as a bitmap file (*.bmp). If you are familiar with *Photoshop* you can record all of this as an 'Action' and then do batches. We have been reducing our images to 35% (with 'constrain properties' ticked and using the 'bicubic interpolation') before saving them. *Scion Image* analysis can also be used with *.tif formatting but not *.jpg.

4.4 Calibration

Open the *.bmp file in *Scion Image*. Calibration sets the scale for the image and can be done by selecting the tool that allows you to draw a straight line. Go to the ruler (within your image) and draw a straight line over a known length. Then select *>Analyse >Set scale* from the drop-down menus. Fill in the table that appears, making sure that you correctly identify the known length and measurement units. To check if the calibration of the scale is correct select *>Analyse >Measure* and then *>Analyse >Show results* (this should tell you the length of your straight line in millimetres). You should only need to do this calibration once in any session (i.e. while *Scion Image* is open), assuming that the size of your images does not change. Nonetheless, it may be a good idea to check the calibration every ten samples or so.

4.5 Setting measurement parameters, analysing and showing results

Select *>Analyse >Options* from the drop-down menus and set the maximum measurement as 8000. Then use the circle tool to select the area to be analysed (hold the shift key down to make it a perfect circle). The area to be analysed should include all charcoal particles within the Petri dish. The selected area can also be moved around using the arrow keys.

Select *>Options >density slice* from the drop-down menus. The LUT (Look-Up Table) toolbar should then appear on the left-hand side of the screen; this allows all pixels in the image between an upper and lower threshold to be selected. Moving both the upper and lower limit in the LUT toolbar up or down either selects or deselects material in the Petri dish. This is the most subjective stage of the procedure, but subjectivity can be minimised by comparing the selection with the actual charcoal sample. The goal is that all charcoal particles in the sample should be highlighted in the image. The lower threshold on the LUT tool bar should be at the base (256 or pure black) but the upper threshold will need to be varied so that all charcoal particles are selected; this may take some practice.

Select *>Analyse >Analyse particles* from the drop-down menus, making sure the following boxes are ticked: "Label", "Outline", "Reset". Also make sure that min = 1, max= 99999 are chosen.

Select *>Analyse >Show results* from the drop-down menus and a table will appear showing the results of the different parameters for *each* charcoal fragment. Select *>Edit >Copy measurements* from the drop-down menus and paste the results into an Excel workbook. Areas can then be summed to obtain the total area of charcoal for the sample. The number of particles can also be recorded. Other useful statistics may also be calculated, such as modal charcoal size, standard deviation *etc*.

5. A METHOD FOR QUANTIFYING MICROSCOPIC CHARCOAL IN POLLEN SLIDES (PARTICLES <200–500 µm)

Preparation for microscopic charcoal analysis is usually done following conventional palynological preparation procedures (e.g. Moore *et al*. 1991). Minimum sampling volume is usually 0.5–1 cm^3. Tools providing standard volumes should be used for sub-sampling. Exotic marker grains (e.g. *Lycopodium* spores) should be added to the known volume of sample at the start of processing to enable estimation of absolute charcoal values (i.e. concentrations, influx).

To allow comparisons amongst different laboratories, pollen sample preparation should involve the 10 % HCl, 10 % KOH, sieving (excluding material >200–500 µm), decanting (to remove heavy particles such as sand), acetolysis and HF treatments that are conventionally applied; see e.g. the protocol for preparation of samples for pollen analysis later in this volume. When preparing peat material, treatment with HF (which removes silica) might be skipped if mineral content is low. Procedures that lead to microscopic particle breakage should be minimised (Clark 1984). After extraction and mounting, pollen slides are analysed under a transmitted light microscope at 200–400×

magnification. Only black, completely opaque, angular fragments (Swain 1973, Clark 1988a) more than 10 µm long should be counted. Counting of charcoal (area estimates are superfluous for this method, see Tinner & Hu 2003) should proceed until a sum of at least 200 items (i.e. charcoal and exotic marker grains) is reached (Finsinger & Tinner 2005). If the charcoal : marker grain ratio is extremely high or low (>0.9 or <0.1), the concentration of marker grains should be reduced or increased prior to processing a new sample (for details see Finsinger & Tinner 2005).

The concentration of charcoal particles in the sample (particles cm^{-3}) can be calculated using the number of marker grains originally added (Moore *et al*. 1991). The concentration of microscopic charcoal on standard pollen slides can be estimated as an area (mm^2 cm^{-3}) using the following regression equation (Tinner *et al*. 1998):

$$\ln A = -7.418 + 0.936 \ln N \quad [3]$$

where A is the area concentration (mm^2 cm^{-3}) and N is the number concentration (charcoal particles cm^{-3}) of charcoal particles longer than 10 µm. A concentration of 100,000 particles cm^{-3} thus leads to an area concentration estimate of 28.7 mm^2 cm^{-3}.

This regression equation has been tested in deciduous and evergreen vegetation in the arctic, boreal, and temperate biomes of two continents; and provides reasonable estimates for both glycerine and silicon-oil pollen slides (Tinner & Hu 2003). It has been established with the aid of high-resolution image analysis techniques and statistically tested for very low (<2 mm^2 cm^{-3}) to very high (>500 mm^2 cm^{-3}) charcoal concentrations (Tinner *et al*. 1998, Tinner & Hu 2003). Area estimates can be compared with those obtained using other techniques such as the point-count method (PCM) of Clark (1982). This is especially helpful if the intention is to compare absolute charcoal numbers and areas between samples or sites that have been analysed using different techniques.

It is then possible to estimate charcoal number (particles cm^{-2} yr^{-1}) or area (mm^2 cm^{-2} yr^{-1}) influx (i.e. CHAR (charcoal accumulation rate) using an age-depth model (and thus sedimentation rates). The quality of charcoal influx estimates depends primarily on the accuracy of the chronology. Charcoal influx is indispensable for (absolute) comparison across different sites and for calibration studies, but should only be calculated if the chronology and age-depth modelling is reliable.

6. CONCLUSIONS

Iversen's (1941) pioneering work on the charcoal record of Ordrup Mose (in Denmark) was not taken up by other scientists until the mid-to-late 1960s (Tolonen 1986); but charcoal analysis has undergone a remarkable expansion in the last *ca* 40 years and we look forward to it continuing!

Charcoal preserved in anoxic organic sediments provides information on past fire occurrence over much longer timespans than is available from other sources (Whitlock *et al.* 2003), and so finds many applications.

The quantification of charcoal can provide interesting information on past fire activity within a spatial scale that depends mainly on the intensity/severity of the fire, the size of the charcoal fraction quantified and the size of the deposit studied. The size of the site should be chosen with the spatial scale of the disturbance in mind—small sites are probably best suited to address questions about local fires.

Charcoal accumulation reflects fire within the charcoal catchment, an area which is not fixed from one fire to the next, and which could conceivably change with time (e.g. in windy climates). Importantly, although various studies demonstrate that the presence of larger pieces of charcoal is a robust indicator of local fire events, most also find a high level of spatial variability within a fire boundary. This suggests that the *absence* of charcoal is a less than emphatic indicator for the absence of fire.

The satisfactory interpretation of sedimentary charcoal records requires consideration of their accuracy and precision. As Higuera *et al*. (2005) point out, any interpretation should take into account how well a sedimentary charcoal sequence records fire and what biases are likely.

Like all palaeoenvironmental analyses, documenting fire history benefits from a multiproxy approach (Tolonen 1986). The use of charcoal and other fire-sensitive records (fire scars in tree rings, magnetic records, historical records, palynology, macrofossils, geochemistry) may be necessary to constrain multiple working hypotheses and to further test methods in a variety of landscapes.

There are still issues to be resolved with regards to charcoal analysis, for example;

- What is the relationship between the various aspects of a fire 'regime' and charcoal taphonomy? Do charcoal records faithfully depict all fire types and frequencies, or is the record that we see biased towards large, severe

or infrequent fires?

- Does the background component of CHAR—or indeed a microscopic charcoal record—follow biomass, as seems to be the case in western North America (e.g. Marlon *et al*. 2006), due to an overriding climatic signal (as suggested by Power *et al*. 2008)? Or are there other major controls on regional fire activity (e.g. Whitlock & Larsen 2001)?
- Is it possible to derive error terms around derived fire frequencies across various ecosystems?
- What role have humans played in past fire regimes? For example, has Aboriginal use of fire resulted in land cover change? Did anthropogenic fire play a role in some of the major human transitions in prehistory? Can we make any meaningful statements, beyond generalisations, about fire in settler societies? And how can we use such knowledge to inform future natural resource management?

Our knowledge on all of these aspects would benefit from detailed charcoal analyses and their comparison with other fire-sensitive proxies. Only carefully designed experiments, especially to examine the relationship between charcoal taphonomy and fire events—like those completed in western North America and western Europe—will answer these questions. Clark & Royall (1995, p. 80) note that interpretation of sediment records of burning have been 'frustrated' by a lack of calibration, and this remains an issue in many regions and ecosystems of the world.

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