Evidence of wildfire in the British Isles during the Last Glacial- Interglacial Transition; revealing spatiotemporal patterns and controls

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Abstract

Charcoal records are now widely used to reconstruct past burning activity as there is an increasing global interest in understanding the complex interactions between fire, climate, vegetation and human activity. However, this topic has been relatively overlooked in the British Isles, as the region is generally thought to not support natural burning regimes. Here, for the first time, we present a synthesis of previously published charcoal data for 238 sites and demonstrate the widespread occurrence of charcoal in sediments that span the Last Glacial-Interglacial Transition (LGIT; c. 17-8.3 ka cal. BP) in the British Isles. Analysis is based upon a semi-quantitative analysis of the assembled dataset; the common patterns are identified and are considered in relation to independent reconstructions of climate, vegetation and anthropogenic activity. No causal relationships with vegetation are identified, while charcoal is also prominent during periods when archaeological evidence for human occupation of the British Isles is absent or scarce. Climate is very likely to have controlled the fire regimes during the LGIT. We conclude with ten research priorities to further advance our understanding palaeofire drivers during the Lateglacial-Early Holocene.

Keywords: Fire; Charcoal; Lateglacial; Early Holocene; Late Upper Palaeolithic; Mesolithic; Humans; 9.3 ka event; climate change; radiocarbon

1. Introduction

Wildfire is a key component of the Earth System and operates on a plethora of spatiotemporal scales (Falk *et al.*, 2007; Whitlock *et al.*, 2010). There is a variety of wildfire proxies preserved in the sedimentary record (Conedera *et al.*, 2009; Hawthorne *et al.*, 2017), but the most widely used for understanding past wildfire occurrence is charcoal (see Brown and Power, 2013; Aleman *et al.*, 2018), which is the relatively chemically inert product of the incomplete combustion of organic matter (Scott, 2010).

Charcoal records have been in recent decades widely used to reconstruct wildfire activity on centennial to millennial temporal scales, and from local (e.g. Florescu *et al.*, 2018) to global (e.g. Power *et al.*, 2008) spatial scales. The primary goal of such research is to understand what drove wildfire in the past and there is an increasing interest in applying the knowledge gained from long term data into present and future fire and ecosystem management (see Aleman *et al.,* 2018).

On centennial to millennial timescales, for example, wildfire is controlled by a complex interplay between vegetation, humans, and climate (Whitlock *et al.*, 2010). Climate is the dominant top-down wildfire driver worldwide (Power *et al.,* 2008; Bowman *et al.,* 2009). It determines wildfire expression by directly controlling fire-weather (i.e. weather conductive to burning) and indirectly, through conditioning the composition and moisture content of the vegetation (Marlon *et al.,* 2009; Whitlock *et al.,* 2010). Vegetation composition on the other hand can act as bottom-up determinant for wildfire to occur (Whitlock *et al.,* 2010). On centennial to millennial timescales, however, vegetation composition is to a large extent affected by climate, thus highlighting the interlinked effect climate and vegetation have on the wildfire regimes. Finally, humans can influence fire regimes through manipulating the fuels and altering ignition probabilities through setting fires deliberately, managing fuels or through escapes (i.e. wildfires starting accidentally, for example, from hearths). The effect they can have, however, on a certain environment is largely determined by the climate and vegetation (Whitlock *et al.*, 2010). Albeit challenging and highly complex, long term data can thus significantly aid in disentangling the effect of these drivers and thus help us gain a thorough understanding of the mechanisms controlling wildfire for the future.

Studies exploring the underlying drivers of wildfire drivers in the British Isles are scant, which is in sharp contrast to the long history of paleoecological analyses that has been undertaken in the region. Charcoal has most often been argued to have been a result of anthropogenic ignition (e.g. Bennett, Simonson and Peglar, 1990; Day, 1996; though notably some have also implicated climate: Moore, 1996; Tipping, 1996; 2004) as the region is not thought to support natural burning regimes; at least not in modern day woodland ecosystems (e.g. Rackham, 1986).

One particularly interesting period to test this long held idea is the Last Glacial-Interglacial Transition (LGIT; *c.* 17-8.3 ka BP). This is because the LGIT was a period of limited human occupation and thus disentangling fire drivers can be relatively straightforward. Furthermore, because the LGIT was a period of multiple abrupt climatic shifts (Hoek, 2008; Lowe *et al.,* 2008) it is very interesting to test if particular climates/shifts in aridity/temperature promoted wildfire. Charcoal records spanning the LGIT do exist in the British Isles but no extensive synthesis has been undertaken to collate these data. Edwards *et al.* (2000) considered patterns of charcoal deposition in Scotland in Lateglacial deposits, concluding that more charcoal records from in and beyond Scotland are required if an improved understanding of charcoal distributions, and thus regional occurrence of fire, is to be gained for this period. Recently, Hawthorne and Mitchell (2018) investigated wildfire patterns in Ireland and their relation to regional trends from c. 17.5 ka BP onwards utilising their data along with data deposited within the Global Charcoal Database (GCD), but this only included six sequences for Britain. While the general trends in charcoal activity mirrored those of the European record for this period, there were too few sites drawn on to investigate regional heterogeneity.

Here we have compiled charcoal data from 238 sites whose records span all, or parts, of the LGIT in the British Isles. Analyses are based upon semi-quantitative analysis (presence-absence categorization) and quantitative chronological modelling of the assembled dataset. While this combination of methods limits the ability to undertake any quantitative analysis (e.g. Hawthorne and Mitchell, 2018), it has the advantage of allowing the identification of patterns over a wider area utilising a much larger number of sites. Furthermore, the charcoal data have been assessed using independent regional climate records, associated pollen records and palaeodemographic modelling, which has allowed us to examine potential drivers of fire regimes on a regional scale. Finally, by reviewing the *corpus* of previous studies, it has permitted us to identify 10 research priorities for advancing our understanding of both the drivers and potential role of past wildfires.

2. Methods and definitions

2.1 Collection and assignment of charcoal data

An extensive literature review was undertaken in order to identify and collate sites from the British Isles which contain LGIT charcoal data. A predefined keyword search strategy was performed in the following databases: *Web of Science*, *Scopus* and *Google Scholar*, however, this only revealed a relatively limited number of literature. This was because in many cases, charcoal was not the primary focus of the investigation and thus not included in the title, keywords, or abstract, and was simply reported as complementary to other techniques, such as plant macrofossil, palynological, archaeological and/or stratigraphical investigations. Consequently, a “bottom-up” search strategy was also employed, articles by key authors were retrieved and the reference list of each article was reviewed in order to find additional articles. These included peer-reviewed published papers, unpublished theses, grey literature and commercial reports. Everything with any type of charcoal information was included, even the ones that simply reported charcoal missing from the entirety of the investigation, as long as there was an indication of the deposit’s age. Where appropriate the data were digitised from the original publications (see below).

Where charcoal had been systematically quantified at regular intervals (hereafter termed *charcoal records*), these records were further classified by their extraction method [pollen-slide (microscopic charcoal; usually <125 µm) vs sieved (macroscopic charcoal; usually >125 µm) charcoal]. Where charcoal had been reported exclusively for one or limited strata, for example distinct macroscopic charcoal horizons, and usually not quantified, these were recorded and are described here as *charcoal bands*.

A variety of methods have been used to quantify charcoal in the British Isles (Kangur, 2002), most commonly quantitative estimates of charcoal concentration (typically reported as number (# cm^{-3}), area (mm^2 cm^{-3}) and more rarely volume (mm^3 cm^{-3})) and semi-qualitative estimates (e.g. absent, rare, common, abundant). Other calculations such as charcoal to pollen ratio and charcoal accumulation rate (CHAR; concentration yr^{-1}) are also reported.

In this paper, however, focus has largely been given to the presence or absence of charcoal over time and space. This was because the scope of this research was not to produce an amalgamated charcoal curve, but rather investigate the spatiotemporal occurrence of charcoal including as many charcoal data as possible, examine it in relation to patterns in climate, vegetation, and humans, and highlight how it can be better understood. This specific approach was also preferred because of the following considerations:

i. The wide range of diverse sedimentary contexts represented (e.g. lacustrine, peat bog and fluvial sedimentary systems) means detailed intercomparison between charcoal records is highly complex (Florescu *et al.,* 2018). This is because differential charcoal sedimentation and accumulation between bogs and lakes has been repeatedly documented in the literature (see Conedera *et al.*, 2009, Rius *et al.*, 2011, Feurdean *et al.*, 2012; Remy *et al.*, 2018);

ii. The regionallity and timespan covered by this synthesis introduces taphonomic factors which might affect charcoal content. For example, the “tripartite sequence” (see Walker and Lowe, 2017), indicative of different sedimentological regimes, is a classic feature of LGIT sequences in the British Isles. These abrupt lithological changes indicate non-isotaphonomic (i.e. non-equal taphonomic probabilities for charcoal to be transported and accumulated) processes within individual deposits.

iii. Vegetation shifts throughout the LGIT reflect changes in the availability of fuel, vegetation structure (e.g. vegetation coming in and acting as a barrier for charcoal transport) and fire regime characteristics (e.g. crown fires versus surface fires) (Lynch *et al.,* 2004; Scott, 2010);

iv. Geochronological controls vary between sites, with some having no secure dating controls. Some sites, without direct dating, can be [Bio-]stratigraphically associated with a given climatic stage permitting their inclusion; and

v. Where chronological information is available, these are primarily derived from radiocarbon dates which may have been produced using different pre-treatments procedures, sample types (e.g. bulk sediment vs short-lived macrofossils), and levels of precision (e.g. age errors) making correlation of individual ‘events’ between sequences, at fine-resolution, unattainable across a wide number of studies.

Accepting these limitations of the available dataset, it is possible to still identify broad patterns in the charcoal records; these are described and investigated, and in the case of records with good chronological control, new modelled ages for levels of interest (i.e. where peaks in charcoal concentration have been identified by the original authors) are obtained (see below). We believe that the combination of these methods can lead to a more rigorous qualitative assessment, without the limitations of amalgamated charcoal records, especially in a study region where the primary concern is whether natural wildfire regimes even existed (Rackham, 1986).

The data were transformed into presence / absence charcoal data and each study was assigned to one or more of the major climatic intervals of the LGIT that they spanned. Within the range of research reviewed (published 1963 - 2017) many LGIT stratigraphic schema have been utilised. For the purposes of this synthesis the LGIT was divided into four intervals (Table 1), as defined by the INTIMATE event stratigraphy, based upon the oxygen isotope signal in the Greenland ice cores, underpinned by the GICC05 timescale (Rasmussen *et al.,* 2014). It is important to note that we do not assume that the climatic transitions occurred synchronously between Greenland and the British Isles, and indeed evidence exists for asynchronous responses, particularly during the early stages of the LGIT (e.g. Walker *et al.,* 2003; Blockley *et al.,* 2004). The quantity of charcoal (if quantitative information was available) or duration for which charcoal was present in a deposit was not taken into account; as long as charcoal (micro, macro or band) was present within a time interval this was considered a 'presence' point.

Table 1: Regional correlatives of the GICC05 intervals in the UK, Ireland and Northern Europe. For the purposes of this review, and to aid simplicity, the UK terminology is coupled with the GICC05 derived ages, with certain caveats (see Lowe et al., 1995)

Age (cal ka BP)	**GICC05 intervals**	**UK**	**Ireland**	**NW Europe**
11.65-8.28	Early Holocene, ~ Greenlandian[1]			
12.85-11.65	Greenland Stadial-1 (GS-1) [2]	Loch Lomond Stadial	Nahanagan Stadial	Younger Dryas

14.65-12.85	Greenland Interstadial 1 (GI-1) [2]	Windermere Interstadial	Woodgrange Interstadial	Bølling–Allerød Interstadial
Pre-14.65	Greenland Stadial-2.1a (GS-2.1a) [2]	Dimlington Stadial	Glenavy Stadial	Pleniglacial/Oldest Dryas

[1]Cohen *et al.,* 2013; (updated); [2]Rasmussen *et al.,* 2014

It is also important to note that we do not assume that all charcoal represents contemporary fire events, as the relationship between wildfire and charcoal content in a deposit is not necessarily straightforward. The possibility of reworking of older charcoal due to landscape instability and enhanced erosion, especially during cold intervals, cannot be excluded, while charcoal deposition following a wildfire is influenced by many factors, including fire type (e.g. crown versus surface fire), intensity, type of fuel, and taphonomic processes (Scott, 2010).

2.2 Assessing the role of humans

In order to understand and explore the role of humans as an explanatory factor of fire through the LGIT we have assessed changes in past human population intensity and demographic trends in the British Isles for the intervals during which associated archaeology has been found. To do this we utilise the 'dates as data' approach (Rick, 1987), where the frequency and distribution of radiocarbon dates relating to archaeological activity are used as a demographic proxy. Commonly cumulative probability functions (CPFs) have been employed, which involve calibrating a large number of radiocarbon dates and then computing the dates' summed probability distribution; often this is done using the *Sum* function in OxCal (Bronk Ramsey, 2001).

There are certain caveats with this approach, and many researchers are sceptical of using this method to understand palaeodemography (particularly in older time periods like the Palaeolithic) considering it 'rarely reliable' (Dogandžić and McPherron, 2013) and even a 'black art' (Kuhn, 2012).

Chiverrell *et al.* (2011) point out that the use of CPFs for analysis of radiocarbon ages can also be problematic due to the impact of scatter, non-contemporaneity and directional lags, as well as the 'suck in and smear' issues in radiocarbon calibration. For example, CPFs contain noisy fluctuations which can be caused by the 'wiggles' or shape of the ^{14}C calibration curve. A recent method put forward to help deal with this issue and also avoid the opposite problem of failing to detect real patterns (e.g. over smoothing) is that of kernel density estimation (KDE) plots (*KDE_Plot* & *KDE_Model* functions in OxCal) which can help retain signal whilst also suppressing noise (Bronk Ramsey, 2017); this is the approach used in this paper. The second limitation of using CPFs involves changing archaeological preservation potential over time (e.g. taphonomic factors and datable material preservation) and the focus of archaeological research on 'favoured' time periods or important sites. With these points in mind we view our plots as a coarse guide to understanding intensity and demographic trends in the British Isles.

It is beyond the scope of this study to produce a bespoke radiocarbon database for Britain and Ireland (and indeed this may produce unconscious biases) so instead we use the PACEA Geo-Referenced Radiocarbon Database (D'Errico *et al.*, 2011) for GI-1 and GS-1 and the newer Holocene dataset collated from various sources by Bevan *et al.* (2017). All radiocarbon ages have been calibrated using the IntCal13 calibration curve (Reimer *et al.,* 2013).

2.3 Disentangling the effect of humans or climate as drivers of the regimes

We tested the relative phasing of charcoal peaks (i.e. abrupt shifts in charcoal deposition that probably signify a change in the wildfire regime) in order to assess the role of climate in driving the changes in fire regimes, as well as their association with trends in past human population intensity and demographic trends on a regional scale. To do this, we have produced new age-depth models using OxCal 4.2 (Bronk Ramsey, 2001; 2008) calibrated with IntCal13 (Reimer *et al.,* 2013) for charcoal records with good chronological control, defined as having at least three radiocarbon dates for ±3 ka years from the period or event of interest (average here: 4.2) and a radiocarbon date every

~1000 years (Min: 260, Max: 1100, Average: 615 years) alongside distinct charcoal peaks in GI-1 and Early Holocene. To assess synchronicity of age estimates across different records a Bayesian modelling approach was used adopted constructing simple '*Phase*' models within OxCal (Bronk Ramsey and Lee, 2013). The results for both intervals were then compared against the archaeological and climatic events.

3. The temporal and spatial distribution of sedimentary charcoal and palaeoenvironment of the British Isles during the LGIT

The presence / absence of charcoal in sediments spanning the LGIT in Britain and Ireland was investigated based on published charcoal data from 238 sites (Figure 1; Supplementary Material for site names and the list of publications). Distribution of studies is uneven, with Scotland, NE and SE England having the highest density of records. Charcoal bands were reported for 33 sites, while charcoal records were published for 205 sites. In these 205 sites, 245 charcoal records are available altogether, as 190 of these refer to pollen-slide charcoal and 55 to sieved charcoal. Records with paired micro- and macro-charcoal records were available for 36 sites.

The assignment of the presence / absence charcoal data into the major climatic intervals of the LGIT is presented in Figure 2. There is a limited number of studies spanning the early intervals of the LGIT (GS-2.1a: n = 6; GI-1: n = 55; GS-1: n = 56); this is in sharp contrast with the plethora of available sites spanning the Early Holocene (n = 218). Despite the uneven temporal and spatial distribution of the available sites, Figure 2 illustrates the widespread occurrence of charcoal in records spanning the LGIT. Figure 2 also highlights the limited availability of macroscopic charcoal records against the much more frequent microscopic records for the entirety of the LGIT.

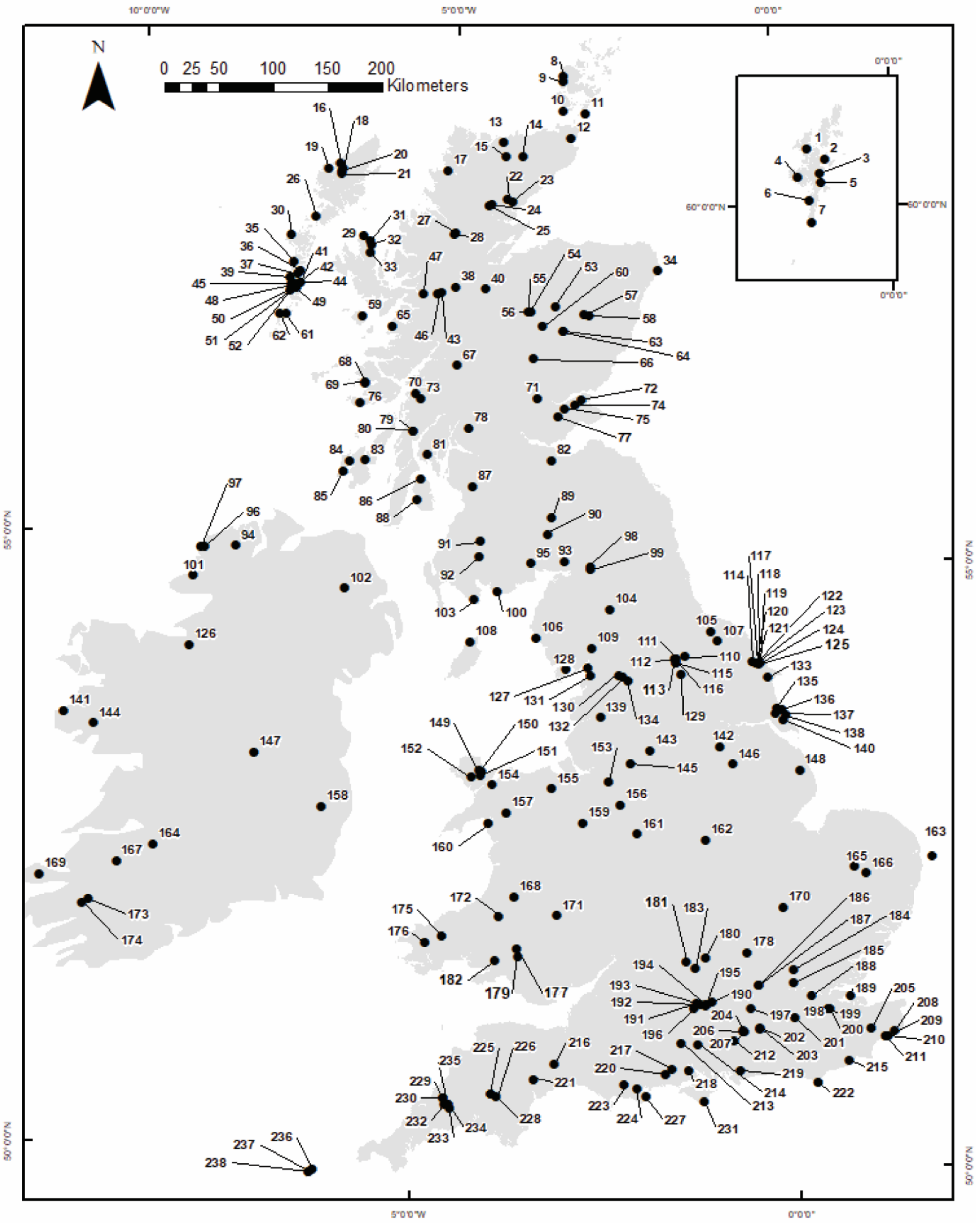

Figure 1: Site included in this synthesis. For all site names and list of publications see Supplementary Material 1.

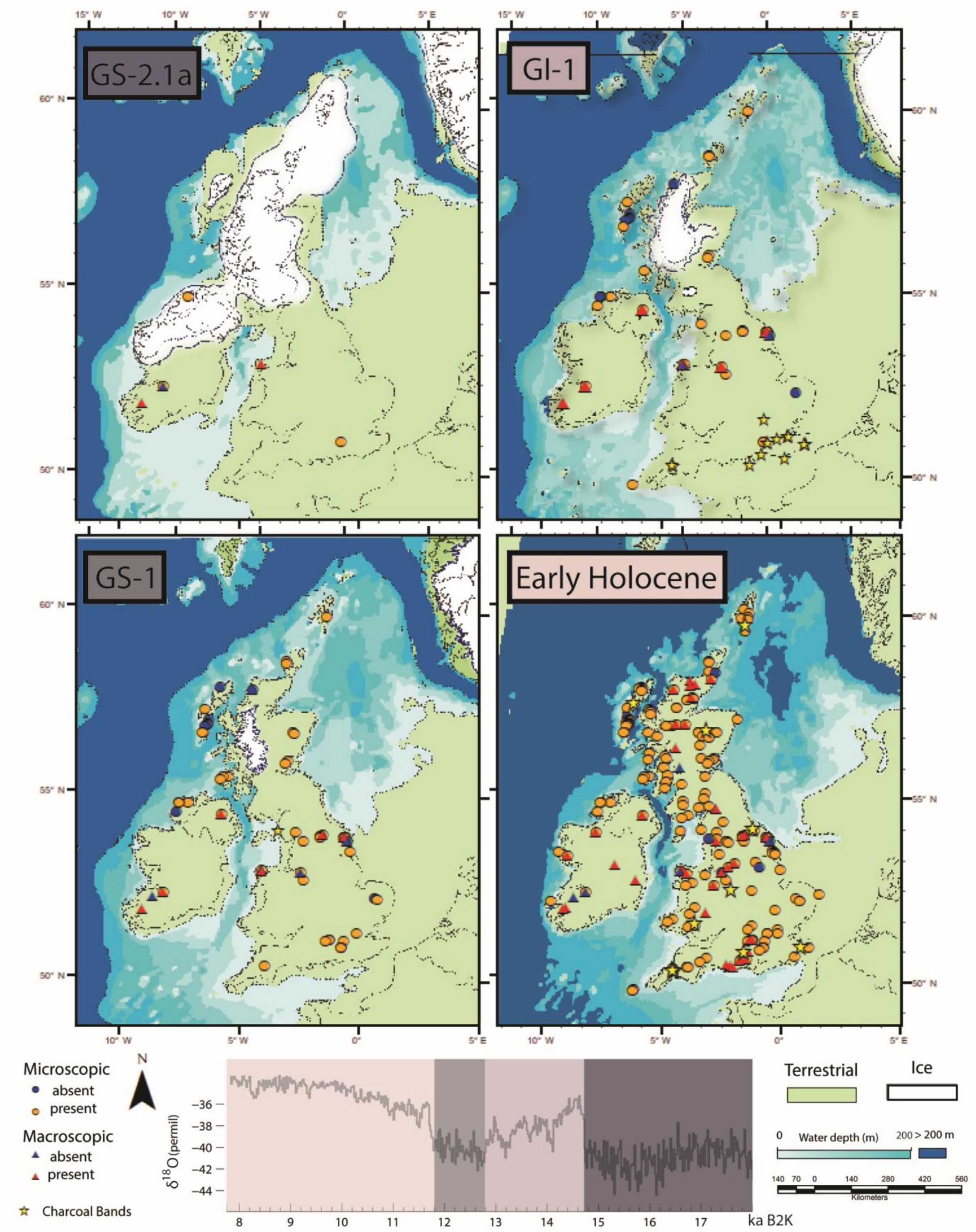

Figure 2: Presence-absence of charcoal depicted on time slices map for the available sediments that span the LGIT in the British Isles. Palaeoshoreline drawn after Ward *et al*. (2016). Ice limits drawn after Hughes *et al*. (2016). The ice extents roughly correspond for each timeslice: GS-2.1a = 18 ka BP, GI-1 = 14 ka BP, GS-1 = 12 ka BP, in each of which the solid line represents the maximum extent and

the dotted line represents the minimum extent of the ice. $d^{18}O$ of the GRIP ice core re-drawn after Rasmussen *et al.* (2014).

3.1 GS-2.1a (c.17,430 – 14,650 cal. BP)

3.1.1. Vegetation

The ice-free areas are believed to have been covered in a treeless steppe-tundra, although cryptic refugia may have persisted in SW England (Kelly *et al.,* 2010).

3.1.2 Archaeological Record

Currently there is no strong evidence for human occupation of the British Isles during the Dimlington Stadial (Pettitt and White 2012; Tallavaaraa *et al.,* 2015), with the earliest evidence of recolonization occurring just before the onset of the Lateglacial Interstadial (Jacobi and Higham, 2011).

3.1.3 Charcoal Record

There are six charcoal records, originating from five sites in Ireland (sites 94, 164 and 174), Wales (site 150) and SE England (site 207). The microscopic records from sites 94 and 164, and the macroscopic charcoal from site 174, show high charcoal values during this period which drop around the end of this climatic interval (Figure 3). The same pattern, albeit less distinctive, can also be observed at sites 150 and 207. At site 174, statistical decomposition techniques, which can identify robust fire events (see Higuera *et al.*, 2009; Blarquez *et al.*, 2013), have been used and identified two wildfire events taking place between 17.5 to 15.5 ka cal. BP (Hawthorne and Mitchell, 2016). This period of burning occurs broadly contemporaneously with the abrupt climatic changes associated with Heinrich Stadial 1 (HS1; see Daniau *et al.,* 2010) and spans the so-called 'Mystery Interval' (Denton, 2006).

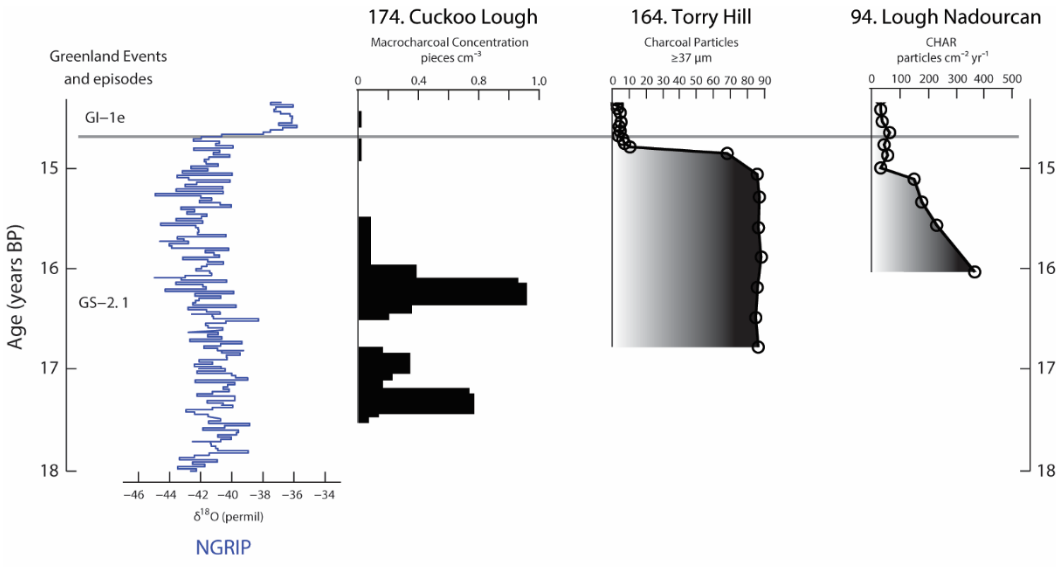

Figure 3: Concurrent high charcoal values that cease around the onset of interstadial warming. Charcoal data shown against the NGRIP oxygen isotope record, defined after the INTIMATE event stratigraphy (see Rasmussen *et al.,* 2014). Note all data have been adjusted to a yrs BP (1950) timescale.

Data from: (174) Hawthorne and Mitchell (2016), (164) O'Connell *et al.* (1999), (94) Jeffers *et al.* (2011)

3.2 GI-1 (c. 14,650 – 12,850 cal. BP)

3.2.1 Vegetation

Following the initial warming, coupled with the connection still between Britain and mainland Europe, plant species were expanding from their refugia and migrating into Britain. Landscape responses lagged the initial climatic amelioration as vegetation continued to be dominated by open-ground pioneer taxa such as *Empetrum, Rumex*, *Artemisia*, Poaceae and *Salix* until *c.* 14 ka BP (*c.* 700 yrs after the initial amelioration; Walker *et al.*, 1993; Birks and Birks 2014; Walker and Lowe 2017). During the latter part of GI-1 (after *c.* 14 ka BP) *Betula* woodland formed in southern Britain whereas in Scotland *Juniperus* became the dominant taxon (Birks and Birks, 2014; Walker and Lowe 2017), with ericaceous heath (*Empetrum* and *Erica*) and perhaps *Betula nana* or isolated patches of *Betula pubescens* dominating in the later Interstadial (Walker and Lowe, 2017). In Ireland, woodland probably did not form in the later parts of the Interstadial (see Birks and Birks, 2014).

3.2.2 Archaeological evidence

The earliest evidence for the re-colonization of the British Isles after the Last Glacial Maximum comes from Cheddar Gorge and the Wye Valley, marking the beginning of the Late Upper Palaeolithic. Here radiocarbon determinations have been made on human and cut-marked animal bones which suggest short-lived phases of occupation occurring closely to the abrupt warming of the Lateglacial Interstadial at c.14.7 ka yrs BP in Greenland (Jacobi and Higham, 2009; 2011). The associated stone tools from Goughs Cave have been interpreted as Creswellian (comparable to the Late Magdalenian in Europe), which is the first Late Upper Palaeolithic industry present in the British Isles. Creswellian stone tools are found across southern England and Wales, and as far north as Derbyshire (Barton *et al.,* 2003) and, tentatively, southern Scotland (Saville, 2004).

The use of Creswellian stone tools in the British Isles spans most of the early Lateglacial Interstadial (i.e. > 14 ka cal BP; Jacobi and Higham, 2011), before being replaced by *Federmesser* culture during the latter stages (Barton *et al.,* 2009; Jacobi *et al.,* 2009) up to the Interstadial-Stadial boundary (Smith *et al.,* 2013). *Federmesser* technocomplexes have most commonly been found in southern England, but are also located in NE England, the Peak District, SW Wales, and southern and western Scotland (Saville and Ballin, 2009; Ballin *et al.,* 2018). The comparative geography of Creswellian and *Federmesser* artefacts has led some to suggest that during the latter, human activity was more evenly spread across the British landscape, and less limited to upland areas (Barton *et al.,* 2003), although in some locations both industries have been found stratigraphically superimposed on each other (e.g. Harding *et al.,* 2014).

The summed probability distribution of archaeology dates falls within the earlier stages of GI-1 while charcoal (only) dates from archaeological contexts fall within the latter stages of GI-1 (Figure 4).

However, it should be noted that in these analyses the number of archaeological dates (all and charcoal only) are likely to be at least partly the result of research focus and also the shift from cave to predominantly open sites contexts. Open site contexts dominate during the latter Lateglacial Interstadial (< 14 ka cal BP) with Final Upper Palaeolithic open-air sites in Britain having proven difficult to derive conclusive chronologies (Barton *et al.*, 2009).

3.2.3 Charcoal Record

Fifty published charcoal records span GI-1. These are mainly located towards the North of Britain and Ireland. Microscopic charcoal is present in Scotland in sites 3, 8, 9, 30, 62, 75, 77 and 84 but not in sites 17, 36, 41, 49 and 52. In England, microscopic charcoal was reported for sites 106, 113-116, 120, 123, 124, 125, 130, 150 153, 156, 206 and 238, but was absent from sites 133 and 165. For Ireland, microscopic charcoal was present in sites 101, 102, 94 and 164 but not in sites 96 and 97. Microscopic charcoal was also present in Wales (site 150). Macroscopic charcoal was present in Ireland (sites 17 and 102), England (sites 120, 123, 124, 125, 153), Wales (site 150), and Ireland (sites 164 and 174).

Some common patterns can be discerned from the sites listed above. Of the records with charcoal present, the charcoal curves fall within two categories: 1) they contain one, two, or three clear charcoal peaks (e.g. sites 77 and 120); or 2) they are highly variable or 'spikey' (e.g. sites 30 and 115).

There is currently too much uncertainty within the available dataset to undertake detailed analyses in relation to vegetation. This is primarily because the relative abundance of pollen at a particular site does not have a linear relationship to the pollen record (Fyfe *et al.,* 2013) and therefore, within this paper, only broad comparisons with vegetation are made. Vegetation modelling based on pollen archives is a specialized field that is beyond the scope of the current paper.

The presence/absence of charcoal does not seem to be associated with geographical distribution or with the geographical extent of human occupation (see Figures 11 and 12 in Jacobi and Higham, 2009). Interestingly charcoal is widespread during the Interstadial, being found in Ireland, the

Scottish mainland and Scottish isles (e.g. Orkneys, Hebrides, and Shetland), where no associated archaeology has been found. However, sites of this age have arguably a very high likelihood to have been destroyed or hidden, or in other words the absence of evidence does not necessarily imply absence of people.

Charcoal is also very prominent in SW and SE England during this period, where human occupation at this timeframe has been recorded. Especially in SE England distinct charcoal bands in stratigraphical investigations of dry valleys have been associated with the widespread Pitstone palaeosol (e.g. Kerney, 1963; 1964; Preece and Bridgland, 1999; Allen, 2008).

Very few records with distinct charcoal peaks were suitable for the construction of new age-depth models through the GI-1, thus precluding the formation of new modelled ages of the charcoal peaks, which would make pinpointing the timing in which burning occurred possible (see Figure 4 for the scale of the problem). However, radiocarbon dates retrieved from the Pitstone soil in SE England clearly show higher charcoal abundances during the latter stages of the Interstadial, with charcoal dates peaking around 13.5-12.9 ka cal. BP (Figure 4). The same finding is also observed in mainland Europe: very similar results were reached by Keiser *et al.* (2009) in their chronological investigations on charcoal fragments retrieved from the Usselo and Finow palaeosols in northern central Europe (Keiser *et al.*, 2009; Fig. 8). This important because in the Usselo soils *Pinus* charcoal is abundant, along with smaller amounts of *Betula* sp., *Populus tremula*, *Salix* and *Juniperus*, whereas in the Pitstone soil, charcoal fragments consist mainly of *Betula* and *Salix*. Therefore, the very similar age distribution results reached in our analysis and by Keiser *et al.* (2009) imply contemporaneous burning on different woodland ecosystems across a broad geographical area. Based also on the findings of Figure 4 no direct link between human density and wildfire expression is evident.

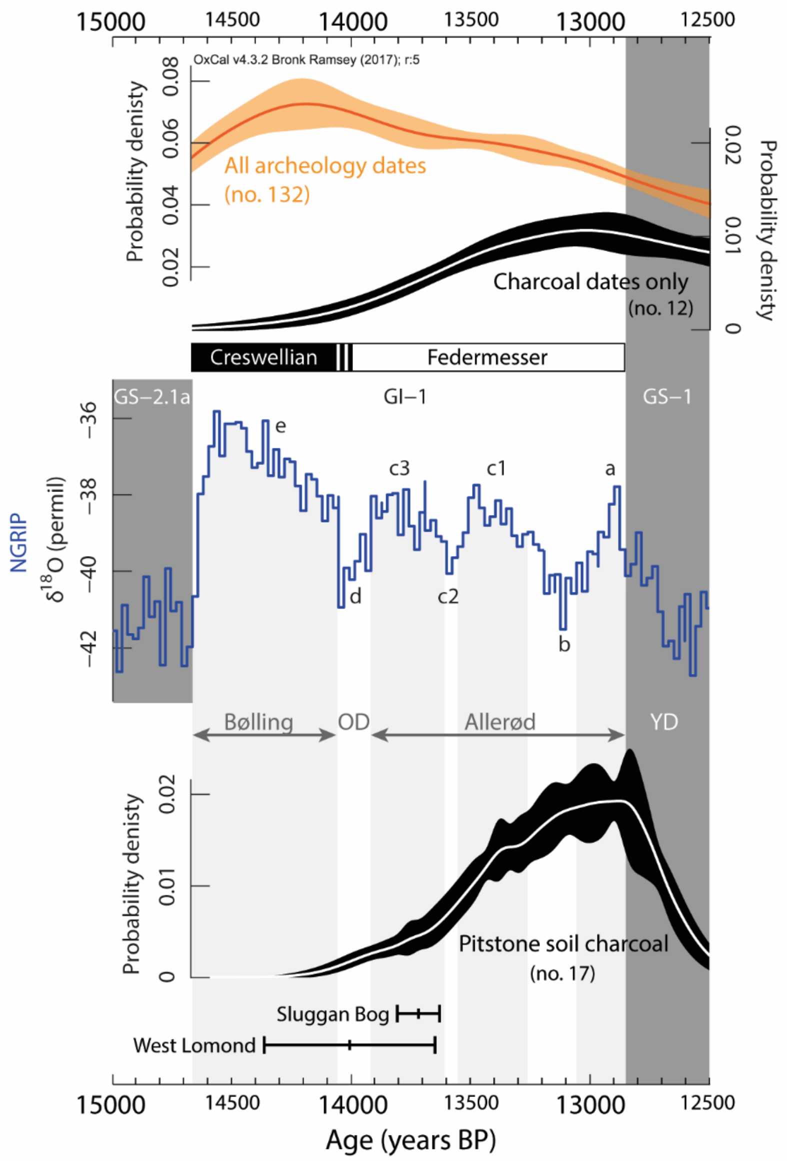

Figure 4: *KDE_Model* for archaeology dates & charcoal dates (for full dataset see D'Errico *et al.*, 2011; a map of all modelled dates is available in the supplementary information), the NGRIP oxygen isotope record (Rasmussen *et al.,* 2014) and radiocarbon dates on charcoal from the Pitstone soil (taken from: Allen (2008), (Kerney 1963; 1964), Evans (1986), Preece and Bridgeland (1999), Preece (2009) and Allen *et al.,* (2006)). Age estimates for charcoal peaks in 1) Sluggan Bog (102) is taken from Walker *et al.* (2012) and 2) West Lomond (78; Edwards and Whittington, 1997) have been produced using OxCal age-depth model. Note all data have been adjusted to a yrs BP (1950) timescale.

3.3 GS-1 (c. 12,850 – 11,650 cal. BP)

3.3.1 Vegetation

Palynological records show that vegetation succession was interrupted, with the tree components present during the Interstadial replaced by grasslands comprised of arctic shrub tundra and open ground taxa such as Poaceae, *Artemisia* and Cyperaceae (e.g. Walker and Lowe 2017). In Ireland there was development of arctic shrub tundra as well, with plant communities associated with bare and unstable ground (Walker *et al.,* 2012).

3.3.2 Archaeological evidence

Evidence for human occupation in the British Isles during GS-1 is sparse (Cook and Jacobi, 1994). Unlike GI-1 and the Early Holocene (sections 3.2.2 and 3.4.2 respectively) no human remains have been securely dated to this timeframe (Barton *et al.,* 2003). However, some sites with long-blade and 'bruised' blades flint tools (Terminal Upper Palaeolithic artefacts) have been interpreted as fleeting phases of occupation during the final stages of the Stadial. The timing for the initiation of Terminal Upper Palaeolithic activity is poorly constrained (Conneller *et al.,* 2016). The finding of bruised-edge 'long blades' in close proximity to dated horse remains at Three Ways Wharf, SE England, does potentially suggest a cold, Stadial climate during occupation (Lewis and Rackham, 2011) if the bones and archaeology are coeval.

Evidence of these tool types also exist in NE England (Conneller, 2007) and western Scotland (Mithen *et al.,* 2015) suggesting that Terminal Upper Palaeolithic populations were mobile and migrated significant distances into the British Isles. The first evidence of human activity in Ireland during the LGIT occurs during GS-1 via a radiocarbon dated butchered brown bear bone (UBA-20194: 10,798 ± 71BP; OxA-29358: 10,850 ± 50BP), from a cave site from County Clare, western Ireland (Dowd and Carden, 2016). These examples appear to represent outliers, with the vast majority of evidence coming from open air sites in East Anglia and SE England (Woodman, 2015).

3.3.3 Charcoal Record

Charcoal is present in the majority of the 67 records that span GS-1. Microscopic charcoal was reported as being present in Scotland (sites 3, 8, 9, 30, 41, 57, 58, 61, 62, 75, 77, 83, 84, 85), Ireland (sites 94, 97, 102, 164, 166), England (sites 109-110, 113-116, 123-125, 130, 137, 153, 156, 185, 195-197, 204, 206, 207 and 225) and Wales (site 150), but absent from sites 16, 17, 36, 49, 52 in Scotland, sites 96 and 101 in Ireland and sites 120, 133, 165 and 193 in England. One band of charcoal has been reported in Leicestershire (site 106). Macroscopic charcoal was present in Ireland (site 102), England (site 110, 123, 124, 125), Wales (site 151) and Ireland (site 164 and 174) but absent from Scotland (site 17) and England (site 120, 133 and 153).

No common temporal patterns can be discerned from the above, possibly due to the short-lived nature of this climatic interval and the non-contiguous sampling for most of the sites, which has meant that charcoal has often been quantified for very few stratigraphic levels during GS-1. However, for many sites charcoal content is high or constantly present for sites all across the study area (e.g. England: sites 113, 137, 166, 225, Ireland: sites 102 and 164). The same finding has been noted by Edwards *et al.* (2000) in their study in Scotland. The risk of reworking cannot be excluded, especially during cold conditions and enhanced sediment input (e.g. Busfield *et al.*, 2015). The problem of reworking during GS-1 is demonstrated best by Walker and Lowe (1990) who showed remobilisation of *Empetrum* pollen grains from eroding Interstadial catchment soils in Scottish lake sediments. However, there is evidence for burning during GS-1 within the well-dated Sluggan Bog record (site 102) in Northern Ireland (Walker *et al.,* 2012), which included direct radiocarbon dating of a charcoal fragment within GS-1 (SUERC-12332: 10195 ± 44 BP; Walker *et al.,* 2012).

3.4 Early Holocene (or Greenlandian Stage, c.11,650 – 8,276 cal. BP)

3.4.1 Vegetation

The Early Holocene warming led to the appearance of thermophilic species, including high *Corylus* values that are typically followed by *Ulmus*, *Quercus* and *Alnus* (Bennett, 1988; Tallantire, 1992), although the landscape is thought to have been predominantly open (Fyfe *et al.*, 2013).

3.4.2 Archaeological evidence

It is arguable that Late Upper Palaeolithic and Terminal Upper Palaeolithic sites in the British Isles most likely represent sporadic or relatively fleeting visits by past human populations. The Terminal Upper Palaeolithic long blade industries described above appear to exist into Holocene times, disappearing between 11695-9790 yrs BP (95% probability; Conneller *et al.,* 2016). The continuation of these industries suggests a degree of cultural continuity over the glacial-interglacial boundary (Barton *et al.,* 1991). The beginning of the Mesolithic, by contrast, contains strong evidence for continuous year-round human presence and settlement (Conneller *et al.,* 2012). Several stone tool assemblage types appear during the Early Mesolithic, some more long-lived than others. Here we simply outline the timing of first and last appearance, relying heavily on the recent geochronological modelling work of Conneller *et al.* (2016) and, more broadly, discuss the geography of the first Mesolithic across the British Isles (i.e. leads and lags in the spread of humans across the region).

Star-Carr-type and Deepcar-type stone tool assemblages (from site 120) appear around 11.5 and 11 ka yrs BP respectively, lagging the onset of the Holocene by *c.* 200-300 years, before disappearing by roughly *c.* 9.8 ka years BP (Conneller *et al.,* 2016; Blockley *et al.,* 2018). In general, Star Carr-type and other Early Mesolithic sites (i.e. pre *c.* 10.5 ka yrs BP) occur first across North Yorkshire, East Anglia and southern England (Woodman, 2015), appearing very soon after (by at least c. 10 ka yrs BP) on the western shores of England and Wales (Bell, 2007; David, 2007) and in lowland Scotland (Lawson 2001; Saville, 2008). The Irish Early Mesolithic significantly lags the first evidence of Mesolithic populations in England, Scotland and Wales, with the earliest reliable evidence of occupation occurring at 9.75 ka yrs BP (Bayliss and Woodman, 2009) but good evidence for continuous occupation from that point in time onwards.

3.4.3 Charcoal record

Only two charcoal records included in this synthesis do not extend into the Early Holocene (sites 124 and 150). Charcoal is present in almost all the available sites (with the exception of 11, 35, 49 and 54 in Scotland and sites 128, 133, 146, 153 and 193 in England) and has also been reported as charcoal bands from 10 sites located across Britain.

The records are overall spikey or with distinct peaks. Possibly due to the large number of sites, as well as the long-lasting nature of this climatic interval no patterns emerged. Some authors state clear increases in fire frequency / intensity in some records (e.g. site 208: "a marked spike in charcoal […], this dates to 8600 14C yr BP (c. 9600 cal. yrs BP)"; Bates *et al.* 2008; site 184: frequent fire nearby, or upstream, in the Early Holocene from 9500 BP up to 8500 BP"; Chambers *et al.* 1996), though in general many records suffer from low sampling resolutions (e.g. sampling at 4-8cm, roughly equating to ~300-600 years between samples). However, despite this, phases of increased charcoal were evident across multiple records where temporal resolution was ~100 years or less between charcoal data points. For those with available chronology, new age-depth models were constructed in order to obtain new modelled ages for the charcoal peaks (from the following sites: 16, 17, 30, 36, 37, 45, 84, 108, 154, 157, 183, 184, 186, 192, 208, 215, 220, 225, and 230).

Many records produced large, multi-millennial age uncertainties preventing useful comparison, while poor chronological control in many of the records has limited the ability to say with confidence where these peaks sit temporally. However, it is evident that concurrent peaks can be broadly located in a number of sites either at ~10 ka cal. BP (e.g. site 84 as well as sites 173, 174), ~9.3 ka cal. BP (e.g. sites 36, 77, 88, 108, 208, 230, 220, 186) or both (e.g. site 16, 30, 45, 66, 154, 192, 184). Reasonable age estimates were possible for 10 sites across the British Isles, presented in Figures 5 and 6. These ages (light grey) have also been placed into a phase model, demonstrating that they overlap (within chronological uncertainty) potentially occurring over an interval of between 0-740 years, spanning a period from 9.73-9.12 ka cal. BP (at 1σ). We then compared these data against our *KDE_Model* for archaeological radiocarbon dates (data from Bevan *et al.*, 2017), Mesolithic assemblage shifts (from Conneller *et al.,* 2016) and the NGRIP oxygen isotope record (Rasmussen *et al.,* 2014).

The KDE_Model shows that during the timeframe in which the charcoal peaks occur the Deepcar-type and Star Carr-type stone tool assemblages disappear while we see the biggest peak in archaeologically derived charcoal dates (black curve; see Fig. 6), and the second biggest peak when all dates are considered (orange curve), which could suggest large shifts in human intensity during this timeframe. Alternatively, these signals could simply reflect the result of archaeological research interest, combined with particularly well-studied sites, as noted for the Early Mesolithic by Weninger *et al.* (2009).

Comparisons with the NGRIP oxygen isotope record show that within the same timeframe the 9.3 ka BP event is encompassed. The event was first recorded in the Greenland Ice Core record (Rasmussen *et al.*, 2007; shown in Fig. 6), in the British Isles it has also been recorded by isotope (Marshall *et al.,* 2007; Whittington *et al.,* 2015) and chironomid (C-IT) based reconstructions (Marshall *et al.,* 2007, Lang *et al.,* 2010, Whittington *et al.,* 2015). These studies suggest that the 9.3 ka event had at least as significant a climatic impact as the more extensively studied 8.2 ka BP event, even though the former may have been much shorter in duration (~50 yrs; Marshall *et al.,* 2007). The 9.3 ka BP event depressed mean annual temperatures across the British Isles by around 2˚C (Marshall *et al.,* 2007), whilst there is also evidence to suggest that *Corylus* and other frost sensitive vegetation declined at around this time (Ghilardi and O'Connell, 2013).

Taken together these data demonstrate that these charcoal depositional events occurred in multiple sites at statistically similar ages (within age uncertainty) focused upon c. 9.3 ka BP during which there might have been a shift in human intensity on the landscape. That these sites are widely distributed across the British Isles means that the coincident increases in charcoal abundance are unlikely to derive from site-specific taphonomic processes, and most likely represents higher volumes of charcoal production within the landscape. What is also notable is that at sites where the charcoal peak is evident, palynological records indicate different catchment vegetation (notably a difference between southern England and Scotland). Furthermore, for 6 sites (16, 36, 184, 208, 220, 223) of the 10 sites there is available information on the ratio between Arboreal (AP) and Non-Arboreal Pollen (NAP), which is often used as a proxy of woodland cover. In 5 of these (36, 184, 208, 220, 223) a pronounced shift in the AP/NAP ratio is evident at or just after the charcoal peak, implying that fire could have acted as a significant driver of vegetation turnover alongside the climate impacts discussed above.

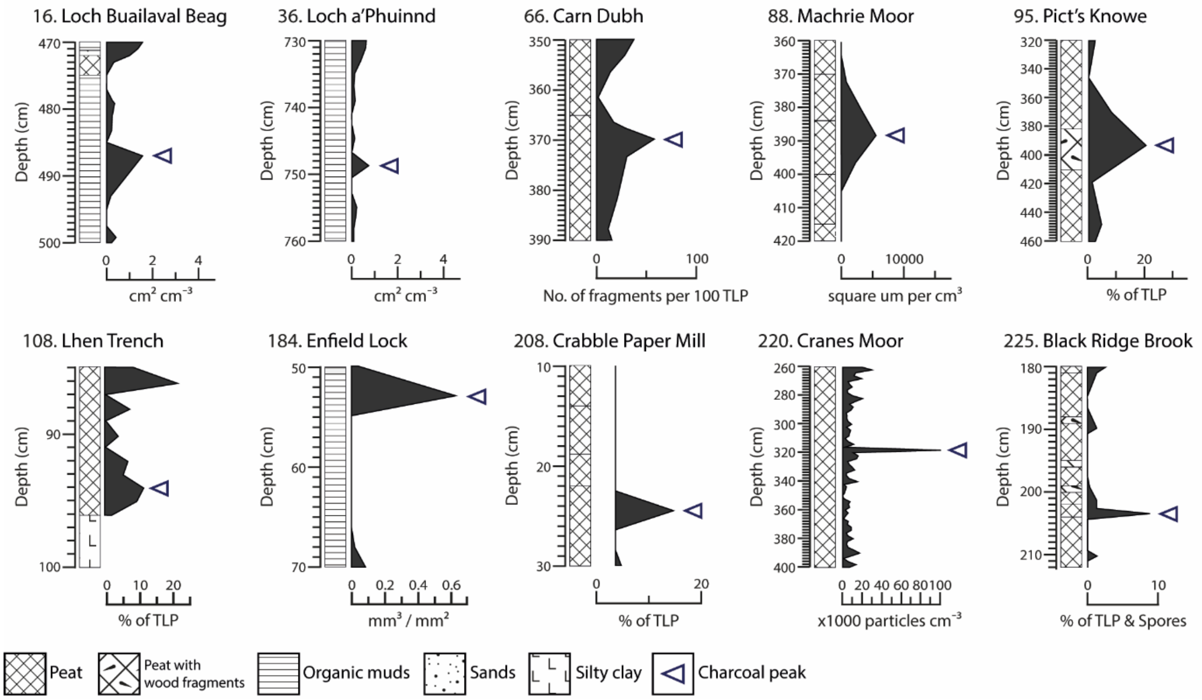

Figure 5: Occurrence of charcoal peaks at c.9.3 ka BP from selected sites from across the British Isles showing the abrupt shift in microscopic charcoal values plotted against depth, note ~1000 years of deposition is shown above and below the indicated charcoal peak (apart from site 184). Changes in lithology are also indicated.

Data from: (16) Fossit (1996), (36) Fossit (1996), (66) Tipping (1995), (88) Robinson and Dickson (1988), (95) Milburn and Tipping (1999), (108) Innes *et al.* (2003), (184) Chambers *et al.* (1996), (208) Bates *et al.* (2008), (220) Grant *et al.* (2014), (225) Caseldine and Maguire (1986)

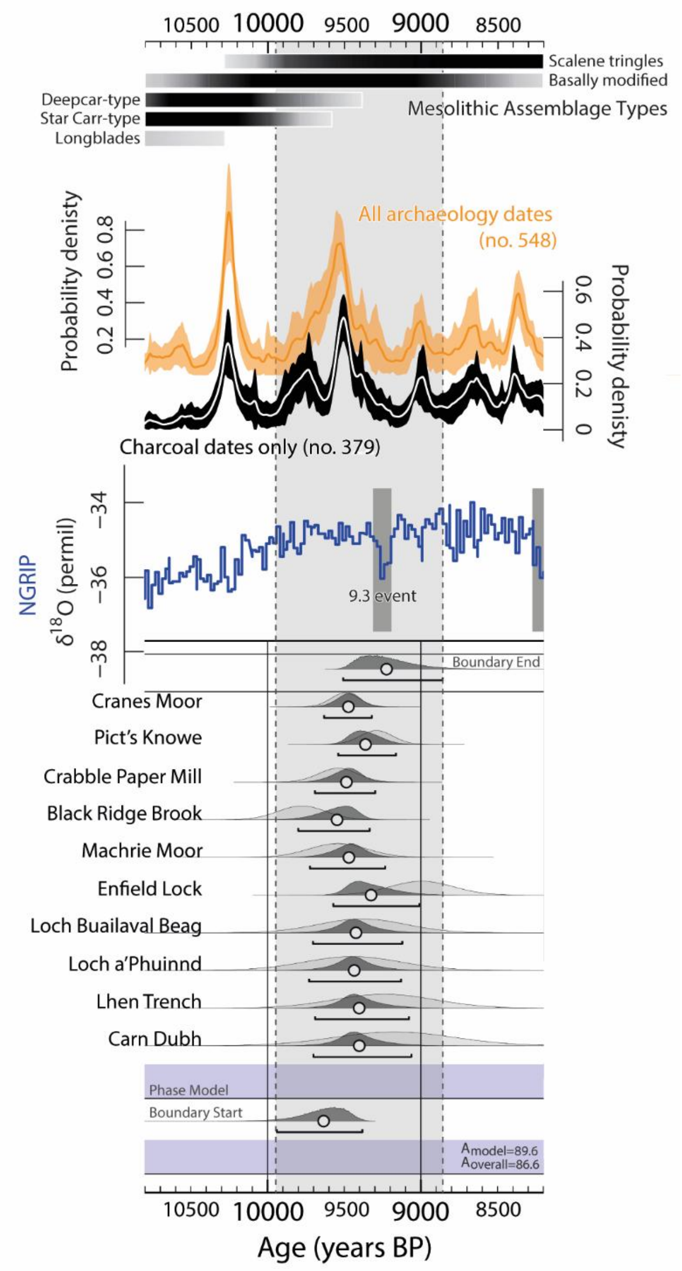

Figure 6: The chronology of lithic assemblage types has been taken from Conneller *et al.* (2016) with darker shading reflecting increased probability that an assemblage type was in use. Below this is a *KDE_Model* for archaeology dates & charcoal dates (for full dataset see Bevan *et al.* (2017); a map of all modelled dates is available in the supplementary information). The NGRIP oxygen isotope record

with the 9.3 ka event is defined after the INTIMATE event stratigraphy (Rasmussen *et al.,* 2014). Finally, the results of the OxCal age-depth modelling for age estimate of the indicated charcoal peaks presented in Figure 5 for individual sites (light grey) and as a *Phase Model* (dark grey). The *Boundary Start* and *Boundary End* indicate the estimated span of time charcoal deposition took place considering all sites, all age estimates are plotted at 95.4% probability. Note all data have been adjusted to a yrs BP (1950) timescale.

4. Discussion

4.1 Biomass burning during the LGIT in the British Isles

Based on the ubiquity of occurrence of charcoal within the data presented here it seems probable that wildfire did play a role during the LGIT of the British Isles. Notwithstanding that possibly not all the charcoal corresponds to contemporary fire events, or some of it could be derived from hearths, our findings indicate that wildfire was most likely a common component of the British Isles' palaeolandscape.

The increase of charcoal values during millennial scale warming has been very well documented worldwide (Power *et al.*, 2008) and in the British Isles (see Figure 4 in Hawthorne and Mitchell, 2018). However, of special interest to note here is the identification of robust fire events (see Higuera *et al.*, 2009; Blarquez *et al.*, 2013) during GS-2.1a in Ireland (Hawthorn and Mitchell, 2016) as well as the presence of charcoal, and in particular, with high values, during the cold intervals GS-2.1a and GS-1.

Our understanding of fire ecology during glacial times is incomplete. Not precluding the fact that some of the charcoal evidence presented during the cold intervals may be a result of reworking, it is important to note that studies do show the occurrence of wildfire, albeit limited, during glacial times globally (e.g. Power *et al.*, 2008; Daniau *et al.*, 2012) as well as more regionally (Carcaillet and Blarquez, 2017). Enhanced seasonality or aridity could have promoted wildfire during these cold intervals (Isarin *et al.*, 1998; Denton 2006). Notwithstanding that vegetation both cold intervals in the British Isles, findings from another geographic region and from another time interval hint that it is likely that there has been at least some vegetation capable to promote wildfire in the British Isles, maybe even close to glaciers: e.g. Zale *et al.* (2018), demonstrate the existence of plants on supraglacial debris in Scandinavia, and Froyd (2005) shows the presence of *Pinus* through fossil stomata despite it not being evident in pollen records in the Early Holocene.

4.2 Potential Wildfire Drivers and comparisons to the continental record

Most of the studies included in this synthesis contain palynological data. Some studies have specifically examined the relationship between charcoal deposition and specific pollen types (Edwards *et al.*, 1995; Froyd, 2006; Grant *et al.,* 2014), though these are generally the exceptions. Albeit not an exhaustive list, we now refer to the most commonly associated taxa with fire in the British Isles. It has, for example, been postulated that the only tree species susceptible to burning in the British Isles is *Pinus* (Rackham, 1986) and that *Pinus* might be pyrophilous (Bradshaw, 1993). However, *Pinus* pollen is not correlated with charcoal abundance in the British Isles and in some cases thrives during periods with low charcoal values (e.g. Bradshaw and Browne, 1987; Froyd, 2006; Grant *et al.*, 2014). *Calluna vulgaris*, which commonly forms the ground-layer in *Pinus* woodlands as well as being an important component of heathlands, has in some cases been correlated with charcoal (Froyd 2006; Grant *et al.,* 2014). However, this relationship was inconsistent across all sites studied by Edwards *et al.* (1995) in the Outer Hebrides. Another taxon that has been closely examined in relation to fire is *Corylus* (e.g. Smith, 1970; Edwards, 1990), however, no consistent relationship has been established here either. For example, in some cases *Corylus* pollen and charcoal appear to co-exist (sites 4, 8, 9 and 12), while in other sites *Corylus* pollen is present in the absence of- or in records containing limited charcoal (sites 61 and 120). In other sites once *Corylus* establishes charcoal values become very low (sites 75 and 85), or there appears to be no association between their values (41, 48, 52, 62, 108, 180, 184, 220 and 230).

Thus, although vegetation may have played a role on a local scale, these regional inconsistencies indicate that wildfire has not been primarily controlled by, or promoted, a certain vegetation type (at least distinguishable within the pollen record). Further evidence to attest to this is the clustering of radiocarbon dates from woody charcoal fragments for the Pitstone soil, during the later stages of GI-1 (Figure 4), which in conjunction with the very similar age distribution results reached by Keiser *et al.* (2009) imply contemporaneous burning on different woodland ecosystems across a broad geographical area (section 3.2.3). Moreover, during the 9.3 ka charcoal peak the vegetation in most sites is in a different stage of successional and migration development, yet all show an enhanced burning signal within a short temporal window (section 3.4.3). These facts in conjunction with the inconsistencies highlighted above imply that vegetation was probably not the primary driver of wildfire regimes on a regional scale throughout the LGIT.

With regards to anthropogenic activity as a key driver of fire regimes, it is overwhelmingly likely that throughout the LGIT, Upper Palaeolithic and Mesolithic populations occupying the British Isles would have had a strong working knowledge of fire. Charcoal records are often described alongside lithics or as part of hearth or 'hearth-like' features. Hearths have been described alongside Creswellian and *Federmesser* archaeology in England (e.g. Jacobi and Roberts, 1992; Roberts, 1992; 1996) and also flint tools and bone noted as burnt, thus reflecting activities taking place in association with fire (e.g. Cooper, 2002; Barton and Roberts, 1996). A microscopic charcoal peak occurring in a lacustrine record from Star Carr, Yorkshire (site 120) and dating to GI-1 has been attributed to Upper Palaeolithic occupation of the site (Day, 1996). Some evidence also exists for hearths (Conneller, 2007) or hearth-related activities (Cooper, 2006) during phases of GS-1. The onset of the Mesolithic sees much richer evidence for potential human-induced fire from across the British Isles. Evidence for the use of fire in the Early Holocene includes not only fireplace activities but also larger-scale intentional landscape burning from both upland and lowland areas. The first and/or last appearance of archaeology at a site is often intimately associated with evidence of fire; for example, two increases in microscopic charcoal, overlying a flint-flake at Newlands Cross in Ireland were likely attributable to Mesolithic peoples undertaking prescribed burning (Preece *et al.,* 1986). In the Severn Estuary, a thin band of charcoal-rich clay separates estuarine sediments from an underlying inundated Mesolithic soil (Caseldine, 2000). Evidence for the burning of waterside reedswamp and shrubs has also been suggested for other lowland sites in England, Wales and Ireland (e.g. Bell, 1999; Barnett 2009; Mossop and Mossop, 2009; Fyfe *et al.,* 2003). Upland areas may have also been exploited, for example Smith and Cloutman (1988) put forward circumstantial evidence for the maintenance of upland heathland in the Black Mountains in S Wales c. 8000 ka BP via episodic burning. The use of fire ecology from England, in the Pennines has also been proposed (Jacobi, 1976).

Anthropogenic burning during the Mesolithic could also have been used to maintain more open landscapes and promote the growth of flora such as nuts, fruits and shrubs to aid subsistence (Zvelebil, 1994), as well as aiding the hunting of large game (Mellars, 1976; Simmons, 1996; Walker *et al.,* 2006). Some of the most compelling evidence of human induced fire-ecology from the Early Holocene comes from Star Carr (site 122), where exceptional preservation and decades of investigations have revealed much about human-fire manipulation of the environment (see Mellars and Day, 1998), permitting burning to be placed temporally against archaeological and environmental events during the Early Holocene (Blockley *et al.,* 2018).

Therefore, the available evidence supports that Palaeolithic and Mesolithic populations utilised fires through the LGIT. However, in the case of GS-2.1a and GS-1, although charcoal abundances are often found to be high, there is limited evidence for substantial human activity across the British Isles. It is therefore unlikely that charcoal preserved in sediments of this age derive primarily from anthropogenic ignition. For GI-1, charcoal is prominent in Ireland when humans were absent, while in Britain the geographical distribution of the available records does not correlate with the known geographical extent of human occupation (see Figures 11 and 12 in Jacobi and Higham, 2009), notably in regions of the Scottish mainland and Isles (e.g. the Orkneys, Hebrides, and Shetland) where associated archaeology is sparse (Ballin *et al.*, 2018), while no direct link between human density and wildfire expression is evident based on the findings from the Pitstone paleosol (Figure 4).

The available evidence thus suggests that wildfire, at the regional scale, would have been at least in part controlled by climate within the British Isles during the LGIT. Burning during GS-2.1a can be more confidently related to sub-orbital forcing given there is no evidence for humans in either Britain or Ireland at this time. The patterns identified during GI-1 could be related with the multiple climatic oscillations. Dating uncertainties surrounding the evident peaks in the records preclude a direct relationship to be inferred. However, cumulative probabilities for charcoal found in the Pitstone soil in SE England indicate enhanced burning during the latter part of the interstadial (13.5-12.9 ka BP). This may be related to a period known as pre-Younger-Dryas warming, and thus may correspond to enhanced burning during centennial scale warming, which likely increased the net primary production and fuel availability. On the other hand, it is also likely that the various ecosystems responded differently to the multiple oscillations and ameliorations recorded within this interstadial, reaching tipping points at different timings, if at all. The phases of episodic burning suggested during GS-1 may be related to a more arid hydroclimatic regime (e.g. Bohncke et al., 1988; Bohncke, 1993). For example, it is possible that the abrupt onset of cold conditions with the onset of the GS-1 led to increased tree mortality which in turn increased woody fuel availability and might have, in conjunction with enhanced aridity (Isarin *et al.,* 1998; Rach *et al.,* 2014), promoted wildfires.

With regards to the Early Holocene, the plethora of available records implied some common patterns that could be related to climate. However, humans being active in the landscape utilising fire do add complexity to disentangling primary drivers of wildfire at this time. Nevertheless, with regards especially to the 9.3 ka BP event, the pronounced shift in charcoal values identified from dated sites from across the British Isles suggest at least a partial climatic control. Interestingly, a significant increase in burning has been related to the 9.3 ka BP event from across the North Sea at localities in Belgium and the Netherlands (Crombé, 2016), and alongside concurrent climate, fluvial and vegetation shifts, has been suggested as a potential trigger of the sociocultural shift seen between Early and Middle Mesolithic stone tool technologies in this region (Robinson *et al.,* 2013; Crombé, 2018). Therefore, our findings fit with the growing evidence for enhanced wildfire regimes from Northern Europe (Crombé, 2016) associated with this abrupt climatic oscillation. In these instances, desiccating *Pinus* forest is attributed to the change in fire regimes, providing high volumes of flammable material with which to catalyse burning. Similar mechanisms could also explain the rise in fire regimes in the British Isles with the decline in *Corylus* woodland increasing fuel availability. A climatic control for wildfire has also been proposed by Grant *et al.* (2014) for the Early Holocene at Cranes Moor, Hampshire (Site 220), via a strong correlation between reconstructions of Bog Surface Wetness (BSW) and reconstructed fire frequency. Studies looking into wildfire drivers in Sweden (Olsson *et al.,* 2010) and Fennoscandinavia (Clear *et al.,* 2014) for the same timeframe (i.e. broadly the Early Holocene) also suggest a climatic control. Finally, the same result was reached by a modelling study (Molinari, *et al.,* 2013), which although identified humans as the dominant driver of wildfire regimes for the entirety of the Holocene, suggested that Early Holocene fire regimes were controlled by climate for the British Isles and mainland Europe.

5. Key Findings

Our synthesis of charcoal data from 238 sites in the British Isles spanning the LGIT showed the widespread occurrence of charcoal. No wide charcoal-free areas have emerged within the coverage of the available records. Our synthesis is the first that considers the whole of the British Isles for the entirety of the LGIT, and clearly illustrates the possibility that wildfire was an important component in conditioning the palaeolandscape of the British Isles for the entirety of the LGIT and, critically, during periods (and in areas) where humans were absent. Specifically, there have been four principal findings:

1) high charcoal values during GS-2.1a that cease with the onset of the initial Interstadial warming at c. 14.7 ka cal. BP;
2) spikey or distinct peaks in charcoal records spanning GI-1, as well as enhanced landscape burning during the latter stages of the Interstadial (~13.5-12.85 cal ka BP);
3) high charcoal values during GS-1; and
4) multiple charcoal peaks in the Early Holocene with a coincident large peak identified in multiple sites across Britain at ~9.3 ka cal. BP

High charcoal values have been previously noted for certain parts of the LGIT (e.g. Lateglacial: Edwards *et al.,* 2000; postglacial: Chambers *et al.,* 1996) and although in many individual cases reasons to explain this have been postulated, robust relationships have yet to be established. However, the common patterns identified in conjunction with the absence of humans for certain periods and regions suggest a climatic control.

The findings of our synthesis highlight a gap in our knowledge by adding to a long-going debate on the importance of fire in temperate oceanic and periglacial climate-landscapes. Notions that the British landscape does not naturally burn are incorrect.

6. Ten research priorities for understanding better palaeofire drivers in the British Isles

In light of our synthesis, and the questions raised within, we finish here with ten research priorities which we believe will improve our understanding of palaeofire for the British Isles and similar regions. Some of the points below may be expensive, both analytically and financially, we therefore recommend that they are standard considerations in large projects, where feasible.

1. Workers researching the LGIT should routinely quantify charcoal content, ideally contiguously to allow reconstruction of fire return intervals and reduce the risk that short-lived intervals of past burning are not overlooked (e.g. Grant *et al.,* 2014; Hawthorne and Mitchell*,* 2016).

2. Charcoal records should, wherever possible, be tied with parallel biological (e.g. pollen, plant macrofossils), lithological (e.g. Loss on ignition) and climatic (e.g. stable isotopes, C-ITs) proxies. This allows both local and extra local factors that cause or constrain landscape fire over the British Isles to be better understood. In particular, this is critical for understanding the relationship of fire to short-lived climatic episodes, and also the role of fire during periods of abrupt climatic change and resultant ecological shifts.
3. To better understand the relationship between fire and abrupt climatic events targeted dating of events that could potentially allow disentanglement of potential coeval events is needed. Where radiocarbon dating is undertaken multiple determinations should be sought on suitable short-lived material to allow Bayesian approaches to constrain the age of dated events.
4. In order to better understand millennial and sub-millennial palaeofire patterns robust high-resolution chronologies will be required, in particular for determining precisely any leads and lags in fire across the British Isles, which could help reveal climate vs human driven fire regimes. The application of tephrochronology used alongside traditional geochronological techniques such as radiocarbon may assist in testing these hypotheses (Blockley *et al.,* 2014).
5. Less attention has been focused on understanding palaeofire from more complex sedimentary environments such as fluvial or alluvial deposits. Although understanding burning over several millennial is often difficult (if not impossible) from these types of records, we wish to underline, as have other workers (e.g. Scott *et al.,* 2017) that these records often contain larger charcoal fragments. This can allow rich information about palaeo-fire regimes to be gained utilising techniques that require larger charcoal pieces, including identifying the fuel sources being burnt (see point 6 below).
6. Charcoal is information rich and techniques developed within the discipline of coal geology are currently being underutilised within Quaternary Science charcoal studies (Scott, 2010). Charcoal reflectance can allow the minimum charring temperatures to be assessed (Scott, 1989; Jones

and Chaloner, 1991; Scott and Jones, 1994; McParland *et al.,* 2009) and thus inferences on past fire regimes (Scott, 2010; Hudspith *et al.,* 2015) and even archaeological formation (McParland *et al.,* 2009) to be made.

7. Macrocharcoal can help identify what the fuel source was, which can be particularly important for when considering what flora might encourage increased flammability. This can be achieved via microscopy and/or Scanning Electron Microscopy (SEM) that can allow botanical identification. Utilization of charcoal morphotypes could also provide information on what was burning (Mellars and Dark, 1998; Jensen *et al.,* 2007; Aleman *et al.,* 2013; Mustaphi and Pisaric, 2014; Crawford and Belcher, 2014).

8. Increased use of more novel proxies of fire in the British Isles, in particular polyaromatic hydrocarbons (PAH) biomarkers (Chiverrell *et al.,* 2008), may again reveal more about fire regimes. Other methods currently in development, for example Fourier Transformed Infrared Spectroscopy, also show great potential (Gosling *et al.*, 2019).

9. More research is needed to understand if charcoal records from different sedimentological contexts (i.e. peat, lakes, loess, soils) are comparable and can thus be used to infer past wildfire activity on regional and extra-regional scales (e.g. Robin *et al.*, 2013; Florescu *et al.,* 2018; Hawthorne *et al.*, 2018).

10. Finally, modelling studies incorporating palaeoclimatic, vegetation, and human population data in ecosystem modelling could significantly aid in quantitatively disentantingling the effects of each driver (e.g. Molinari *et al.,* 2013).

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References

Aleman, J. C., Blarquez, O., Bentaleb, I., Bonté, P., Brossier, B., Carcaillet, C., Gond, V., Gourlet-Fleury, S., Kpolita, A., Lefèvre, I., Oslisly, R. Power, M.J., Yongo, O., Bremond, L., Favier, C. 2013. Tracking land-cover changes with sedimentary charcoal in the Afrotropics. The Holocene, 23(12), 1853-1862. https://doi.org/10.1177/0959683613508159

Aleman, J., Hennebelle, A., Vannière, B., Blarquez, O., 2018. Sparking New Opportunities for Charcoal-Based Fire History Reconstructions. Fire 1, 7. https://doi.org/10.3390/fire1010007

Allen M.J., Barclay, A., Bayliss, A., Hayden, C., 2006. The radiocarbon dates from White Horse Stone, Aylesford, Kent. CTRL Specialist Archive Report.

Allen, M.J., 2008. Late Upper Palaeolithic (Area 3): Environmnental Evidence for the Former Environment and Possible Human Activity. In: Fitzpatrick, A.P., Powell, A.B., Allen, M.J. (Eds.) Archaeological Excavations on the Route of the A27 Westhampnett Bypass, West Sussex.

Ballin, T.B., Saville, A., Tipping, R., Ward, T., Housely, R., Verrill, L., Bradley, M., Wilson, C., Lincoln, P.C., MacLeod, A. 2018. Reindeer hunters at Howburn Farm, South Lanarkshire: A late Hamburgian settlement in southern Scotland - its lithic artefacts and natural environment. Archaeopress. ISBN 9781784919016

Barnett, C. 2009. The Chronology of Early Mesolithic Occupation and Environmental Impact at Thatcham Reedbeds, Southern England. In: Crombé, P., Van Strydonck, M., Boudin, M. and Bats, M. (eds.) Chronology and Evolution within the Mesolithic of North-West Europe. Cambridge Scholars Publishing, Cambridge, 57-76

Barton, R. N. E., Jacobi, R. M., Stapert, D., Street, M. J., 2003. The Late-glacial reoccupation of the British Isles and the Creswellian. Journal of Quaternary Science, 18(7), 631-643. https://doi.org/10.1002/jqs.772

Barton, R.N.E., Ford, S., Collcutt, S.N., Crowther, J., Macphail, R.I., Rhodes, E., Van Gijn, A., 2009. A Final Upper Palaeolithic site at Nea Farm, Somerley, Hampshire (England) and some reflections on the occupation of Britain in the Lateglacial Interstadial. *Quartär*, 56, 1-29.

Barton, R.N.E., Roberts, A.J., 1996. Reviewing the British Late Upper Palaeolithic: new evidence for chronological patterning in the Lateglacial record. Oxford Journal of Archaeology, 15(3), pp.245-265. https://doi.org/10.1111/j.1468-0092.1996.tb00085.x

Bates, M.R., Barham, A.J., Jones, S., Parfitt, K., Parfitt, S., Pedley, M., Preece, R.C., Walker, M.J.C., Whittaker, J.E., 2008. Holocene sequences and archaeology from the Crabble Paper Mill site, Dover, UK and their regional significance. Proceedings of the Geologists' Association 119, 299–327. https://doi.org/10.1016/S0016-7878(08)80308-2

Bayliss, A., Woodman, P., 2009. A new Bayesian chronology for Mesolithic occupation at Mount Sandel, Northern Ireland. *Proceedings of the Prehistoric Society* vol. 75, pp. 101-123. Cambridge University Press. https://doi.org/10.1017/S0079497X00000311

Bell, M. 1999. Prehistoric settlements and activities in the Welsh Severn Estuary. In: Coles, B., Coles, J., Schou Jørgensen, M. (eds), Bog Bodies, Sacred Sites and Wetland Archaeology: 17–25. Exeter: WARP Occasional Paper 12

Bell, M. 2007. Prehistoric coastal communities: The Mesolithic in western Britain. CBA Research Report 149. York: Council for British Archaeology.

Bennett, K. D., Simonson, W. D., Peglar, S. M. 1990. Fire and man in post-glacial woodlands of eastern England. Journal of Archaeological Science, 17(6), 635-642. https://doi.org/10.1016/0305-4403(90)90045-7

Bennett, K.D. (1988). Holocene Pollen Stratigraphy of Central East Anglia, England, and comparison of pollen zones across the British Isles. New Phytologist 109 (2), 237-253. **https://doi.org/10.1111/j.1469-8137.1988.tb03712.x**

Bevan, A., Colledge, S., Fuller, D., Fyfe, R., Shennan, S.,Stevens, C., 2017. Holocene fluctuations in human population demonstrate repeated links to food production and climate. *Proceedings of the National Academy of Sciences*, 201709190. https://doi.org/10.1073/pnas.1709190114

Birks, H.H., Birks, H.J.B., 2014. To what extent did changes in July temperature influence Lateglacial vegetation patterns in NW Europe? Quaternary Science Reviews 106, 262–277. https://doi.org/10.1016/j.quascirev.2014.06.024

Blarquez, O., Girardin, M. P., Leys, B., Ali, A. A., Aleman, J. C., Bergeron, Y., Carcaillet, C., 2013. Paleofire reconstruction based on an ensemble-member strategy applied to sedimentary charcoal. Geophysical Research Letters, 40(11), 2667-2672. **https://doi.org/10.1002/grl.50504**

Blockley, S.P., Candy, I., Matthews, I., Langdon, P., Langdon, C., Palmer, A.P., Lincoln, P., Abrook, A., Taylor, B., Conneller, C., Bayliss, A., MacLeod, A., Deeprose, L., Darvill, C., Kearney, R., Beavan, N., Staff, R., Bamforth, M.G., Taylor, M., Milner, N., 2018, The resilience of postglacial hunter-gatherers to abrupt climate change. *Nature Ecology and Evolution*, vol 2, no. 4, pp. 810-818. https://doi.org/10.1038/s41559-018-0508-4

Blockley, S.P., Lowe, J.J., Walker, M.J., Asioli, A., Trincardi, F., Coope, G.R. and Donahue, R.E., 2004. Bayesian analysis of radiocarbon chronologies: examples from the European Late-glacial. Journal of Quaternary Science, 19(2), pp.159-175. **https://doi.org/10.1002/jqs.820**

Bohncke, S.J.P. 1993. Lateglacial environmental changes in the Netherlands: spatial and temporal patterns. *Quaternary Science Reviews* 12, 707-717. https://doi.org/10.1016/0277-3791(93)90008-A

Bohncke, S., Vandenberghe, J. & Wijmstra, T.A. 1988. Lake level changes and fluvial activity in the Late Glacial lowland valleys. *In* Lang, S. & Schluchter, C. (eds) *Lake, Mire & River Environments in the Past 15,000 Years*. Rotterdam: Balkema, 115-121.

Bowman, D.M., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M., Antonio, C.M., Defries, R., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M., 2009. Fire in the Earth System. Science 324, 481–484. https://doi.org/10.1126/science.1163886

Bradshaw, R. H., Browne, P., 1987. Changing patterns in the post-glacial distribution of Pinus sylvestris in Ireland. *Journal of Biogeography*, 237-248. https://doi.org/10.2307/2844894

Bradshaw, R., 1993. Forest response to Holocene climatic change: equilibrium or non-equilibrium. In: Chambers, F.M. (Ed.), Climate change and human impact on the landscape. Springer, Dordrecht, pp. 57-65

Bronk Ramsey, C, 2017. Methods for summarizing radiocarbon datasets. *Radiocarbon*, *59*(6), pp.1809-1833. https://doi.org/10.1017/RDC.2017.108

Bronk Ramsey, C., 2001. Development of the radiocarbon calibration program OxCal. Radiocarbon 43 (2), 355-363 https://doi.org/10.1017/S0033822200038212

Bronk Ramsey, C., 2008. Deposition models for chronological records. *Quaternary Science Reviews*, *27*(1-2), 42-60. https://doi.org/10.1016/j.quascirev.2007.01.019

Bronk Ramsey, C., Lee, S., 2013. Recent and planned developments of the program OxCal. *Radiocarbon*, *55*(2), 720-730. https://doi.org/10.1017/S0033822200057878

Brown, K. J., Power, M. J. 2013. Charred particle analyses.

Busfield, M.E., Lee, J.R., Riding, J.B., Zalasiewicz, J. and Lee, S.V., 2015. Pleistocene till provenance in east Yorkshire: reconstructing ice flow of the British North Sea Lobe. Proceedings of the Geologists' Association, 126(1), pp.86-99. https://doi.org/10.1016/j.pgeola.2014.12.002

Carcaillet, C., Blarquez, O., 2017. Fire ecology of a tree glacial refugium on a nunatak with a view on Alpine glaciers. *New Phytologist*, *216*(4), 1281-1290. **https://doi.org/10.1111/nph.14721**.

Caseldine, A., 2000. 'The vegetation history of the Goldcliff area'. In: Bell, M., Caseldine, A., Neumann, H. (eds), Prehistoric Intertidal Archaeology in the Welsh Severn Estuary, CBA Research Report 120, York: Council for British Archaeology. 208-244.

Caseldine, C., Maguire, D., 1986. Lateglacial / early Flandrian vegetation change on northern Dartmoor, south-west England. Journal of Biogeography 13, 255–264. https://doi.org/10.2307/2844924

Chambers, F.M., Mighall, T.M., Keen, D.H., 1996. Early Holocene pollen and molluscan records from Enfield Lock, Middlesex, UK. Proceedings of the Geologists' Association 107, 1–14. https://doi.org/10.1016/S0016-7878(96)80063-0

Chiverrell, R. C., Oldfield, F., Appleby, P. G., Barlow, D., Fisher, E., Thompson, R., Wolff, G., 2008. Evidence for changes in Holocene sediment flux in Semer Water and Raydale, North Yorkshire, UK. Geomorphology, 100(1-2), 70-82. https://doi.org/10.1016/j.geomorph.2007.04.035

Chiverrell, R.C., Thorndycraft, V.R., Hoffmann, T.O., 2011. Cumulative probability functions and their role in evaluating the chronology of geomorphological events during the Holocene. Journal of Quaternary Science, 26(1), 76-85. https://doi.org/10.1002/jqs.1428

Clear, J.L., Molinari, C., Bradshaw, R.H.W., 2014. Holocene fire in Fennoscandia and Denmark. International Journal of Wildland Fire 23, 781–789. https://doi.org/10.1071/WF13188

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F., Krebs, P., 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews*, *28*(5-6), 555-576. https://doi.org/10.1016/j.quascirev.2008.11.005

Conneller C., Bayliss A., Milner N., Taylor B., 2016. The Resettlement of the British Landscape: Towards a chronology of Early Mesolithic lithic assemblage types. Internet Archaeology 2016, 42. http://dx.doi.org/10.11141/ia.42.11

Conneller, C. 2007. Inhabiting new landscapes: settlement and mobility in Britain after the Last Glacial Maximum. *Oxford Journal of Archaeology, 26*(3), 215-237. **https://doi.org/10.1111/j.1468-0092.2007.00282.x**

Conneller, C., 2012. *An archaeology of materials: substantial transformations in early prehistoric Europe*. Routledge. https://doi.org/10.4324/9780203833728

Cook, J., Jacobi, R., 1994. A reindeer antler or 'Lyngby' axe from Northamptonshire and its context in the British Late Glacial. Proceedings of the Prehistoric Society 60, 75–84. https://doi.org/10.1017/S0079497X0000339X

Cooper, L. 2006. Launde: a Terminal Palaeolithic camp site in the English Midlands and its North European context. Proceedings of the Prehistoric Society 72: 53–94.

Cooper, L., 2002. A Creswellian campsite, Newtown Linford. Transactions of the Leicestershire Archaeological and Historical. Society 76: 78–80.

Crawford, A. J., Belcher, C. M., 2014. Charcoal morphometry for paleoecological analysis: The effects of fuel type and transportation on morphological parameters. Applications in plant sciences, 2(8). **https://doi.org/10.3732/apps.1400004**

Crombé, P., 2016. Forest fire dynamics during the early and middle Holocene along the southern North Sea basin as shown by charcoal evidence from burnt ant nests. Vegetation History and Archaeobotany 25, 311–321. https://doi.org/10.1007/s00334-015-0550-y

Crombé, P., 2018. Abrupt cooling events during the Early Holocene and their potential impact on the environment and human behaviour along the southern North Sea basin (NW Europe). Journal of Quaternary Science, 33(3), 353-367. **https://doi.org/10.1002/jqs.2962**

D'Errico, F., Banks, W. E., Vanhaeren, M., Laroulandie, V., Langlais, M., 2011. PACEA geo-referenced radiocarbon database. *PaleoAnthropology*, *2011*, 1-12. https://doi.org/10.4207/PA.2011.ART40

Daniau, A. L., Harrison, S. P., Bartlein, P. J., 2010. Fire regimes during the Last Glacial. Quaternary Science Reviews, 29(21-22), 2918-2930. https://doi.org/10.1016/j.quascirev.2009.11.008

Daniau, A.L., Bartlein, P.J., Harrison, S.P., Prentice, I.C., Brewer, S., Friedlingstein, P., Harrison-Prentice, T.I., Inoue, J., Izumi, K., Marlon, J.R., Mooney, S., Power, M.J., Stevenson, J., Tinner, W., Andri??, M., Atanassova, J., Behling, H., Black, M., Blarquez, O., Brown, K.J., Carcaillet, C., Colhoun, E.A., Colombaroli, D., Davis, B.A.S., D'Costa, D., Dodson, J., Dupont, L., Eshetu, Z., Gavin, D.G., Genries, A., Haberle, S., Hallett, D.J., Hope, G., Horn, S.P., Kassa, T.G., Katamura, F., Kennedy, L.M., Kershaw, P., Krivonogov, S., Long, C., Magri, D., Marinova, E., McKenzie, G.M., Moreno, P.I., Moss, P., Neumann, F.H., Norstrm, E., Paitre, C., Rius, D., Roberts, N., Robinson, G.S., Sasaki, N., Scott, L., Takahara, H., Terwilliger, V., Thevenon, F., Turner, R., Valsecchi, V.G., Vanniere, B., Walsh, M., Williams, N., Zhang, Y., 2012. Predictability of biomass burning in response to climate changes. Global Biogeochemical Cycles 26, 1–12. https://doi.org/10.1029/2011GB004249

David, A., 2007. Palaeolithic and Mesolithic Settlement in Wales, with Special Reference to Dyfed.British Archaeological Report 448, Archaeopress, Oxford.

Day, S.P., 1996. Devensian Late-glacial and early Flandrian environmental history of the Vale of Pickering, Yorkshire, England. Journal of Quaternary Science 11, 9–24. **https://doi.org/10.1002/(SICI)1099-1417(199601/02)11:1<9::AID-JQS210>3.0.CO;2-5**

Denton, G.H., Broecker, W.S., Alley, R.B., 2006. The Mystery Interval 17.5 to 14.5 kyrs ago. Science Highlights: U.S. ESH Program 14, 14–16.

Dogandžić, T., McPherron, S.P., 2013. Demography and the demise of the Neanderthals: a comment on ‘Tenfold Population Increase at the Neanderthal-to-Modern-Human Transition’. *Journal of Human Evolution* 64 (4): 311–313.

Dowd, M., Carden, R.F., 2016. First evidence of a Late Upper Palaeolithic human presence in Ireland. Quaternary Science Reviews, 139, pp.158-163. https://doi.org/10.1016/j.quascirev.2016.02.029

Edwards, K.J. 1990. Fire and the Scottish mesolithic: evidence from microscopic charcoal. In Vermeesch, P.M. & Van Peer, P. (eds) Contributions to the Mesolithic in Europe. Leuven: Leuven University Press, 71-79.

Edwards, K. J., Whittington, G., Hirons, K. R., 1995. The relationship between fire and long-term wet heath development in South Uist, Outer Hebrides, Scotland. Heaths and Moorlands: Cultural Landscapes. Edinburgh: HMSO, 240-248.

Edwards, K.J., Whittington, G., 1997. A 12 000-year record of environmental change in the Lomond Hills, Fife, Scotland: Vegetational and climatic variability. Vegetation History and Archaeobotany 6, 133–152. https://doi.org/10.1007/BF01372567

Edwards, K.J., Whittington, G., Tipping, R., 2000. The incidence of microscopic charcoal in Lateglacial deposits. Palaeogeography, Palaeoclimatology, Palaeoecology 164, 247–262. https://doi.org/10.1016/S0031-0182(00)00189-9

Falk, D. A., Miller, C., McKenzie, D., Black, A. E., 2007. Cross-scale analysis of fire regimes. *Ecosystems*, *10*(5), 809-823. https://doi.org/10.1007/s10021-007-9070-7

Feurdean, A., Spessa, A., Magyari, E.K., Willis, K.J., Veres, D., Hickler. T., 2012. Trends in biomass burning in the Carpathian region over the last 15,000 years. *Quaternary Science Reviews* 45, 111-125. https://doi.org/10.1016/j.quascirev.2012.04.001

Florescu, G., Vannière, B., Feurdean, A., 2018. Exploring the influence of local controls on fire activity using multiple charcoal records from northern Romanian Carpathians. Quaternary International 1–17. https://doi.org/10.1016/j.quaint.2018.03.042

Fossitt, J.A.A., 1996. Late Quaternary vegetation history of the Western Isles of Scotland. New Phytologist 132, 171–196. **https://doi.org/10.1111/j.1469-8137.1996.tb04522.x**

Froyd, C. A., 2005. Fossil stomata reveal early pine presence in Scotland: implications for postglacial colonization analyses. *Ecology*, *86*(3), 579-586. **https://doi.org/10.1890/04-0546**

Froyd, C.A., 2006. Holocene fire in the Scottish Highlands: evidence from macroscopic' charcoal records. Holocene 16, 235–249. https://doi.org/10.1191/0959683606hl910rp

Fyfe, R.M., Brown, A.G. and Coles, B.J., 2003. Mesolithic to Bronze Age vegetation change and human activity in the Exe Valley, Devon, UK. *Proceedings of the Prehistoric Society* 69, pp. 161-181. Cambridge University Press. https://doi.org/10.1017/S0079497X00001298

Fyfe, R. M., Twiddle, C., Sugita, S., Gaillard, M. J., Barratt, P., Caseldine, C. J., Dodson, J., Edwards, K. J., Farrell, M., Froyd, C., Grant, M. J., Huckerby, E., Innes, J. B., Shaw, H., Waller, M., 2013. The Holocene vegetation cover of Britain and Ireland: overcoming problems of scale and discerning patterns of openness. *Quaternary Science Reviews*, *73*, 132-148. https://doi.org/10.1016/j.quascirev.2013.05.014

Ghilardi, B., O'Connell, M., 2013. Early Holocene vegetation and climate dynamics with particular reference to the 8.2 ka event: pollen and macrofossil evidence from a small lake in western Ireland. *Vegetation History and Archaeobotany*, *22*(2), 99-114. https://doi.org/10.1007/s00334-012-0367-x

Gosling, W. D., Cornelissen, H. L., McMichael, C. N. H., 2019. Reconstructing past fire temperatures from ancient charcoal material. *Palaeogeography, palaeoclimatology, palaeoecology*, *520*, 128-137. https://doi.org/10.1016/j.palaeo.2019.01.029

Grant, M.J., Hughes, P.D.M., Barber, K.E., 2014. Climatic influence upon early to mid-Holocene fire regimes within temperate woodlands: A multi-proxy reconstruction from the New Forest, southern England. Journal of Quaternary Science 29, 175–188. https://doi.org/10.1002/jqs.2692

Harding, P., Ellis, C. and Grant, M. J., 2014. Late upper palaeolithic Farndon Fields. In N. Cooke, A. Mudd (Eds.), A46 Nottinghamshire: The Archaeology of the Newark to Widmerpool Improvement Scheme, 2009. Salisbury, Cotswold-Wessex Archaeology, 12-70.

Hawthorne, D., Mitchell, F.J.G., 2016. Identifying past fire regimes throughout the Holocene in Ireland using new and established methods of charcoal analysis. Quaternary Science Reviews 137, 45–53. https://doi.org/10.1016/j.quascirev.2016.01.027

Hawthorne, D., Mitchell, F.J.G., 2018. Investigating patterns of wildfire in Ireland and their correlation with regional and global trends in fire history. Quaternary International 44, 58-66. http://dx.doi.org/10.1016/j.quaint.2017.06.067

Hawthorne, D., Mustaphi, C. J. C., Aleman, J. C., Blarquez, O., Colombaroli, D., Daniau, A. L., Marlon, J. R., Power, M., Vannière, B., Han, Y., Hantson, S., Kehrwald, N., Magi, B., Yue, X., Carcaillet, C., Marchant, R., Ogunkoya, A., Githumbi, E. N., Muriuki, R. M. 2018. Global Modern Charcoal Dataset (GMCD): A tool for exploring proxy-fire linkages and spatial patterns of biomass burning. Quaternary international 488, 3-17. https://doi.org/10.1016/j.quaint.2017.03.046

Higuera, P. E., Brubaker, L. B., Anderson, P. M., Hu, F. S., Brown, T. A., 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecological Monographs 79(2), 201-219. https://doi.org/10.1890/07-2019.1

Hoek, W.Z., 2008. The Last Glacial-Interglacial Transition. Episodes 31, 226–229.

Hudspith, V. A., Belcher, C. M., Kelly, R., Hu, F. S., 2015. Charcoal reflectance reveals early Holocene boreal deciduous forests burned at high intensities. PloS one, 10(4). https://doi.org/10.1371/journal.pone.0120835

Hughes, A. L., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., Svendsen, J. I., 2016. The last Eurasian ice sheets–a chronological database and time-slice reconstruction, DATED-1. *Boreas*, *45*(1), 1-45. **https://doi.org/10.1111/bor.12142**

Innes, J.B., Blackford, J.J., Davey, P.J., 2003. Dating the introduction of cereal cultivation to the British Isles: Early palaeoecological evidence from the Isle of Man. Journal of Quaternary Science 18, 603–613. https://doi.org/10.1002/jqs.792

Isarin, R.F., Renssen, H. and Vandenberghe, J., 1998. The impact of the North Atlantic Ocean on the Younger Dryas climate in northwestern and central Europe. Journal of Quaternary Science, 13(5), pp.447-453. **https://doi.org/10.1002/(SICI)1099-1417(1998090)13:5<447::AID-JQS402>3.0.CO;2-B**

Jacobi, R. M., Higham, T.F.G., 2009. The early Lateglacial re-colonization of Britain: new radiocarbon evidence from Gough's Cave, southwest England. *Quaternary Science Reviews*, 28(19-20), 1895-1913. https://doi.org/10.1016/j.quascirev.2009.03.006

Jacobi, R.M. 1976. Britain inside and outside Mesolithic Europe. Proceedings of the Prehistoric Society 42, 67–84.

Jacobi, R.M., Higham, T.F.G., 2011. The Late Upper Palaeolithic recolonization of Britain: new results from AMS radiocarbon dating. In: Ashton, N.M., Lewis, S.G., Stringer, C.B. (eds). The Ancient Human Occupation of Britain. Elsevier, Amsterdam, 223–247.

Jacobi, R.M., Roberts, A.J., 1992. A New Variant on the Creswellian angle-backed Blade. Lithics 13, 33-9.

Jeffers, E.S., Bonsall, M.B., Brooks, S.J., Willis, K.J., 2011. Abrupt environmental changes drive shifts in tree-grass interaction outcomes. Journal of Ecology 99, 1063–1070. https://doi.org/10.1111/j.1365-2745.2011.01816.x

Jensen, K., Lynch, E. A., Calcote, R., Hotchkiss, S. C., 2007. Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes? The Holocene, 17(7), 907-915. https://doi.org/10.1177/0959683607082405

Jones, T. P., Chaloner, W. G., 1991. Fossil charcoal, its recognition and palaeoatmospheric significance. Palaeogeography, Palaeoclimatology, Palaeoecology, 97(1-2), 39-50. https://doi.org/10.1016/0031-0182(91)90180-Y

Kaiser, K., Hilgers, A., Schlaak, N., Jankowski, M., Kühn, P., Bussemer, S., Przegiętka, K., 2009. Palaeopedological marker horizons in northern central Europe: characteristics of Lateglacial Usselo and Finow soils. Boreas 38, 591–609. https://doi.org/10.1111/j.1502-3885.2008.00076.x

Kangur, M., 2002. Methodological and practical aspects of the presentation and interpretation of microscopic charcoal data from lake sediments. Vegetation History and Archaeobotany 11(4), 289-294. https://doi.org/10.1007/s003340200041

Kelly, A., Charman, D.J., Newnham, R.M., 2010. A Last Glacial Maximum pollen record from Bodmin Moor showing a possible cryptic northern refugium in southwest England. Journal of Quaternary Science 25, 296–308. https://doi.org/10.1002/jqs.1309

Kelly, A., Charman, D.J., Newnham, R.M., 2010. A Last Glacial Maximum pollen record from Bodmin Moor showing a possible cryptic northern refugium in southwest England. Journal of Quaternary Science 25, 296–308. https://doi.org/10.1002/jqs.1309

Kerney, M. P., 1963. Late-glacial deposits on the Chalk of south-east England. Phil. Trans. R. Soc. Lond. B, 246(730), 203-254.

Kerney, M. P., Brown, E. H., Chandler, T. J., 1964. Late-glacial and Post-glacial history of the Chalk escarpment near Brook, Kent. Phil. Trans. R. Soc. Lond. B, 248(745), 135-204.

Kuhn, S.L. (2012). Emergent patterns of creativity and innovation in early technologies. *Developments in Quaternary Science* 16: 69–87. https://doi.org/10.1016/B978-0-444-53821-5.00006-3

Lang, B., Brooks, S.J., Bedford, A., Jones, R.T., Birks, H.J.B., Marshall, J.D., 2010. Regional consistency in Lateglacial chironomid-inferred temperatures from five sites in north-west England. Quaternary Science Reviews 29, 1528–1538. https://doi.org/10.1016/j.quascirev.2009.02.023

Lawson, J. 2001. A list of archaeological radiocarbon dates (Cramond, Edinburgh)' in: Turner R. (ed) *Discovery and Excavation in Scotland*. New Series, Volume 2, Musselburgh: Council for Scottish Archaeology. 124.

Lewis, J. S. C., Rackham, J. 2011. Three Ways Wharf, Uxbridge. A Lateglacial and Early Holocene hunter-gatherer site in the Colne valley. London, Mola Monograph Series 51 Isbn 978-1-901992-97-7

Lowe, J.J., Coope, G.R., Sheldrick, C., Harkness, D.D., Walker, M.J.C., 1995. Direct comparison of UK temperatures and Greenland snow accumulation rates, 15000—12000 yr ago. Journal of Quaternary Science, 10(2), pp.175-180. **https://doi.org/10.1002/jqs.3390100207**

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J., Yu, Z.C., 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. Quaternary Science Reviews, 27(1), pp.6-17. https://doi.org/10.1016/j.quascirev.2007.09.016

Lynch, J. A., Clark, J. S., Stocks, B. J., 2004. Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: interpreting fire regimes from charcoal records in boreal forests. Canadian Journal of Forest Research, 34(8), 1642-1656. https://doi.org/10.1139/x04-071

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J., Anderson, R.S., Briles, C., Brunelle, a, Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, C., Minckley, T., Richard, P.J.H., Scott, a C., Shafer, D.S., Tinner, W., Umbanhowar, C.E., Whitlock, C., 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences of the United States of America 106, 2519–2524. https://doi.org/10.1073/pnas.0808212106

Marlon, J.R., Kelly, R., Daniau, A.L., Vannière, B., Power, M.J., Bartlein, P., Higuera, P., Blarquez, O., Brewer, S., Brücher, T., Feurdean, A., Romera, G.G., Iglesias, V., Yoshi Maezumi, S., Magi, B., Mustaphi, C.J.C., Zhihai, T., 2016. Reconstructions of biomass burning from sediment-charcoal records to improve data-model comparisons. Biogeosciences 13, 3225–3244. https://doi.org/10.5194/bg-13-3225-2016

Marshall, J.D., Lang, B., Crowley, S.F., Weedon, G.P., van Calsteren, P., Fisher, E.H., Holme, R., Holmes, J.A., Jones, R.T., Bedford, A., Brooks, S.J., Bloemendal, J., Kiriakoulakis, K., Ball, J.D., 2007. Terrestrial impact of abrupt changes in the North Atlantic thermohaline circulation: Early Holocene, UK. *Geology* 35, 639–642. https://doi.org/10.1130/G23498A.1

McParland, L. C., Collinson, M. E., Scott, A. C., Campbell, G., 2009. The use of reflectance values for the interpretation of natural and anthropogenic charcoal assemblages. Archaeological and Anthropological Sciences, 1(4), 249. https://doi.org/10.1007/s12520-009-0018-z

Mellars, P. A., 1976. Fire ecology, animal populations and man: a study of some ecological relationships in prehistory. Proceedings of the Prehistoric Society, 42, 15-45. https://doi.org/10.1017/S0079497X00010689

Mellars, P., Dark, P. (eds.), 1998. Star Carr in context: new archaeological and palaeoecolgical investigations at the early Mesolithic site of Star Carr, North Yorkshire. McDonald Institute of Archaeological Research, Cambridge.

Milburn, P., Tipping, R.M., 1999. Pict's Knowe: early-mid Holocene vegetation history and groundwater fluctuations. In: Tipping R.M. (Ed.), The Quaternary of Dumfries and Galloway. Field Guide, Quaternary Research Association, London, 75-80.

Milner, N., Craig, O.E., Bailey, G.N., Pedersen, K. and Andersen, S.H., 2004. Something fishy in the Neolithic? A re-evaluation of stable isotope analysis of Mesolithic and Neolithic coastal populations. Antiquity, 78(299), pp.9-22. https://doi.org/10.1017/S0003598X00092887

Mithen, S., Wicks, K., Pirie, A., Riede, F., Lane, C., Banerjea, R., Cullen, V., Gittins, M. and Pankhurst, N., 2015. A Lateglacial archaeological site in the far north-west of Europe at Rubha Port an t-Seilich, Isle of Islay, western Scotland: Ahrensburgian-style artefacts, absolute dating and geoarchaeology. Journal of Quaternary Science, 30(5), pp.396-416. https://doi.org/10.1002/jqs.2781

Molinari, C., Lehsten, V., Bradshaw, R.H.W., Power, M.J., Harmand, P., Arneth, A., Kaplan, J.O., Vannière, B., Sykes, M.T., 2013. Exploring potential drivers of European biomass burning over the Holocene: A data-model analysis. Global Ecology and Biogeography 22, 1248–1260. https://doi.org/10.1111/geb.12090

Moore, J. 1996. Damp squib: how to fire a major deciduous forest in an inclement climate. In Pollard, T. & Morrison, A. (eds) The Early Prehistory of Scotland. Edinburgh: Edinburgh University Press, 62-73.

Mossop M., Mossop E. (2009) – *M3 Clonee-North of Kells: Contract 2 Dunshaughlin – Navan, Report on the Archaeological Excavation of Clowanstown 1, Co. Meath*, final excavation report (Ministerial Directions No. A008/011 E3064)

Mustaphi, C.J.C., Pisaric, M. F., 2014. A classification for macroscopic charcoal morphologies found in Holocene lacustrine sediments. Progress in Physical Geography, 38(6), 734-754. https://doi.org/10.1177/0309133314548886

O'Connell, M., Huang, C.C., Eicher, U., 1999. Multidisciplinary investigations, including stable-isotope studies, of thick Late-glacial sediments from Tory Hill, Co. Limerick, western Ireland. Palaeogeography, Palaeoclimatology, Palaeoecology 147, 169–208. https://doi.org/10.1016/S0031-0182(98)00101-1

Olsson, F., Gaillard, M. J., Lemdahl, G., Greisman, A., Lanos, P., Marguerie, D., Marcoux, N., Skoglund, P., Wäglind, J., 2010. A continuous record of fire covering the last 10,500 calendar years from southern Sweden—The role of climate and human activities. Palaeogeography, Palaeoclimatology, Palaeoecology, 291(1-2), 128-141. https://doi.org/10.1016/j.palaeo.2009.07.013

Pettitt, P., White, M., 2012. The British Palaeolithic: Human Societies at the Edge of the Pleistocene World. Routledge, London. https://doi.org/10.4324/9780203141441

Power, M.J., Marlon, J., Ortiz, N., Bartlein, P.J., Harrison, S.P., Mayle, F.E., Ballouche, A., Bradshaw, R.H.W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P.I., Prentice, I.C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A.A., Anderson, R.S., Beer, R., Behling, H., Briles, C., Brown, K.J., Brunelle, A., Bush, M., Camill, P., Chu, G.Q., Clark, J.S., Colombaroli, D., Connor, S., Daniau, A.-L., Daniels, M., Dodson, J.R., Doughty, E., Edwards, M.E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M.-J., Gavin, D.G., Gobet, E., Haberle, S.G., Hallett, D.J., Higuera, P.E., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L., Kong, Z.C., Larsen, C., Long, C.J., Lynch, J., Lynch, E.A., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D.M., New, J., Newnham, R.M., Noti, R., Oswald, W., Pierce, J., Richard, P.J.H., Rowe, C., Sanchez Goñi, M.F., Shuman, B.N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D.H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., Zhang, J.H., 2007. Changes in fire activity since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics 30, 887–907. https://doi.org/10.1007/s00382-007-0334-x

Preece, R.C., 2009. Late-glacial slope deposits at Watcombe Bottom near Ventnor, in: Briant, R.M., Bates, M.R., Hosfield, R.T., Wenban-Smith, F.F. (Eds.), The Quaternary of the Solent Basin and West Sussex Raised Beaches. pp. 138–144.

Preece, R.C., Bridgland, D.R., 1999. Holywell Coombe, Folkestone: A 13,000-year history of an English Chalkland Valley. *Quaternary Science Reviews* 18, 1075–1125. https://doi.org/10.1016/S0277-3791(98)00066-3

Preece, R.C., Bridgland, D.R., 1999. Holywell Coombe, Folkestone: A 13,000-year history of an English Chalkland Valley. Quaternary Science Reviews 18, 1075–1125. https://doi.org/10.1016/S0277-3791(98)00066-3

Preece, R.C., Coxon, P. and Robinson, J.E., 1986. New biostratigraphic evidence of the Post-glacial colonization of Ireland and for Mesolithic forest disturbance. Journal of Biogeography, 13, 487-509 https://doi.org/10.2307/2844814

Rach, O., Brauer, A., Wilkes, H., Sachse, D., 2014. Delayed hydrological response to Greenland cooling at the onset of the Younger Dryas in western Europe. Nature Geoscience 7, 109–112. https://doi.org/10.1038/ngeo2053

Rackham, O., 1986. The history of the countryside: the full fascinating story of Britain's landscape. London: JM Dent & Sons Ltd.

Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B.M., Walker, M.J.C., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy. Quaternary Science Reviews 106, 14–28. https://doi.org/10.1016/j.quascirev.2014.09.007

Rasmussen, S.O., Vinther, B.M., Clausen, H.B., Andersen, K.K., 2007. Early Holocene climate oscillations recorded in three Greenland ice cores. *Quaternary Science Reviews* 26, 1907–1914. https://doi.org/10.1016/j.quascirev.2007.06.015

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0e 50,000 years cal BP. Radiocarbon 55(4), 1869-1887. https://doi.org/10.2458/azu_js_rc.55.16947

Remy, C. C., Fouquemberg, C., Asselin, H., Andrieux, B., Magnan, G., Brossier, B., Grontin, P., Bergeron, Y., Talon, B., Girrardin, M.P., Blarquez, O., Ali., A.A., 2018. Guidelines for the use and interpretation of palaeofire reconstructions based on various archives and proxies. *Quaternary Science Reviews*, *193*, 312-322. https://doi.org/10.1016/j.quascirev.2018.06.010

Rick, J.W., 1987. Dates as data: an examination of the Peruvian preceramic radiocarbon record. *American Antiquity* 52 (1): 55–73. https://doi.org/10.2307/281060

Rius, D., Vannière, B., Galop, D., Richard, H., 2011. Holocene fire regime changes from multiple-site sedimentary charcoal analyses in the Lourdes basin (Pyrenees, France). *Quaternary science reviews*, *30*(13-14), 1696-1709. https://doi.org/10.1016/j.quascirev.2011.03.014

Roberts, A. J., 1995. Digging and delving in the Diluvium: Past and present work in the caves of south Devon. *Torquay Natural History Society*, *150*, 47-65.

Roberts. A., 1992: Torbryan. British Museum Society Bulletin II, 19.

Robin, V., Knapp, H., Bork, H.R. and Nelle, O., 2013. Complementary use of pedoanthracology and peat macro-charcoal analysis for fire history assessment: illustration from Central Germany. Quaternary International, 289, 78-87. https://doi.org/10.1016/j.quaint.2012.03.031

Robinson E, Gelorini V, Van Strydonck M, Crombé, P., 2013. Radiocarbon chronology and the correlation of hunter-gatherer sociocultural change with abrupt palaeoclimate change: the Middle Mesolithic in the Rhine-Meuse-Scheldt area of northwest Europe. Journal of Archaeological Science 40, 755–763. https://doi.org/10.1016/j.jas.2012.08.018

Robinson, D.E., Dickson, J.H., 1988. Vegetational history and land use: a radiocarbon-dated pollen diagram from Machrie Moor, Arran, Scotland. New Phytologist 109, 223–251. https://doi.org/10.1111/j.1469-8137.1988.tb03711.x

Saville, A., 2004. The Material Culture of Mesolithic Scotland. In: Saville, A. (ed.), Mesolithic Scotland and its Neighbours. The Early Holocene Prehistory of Scotland, its British and Irish Context, and some Northern European Perspectives. Society of Antiquaries of Scotland, Edinburgh: p. 185-220.

Saville, A., 2008. The beginning of the Later Mesolithic in Scotland. In: Sulgostowska, Z., Tomaszekswi, A.J. (eds.), *Man-millennia-environment studies in honour of Romuald Schild*, Warsaw: Institute of Archaeology and Ethnology, Polish Academy of Sciences. 207-13.

Saville, A., Ballin, T.B., 2009. Upper Palaeolithic evidence from Kilmelfort Cave, Argyll: a re-evaluation of the lithic assemblage. Proceedings of the Society of Antiquaries of Scotland, Vol.139 pp.9-45.

Scott, A. C., 1989. Observations on the nature and origin of fusain. International Journal of Coal Geology, 12(1-4), 443-475. https://doi.org/10.1016/0166-5162(89)90061-X

Scott, A. C., Jones, T. P., 1994. The nature and influence of fire in Carboniferous ecosystems. Palaeogeography, Palaeoclimatology, Palaeoecology, 106(1-4), 91-112. https://doi.org/10.1016/0031-0182(94)90005-1

Scott, A.C., 2010. Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. Palaeogeography, Palaeoclimatology, Palaeoecology 291, 11–39. https://doi.org/10.1016/j.palaeo.2009.12.012

Scott, A.C., Hardiman, M., Pinter, N., Anderson, R.S., Daulton, T.L., Ejarque, A., Finch, P., Carter-champion, A., 2017. Interpreting palaeofire evidence from fluvial sediments: a case study from Santa Rosa Island, California, with implications for the Younger Dryas Impact Hypothesis. Journal of Quaternary Science 32, 35–47. https://doi.org/10.1002/jqs.2914

Simmons, I. G., 1996. The Environmental Impact of Later Mesolithic Cultures. Edinburgh: Edinburgh University Press.

Smith, A.G., 1970. The influence of Mesolithic and Neolithic man on British vegetation: a discussion. In: Walker, D., West, R.G. (Eds.), Studies in the Vegetational History of the British Isles. Cambridge University Press, Cambridge.

Smith, A.G., Cloutman, E.W., 1988. Reconstruction of Holocene vegetation history in three dimensions at Waun-Fingen-Felen, an upland site in South Wales. Philosophical Transactions of the Royal Society of London B: Biological Sciences 322, 159–219. **https://doi.org/10.1098/rstb.1988.0124**

Smith, I.R., Wilkinson, D.M., O'Regan, H.J., 2013. New Lateglacial fauna and early Mesolithic human remains from Northern England. Journal of Quaternary Science, 28(6), pp.542-544. **https://doi.org/10.1002/jqs.2655**

Tallantire, P. A., 1992. The alder [Alnus glutinosa (L.) Gaertn.] problem in the British Isles: a third approach to its palaeohistory. *New Phytologist*, *122*(4), 717-731. **https://doi.org/10.1111/j.1469-8137.1992.tb00101.x**

Tallavaaraa, M., Luoto, M., Korhonen, N., Järvinen, H., Seppä, H., 2005. Human population dynamics in Europe over the Last Glacial Maximum. PNAS 112(27), 8232-8237. https://doi.org/10.1073/pnas.1503784112

Tipping, R., 1995. Holocene landscape change at Carn Dubh, near Pitlochry, Perthshire, Scotland. Journal of Quaternary Science 10, 59–75. https://doi.org/10.1002/jqs.3390100107

Tipping, R. 1996. Microscopic charcoal records, inferred human activity and climate change in the mesolithic of northernmost Scotland. In Pollard, A. & Morrison, A. (eds) The Early Prehistory of Scotland. Edinburgh: Edinburgh University Press, 39-61.

Tipping, R. 2004. Interpretative issues concerning the driving forces of vegetation change in the early Holocene of the British Isles. In Saville, A. (ed) Mesolithic Scotland and its Neighbours: The Early Holocene Prehistory of Scotland, its British and Irish Context, and some Northern European Perspectives. Edinburgh: Society of Antiquaries of Scotland, 45-54.

Walker, M. J., Lowe, J. J., 1990. Reconstructing the environmental history of the last glacial-interglacial transition: evidence from the Isle of Skye, Inner Hebrides, Scotland. Quaternary Science Reviews, 9(1), 15-49. https://doi.org/10.1016/0277-3791(90)90003-S

Walker, M., Jones, S., Hussey, R., Buckley, S., 2006. Mesolithic burning in the uplands of Wales: evidence from Esgair Ffraith, near Lampeter, west Wales. Archaeology in Wales, 46, 3-10.

Walker, M., Lowe, J., 2017. Lateglacial environmental change in Scotland. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 1–26. https://doi.org/10.1017/S1755691017000184

Walker, M., Lowe, J., Blockley, S.P.E., Bryant, C., Coombes, P., Davies, S., Hardiman, M., Turney, C.S.M., Watson, J., 2012. Lateglacial and early Holocene palaeoenvironmental "events" in Sluggan Bog, Northern Ireland: Comparisons with the Greenland NGRIP GICC05 event stratigraphy. Quaternary Science Reviews 36, 124–138. https://doi.org/10.1016/j.quascirev.2011.09.008

Walker, M.J.C., Coope, G.R., Lowe, J.J., 1993. The Devensian (Weichselian) Lateglacial palaeoenvironmental record from Gransmoor, East Yorkshire, England: A contribution to the 'North Atlantic seaboard programme'of IGCP-253, 'Termination of the Pleistocene'. Quaternary Science Reviews, 12(8), pp.659-680. https://doi.org/10.1016/0277-3791(93)90006-8

Walker, M.J.C., Coope, G.R., Sheldrick, C., Turney, C.S.M., Lowe, J.J., Blockley, S.P.E. and Harkness, D.D., 2003. Devensian Lateglacial environmental changes in Britain: a multi-proxy environmental record from Llanilid, South Wales, UK. Quaternary Science Reviews, 22(5-7), pp.475-520. https://doi.org/10.1016/S0277-3791(02)00247-0

Ward, S. L., Neill, S. P., Scourse, J. D., Bradley, S. L., Uehara, K., 2016. Sensitivity of palaeotidal models of the northwest European shelf seas to glacial isostatic adjustment since the Last Glacial Maximum. Quaternary Science Reviews, 151, 198-211. https://doi.org/10.1016/j.quascirev.2016.08.034

Weninger, B., Edinborough, K., Bradtmöller, M., Collard, M., Crombé, P., Danzeglocke, U., Holst, D., Jöris, O., Niekus, M., Shennan, S., Schulting, R., 2009. A Radiocarbon Database for the Mesolithic and Early Neolithic in Northwest Europe. *Chronology and Evolution within the Mesolithic of North-West Europe: Proceedings of an International Meeting, Brussels, May 30th-June 1st 2007* (pp. 143–176). Presented at the Chronology and Evolution within the Mesolithic of North-West Europe, Newcastle: Cambridge Scholars Publishing.

Whitlock, C., Higuera, P.E., McWethy, D.B., Briles, C.E., 2010. Paleoecological Perspectives on Fire Ecology: Revisiting the Fire-Regime Concept. The Open Ecology Journal 3, 6–23. https://doi.org/10.2174/1874213001003020006

Whittington, G., Edwards, K.J., Zanchetta, G., Keen, D.H., Bunting, M.J., Fallick, A.E., Bryant, C.L., 2015. Lateglacial and early Holocene climates of the Atlantic margins of Europe: Stable isotope, mollusc and pollen records from Orkney, Scotland. *Quaternary Science* Reviews 122, 112–130. https://doi.org/10.1016/j.quascirev.2015.05.026

Woodman, P., 2015. Ireland's first settlers: time and the Mesolithic. Oxbow Books

Zale, R., Huang, Y. T., Bigler, C., Wood, J. R., Dalén, L., Wang, X. R., Segestrom, U., Klaminder, J. 2018. Growth of plants on the Late Weichselian ice-sheet during Greenland interstadial-1? *Quaternary Science Reviews*, *185*, 222-229. https://doi.org/10.1016/j.quascirev.2018.02.005

Zvelebil, M., 1994. Plant Use in the Mesolithic and its Role in the Transition to Farming. *Proceedings of the Prehistoric Society* 60, 35-74. https://doi.org/10.1017/S0079497X00003388

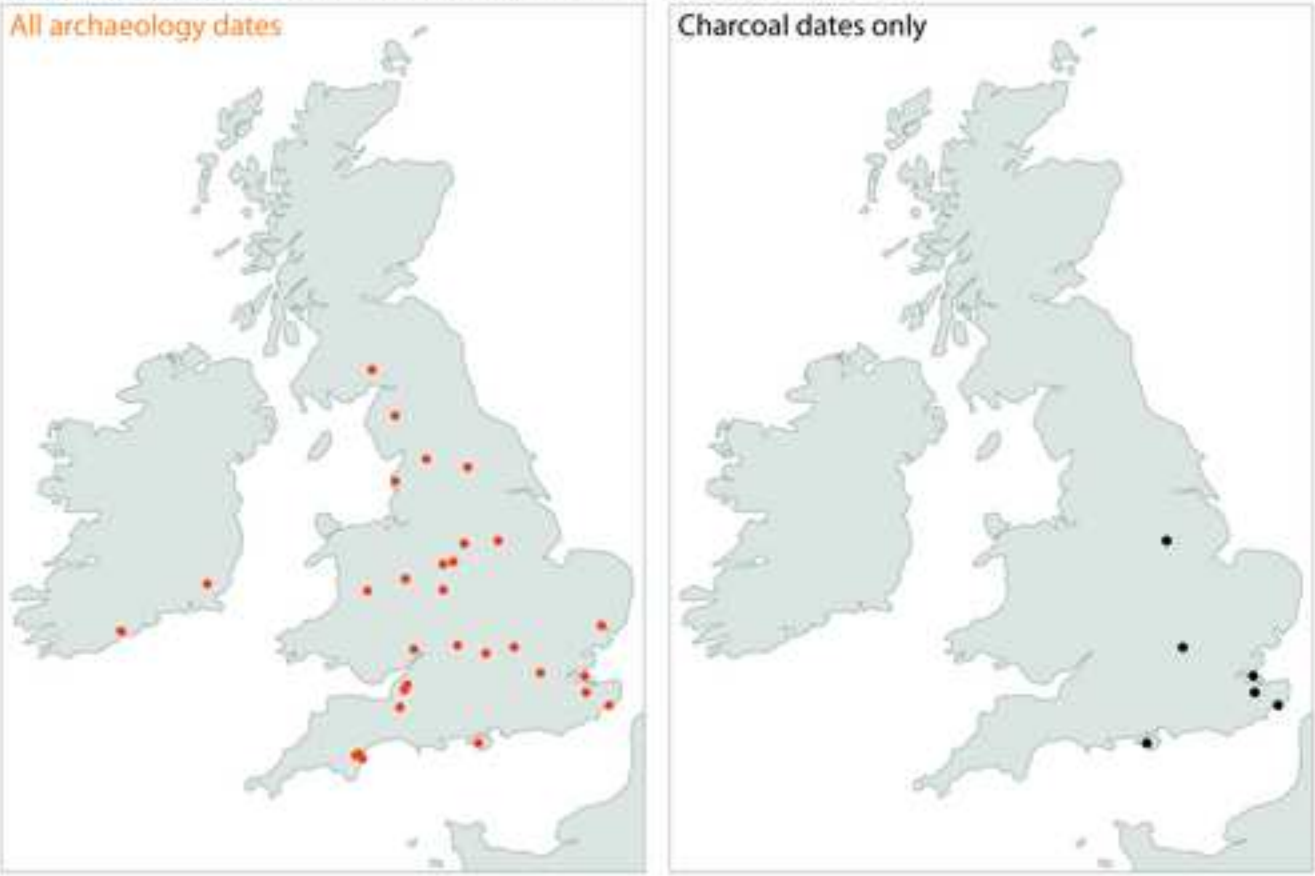
Table

Table 1: Regional correlatives of the GICC05 intervals in the UK, Ireland and Northern Europe. For the purposes of this review, and to aid simplicity, the UK terminology is coupled with the GICC05 derived ages, with certain caveats (see Lowe et al., 1995)

Age (cal ka BP)	GICC05 intervals	UK	Ireland	NW Europe
11.65-8.28	Early Holocene, ~ Greenlandian[1]			
12.85-11.65	Greenland Stadial-1 (GS-1) [2]	Loch Lomond Stadial	Nahanagan Stadial	Younger Dryas
14.65-12.85	Greenland Interstadial 1 (GI-1) [2]	Windermere Interstadial	Woodgrange Interstadial	Bølling–Allerød Interstadial
Pre-14.65	Greenland Stadial-2.1a (GS-2.1a) [2]	Dimlington Stadial	Glenavy Stadial	Pleniglacial/Oldest Dryas

[1] Cohen *et al.*, 2013; (updated); [2] Rasmussen *et al.*, 2014

14,650-12,500 cal years BP - data taken from D'Errico et al. (2011)



10,800-8,200 cal years BP - data taken from Bevan et al. (2017)