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Climatic influence upon early to mid-Holocene fire regimes within temperate woodlands: a multi-proxy reconstruction from the New Forest, southern England

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ABSTRACT: A combined pollen, charcoal and climatic record is presented from Cranes Moor, southern England, covering the period *c.* 10 500–5850 cal a BP. It is shown that the occurrence of burning is closely related to natural processes, including prevailing climatic conditions and vegetation composition. These burning events are often linked to an increase in the summer moisture deficit, implying that the timing of burning events is linked to periods of warmer/drier climate during the Holocene Thermal Maximum (*c.* 11 000–5000 cal a BP). These events play an important role in the vegetation composition and succession around the site. The nature of the burning recorded at the site shows strong similarities with other records from northern Europe. This study throws caution on suggestions that fire in the Holocene record from areas such as the British Isles is linked only to human activity, and enhances the possibility that natural fire incidence played an important role in natural woodland structure dynamics.

KEYWORDS: bog surface wetness; burning; Holocene; New Forest; palaeoclimate.

Introduction

The occurrence of burning during the early to middle Holocene is widely recognized yet interpretations of its causes are still heavily debated. In contrast to studies from North America where a fire–climate relationship is widely discussed (e.g. Long *et al.*, 1998; Carcaillet and Richard, 2000; Millsaugh *et al.*, 2000; Paduano *et al.*, 2003; Marlon *et al.*, 2006; Whitlock *et al.*, 2007), few European studies make the same connection, and human activity is often proposed as the primary cause of fire. However, a series of recent studies encompassing a range of different ecosystems (e.g. Power *et al.*, 2008; Olsson *et al.*, 2010; Rius *et al.*, 2012; Marlon *et al.*, 2013) have suggested a climatic control during the early to middle Holocene within a European context. This is in contrast to the view, notably among archaeologists from Britain, that burning is largely anthropogenic in origin. In this region evidence of Mesolithic activity is frequently found together with evidence for burning; for example, at lowland sites such as Thatcham (Barnett, 2009), Star Carr (Mellars and Dark, 1998), Three Ways Wharf (Grant *et al.*, 2014) and along the Severn Estuary (Bell *et al.*, 2002), and at upland sites such as the North York Moors (Innes and Simmons, 2000; Innes *et al.*, 2004), Dartmoor (Blackford *et al.*, 2006) and Waun-Fignen-Felen (Smith and Cloutman, 1988; Barton *et al.*, 1995). Consequently, natural causes of ignition are often downplayed or dismissed (e.g. Rackham, 1980; Simmons, 1996; Barnett, 2009). However, because these study sites are intrinsically linked to local Mesolithic human occupation, and burning of wetland and woodland edge environments, they may not be representative of the wider landscape processes. Brown (1997), Moore (2000) and Tipping (1996) have cautioned that evidence for anthropogenic impact requires a more balanced understanding of the role of other natural factors and ecological processes.

The prevalence of the anthropogenic burning view in Britain arises in part because of the assumption that Holocene woodland is non-flammable and natural sources of ignition (e.g. lightning) are too sparse temporally and spatially. However, these assumptions do not take full account of past climatic conditions, changes in woodland composition or indeed woodland structure (see Clifford and Booth, 2013). For example, the climate of the early Holocene in Northwest Europe differed substantially from modern conditions. Across Northwest Europe large terrestrial landscapes were exposed by reduced sea levels (e.g. Doggerbank; Shennan *et al.*, 2000) and coupled with the precession-driven insolation peak at 10 ka BP, much of the region experienced more continental climatic conditions than present (Briffa and Atkinson, 1997). This regime changed substantially throughout the early to middle Holocene with the flooding of the southern North Sea basin by *c.* 7.8 ka BP when a more maritime climate became established. The Holocene climatic regime also became more stable with the end of the major meltwater pulses into the North Atlantic by *c.* 6.8 ka BP (Carlson *et al.*, 2008; Törnqvist and Hijma, 2012).

Discussions over the possible structure of mid-Holocene temperate woodland of Northwest Europe have often suggested fire played some role in natural woodland dynamics (e.g. Svenning, 2002; Bradshaw and Hannon, 2004; Hodder *et al.*, 2005), such as the maintenance of light-demanding or short-stature woody species within closed forests (Svenning, 2002). Similarly, investigations in Ireland have suggested an extensive role for fire in maintaining *Pinus sylvestris* within primarily deciduous forest (Bradshaw and Browne, 1987; Dodson and Bradshaw, 1987; Bradshaw, 1993). Studies from Scandinavia (Lindbladh and Bradshaw, 1998; Lindbladh *et al.*, 2000; Bradshaw and Hannon, 2004) have also suggested that fire may have been an important natural disturbance factor.

Given the debate outlined above, there is a need to better understand the baseline interactions between vegetation, fire and climate. The early- to mid-Holocene provides a suitable study period to explore how vegetation communities respond to burning and climate change over millennial timescales because of its high climate variability. This will provide a basis for understanding the drivers of long-term vegetation stability and change. A site in southern England was selected because this region is situated in a particularly sensitive area for registering North Atlantic-wide climate changes, as well as

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important regional changes driven by the reorganization of the palaeogeography of the Northwest European coastal zone.

This paper presents parallel plant macrofossil, pollen and charcoal archives, preserved within a single core from a mire in southern England. This approach allows direct comparisons to be made between the records, eliminating the problem of comparison between proxies when derived from different locations (Charman *et al.*, 2006).

Study Site

Cranes Moor forms part of one of the largest mire systems in southern England, located on the western edge of the New Forest (50.824°N, 1.726°W; NGR SU194028) (Fig. 1). The local geological setting is largely composed of Palaeogene Chama and Becton Sand Formations, which display strong podsol development under extensive areas of surrounding heathland. Local areas of woodland on the heath are dominated by *Pinus sylvestris* originating from 19th-century plantations, with *Betula pendula* forming some localized scrub. *Pteridium aquilinum, Ulex europaeus* and *Erica cinerea* are confined to the dry heath, whereas *Calluna vulgaris, Erica tetralix* and occasionally *Ulex minor* are also found in the mire communities. The current mire vegetation comprises peripheral wet heath, flushed areas along the northern and southern margins with *Schoenus nigricans*, and a well-developed *Sphagnum* lawn across the central area (see Newbould, 1960) containing large regularly spaced pools (up to 5 × 8 m), the latter being the result of past peat cutting. The site is also located in an area with limited evidence of Mesolithic occupation.

Cranes Moor was selected for this study because it contains the deepest *Sphagnum* peat deposits in the New Forest and began accumulating in the early Holocene, unlike most other Northwest European mires, which were in an early successional swamp or sedge fen stage at this time (Hughes *et al.*, 2000). Detailed stratigraphy by Newbould (1953) identified deep, *Sphagnum*-dominated peats, focused predominantly towards the eastern side of Cranes Moor, which shallow towards the western margins where they are replaced by deeper reedswamp peat to the margins along zones of flushing. The presence of extensive oligotrophic *Sphagnum* deposits lying between two zones of flushing and immediately overlying the sand geology (Newbould, 1953) suggests that water movement through the peat strata was minimal in the eastern and central part of the bog from the early Holocene onwards. Although recent peat cutting has removed evidence of the surface profile of the bog, the deeper stratigraphy suggests and that the surface vegetation was likely to have been largely or solely ombrogenous from the early Holocene. Under these conditions the peat archive may contain a sensitive indicator of palaeoclimatic change *sensu* Barber (1981).

Materials and methods

Lithostratigraphy and chronology

Following the results of Newbould's (1953) stratigraphic survey, subsequent work has focused upon the eastern part of the site (Barber and Clarke, 1987; Grant, 2005). In this study a core was sampled from the location that contained the deepest (and thickest) *Sphagnum*-peat deposits and multiple visible pool layers. The upper 40 cm of peat was sampled using a monolith tin, with lower levels recovered using a modified Russian corer (Barber, 1984).

Grant *et al.* (2009) have shown that there is a clear break in this sequence above 80 cm, the result of past peat extraction from the site (Barber and Clarke, 1987). Consequently, results from the upper 80 cm of this sequence are omitted in this paper. A chronological framework for the sequence is provided by seven accelerator mass spectrometry radiocarbon measurements on *Sphagnum* samples (Table 1). Radiocarbon dates were calibrated against the IntCal09 dataset (Reimer *et al.*, 2009) and age–depth modelled using CLAM software, with linear interpolation between the weighted averages of each calibrated date (Blaauw, 2010) (Fig. 2). The radiocarbon dates show that the sequence spans *c.* 10 500–5850 cal a BP.

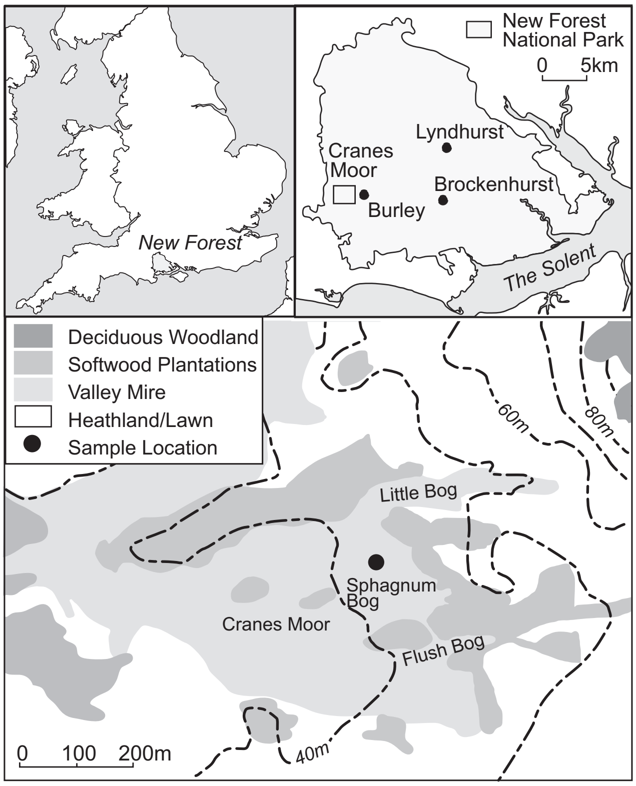

Figure 1. Location of Cranes Moor.

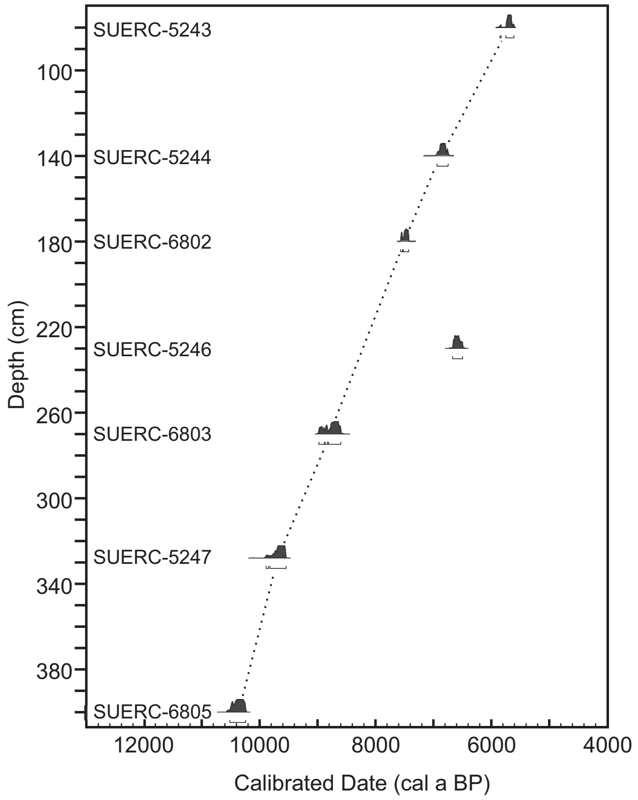

Figure 2. Age–depth model.

Table 1. Radiocarbon dates from Cranes Moor (all material *Sphagnum* leaves and stems).

Lab. no.	Depth (cm)	Radiocarbon age (BP)	$\delta^{13}C$ (‰)	Calibrated date range (95.4% CI)
SUERC-5243	80	4972 ± 31	−26.3	5860–5600
SUERC-5244	140	6000 ± 37	−27.5	6940–6740
SUERC-6802	180	6585 ± 39	−25.9	7570–7420
SUERC-5246	230	5790 ± 34	−27.6	6670–6490
SUERC-6803	270	7909 ± 47	−26.6	8980–8590
SUERC-5247	328	8698 ± 53	−27.5	9890–9540
SUERC-6805	400	9204 ± 57	−23.6	10520–10240

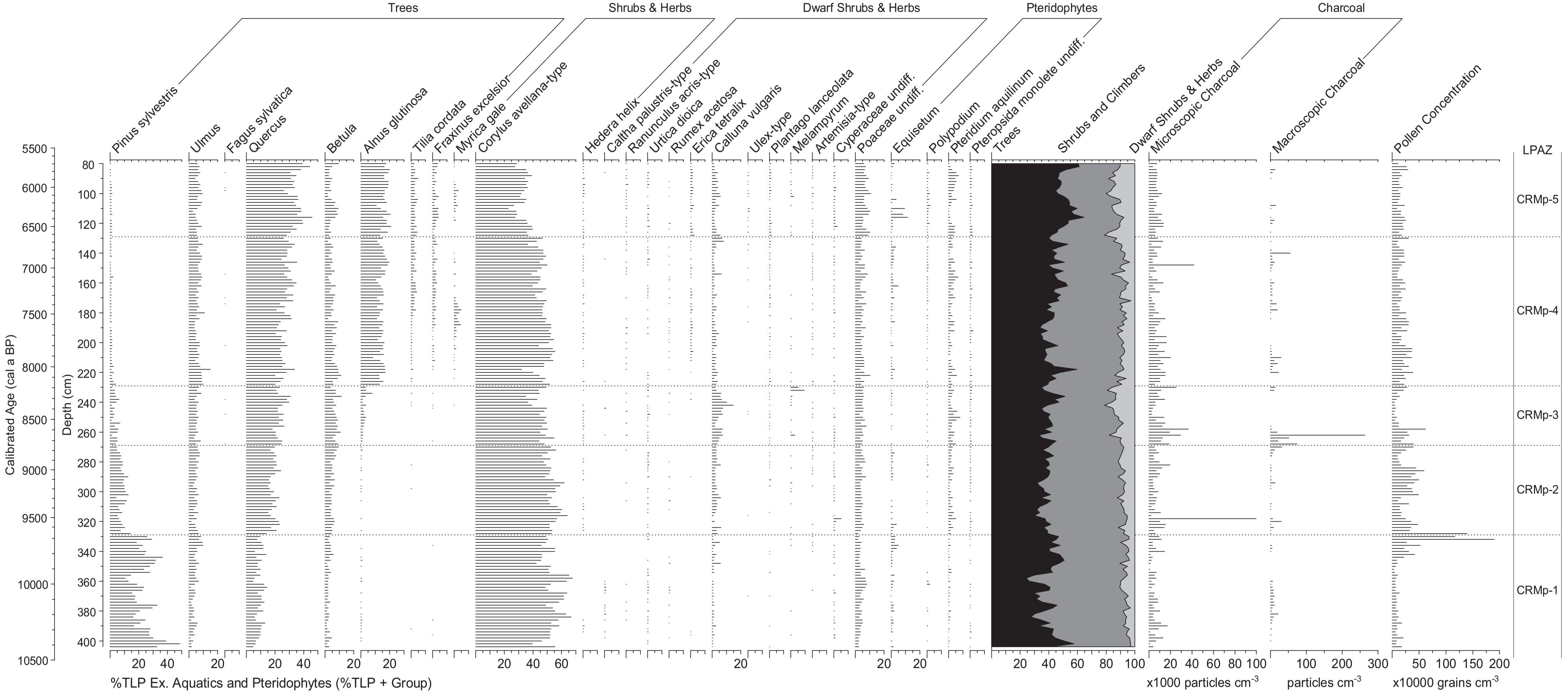

Figure 3. Pollen and charcoal results (selected taxa).

Table 2. Pollen and charcoal assemblages in each local pollen assemblage zone.

Pollen	Charcoal
CRMp-1, 404–329 cm, 10 400–9650 cal a BP *Pinus sylvestris* (15–50%) and *Corylus avellana* (40–67%) are dominant, with *Ulmus* (1–10%), *Quercus* (5–14%) and *Betula* (1–6%) also present. Herb pollen (excluding Poaceae) is sporadic throughout the zone.	Four fire events are recorded in the microscopic charcoal record (10 260, 10 180, 9930 and 9790 cal a BP) with only one recorded in the macroscopic charcoal (10 230 cal a BP). The fire return interval (FRI) for the microscopic charcoal is 180 years, with a fire frequency (FF) of five fires per 1000 years. The maximum peaks in micro- and macroscopic CHAR are 3220 and 15 particles cm^{-2} a^{-1}, respectively.
CRMp-2, 329–269 cm, 9650–8750 cal a BP *Corylus avellana* (46–61%) and *Quercus* (14–23%) dominate. *Pinus sylvestris* decreases from 14% at the start of the zone to 5% by the end. *Calluna vulgaris* (up to 3%) increases throughout the zone. *Ulmus* (1–7%), *Betula* (4–9%) and *Pteridium aquilinum* (1–5% TLP + pteridophytes) are present throughout.	Two fire events are recorded in the microscopic charcoal record (9510 and 9030 cal a BP) with two recorded in the macroscopic charcoal (9590 and 9530 cal a BP). The FRI for the microscopic charcoal is 340 years, with an FF of three fires per 1000 years. The maximum peaks in micro- and macro-scopic CHAR are 46 970 and 18 particles cm^{-2} a^{-1}, respectively.
CRMp-3, 269–229 cm, 8750–8150 cal Yrs BP *Corylus avellana* (34–54%) and *Quercus* (20–30%) dominate, along a high presence of *Calluna vulgaris* (2–14%). *Pinus sylvestris* values fall from *c.* 7% to between 2 and 3% between 242 and 252 cm and above 234 cm. *Betula* (4–11%) values are high, with a consistent presence of *Alnus glutinosa* (up to 7%). Herb pollen increases to *c.* 5% TLP, with peaks of *Melampyrum* at 262 cm (3%) and 232 cm (9%), coinciding with peaks in the charcoal record. *Pteridium aquilinum* increases to 5% (TLP + pteridophytes) at 250 cm.	Four fire events are recorded in the microscopic charcoal record (8720, 8639, 8300 and 8190 cal a BP) with two recorded in the macroscopic charcoal (8750 and 8220 cal a BP). The FRI for the microscopic charcoal is 230 years, with an FF of five fires per 1000 years. The maximum peaks in micro- and macroscopic CHAR are 19 020 and 213 particles cm^{-2} a^{-1}, respectively.
CRMp-4, 229–129 cm, 8150–6650 cal a BP *Corylus avellana* (32–48%) and *Quercus* (20–28%) dominate, along with *Alnus glutinosa* (12–16%). *Pinus sylvestris* values are <1% TLP. *Calluna vulgaris* (1–4%) values are low, with *Tilia cordata* (up to 2%), *Fraxinus excelsior* (up to 2%) and *Myrica gale* (up to 4%) increasing above 190 cm. *Erica tetralix* is present at low values (up to 1.5%). *Pteridium aquilinum* (up to 6% TLP + pteridophytes) decreases initially then increases in the later half of the zone.	Eight fire events are recorded in the microscopic charcoal record (7910, 7770, 7710, 7570, 7150, 6960, 6760 and 6680 cal a BP) with six recorded in the macroscopic charcoal (8050, 7970, 7460, 7380, 6960 and 6850 cal a BP). The FRI for the microscopic charcoal is 220 years, with an FF of five fires per 1000 years. The maximum peaks in micro- and macroscopic CHAR are 20 520 and 18 particles cm^{-2} a^{-1}, respectively.
CRMp-5, 129–80 cm, 6650–5700 cal a BP *Corylus avellana* (20–34%) and *Quercus* (22–37%) dominate, along with *Alnus glutinosa* (13–20%). *Corylus avellana* decreases at the beginning of the zone (34–20%; 128–110 cm), coinciding with increases in *Betula* (up to 8%), *Quercus* (24–39%), *Tilia cordata* (1–4%) and *Fraxinus excelsior* (1–3%). There are increases in *Plantago lanceolata* (up to 1%) and *Melampyrum* (up to 2%). *Erica tetralix* (up to 2% TLP) and *Calluna vulgaris* (1–5%) also increase, with *Ulex* type (up to 1%) also present throughout the zone.	Five fire events are recorded in the microscopic charcoal record (6460, 6340, 6230, 6120 and 6040 cal a BP) with three recorded in the macroscopic charcoal (6460, 6230 and 5810 cal a BP). The FRI for the microscopic charcoal is 190 years, with an FF of five fires per 1000 years. The maximum peaks in micro- and macroscopic CHAR are 3390 and 9 particles cm^{-2} a^{-1}, respectively.

Radiocarbon date SUERC-5246 is clearly anomalous because it represents a clear outlier in the age–depth model.

Pollen analysis

Sub-samples for pollen analysis were processed using standard techniques (Moore *et al.*, 1991), with *Lycopodium* tablets added to enable the calculation of pollen and microcharcoal concentrations (Stockmarr, 1971). The pollen sum was standardized between depth levels using a minimum count of 400 total land pollen (TLP) grains, excluding aquatics and pteridophytes. Zonation was undertaken in Psimpoll (version 4.25; Bennett, 1992), using the method 'Optimal Splitting by Information Content'. Five local pollen assemblage zones (LPAZs) were designated and they are shown in Fig. 3 and described in Table 2. Pollen nomenclature follows Bennett (1994) and Bennett *et al.* (1994), except for Ericaceae which follows Moore *et al.* (1991), with plant nomenclature following Stace (1997).

Charcoal analysis

Microscopic charcoal was quantified on the pollen slides using a method adapted from Clark (1982) whereby a minimum of 200 random fields of view were applied to a slide, and the number, and size, of each charcoal particle observed recorded. The number of *Lycopodium* spores observed in each field of view was also recorded, with a minimum of 50 spores counted from each level. Both area and abundance of charcoal were measured for the microscopic charcoal, with the correlation between these two parameters high (Pearson's $r = 0.933$). Macroscopic charcoal (>125 µm) was prepared and counted following a modified method from Rhodes (1998), using 1 cm^3 of sediment. To estimate the number of fire events, the charcoal accumulation rate (CHAR) was calculated using the computer program CharAnalysis (Higuera *et al.*, 2008) for both the micro- and the macroscopic charcoal size fractions. This program was originally developed for modelling of macroscopic charcoal in lake sediments in North America. However, modelling of the results of both size fractions, to compare local and extra-local/regional burning patterns, was deemed appropriate to identify changes in fire occurrence and allow comparison with vegetation change within a wider catchment area.

CharAnalysis interpolates the actual charcoal counts, sample volume and sample depths by using the median sample

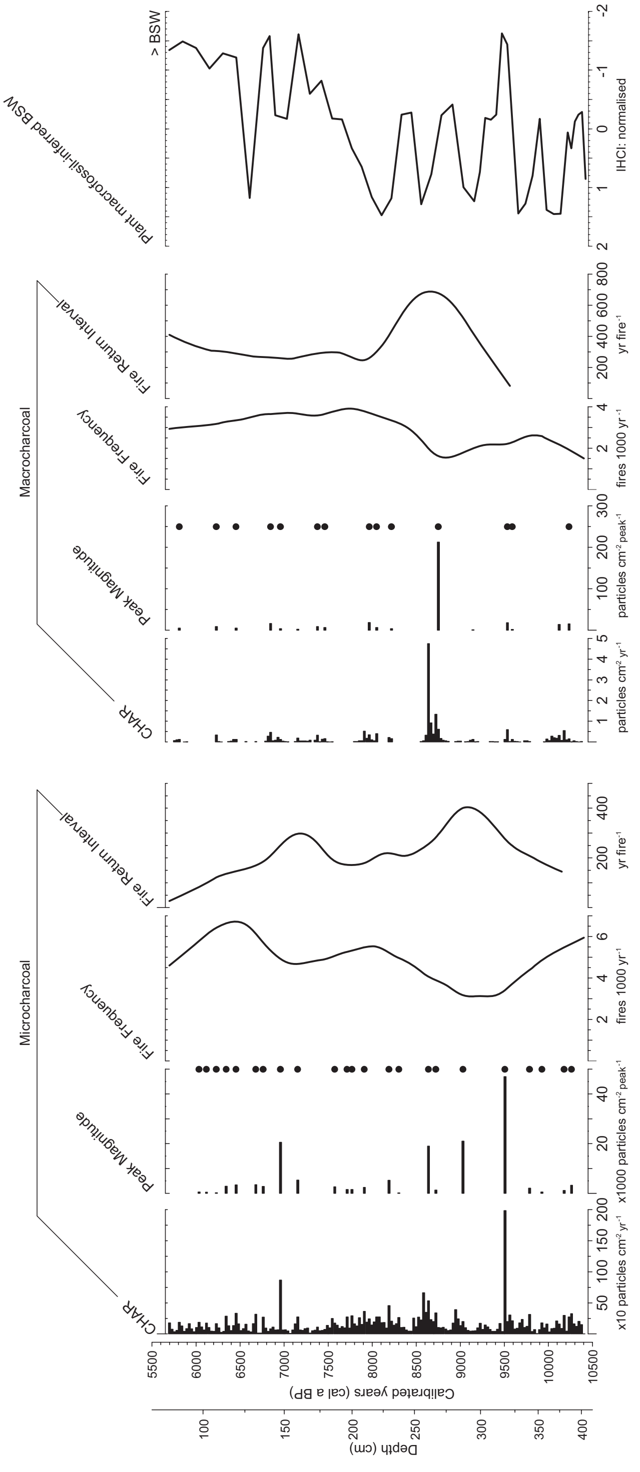

Figure 4. Charcoal accumulation rates (CHAR), peak magnitude (fire events), fire frequency and fire return interval (FRI) calculated from microscopic and macroscopic charcoal data. Results are plotted against the plant macrofossil-inferred bog surface wetness (BSW, derived from the indicator-weighted hydroclimatic index (IHCI) – see Fig 7).

resolution (calculated as 29 years) before calculating CHAR. No transformations were used. CharAnalysis divides CHAR into two components: $C_{\mathrm{background}}$ and C_{peak}. The background component illustrates low-frequency trends reflecting changes in the rates of charcoal production and transportation (Higuera *et al.*, 2008). It also correlates well with long-distance transport from the entire charcoal source area (Higuera *et al.*, 2007). The C_{peak} component identifies the high-frequency variations representing local fire events or episodes in the source area and may correspond to more than one fire. $C_{\mathrm{background}}$ was estimated using a locally weighted Lowess smoother, robust to outliers. The selected smoothing window was calculated based upon a test between the empirical C_{noise} values and the modelled C_{noise} distribution, which provides an index of how well the C_{noise} model fits the empirical data (Higuera *et al.*, 2009). A comparison of both the signal-to-noise index (SNI) and the noise distribution goodness-of-fit (GOF) against different smoothing window widths (in 100-year intervals) identified that a 600-year smoothing window was most appropriate for the two datasets.

The C_{peak} component was calculated as residuals, i.e. $C_{\mathrm{background}}$ subtracted from $C_{\mathrm{interpolated}}$. The threshold value separating fire-related from non-fire-related variability in the peak component was set at the 99th percentile of a Gaussian mixture model. Identified fire episodes are marked with closed circles, with fire return interval (FRI, number of years between fire events) and fire frequency (number of fires 1000 a^{-1}) plotted as a function of time (Fig. 4). The results of the charcoal analyses are shown in Figs 3 and 4 and described in Table 2.

Correlation analysis

Correlation coefficients were calculated to investigate whether a relationship existed between the pollen and charcoal abundances (microscopic and macroscopic). Pollen taxa were included where pollen percentages exceeded 1% TLP and were present at a minimum of five occurrences within the full dataset/subgroup upon which correlation analysis was being undertaken. A *t*-test was used to determine whether correlation coefficients *r* are significantly different from 0 ($r \neq 0$, $P = 0.05$, two-sided, Bahrenbeg *et al.*, 1985; those significantly different are identified on Fig. 5 with close circles). Analysis was undertaken for the whole dataset, individual LPAZs and amalgamated zones reflecting the main vegetation phases (Fig. 5; Supplementary Table S1).

Plant macrofossil analysis

Samples for plant macrofossil analysis were prepared following the methods of Barber *et al.* (1994). Peat slices were sieved through a standard 5 L of water using a 125-μm sieve. The unstained plant remains were quantified using the quadrat and leaf count method (QLC) for the main vegetative components of the peat. Fruits and seeds were quantified using a five-point scale of abundance where 1 = rare, 2 = occasional, 3 = frequent, 4 = very frequent and 5 = abundant (Walker and Walker, 1961). Only selected macrofossils are displayed in Fig. 6 for clarity. Plant remains were identified with reference to the extensive modern type collections held in the Palaeoecology Laboratory at Southampton and with reference to Daniels and Eddy (1990) for *Sphagnum* mosses, Smith (2004) for other bryophytes and Grosse-Brauckmann (1968, 1972) and Katz *et al.* (1977) for the vegetative remains of vascular plants. Nomenclature follows Stace (1997) for vascular plants and Smith (2004) for bryophytes. Local macrofossil assemblage zones (LMAZs) were designated using CONISS and are described in Table 3. The plant macrofossil data were analysed using detrended correspondence analysis (DCA; ter Braak, 1988) in the program CANOCO (version 4.5) to investigate latent environmental gradients. Only the main constituents of the peat matrix, quantified using the QLC system, were included in the ordination with down-weighting of rare species. The Axis 1 score was found to contain a strong hydrological gradient (Fig. 7a). The plant macrofossil results were used to reconstruct bog surface wetness (BSW; see Daley and Barber, 2012) using the indicator-weighted hydroclimatic index (IHCI) devised by Mallon (2012; modified from Dupont, 1986) (Fig. 7b).

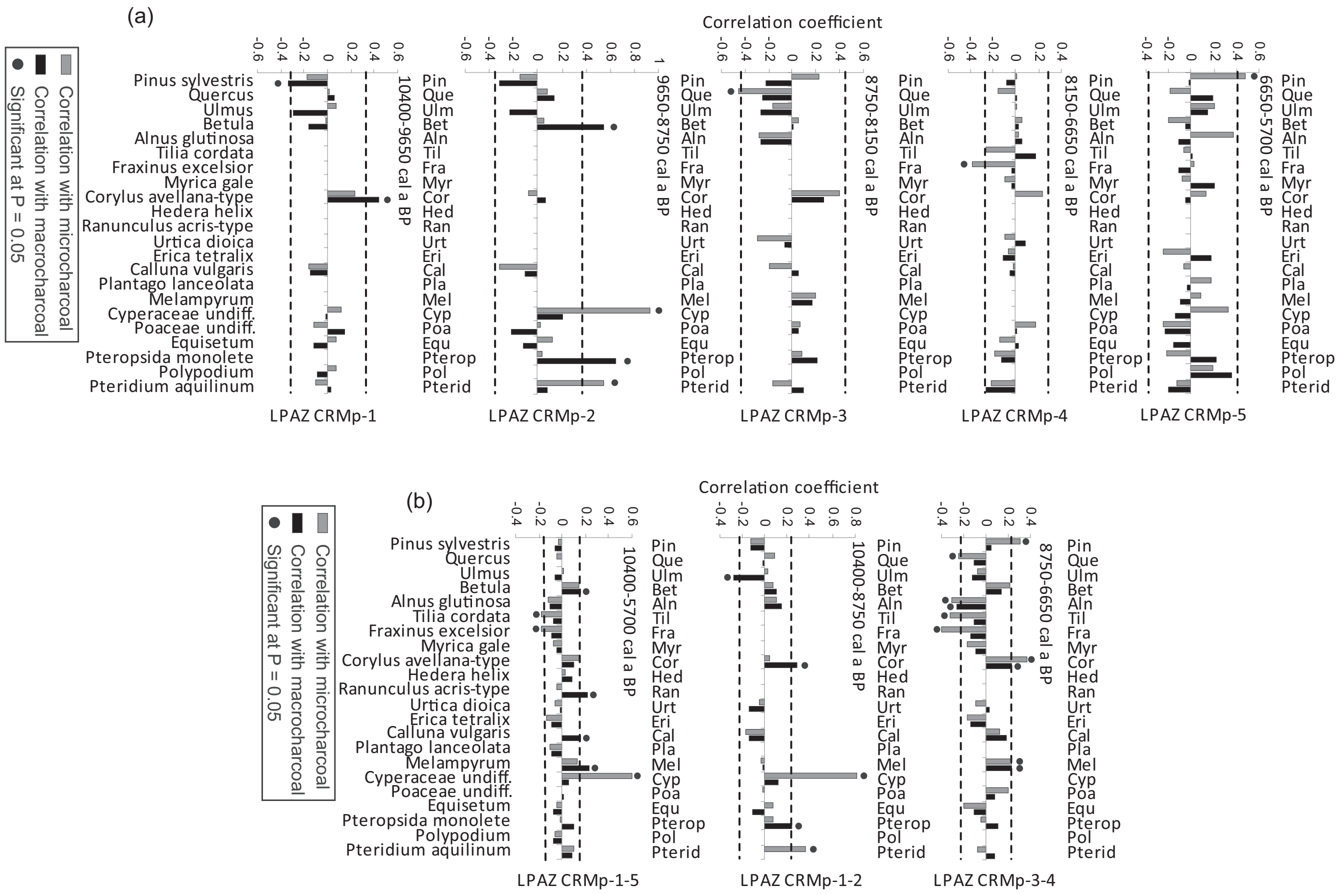

Figure 5. Correlograms showing correlation coefficients between selected pollen types and microscopic (grey)/macroscopic (black) charcoal data. Correlations are calculated for individual local pollen assemblage zones (LPAZ; a), amalgamated LPAZa and the full dataset (b). Correlation coefficients outside the lines are significant at $P = 0.05$, indicated by a bold dot. See Table S1 for tubulized results.

Interpretation of Results

Plant macrofossils

Cranes Moor is one of the few sites in lowland Britain that presents relatively few difficulties for the reconstruction of palaeoclimate records from the surviving peat deposits. The mire complex has developed on base-poor sands in the lee of a sand ridge (Barber and Clarke, 1987) where the area named 'Sphagnum Bog' is protected from flush lines that flow to the north and the south-west of the coring site (Fig. 1). The area of 'Sphagnum Bog' investigated dates from *c.* 10 500 cal a BP, with the basal deposits indicative of an oligotrophic *Sphagnum*-dominated community composed principally of *S. papillosum* and members of the *Acutifolia* section, together with small quantities of *S. austinii* and *S. tenellum*. This basal peat stratum may not have been entirely protected from flushing as the macrofossil assemblage contains traces of *S. palustre*, *Phragmites australis* leaves and *Juncus* species seeds. Most traces of poor fen species disappear from the record above 320 cm (*c.* 9550 cal a BP). The establishment of strongly oligotrophic conditions means that the site became isolated from the surrounding seepages and it is highly probable that this area of the mire became an ombrotrophic centre. In such bogs the water table can be principally related to the length and severity of the summer water deficit (Charman, 2007; Charman *et al.*, 2009). This deficit is a function of the balance between precipitation and evapotranspiration. BSW, as reflected in plant macrofossil assemblages and resultant IHCI (Fig. 7b), can therefore provide a reconstruction of past surface water balance conditions, which is closely related to the atmospheric water balance, in the absence of major human impacts to the bog or catchment.

Phases of pool development can be detected in the macrofossil record commencing at *c* 9500 (but see above), 7500 and 6400–5900 cal a BP. The wet phase recorded at 7500 cal a BP parallels an increase in wetness observed far to the north in the raised bogs at Bolton Fell Moss (Barber *et al.*, 2003) and Walton Moss (Hughes *et al.*, 2000). These three phases also correspond to known humid episodes in other palaeoclimatic records, such as continental lake level data (e.g. Magny *et al.*, 2003) and maritime glacier advances (Nesje *et al.*, 2000), although note that these types of records are likely to be strongly related to winter precipitation rather than summer water deficit. The well-known climatic shift at *c.* 8200 cal a BP (Alley *et al.*, 1997; Magny *et al.*, 2003; Baker, 2012) is clearly expressed here by a wet-shift just before 8200 cal a BP, a dry episode at 8200 cal a BP and a definite wetting trend commencing *c.* 7800 cal a BP. This agrees with other palaeoclimate records from the UK which show a cool, dry climatic anomaly in the region (e.g. Rousseau *et al.*, 1998; Lang *et al.*, 2010), and is clearly recorded in the GISP2 oxygen isotope record (Alley *et al.*, 1997). The broad agreement of the Cranes Moor BSW data with other regional climatic proxies implies that the mire is climatically sensitive through this period.

Interpretation of the pollen and charcoal sequences

Corylus avellana-type and *Pinus sylvestris* are dominant between *c.* 10 500 and *c.* 9650 cal a BP, with pollen percentages closely inter-linked. This may be a result of interdependence within the pollen sum, but also an effect of local burning events, as shown through a statistically significant negative correlation of macroscopic charcoal with *P.*

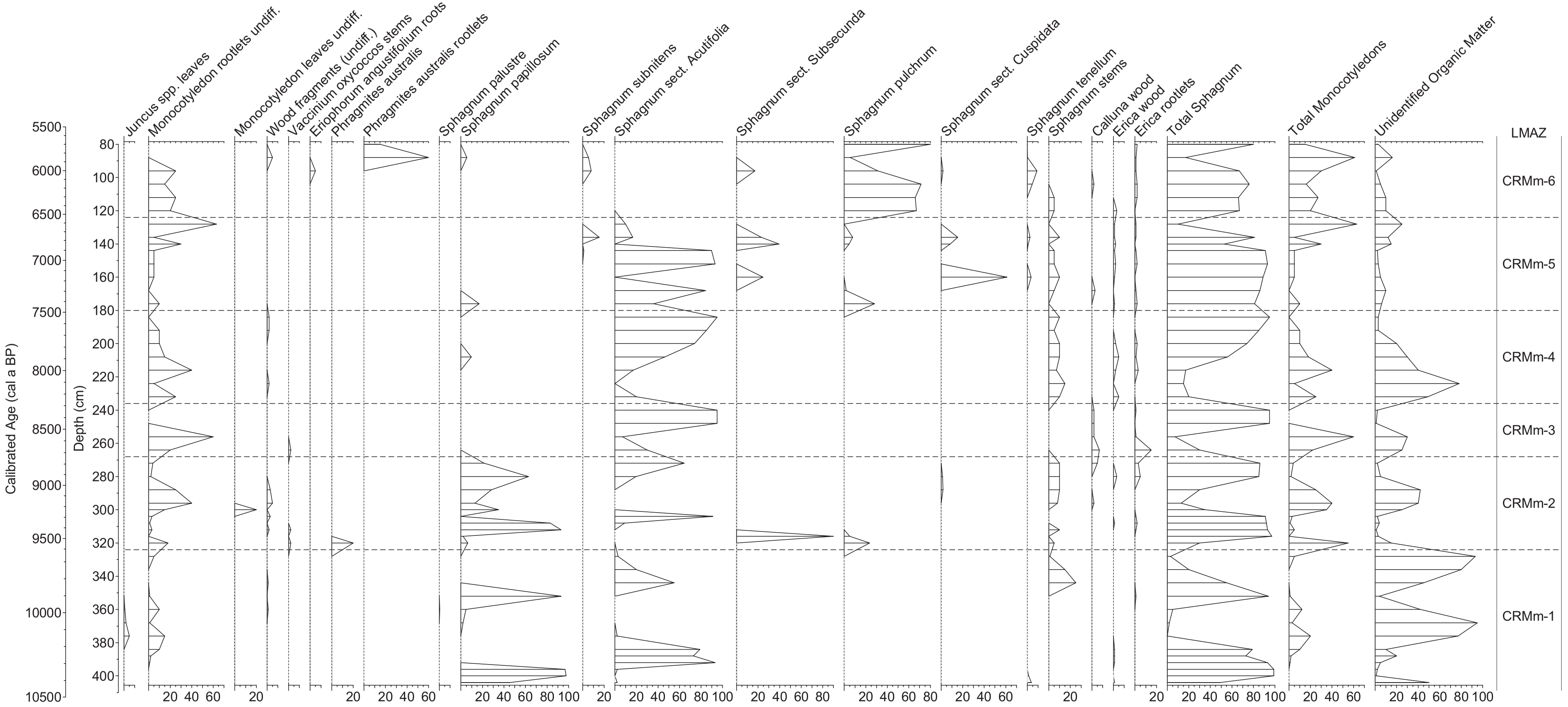

Figure 6. Plant macrofossil results (selected taxa).

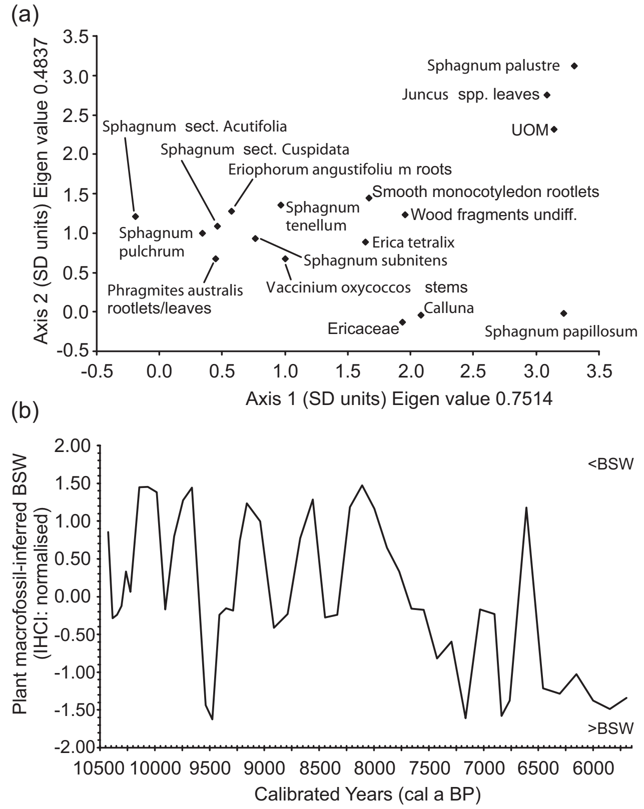

Figure 7. Plant macrofossil statistical analysis: (a) DCA biplot of Axis 1 and Axis 2; (b) reconstruction of bog surface wetness (BSW) using an indicator-weighted hydroclimatic index (IHCI; Mallon, 2012) plotted against calibrated years (cal a BP). Lower values indicate increased Bog Surface Wetness (BSW).

sylvestris and positive correlation with *C. avellana*-type (Fig. 5). The first fire events recorded, at 10 260 and 10 180 cal a BP for microscopic charcoal and 10 230 cal a BP for macroscopic CHAR, suggest that these events are likely to be broadly contemporary with each other. Fire event(s) coincide with reducing *P. sylvestris* values and small increases in *Quercus*, *Ulmus*, *Calluna vulgaris* and *Pteridium aquilinum*. Intermittent increases in *P. aquilinum* are also found associated with the charcoal record, although there is no overall consistent statistical correlation in LPAZ CRMp-1. However, it is possible that burning may have led to increased openness and some partial canopy reduction, leading to understorey development, such as a field layer of *P. aquilinum* and increased flowering/re-sprouting of *C. avellana*-type.

A notable reduction in *Pinus sylvestris* (30–10%) occurs at the LPAZ CRMp-1/2 boundary at *c.* 9650 cal a BP. This is coupled with an increase in *Quercus* and *Betula* and a reduction in *Ulmus*, implying a notable change in the surrounding woodland. FRI is notably longer, extending from 180 years in the previous zone to 340 years in this one. Statistically significant positive correlations are found between the pollen of Cyperaceae and *Pteridium aquilinum* with the microscopic charcoal, and *Betula* and Pteropsida (monolete) indet. with the macroscopic charcoal. This may reflect slightly different spatial source areas, with birch and ferns reflecting very localized burning events (the larger charcoal size fraction), while the changes in the sedges and bracken may be responses to burning occurring at a greater distance. There is also an increase in *Calluna vulgaris*, although this may be related to the onsite of mire vegetation. A low presence of *Plantago lanceolata* and *P. aquilinum* indicates some disturbance probably associated with areas of open ground after burning. The peak in pollen concentrations at the end of this zone might reflect a slow-down in peat accumulation or short-lived change in pollen input because of the changes in the local vegetation.

During LPAZ CRMp-3, *Pinus sylvestris* and *Corlyus avellana*-type decrease, with increases in *Alnus glutinosa* and *Quercus*; *Quercus* was found to have a significant negative correlation with microscopic charcoal. Increases in *Pteridium aquilinum* and *Melampyrum* coincide with peaks in both charcoal size fractions. *Melampyrum* has been found in several studies associated with burning, perhaps of the ground layer, in woodland or at woodland edges (Innes and Simmons, 1988; Caseldine and Hatton, 1993; Innes and Blackford, 2003). For LPAZ CRMp-3 there is no significant correlation between *Melampyrum* and charcoal concentrations. However, when the data from LPAZ CRMp-3 and -4 are combined (along with the total dataset) there is a strong significant positive correlation shown between *Melampyrum* and both charcoal fractions, representing a direct fire response. The peak in macroscopic charcoal at *c.* 8750 cal a BP is the largest recorded from this site, although there was no evidence from the plant macrofossil analyses (e.g. charred plant remains) suggesting burning at the sample location.

Another fire episode, at *c.* 8200 cal a BP, is associated with *Melampyrum* and immediately precedes the expansion of *Alnus glutinosa* at *c.* 8150 cal a BP. Although not statistically significant for LPAZ CRMp-4 alone, when the data from LPAZ

Table 3. Macrofossil assemblages in each local pollen assemblage zone.

CRMm-6, 80–124 cm	*Sphagnum pulchrum* dominates throughout much of this zone, accompanied by small quantities of *S. tenellum*, *S. subnitens*, *S. s. cuspidata* and *S. s. subsecunda*.
CRMm-5, 124–180 cm	A mixed assemblage of *Sphagnum* species dominates the zone with alternations occurring between the *Acutifolia* and *Subsecunda*/*Cuspidata* sections. Unidentifiable organic matter declines to <10% of the assemblage and charcoal is absent.
CRMm-4, 180–236 cm	The lower zone boundary is defined by a marked increase in unidentifiable organic matter to a peak of 80%, accompanied by macroscopic charcoal. In the lower half of the zone total *Sphagnum* drops to <20%. Later *S. s. acutifoila* increases to a peak of 90% at the upper zone boundary. Ericaceae wood fragments are consistently present.
CRMm-3, 236–268 cm	*S. papillosum* disappears from the core site to be replaced by *S. s. acutifolia*. Monocotyledon remains increase and *Calluna* wood is consistently present. Unidentifiable organic matter peaks at 50%.
CRMm-2, 268–324 cm	The lower zone boundary is defined by the appearance of *S. pulchrum* and *Phragmites*. *S. papillosum* and monolocotyledon remains dominate the rest of the zone.
CRMm-1, 324–404 cm	The peat matrix alternates between *S. papillosum*/*S. s. acutifolia* and unidentifiable organic matter. Small quantities of *Juncus* species remains are present between 380 and 360 cm depth.

CRMp-3 and -4 are combined it is shown that there is a negative relationship between *Alnus glutinosa* and both charcoal size fractions. A similar correlation is also found between microscopic charcoal and several other arboreal taxa, including *Quercus*, *Tilia cordata* and *Fraxinus excelsior*, although the correlation with *Corylus avellana*-type remains positive. Values of *Calluna vulgaris*, *Betula* and *Pteridium aquilinum* decrease but there is a continuous presence of *Erica tetralix* recorded from *c.* 7800 cal a BP. Increases in *Myrica gale* are also recorded at this time, although there appears to be no relationship with burning, even though other studies have suggested there may be such a link (e.g. Jacobi *et al.*, 1976). *Myrica gale* is common in the New Forest and is associated with mire systems and margins of alder carr vegetation, and therefore its presence may be related to the marginal mire vegetation zonation. There is a notable reduction in microscopic CHAR around 7500 cal a BP coinciding with the expansions of *Tilia cordata* and *Fraxinus excelsior*. The expansion of these two taxa correspond to a small decrease in *Betula* and slight increases in *Urtica dioica*, *Ulex* type, *Rumex acetosa* type, *Plantago lanceolata* and *P. aquilinum*, all of which may indicate open areas and local disturbance.

From *c.* 6800 cal a BP (LPAZ CRMp-4/5) there are increases in both charcoal size fractions and larger increases in *Erica tetralix*, *Ulex* type, *Calluna vulgaris*, *Plantago lanceolata*, *Melampyrum*, Poaceae and *Pteridium aquilinum*. *Corylus avellana*-type values decrease, with *Quercus*, *Tilia cordata*, *Fraxinus excelsior*, *Betula* and *Myrica gale* increasing. There is also a reduction in the microscopic CHAR FRI to 190 years coupled with charcoal values that show consistency in the size of the peaks recorded in both size fractions.

Discussion

Interaction of fire and vegetation

The data presented here show that there are significant interactions between occurrence of fire and the composition of early and mid-Holocene coniferous and deciduous vegetation communities. Correlation coefficients show several positive correlations with taxa known to be fire-responsive (e.g. *Melampyrum* and Cypercaeae), with negative correlations with fire-sensitive species (such as *Tilia* and *Fraxinus*; Delarze *et al.*, 1992). Kaltenrieder *et al.* (2010) also found correlations between fire-responsive and fire-sensitive species, although notably the Cranes Moor dataset differs with *Alnus* having a negative relationship and *Corylus* a positive one. Tinner and Lotter (2006) also found some statistically significant correlations between pollen and microscopic charcoal, such as positive relationships for *Corylus* and *Urtica* and negative for *Ulmus*. This led the authors to suggest low to moderate effects of fires on forest ecosystems and differences in taxa responses to the occurrence of fire (Tinner and Lotter, 2006, p. 534). Some of these differences may also be related to differences in the speed of first flowering in different taxa, with *Corylus avellana* occurring rapidly within a few years, whereas other arboreal taxa often take longer (e.g. Schütt *et al.*, 2006; Matthias *et al.*, 2012; Waller *et al.*, 2012). Strong correlations between the pollen and charcoal data had not been expected due to pollen being continuously produced from a large pollen source area (extra-local and regional pollen; Jacobson and Bradshaw, 1981), whereas burning is a stochastic event variable spatially and temporally, therefore possibly acting on different scales to the pollen source. This would result in pollen deriving from both affected and unaffected areas simultaneously. Moreover, the incorporation of charcoal into a basin, particularly a mire, could lead to dampening or amalgamation of charcoal peaks which could distort the record, particularly as it is known that charcoal deposition may peak several years after the maximum of forest fires (e.g. Whitlock and Millspaugh, 1996; Tinner *et al.*, 1998).

Relationship between vegetation composition and occurrence of burning

The genus *Pinus* is inextricably linked over space and time with fire (Agee, 1998). *Pinus sylvestris* woodland has a moderate-severity fire regime, including a wider range of fire frequencies and less intense burning than the boreal pines of North America. This can range from an apparent absence of fire near the treeline, as shown from the Scandes Mountains of central Sweden (e.g. Kullman, 1986), to regular FRIs as low as 20 years in Siberia (Sannikov, 1985). Fire plays an important role in the maintenance and regeneration of *P. sylvestris* as it can consume the humus layer exposing mineral soil to allow the establishment of seedlings, which otherwise would be inhibited by the carpet of needles (Sannikov, 1983; Hille and den Ouden, 2004). Vera (2000) suggested that grazing was also important in the removal of the build-up of the ground litter layer, although studies have shown that a substantial increase in browsing can lead to increased seedling mortality through predation (e.g. Scott *et al.*, 2000; Weber *et al.*, 2008). The natural occurrence of small-scale fires in the litter layer would therefore provide a means by which *P. sylvestris* could actively regenerate during the early Holocene. In a study from Thorne and Hatfield Moors, Lincolnshire, Whitehouse (2000) found charcoal and pyrophilous insect fauna associated with repeated burning of *Pinus* during the mid-Holocene. Hodder *et al.* (2005) also demonstrated that mid-Holocene insect assemblages often contained the presence of pyrophilic species, implying that fire was an important process. Studies in Ireland have found that persistence of *Pinus* was closely correlated with the presence of charcoal (Bradshaw and Browne, 1987; Bradshaw, 1993), with the suggestion that a lessening fire regime led to a reduction in the size of *Pinus* populations. Similar results have been derived from Hockham Mere and Quidenham Mere, Norfolk (Bennett *et al.*, 1990), Cothill Fen, Oxfordshire (Day, 1991), and Pannel Bridge, Sussex (Grant and Waller, 2010), where increased quantities of microscopic charcoal were associated with the main *Pinus* phase.

It is notable in the Cranes Moor sequence that a succession from *Pinus* to *Quercus* coincides with a change in the FRI, extending from 180 to 340 years between LPAZ CRMp-1 and -2, and a notable increase in the size of CHAR peaks in both size fractions. This would imply a change from regular, low-intensity fires to less regular, possibly higher intensity ones. It is unclear whether this change is the cause of the reduction in *Pinus* or simply a consequence of it, with a notable high peak in the microscopic charcoal fraction at *c.* 9500 cal a BP, possibly the result of mortality in *Pinus* stands and a greater abundance of dead wood. Tinner and Lotter (2006) found that *Pinus* had significant correlation coefficients with charcoal at negative lags which they suggested could be vegetational changes preceding fires, supporting the idea of increases in fuel availability enabling initial burning events.

It is unlikely that the reduction in *Pinus* values to <20% TLP (the threshold commonly taken to imply local presence; Bennett, 1984) in LPAZ CRMp-2 indicates its local disappearance. Binney *et al.* (2005) showed from modern studies within areas of alder carr that local small stands of *Pinus* were only recorded at *c.* 3% TLP, which they attributed to its pollen representation being suppressed by the *in situ* presence of relatively high pollen-productive vegetation. In lowland southern Britain, Groves *et al.* (2012) found that *Pinus* was competitively excluded by *Corylus avellana* and *Quercus* in many areas with more fertile soils by 9000 cal a BP, and only persisted at floodplain/valley mire sites after *c*. 7500 cal a BP, where it was later replaced by *Alnus glutinosa*. Fire may have also played a role in this succession. Higher ground light levels following fire may have promoted the germination and early growth of *A. glutinosa* (McVean, 1956). An association between charcoal and expansion of *Alnus* has been noted at several sites across Britain (e.g. Bennett *et al.*, 1990; Edwards, 1990; Edwards and MacDonald, 1991; Grant and Waller, 2010), suggesting a causal relationship. Tinner *et al.* (2000) also identified in the southern Alps that *A. glutinosa* (along with *Corylus avellana*) was favoured by fire.

Suggestions have been made concerning the possible role of fire in deciduous woodland dynamics. In eastern North America, *Quercus* dominance at the beginning of the Holocene may have been increased by the incidence of fire (Abrams, 1992; Abrams and Sieschab, 1997). Similar trends also occur in New England where fire was important for oak forests and, in part, controlled by climate (e.g. Foster *et al.*, 2002; Clifford and Booth, 2013). Subsequent suppression of fire by European settlers is associated with a decline in *Quercus* (Crow, 1988; Abrams, 1992; Crow *et al.*, 1994; Foster *et al.*, 2002). A similar situation has been noted in Sweden (Niklasson *et al.*, 2002). However Clark and Royall (1996) and Clark (1997) have demonstrated the persistence of *Quercus* in areas with limited evidence of burning, implying that fire is not the only process sustaining *Quercus* populations.

Mason (2000) has suggested that fire may have led to an increase in acorn production in *Quercus*, further promoting its expansion. At Nissatorp, south-eastern Sweden, a close relationship between the occurrence of charcoal and *Quercus* pollen has also been suggested, which was attributed to a fire regime, probably light ground fires, that would have helped maintain open conditions and permit *Quercus* regeneration (Lindbladh and Bradshaw, 1998). Tipping (1995, 1996) suggested a similar type of fire regime for *Quercus–Ulmus* woodland in Scotland during drier periods before 9000 cal a BP and after 8000 cal a BP, with Clark *et al.* (1989) suggesting that fire may have facilitated a transition from *Corylus*-dominated woodland to mixed-oak forest during the Mesolithic at a site in south-western Germany. The record from Cranes Moor fails to show a positive correlation between *Quercus* and charcoal, although this may in part be related to *Quercus*' long maturation to first flowering (30 years; Schütt *et al.*, 2006) in new growth. The positive correlation between *Corylus avellana*-type and charcoal does imply that open conditions existed. Canopy openness is required for the growth and flowering of this species, and these same conditions would have also favoured *Quercus* growth and competition. However, the low fire frequency evident in the Cranes Moor record does suggest that burning is simply one of many contributing factors.

Cranes Moor today is situated within a large area of lowland heathland, which is regarded as being a cultural landscape. With the exception of sites subject to climatic stress (e.g. coastal heathlands), it has been shown across north-western Europe that burning appears to have been important in the establishment and subsequent maintenance of heathland communities (see Groves *et al.*, 2012). The identification of possible heathland formation and persistence in the Cranes Moor record is, however, difficult. The main taxa associated with this vegetation community are likely to be *Calluna vulgaris* and *Erica tetralix*, although both are shown to be part of the *in situ* mire vegetation (Fig. 6). Huntley and Birks (1983) have suggested that in areas where *C. vulgaris* is abundant, pollen values >25% TLP are frequent, although many of their sites consisted of large ombrotrophic mires where *C. vulgaris* was part of the *in situ* vegetation. Recent modern studies have suggested that the local presence of *C. vulgaris* can only be separated from the background component at distances of 4 m or less (Bunting, 2003; Bunting and Hjelle, 2010). DCA of the pollen data provided no meaningful associations for *C. vulgaris* and *E. tetralix* to enable any separation between local wetland or dryland sources.

The present landscape surrounding Cranes Moor contains large tracts of heathland, yet pollen samples from the upper 80 cm of the mire (above the hiatus) only reach a maximum of 10% *C. vulgaris* (Grant *et al.*, 2009). The consistent low values imply that it is not possible to distinguish the presence of surrounding heathland at this site from the *in situ* mire vegetation, as suggested by Groves *et al.* (2012). Much of the lowland heathland in north-western Europe dates from the Neolithic onwards, therefore post-dating the Cranes Moor sequence. It can be implied that heathland may have been present locally during the early to middle Holocene around Cranes Moor, and may account for the presence of *Ulex*-type pollen throughout the upper part of the record, particularly when associated with the recorded increase in BSW, which could suggest a climatic factor contributing to the development of early tracts of heathland. The correlation analysis indicated no statistically significant relationship between *C. vulgaris* and *E. tetralix* and microcharcoal, although a positive statistical relationship between macrocharcoal and *C. vulgaris* was found across the entire dataset, which may again be a reflection of the limited distance that *C. vulgaris* pollen can be separated from the background component. Fyfe and Woodbridge (2012) found statistically significant correlations between Poaceae and *Calluna* with microcharcoal from early Holocene contexts in the upland moorlands of Dartmoor, which they suggested might indicate that fire played a role in at least initially promoting open vegetation, particularly Poaceae communities. The evidence for local burning and the persistent record of *Betula*, *Ulex*-type and *Pteridium aquilinum* at Cranes Moor make it enticing to suggest local heath formation and persistence throughout much of the Holocene. However, it is probably safe to suggest only that any heathland present was restricted to small localized patches around the study site at this time, rather than the large-scale tracts of heathland that are associated with the modern cultural landscape.

Variations in fire frequency and local prevailing climate

The results from the plant macrofossils imply a sustained period of predominantly drier BSW conditions between *c*. 10 500 and 7800 cal a BP, which coincides with the Holocene Thermal Maximum (HTM; *c* 11 000–5000 cal a BP; Renssen *et al.*, 2012). With the exception of the notable pool layer development at 9500 cal a BP, because of local hydrological disturbances, fire events during this period predominantly coincide with positive (drier) peaks in the BSW (Fig. 4). Charman (2007) and Charman *et al.* (2009) have shown that the BSW climate signal derived from ombrotrophic mires is primarily driven by precipitation, and the resultant signal reflects the length and severity of the summer moisture deficit, reinforced by the summer temperature. As BSW is largely the interplay between precipitation and evapotranspiration occurring over different timescales, it provides a useful indication of moisture balance, which would have provided a key component in controlling fire incidence. This implies that the timing of these fire events is associated with drier local summer conditions. Marlon *et al.* (2013) linked an early Holocene warming trend to increased burning in the British Isles, suggesting that climate was the most important driver of fire. In southern Sweden, Greisman and Gaillard (2009) also found increases in fire activity related to dry and warm climatic conditions by correlation with local proxy climate records.

One of the prevalent climatic systems operating upon Northwest Europe is the North Atlantic Oscillation (NAO). Fluctuations in the NAO are recorded in sea surface temperature (SST) (Andersen *et al.*, 2004) and glacier fluctuations (Nesje *et al.*, 2000). The NAO index quantifies the pressure difference between the Icelandic Low and the Azores High and is dominant over the winter weather system. A deep and northerly located Icelandic Low during the early Holocene (Harrison *et al.*, 1992) could thereby imply climatic conditions with a positive NAO signature. In addition to the NAO, the polar vortex is also suggested to have a strong influence and, when strong, the NAO tends to be positive (Baldwin and Dunkerton, 2001; Walter and Graf, 2005). During periods with strong polar vortex regimes, higher pressures at mid-latitudes drive ocean storms further north, and changes in the circulation pattern bring humid winter weather to Alaska, Scotland and Scandinavia, as well as drier conditions to the western United States and the Mediterranean (Walter and Graf, 2005). De Pablo and Soriano (2007) have suggested, albeit upon a limited dataset, that positive NAO index values will result in increased winter lightning strikes in northern areas of western Europe. The sustained positive NAO indexes, high solar insolation and strong polar vortex observed during the HTM may therefore indicate increased lightning strikes over areas of the British Isles, increasing the potential for natural burns to occur. The continuation of warmer, drier conditions may also be related to periods of persistence in anticyclonic weather patterns over areas of north-western Europe, causing increased incidence of lightning, typical of continental-type climates.

From *c.* 7800 cal a BP the Cranes Moor record demonstrates the beginning of a shift towards a more oceanic climatic regime. This accords with the known timing of the breaching of the Dover Strait (just before 8000 cal a BP; Shennan *et al.*, 2000) and also correlates with pedological evidence from upland regions for accelerated hydromorphism (cf. Bell and Walker, 2005, p. 130) and evidence of major wet shifts recorded in mire records (Hughes *et al.*, 2000). The expansion of *Alnus* at Cranes Moor coincides with this shift towards wetter conditions and is often taken as an indication of increased oceanicity. However, the expansion of *Alnus* in the British record does have significantly variable timings, suggesting that local site factors may principally determine its expansion (Bennett, 1990). The increased oceanicity would be expected to decrease fire incidence after 7500 cal a BP and indeed this is the pattern recorded by Marlon *et al.* (2013, p. 12) who found between *c.* 7000 and 5000 cal a BP low fire activity regionally for the British Isles.

A number of Holocene fire frequency studies are now available from Europe. In northern Sweden, Carcaillet *et al.* (2007) found that in areas dominated by *Pinus sylvestris*, the mean FRI during the Holocene was long and of a similar duration of *c.* 320 years in several different sites. This similarity was suggested as indicating that the ecological processes controlling fire ignition and spread were the same, with shorter FRIs relating to the dominant controlling factor being climatic. Olsson *et al.* (2010) and Rius *et al.* (2012) found periods of increased fire incidence which they attributed to a climatic influence during the early and middle Holocene. Power *et al.* (2008) also suggested that European fire activity was greater than present during the earlier Holocene (8500–6500 cal a BP), regulated by increased seasonality and biomass, whereas a reduction in seasonality coupled with increased anthropogenic activity was an important regulator of fire during the later Holocene. The results from Cranes Moor indicate three phases of increased fire incidence recorded in the microscopic charcoal: 10 500–9500 cal a BP (200 years), 8700–7500 cal a BP (205 years) and 7000–6000 cal a BP (125 years), coinciding with phases of more conducive climatic conditions (Fig. 4).

Conclusions

The presence of periods with warmer/drier summers coincidental with burning episodes recorded at Cranes Moor indicates that climate is an important natural control on fire incidence during the early Holocene in the British Isles, playing an important role in natural woodland dynamics. The possible role of anthropogenic activity cannot be ruled out at this site, although the paucity of evidence for local Mesolithic activity does suggest any activity would have been limited. What is apparent from the data is that the timing of burning does appear to have a climatic control, and the FRI with which burning was occurring was moderately high, suggesting that burning was not a regular long-term landscape maintenance technique employed by humans (average FRI of 190 years for microscopic charcoal). Changes in vegetation are also shown to coincide with adjustments to the occurrence of burning, with similar trends identified in several other contemporary records. However, there are likely to be a range of temporal and regional variations in the specific nature and timing of burning that can be attributed to local prevailing conditions (hydrography, topography, vegetation patchiness and type), which ultimately modulate the fire–climate relationship (Carcaillet *et al.*, 2001; Heyerdahl *et al.*, 2001; Rius *et al.*, 2012). The identification of a series of natural controls on burning in this study should be heeded when discussing Mesolithic use of fire in the wider landscape.

The palaeoclimate record from Cranes Moor itself is also important for understanding the early to middle Holocene in southern Britain as there is a general paucity of information from this region at this time. Although only based upon plant macrofossils, the record demonstrates clear affinities with other palaeoclimatic records that attach a certain level of reliability to the record from this site. The Cranes Moor record offers the possibility for studying precipitation–evaporation records from mid-European latitudes. This will improve the relationship between similar precipitation–evaporation records found at more northern latitudes and the predominantly lake-based proxies from mid-European locations (e.g. Magny *et al.*, 2003).

Supporting Information

Additional supporting information can be found in the online version of this article:

Table S1. Correlation coefficients between selected pollen types and microscopic/macroscopic charcoal data.

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Abbreviations. BSW, bog surface wetness; CHAR, charcoal accumulation rate; FRI, fire return interval; GOF, goodness-of-fit; HTM, Holocene Thermal Maximum; IHCI, indicator-weighted hydroclimatic index; LMAZ, local macrofossil assemblage zone; LPAZ, local pollen assemblage zone; NOA, North Atlantic Oscillation; SNI, signal-to-noise index; SST, sea surface temperature; QLC, quadrat and leaf count method; TLP, total land pollen

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