Proceedings of the Geologists' Association 135 (2024) 569–588

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

Lateglacial Interstadial to mid-Holocene stratigraphy and palynology at Pepper Arden Bottoms, North Yorkshire, UK

James B. Innes [a,*], Mairead M. Rutherford [a], David R. Bridgland [a], Ben R. Gearey [b], Malcolm C. Lillie [c], Wishart A. Mitchell [d], Charlotte E. O'Brien [e], Richard T. Jones [f,1], Gareth J. Thompson [f]

[a] Geography Department, Durham University, Durham DH1 3LE, UK
[b] Department of Archaeology, University College Cork, Cork City T12 CY82, Republic of Ireland
[c] Institute of Archaeology, National Academy of Sciences, Kyiv 04210, Ukraine
[d] Division of Geography, University of Dundee, Dundee DD1 4HN, UK
[e] Archaeological Services, Durham University, Durham DH1 3LE, UK
[f] Department of Geography, University of Exeter, Exeter EX4 4RJ, UK

ARTICLE INFO

Article history:
Received 29 April 2024
Received in revised form 1 August 2024
Accepted 21 August 2024
Available online 27 September 2024

Keywords:
Lateglacial
Early Holocene
Palynology
Lithostratigraphy
North Yorkshire

ABSTRACT

Investigations at Pepper Arden Bottoms, a lake basin site on the interfluve between the rivers Tees and Swale in northeast England, have recovered lithostratigraphical, pollen and plant macrofossil sequences which have allowed the reconstruction of sedimentary and vegetation history from the Lateglacial Interstadial to the post-*Ulmus* Decline mid-Holocene. Although the calcareous nature of the sediment and lack of terrestrial plant macrofossils precluded radiocarbon dating of sediments pre-dating the *Ulmus* Decline, pollen analyses showed sediment accumulation from the middle of the Lateglacial Interstadial, with the lake catchment remaining poorly vegetated until the Holocene, with low values for woody taxa, and grasses and sedges dominant. The late Interstadial cold phase GI-1b is present in the pollen stratigraphy, with a major reduction in *Betula* frequencies, replaced by *Juniperus*, and an increase in cold-tolerant herbs, mainly grasses and sedges. Microcharcoal frequencies are consistently substantial throughout the Lateglacial levels, probably indicating a natural fire regime, but are absent from the Holocene, suggesting little Mesolithic or Neolithic activity nearby, which is confirmed by a lack of pollen indicators of disturbance. The Lateglacial (Loch Lomond) Stadial is entirely dominated by Cyperaceae and Poaceae pollen, with very few trees and shrubs. The successive migration of postglacial thermophilous trees is recorded in the Holocene and possible effects of the Preboreal Oscillation and the 8.2 ka BP cold events are recognised. An *Ulmus* Decline occurs near the top of the profile, after which the assemblage is dominated by *Alnus* as the lake became terrestrialised and was occupied by fen and then alder carr. The very open Lateglacial vegetation adds this site to a northern group in northeast England with poor Lateglacial woodland development, in contrast to sites to the south, in North Yorkshire, where Lateglacial *Betula* woodland was much better established.

1. Introduction

Environmental changes after the MIS-2 (Devensian) deglaciation in lowland northeast England between *c.* 15,500 and 11,700 cal. BP are now broadly understood, as there are several published sites across the region (Fig. 1) that preserve Lateglacial palaeoenvironmental records (Innes, 1999, 2002), particularly regarding vegetation history and depositional environments, some of which have good radiocarbon control. Pollen data provide extra-local to sub-regional vegetational histories which, when combined, allow a reconstruction of the patterns and timings of vegetation change across the region as a whole. Previous palynological research in northern England (*e.g.*, Jones et al., 2002; Matthews et al., 2017; Abrook et al., 2020) has demonstrated that vegetation changes during the Lateglacial and early Holocene were similar in character from site to site during this environmentally transitional period. These changes highlight vegetation response to several climatic fluctuations, events that are recorded as excursions in the Greenland ice-core data (Björck et al., 1998; Rasmussen et al., 2006) and are described here using GRIP chronological terminology (Lowe et al., 2008; Walker et al., 2012). Some of the cold events were relatively short-term, perhaps lasting only a century or two, such as GI-1d which lasted only 120 ice-core years (Björck et al., 1998), but were of high amplitude (Mayle et al., 1999) and elicited rapid biological responses (Birks and Birks, 2000, 2008).

* Corresponding author.
E-mail address: j.b.innes@durham.ac.uk (J.B. Innes).
[1] Deceased.

https://doi.org/10.1016/j.pgeola.2024.08.005

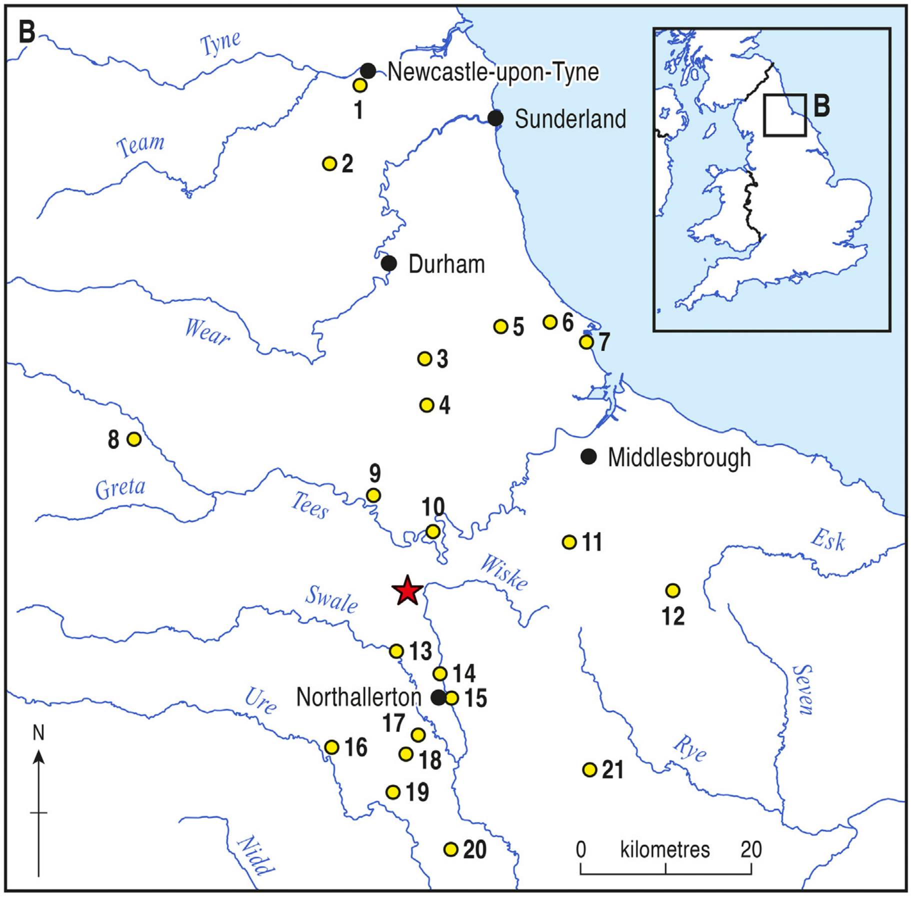

Fig. 1. Location map of Pepper Arden Bottoms (PAB), North Yorkshire, shown by the star, and of other comparable palaeoecological sites in North Yorkshire and south Durham, northeast England. Previous pollen diagrams are numbered as follows: 1. Shibdon Pond (Passmore et al., 1992), 2. Cranberry Bog (Turner and Kershaw, 1973), 3. Bishop Middleham (Bartley et al., 1976), 4. Mordon Carr (Bartley et al., 1976), 5. Hutton Henry (Bartley et al., 1976), 6. Thorpe Bulmer (Bartley et al., 1976), 7. Hartlepool (Innes et al., 2005), 8. Romaldkirk (Bellamy et al., 1966), 9. Burtree Lane (Bellamy et al., 1966), 10. Neasham Fen (Blackburn, 1952; Bartley et al., 1976), 11. Seamer Carrs (Jones, 1976), 12. Kildale Hall (Jones, 1977), 13. Killerby Quarry (Hudson et al., 2023), 14. Newby Wiske (Bridgland et al., 2011), 15. Turker Beck (Young et al., 2021), 16. Marfield (Bridgland et al., 2011), 17. Bedale Beck (Gearey and Allison, 2010), 18. Snape Mires (Bridgland et al., 2011), 19. Nosterfield (Bridgland et al., 2011), 20. Dishforth Bog (Giles, 1992), 21. Gormire Lake (Blackham et al., 1981).

Temperatures rose sharply around *ca.* 15,000 cal. BP (Lowe et al., 1994, 1999; Walker et al., 1994; Walker, 1995; Blockley et al., 2004) at the start of the Lateglacial (Windermere) Interstadial, and this major temperature rise with associated vegetation change has been recorded in the study area, where it is dated as around 15 ka cal. BP in the Tees Valley at Seamer Carrs (Jones, 1976). This date agrees well with other radiocarbon ages from the region for this major climate amelioration, as at The Bog, Roos in east Yorkshire (Beckett, 1981) and at Wykeham Quarry in the Vale of Pickering (Lincoln et al., 2017c, 2020), where the main temperature rise occurs slightly later. This is rather earlier than the age for this change derived from the Greenland ice-cores of about 14.8 ka BP, a difference probably attributable to the latitudinal difference between the two areas, with amelioration occurring later in the much more northerly location. This Interstadial warm period lasted for almost 2000 years, albeit with abrupt changes to short-lived cooler phases within it (Brooks and Birks, 2000; Yu and Eicher, 2001; Rasmussen et al., 2014). These included two quite severe cold and arid events (Lincoln et al., 2020), the effects of which have been recognised in pollen diagrams in the north of England (Levesque et al., 1993), including at Snape Mires (Innes et al., 2009) in the Vale of Mowbray, North Yorkshire (Fig. 1). These cold phases aside, this Interstadial climatic amelioration allowed the immigration and development of tall shrub and then tree taxa, with the latter shading out and replacing the shrub communities as succession progressed and woodland developed. This vegetation change after deglaciation is clearly expressed in the responses of the rapidly changing, successional vegetation communities (Prentice, 1986) that characterised the end of the MIS-2 Devensian Stadial (GS-2) and then the subsequent Lateglacial (Andrieu et al., 1993; Ammann et al., 2013; Paus et al. 2023). These are initially characterised by tundra then open-ground, tall-herb communities with *Rumex* and *Artemisia* succeeded by stable grassland on developing soils and subsequently the localised establishment of low-heath and shrub taxa like *Empetrum* and *Juniperus*, which was then followed by a progression to *Betula* woodland of varying density.

The increasing availability of pollen records as the Interstadial continued, and as more of the drainage channels and kettle-hole basins in the glacigenic sediment plain of lowland northeast England began to accumulate, indicates considerable sub-regional variability in vegetation evolution in the regional lowlands, particularly in the Interstadial, albeit with a similarity in trajectory. Although the composition of some of the variation can be attributed to local soil or geological factors, the major controlling influence appears to have been latitude.

This latitudinal influence on vegetation development is perhaps not surprising and occurred in northern Europe in the Lateglacial, as well as in the subsequent early Holocene (Feurdean et al., 2013; Giesecke et al., 2017), after the cold interlude of the Loch Lomond Stadial/Younger Dryas (GS-1). Whilst the early Holocene (Greenlandian *sensu* Walker et al., 2009, 2012, 2018) progression towards woodland was relatively rapid, it was slower and less complete in the early Lateglacial (Hoek, 2001) as vegetation succession occurred across newly available terrain, probably hindered by restrictive climatic (Coope et al., 1998) and soil (Pennington, 1986) tolerances rather than by lags in speed of immigration (Silvertown, 1985).

In the Lateglacial the immigration of successional tall-shrub and tree taxa from refugia to the south (Tzedakis et al., 2013) should have been relatively rapid, the region not lying far from the Devensian ice limit in eastern England (Wilson et al., 2002; Evans et al., 2005), but it appears that there was a latitudinal time lag as these taxa advanced northwards and became established. It is logical that tall-shrub vegetation with *Juniperus* and then tree *Betula* woodland would have been established earliest in North Yorkshire, the more southerly part of the region, before spreading to the north of the Tees valley, a natural geographical boundary. Previous palynological research, however, indicates that this south–north gradient in vegetation development persisted throughout the Lateglacial Interstadial, extending even into the period of most extensive woodland cover towards its end (Innes et al., 2009).

The progression to *Betula*-dominated woodland seems to have been slower to occur and much less complete in more northerly areas, for example at sites in the northern Vale of Mowbray and especially into County Durham, such as at Thorpe Bulmer (Bartley et al., 1976). In contrast, pollen records from sites further south in the Vale of York, such as Tadcaster (Bartley, 1962), indicate the earlier and eventually full establishment of *Betula* woodland cover, certainly in the later stages of the Interstadial and probably earlier. More records are needed to confirm this vegetation gradient in the transitional area of the Vale of Mowbray, particularly at its northern edge where the River Tees might be expected to have formed a natural obstacle to woodland expansion and at least delayed the northerly spread of full Interstadial tree cover. In this paper we present pollen data from a site at the northern limit of the Vale of Mowbray, on the interfluve at the southern edge of the Tees Valley, and assess the place of this liminal location within the Interstadial gradient of woodland development in lowland northeast England.

2. The study area and site

The study area is the watershed (interfluve) between the River Swale and its tributary the Wiske in the North Yorkshire Vale of Mowbray and the River Tees valley to its north, with its very short tributaries that flow north from the watershed, such as the Dalton Beck (Fig. 2). This interfluve is very important in the drainage of this part of northeast England as it separates the catchments of two major river systems that drain the eastern Pennines. To the south is the Yorkshire Ouse system, with the Swale as its northernmost affluent, collectively draining the Yorkshire Dales *via* the Vale of York, westwards of the North York Moors, and running into the Humber. To the north the Tees system drains the northern Pennines directly eastwards into the North Sea (Fig. 1). Despite its importance, the Tees–Swale interfluve is a relatively recent landscape feature, formed mainly from relatively low-lying glacial morainic deposits emplaced at the southern limit of an ice lobe that occupied the Tees valley during Late Devensian ice retreat from the Vales of York and Mowbray (Mitchell et al., 2010), areas that were ice-covered during the glacial maximum but deglaciated between *c.* 18 ka and 17 ka BP (Clark et al., 2012; Davies et al., 2019). This morainic ridge is termed the Great Smeaton Moraine (Fig. 2).

It is probable that the Swale and the Tees rivers, which are now well incised into glacial deposits (Bridgland et al., 2010), had a different relationship before the Devensian glaciation, with the former perhaps joining the Tees (Mitchell et al., 2010). The pre-glacial river Wiske also could have flowed into the Tees before its diversion south to the Swale, as there is a northward-deepening buried valley beneath the current Wiske that links to the Tees north of Great Smeaton (Frost, 1998). The surface of the moraine complex itself is well dissected and

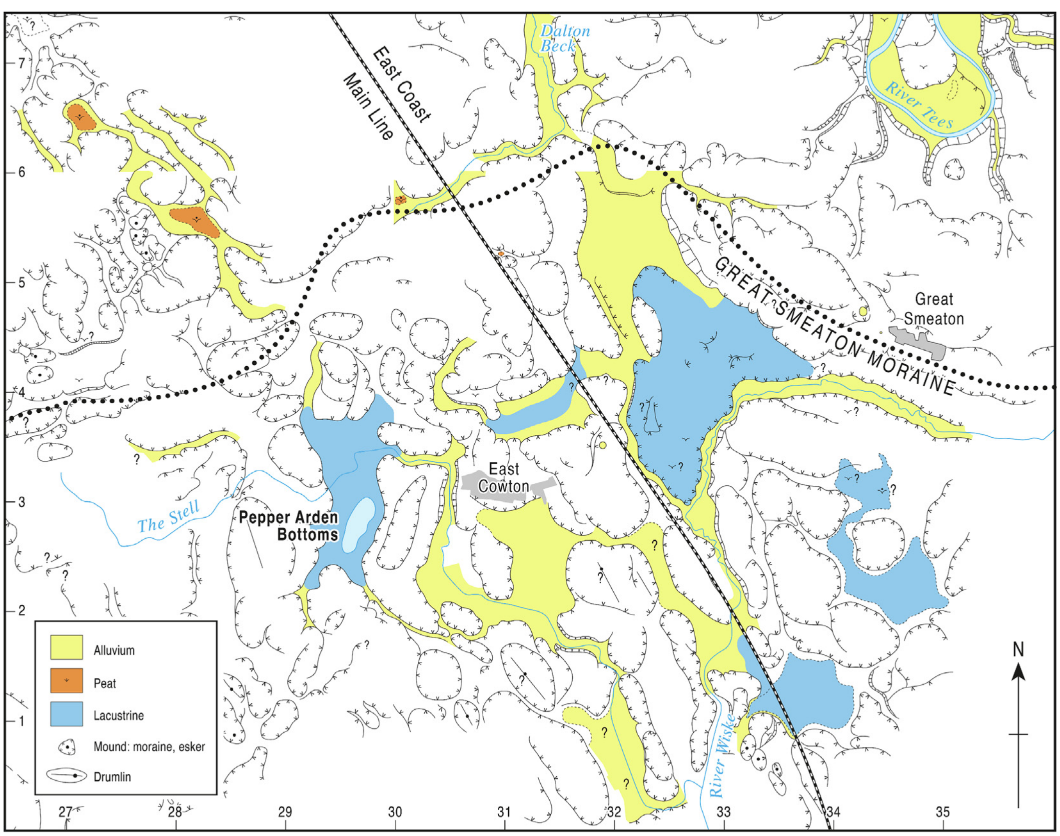

Fig. 2. Geomorphological map of the PAB area (after Mitchell et al., 2010). Geological information has been added from BGS DiGMap and has been verified by fieldwork. The interfluve between the Tees and its tributary, the Dalton Beck, and the Wiske and its tributary, the Stell, is shown by the dotted line. The current PAB lake is shown in light blue within the larger area of dark blue lacustrine sediments which defines the area of the palaeolake.

comprises mounds and ridges that have channels and basins between them, many of which having contained lakes, that have accumulated sediment, as in other regional moraine complexes (*e.g.*, Keen et al., 1984; Hudson et al., 2023).

Whereas Lateglacial palaeoenvironmental studies have been conducted directly to the north and south of this interfluve (Fig. 1), such as at Neasham Fen (Blackburn, 1952; Bartley et al., 1976) and Burtree Lane (Bellamy et al., 1966) in the Tees valley and at Killerby Quarry (Hudson et al., 2023) in the Swale valley, the Late Quaternary environmental history of the interfluve area itself remains virtually unknown and requires research. In this respect, the focus of the current study, the site of Pepper Arden Bottoms (PAB) is one of the several depressions on the Tees–Swale interfluve that, until their modern drainage, all contained water bodies (Fig. 3c) that were gradually filling with sediment and becoming terrestrialised through hydroseral succession. PAB has been partly reflooded recently and now contains shallow open water (Fig. 3a), although representing a much smaller area than its former extent, and surrounded by basin peat deposits (Fig. 3b). Other palaeolakes are now represented by lacustrine sediments (Fig. 2) overlain by drained peatland. The headwaters of the River Wiske rise to east and west of this ancient lake district and flow through it (Fig. 2); the Wiske itself flows south to join the Swale and, like all the rivers flowing from the Yorkshire Dales, forms part of the Ouse–Humber system. PAB was chosen as the research site to investigate the palaeoenvironmental history of the Tees–Swale interfluve.

3. Materials and methods

The nature of the PAB basin has been determined by Lillie and Gearey (1999), who took several cores across the site (Fig. 3) and showed it to be deepest in the middle, and so the new core for analysis was located in the centre of the current lake basin. Its lithology can be compared to their core records, which are shown in Supplementary file S1. Conforming with the recommendations of Birks and Birks

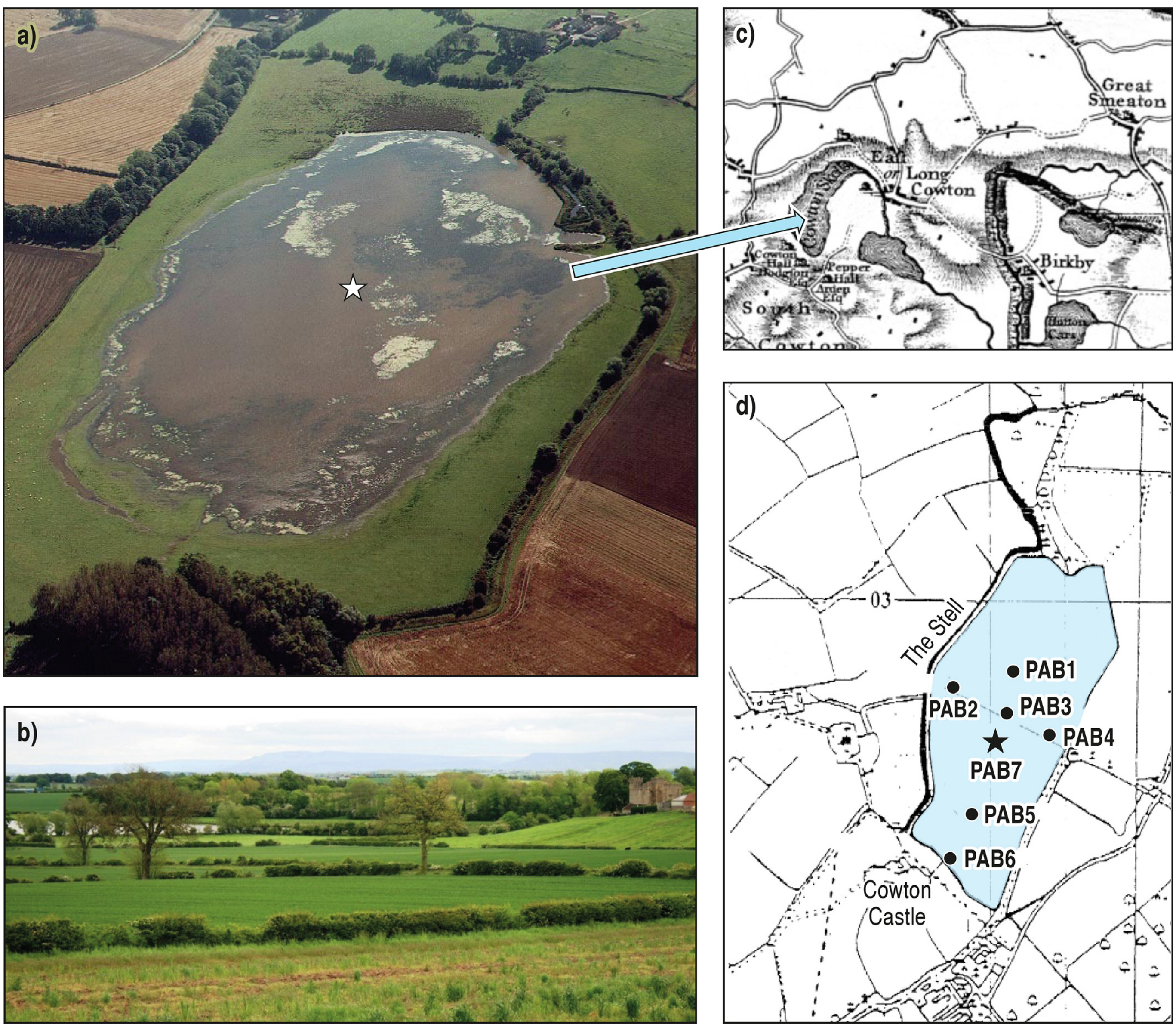

Fig. 3. (a) Aerial photograph of the current shallow lake at Pepper Arden Bottoms, which occupies the southern part of the main sediment-filled depression, which is shown on Fig. 2. The palynological core was recovered from the centre of the current lake, marked by the star (b), the flat, drained lake bed adjacent to the current lake, and the hillslope which marks the boundary of the palaeolake, (c) the 17th century Jeffrey's map which shows the presence of a lake at PAB, plus other small lakes in this area, before their drainage for farming. (d) The stratigraphical cores of Lillie and Gearey (1999) (PAB1–6) are shown by black dots and their stratigraphical records are listed in Supplementary file S1. The new palynological core site (NZ29600260) is termed PAB7 and is shown by a star. Its stratigraphical record is shown in Table 1.

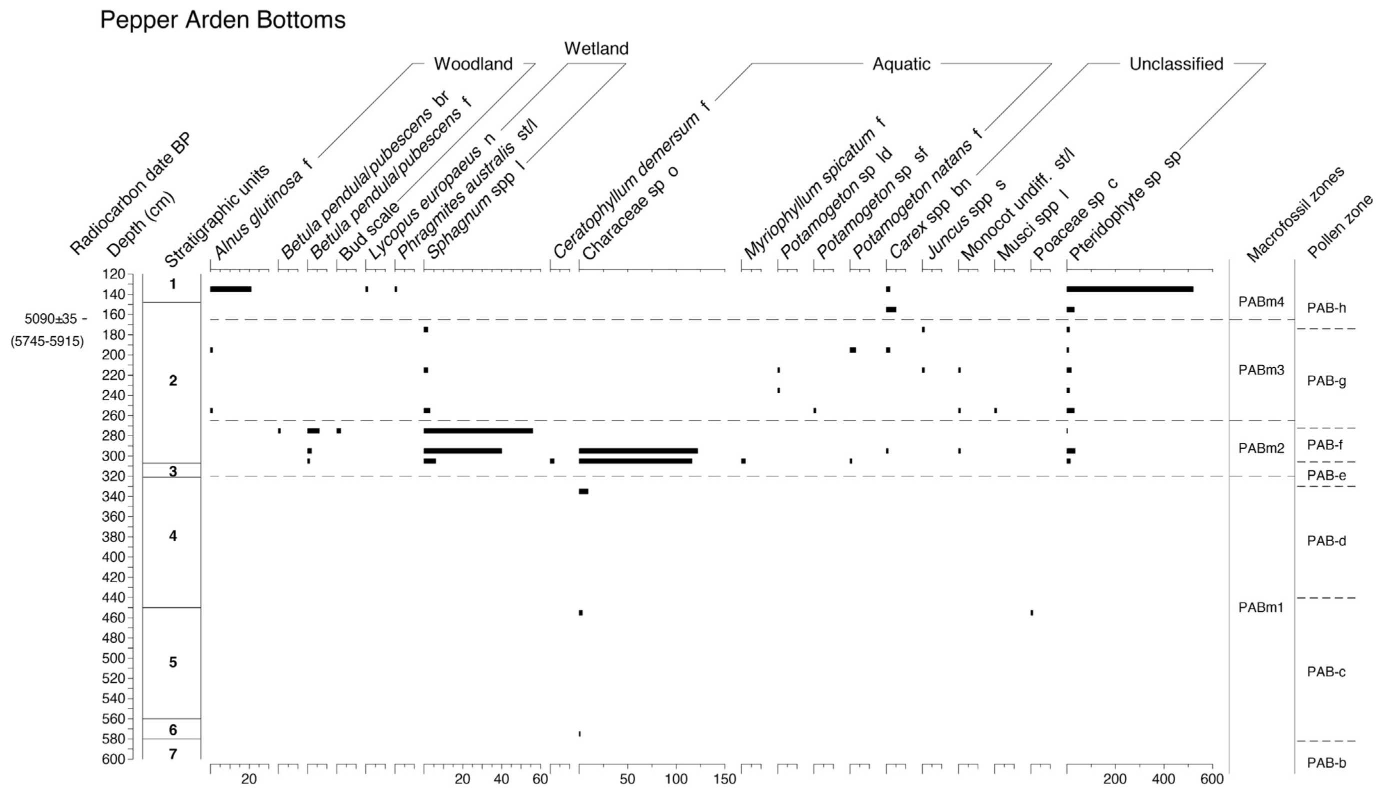

Fig. 4. Raw counts of plant macrofossils at PAB. bn: biconvex nutlet, br: bract, c: caryopsis, f: fruit, l: leaf, ld: lid, n: nutlet, o: oosporangium, s: seed, sf: small fruit, sp: sporangium, and st/l: stems/leaves. Pollen assemblage zones from Figures 4 and 5 are shown for reference. See Table 1 for description of the stratigraphical units.

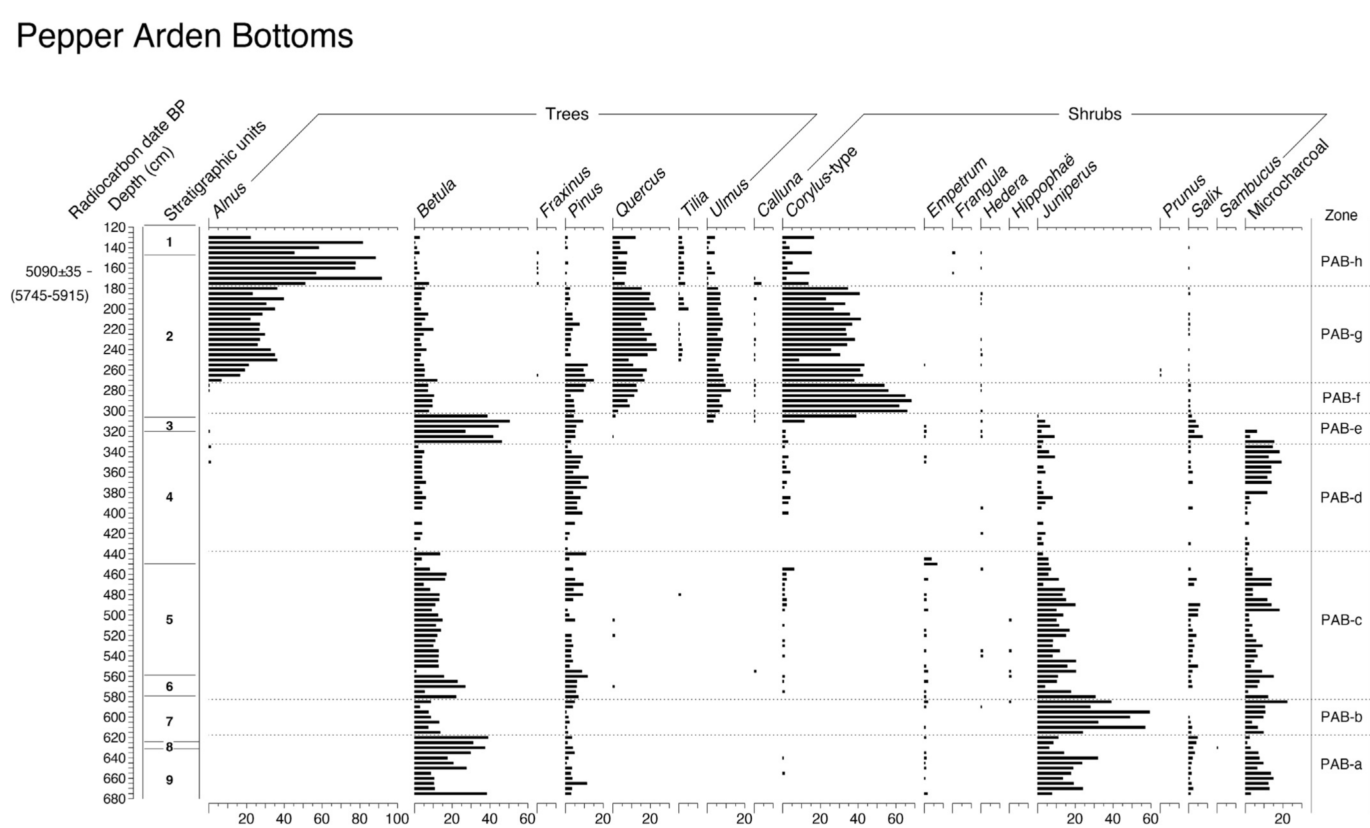

Fig. 5. Tree, shrub and microcharcoal diagram, frequencies calculated as percentages of total land pollen. The radiocarbon date and its calibrated range (Reimer et al., 2020) are shown. See Table 1 for description of the stratigraphical units.

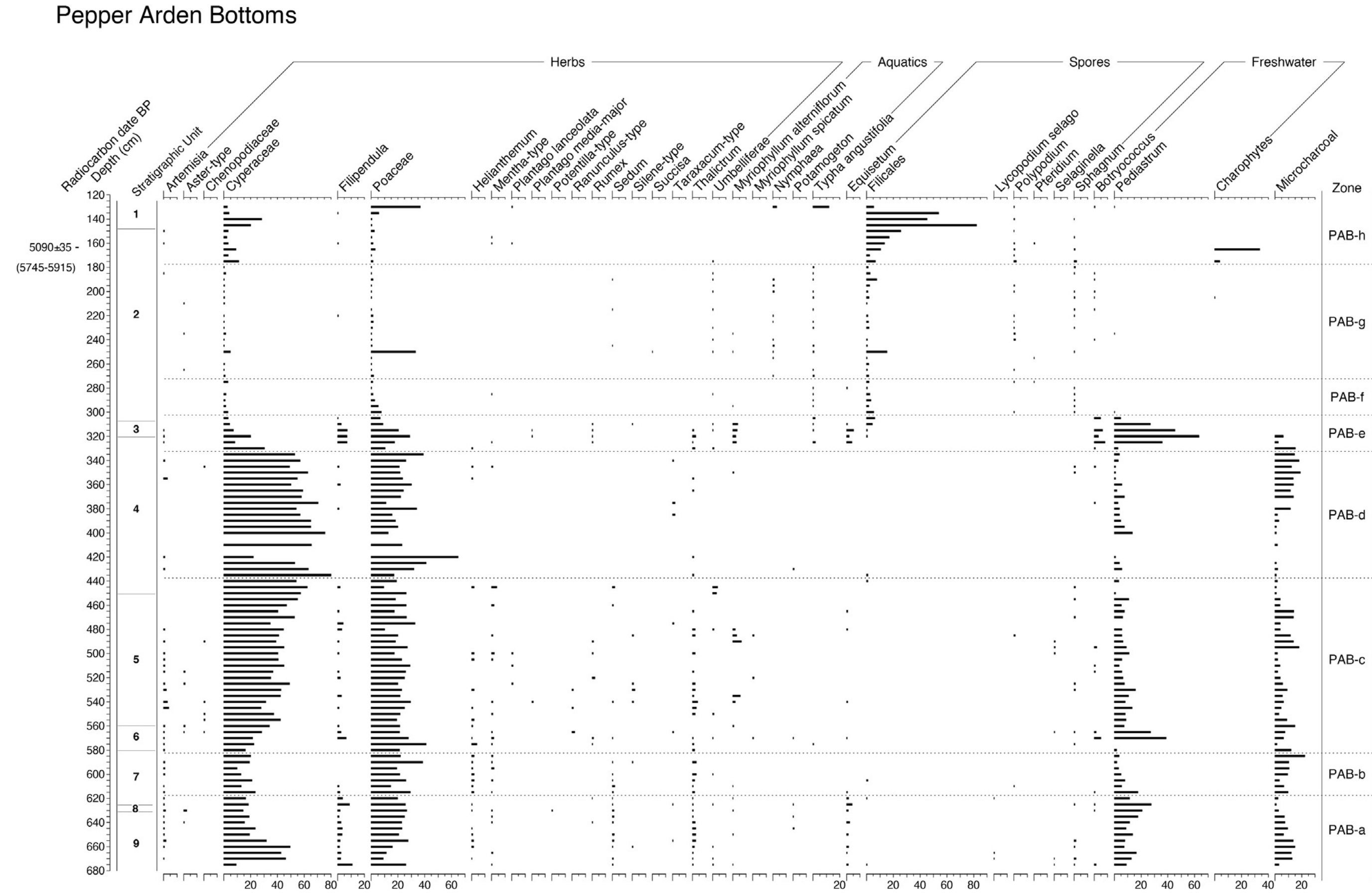

Fig. 6. Herb, aquatic, spore and microcharcoal diagram, frequencies calculated as percentages of total land pollen. The radiocarbon date and its calibrated range (Reimer et al., 2020) are shown. See Table 1 for description of the stratigraphical units.

(2000), macrofossil analyses were made at 20 cm intervals, closing to 10 cm near the base of the organic sequence. 20 ml sub-samples of sediment were disaggregated in warm water and washed through a nest of sieves ranging from 150 to 500 μm size. The residues were scanned for plant macrofossils using a Leica MZ6 stereomicroscope and identification was aided by modern reference collections and the seed atlases of Cappers et al. (2006), Beijerinck (1947) and Katz et al. (1965). Plant macrofossils are presented as raw counts of whole/part individuals (Fig. 4). Macrofossil taxonomic nomenclature follows Stace (1997).

Sub-samples of 0.5 cm^3 volume were taken for pollen analysis every 5 cm throughout the lower part of the new core, stopping when the organic sediments of the upper core became oxidised and pollen was not preserved. Samples were prepared for palynological analysis using standard laboratory techniques, with alkali digestion, sieving at 180 μm, hydrofluoric acid and acetolysis (Moore et al., 1991). Pollen percentage results are shown in Figures 5 and 6. Following Stockmarr (1971) tablets of exotic *Lycopodium* marker spores were added during preparation to enable calculation of pollen concentrations, which are shown for major taxa in Figure 7. Concentrations for total land pollen are shown in Figure 8. The concentration data for these curves are listed in Supplementary file S2. Pollen residues were stained with safranin, mounted on microscope slides in silicone oil and counted at ×400 magnification on a Zeiss 'Standard WL' microscope. Counts were at least 300 land pollen grains except at several levels in the Loch Lomond Stadial phase where very low pollen concentrations restricted counts to 100, which was always achieved after extended counting. Pollen identification and nomenclature follow Moore et al. (1991). Pollen frequencies are shown as percentages of the total land pollen sum, which excludes aquatics and spores although these are shown on the diagrams, also calculated as percentages of the land pollen sum. All microfossil diagrams were constructed using the TILIA program of Grimm (1993, 2004).

Microcharcoal particles were counted as a pollen/charcoal ratio (Robinson, 1984), with microcharcoal calculated as a percentage of the pollen sum. Particles that passed through the 180 μm pollen preparation sieve were recorded relative to the pollen count, with those around 30 μm in diameter being comparable to the average size of pollen grains. This size was regarded as the basic measurement unit and microcharcoal particles were counted relative to this basic 30 μm unit, a method employed in previous papers (*e.g.*, Innes and Simmons, 2000). For example, a microcharcoal fragment 90 μm in size would therefore be counted as three units and equivalent to three pollen grains. Microcharcoal counts comprise multiples of that basic unit and, as it corresponds to the size of marker *Lycopodium* spores, microcharcoal concentrations have also been calculated and these are shown in Figure 8 and listed in Supplementary file S2. Fragments smaller than 30 μm were estimated in size and aggregated to produce countable data. Size class data are not presented, as fragments might well have been broken up during the laboratory preparation process (Clark, 1984), a process not affecting the total count but which makes interpretation of microcharcoal taphonomy much more difficult.

The protocol for radiocarbon dating in such highly calcareous sediment (Marshall et al., 2011) was to date only terrestrial macrofossils, to avoid hardwater error that must have affected the extremely early date for the start of the Lateglacial on basal mosses at nearby Kildale (Keen et al., 1984) or very early dates from Crudale Meadow in Orkney (Whittington et al., 2015), for example. Very few such dateable macrofossils were encountered at PAB, and so only one radiocarbon date is

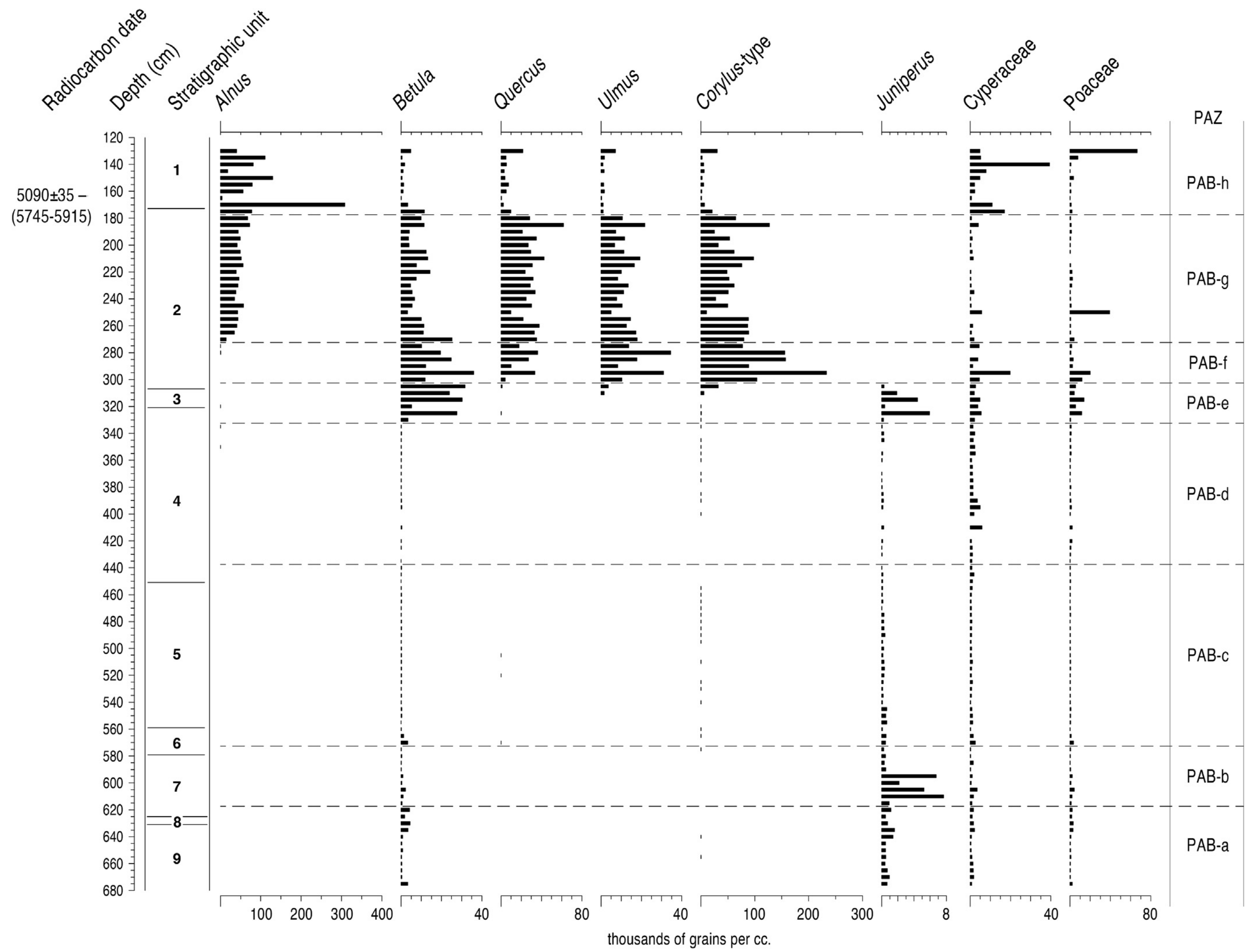

Fig. 7. Pollen concentration data per cm^3 of wet sediment for the major pollen taxa at PAB. Note the considerable changes in scale between the curves. A summary total land pollen concentration curve is shown in Figure 8.

available, from a point several cm above the *Ulmus* pollen decline. This date, from the Scottish Universities Environmental Research Centre Radiocarbon Lab, has been calibrated using OxCal4.4 and IntCal20 (Reimer et al., 2020) and the calibrated age range is shown on the microfossil diagrams. Attempts at dating macrofossils from lower in the core failed. As at other Lateglacial sites with highly calcareous soils and sediments (*e.g.*, Webb and Moore, 1982), radiocarbon ages are lacking at PAB but for the rest of the core, ages can be securely inferred from other nearby dated sites in North Yorkshire (*e.g.*, Lincoln et al., 2020) and from the established event chronology for the British Lateglacial (Lowe et al., 1999; Mayle et al., 1999; Whittington et al., 2015; Walker and Lowe, 2019).

4. Results and interpretation

4.1. Lithostratigraphy

Evidence from the cores (Fig. 3 and Supplementary file S1) of Lillie and Gearey (1999) and the new core (PAB7, Table 1) that was taken for this study from the centre of the current shallow lake allows a reconstruction of the southerly part of the original PAB lake basin and its sedimentary history. Cores PAB2 and PAB4 are shallow, at 380 and 250 cm depths respectively, before ending in stiff clay with sand and gravel that will represent the surface of glacial till, which crops out at several places in the surrounding area (Mitchell et al., 2010). The locations of these cores must be close to the edges of the lake basin as the other cores have much greater depth, at around 7 m, with records of other sediment types resting upon the till surface. That the thickest sequence above till coincides with PAB1 suggests that the basin is elongate in shape, with its deepest part to the northeast of the current investigation, perhaps beyond the boundary of the current waterbody and under the area of terrestrial peat. The sediments above the till are all lacustrine, and sometimes laminated, but they vary in nature, generally being clastic but with some organic content and containing detrital organic material such as wood pieces or mollusc shells, with these being intercalated with fully clastic silt and clay layers. Except for PAB5 and PAB6 from the southwestern end of the site, the cores are alike in containing a blue–grey alluvial silt in mid-profile. This unit probably represents a flood horizon and inwash of fine-grained mineral material from the surrounding slopes. Destabilisation of adjacent slopes could have resulted from climate events with heavy rainfall but could also represent colluvial material (slopewash) eroded into the wetland after human activity and vegetation disturbance. In Table 1 the stratigraphical position of this silt (unit 3) indicates an early Holocene age, so any human impact would have been caused by Early Mesolithic hunter–gatherers. Present in mid-profile in most cores, this blue–grey unit might well represent a time-equivalence horizon, but this is conjectural. The development of

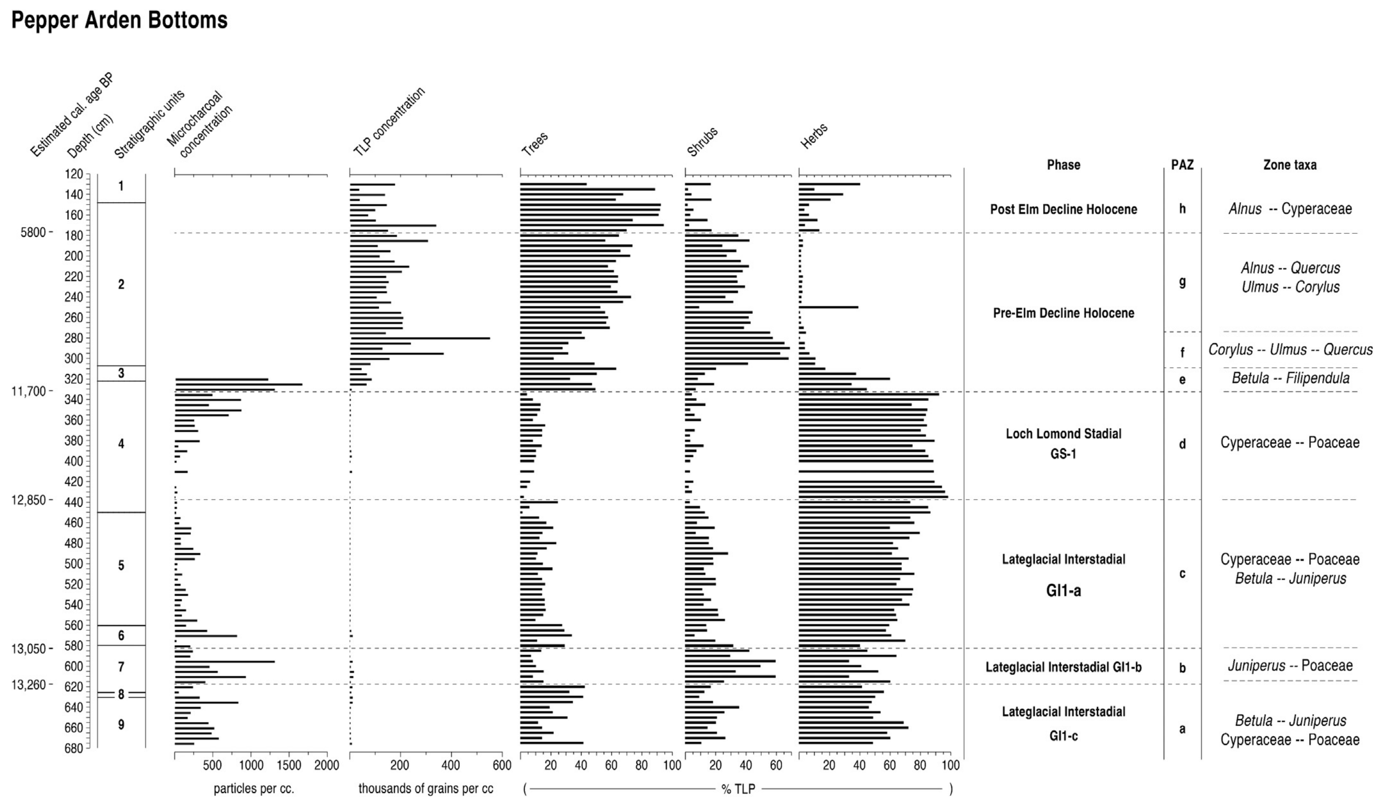

Fig. 8. Life-form summary diagram (total trees, shrubs and herbs) from PAB calculated as percentages of total land pollen. Concentration curves for total land pollen and microcharcoal per cm^3 of wet sediment are also shown, note the differences in the scales for the two concentration curves. Phase labels follow the terminology of the Greenland Ice-Core Record (Lowe et al., 1994; Björck et al., 1998), and phase boundaries have calibrated dates BP (pre-1950) derived from Whittington et al. (2015). Pollen zones and their component taxa are also shown, derived from Figures 5 and 6. See Table 1 for description of the stratigraphical units.

peats and other mainly organic sediments higher in the profile indicates a more biologically productive environment during the Holocene and the eventual colonisation of the coring site by aquatic wetland plants and then more terrestrial plant cover as the basin continued to be infilled with sediment.

Table 1
Lithostratigraphy at Pepper Arden Bottoms palynology core (PAB7, Fig. 3d).

Depth (cm)	Unit	Description
0–120	0	Water
120–148	1	Stiff grey alluvial clays, oxidised with rusty mottles forming a distinct boundary with unit 2.
148–307	2	Humified peat, dark brown at the top and becoming lighter towards the base of the unit. Small wood fragments between 300 and 305 cm. Sediment forms a diffuse boundary to unit 3.
307–321	3	Blue–grey organic silts with *Phragmites* remains. Darker well-humified organic material towards the base of the unit. A clear boundary to unit 4.
321–450	4	Orange–brown, saturated fine clay. Very small herbaceous detritus fragments between 321 and 345 cm, and 413 and 417 cm. Faint fine laminae <1 mm. Diffuse boundary to unit 5.
450–560	5	Stiff, red–brown clay–silts. Thin yellow–green layer at 514 cm. Clearer, dark and light laminae present. Diffuse boundary to unit 6.
560–580	6	Grey–brown organic silts with very faint laminae. Diffuse boundary to unit 7.
580–626	7	Stiff red–brown clay–silts with clear laminae. Diffuse boundary to unit 8.
626–631	8	Grey–brown organic silts with very faint laminae. Diffuse boundary to unit 9.
631–700	9	Silty sands becoming increasingly silty towards the base. Orange–red laminae present. Very small sedge fragments and occasional twigs present, too small to identify.

4.2. Macrofossil analyses

Plant macrofossils are low in number and diversity throughout the core. This may in part be due to the small sample size resulting from the narrow diameter of the core, although it is also likely to reflect

Table 2
Macrofossil assemblage zone (MAZ) descriptions from Pepper Arden Bottoms (Fig. 4).

Depth (cm)	MAZ	Major taxa
580–320	PABm1	Characeae spp.
Plant macrofossils consisted of low numbers of oosporangia of Characeae spp. (Stoneworts) and a Poaceae sp. caryopsis. Bryozoan statoblasts, ostracods and chironomids were also recorded, particularly at the start of the zone.		
320–265	PABm2	Characeae–*Sphagnum*
The number and diversity of plant remains increase, with remains of Characeae spp. and *Sphagnum* spp. being the most abundant taxa. Other aquatic taxa were *Ceratophyllum demersum* (rigid hornwort), *Myriophyllum spicatum* (spiked water-milfoil) and *Potamogeton natans* (broad-leaved pondweed). Arboreal remains consisted of bud scales and *Betula pendula*/*pubescens* (silver/downy birch) fruit and bracts. *Carex* spp. (sedges) nutlets, monocot stems and Pteridophyta (fern) sporangia were present in this zone. Ephippia (resting bodies) of Cladocera and Bryozoan statoblasts were also recorded.		
265–165	PABm3	*Potamogeton*–*Sphagnum*–Pteridophyta
Very few plant macrofossils were present, and consisted of a few remains of *Alnus glutinosa* (alder), *Sphagnum* spp., *Potamogeton* spp., *Carex* spp., *Juncus* spp. (rushes), monocots undiff., Musci spp. (mosses) and Pteridophyta. Cladocera ephippia were also present.		
165–130	PABm4	*Alnus*–*Carex*–Pteridophyta
A restricted assemblage, dominated by wood fragments. An *Alnus glutinosa* fruit was present and Pteridophyta sporangia, with a few remains of *Lycopus europaeus* (gipsywort), *Phragmites australis* (common reed) and *Carex* spp. Cladocera were also recorded.		

Table 3
Pollen assemblage zone (PAZ) descriptions from Pepper Arden Bottoms (Figs. 5 to 7).

Depth (cm)	PAZ	Major taxa
675–617.5	PAB-a	*Betula*–*Juniperus*
Characterised by *Betula* and *Juniperus*, with some *Empetrum* and *Salix*. Cyperaceae and Poaceae are moderate and *Filipendula* is important. *Helianthemum* and *Thalictrum* are consistently present in low frequencies. *Equisetum* and *Pediastrum* algae are common. Microcharcoal is present in high values.		
617.5–582.5	PAB-b	*Juniperus*–Poaceae
Characterised by *Juniperus*, with Poaceae and lesser frequencies of *Betula* and Cyperaceae. *Salix* declines sharply. *Filipendula* is almost absent but *Helianthemum* increases. *Thalictrum* and microcharcoal remain important, the latter fluctuating but showing peaks in frequency.		
582.5–437.5	PAB-c	Cyperaceae–Poaceae–*Juniperus*–*Betula*
Characterised by Cyperaceae and Poaceae and frequencies for *Juniperus* fall sharply. *Betula* and *Salix* increase slightly. *Helianthemum*, *Thalictrum* and *Artemisia* are present sporadically. *Pediastrum* is significant and peaks of *Myriophyllum alterniflorum* occur. Microcharcoal is consistently present and achieves peak values later in the zone.		
437.5–332.5	PAB-d	Cyperaceae–Poaceae
Characterised by Cyperaceae and Poaceae. *Betula* and *Juniperus* fall to low values, whilst *Pinus* is slightly increased. All other taxa are only sporadically present. *Pediastrum* occurs in low frequencies, whilst microcharcoal is very low until rising to high frequencies in the second half of the zone.		
332.5–302.5	PAB-e	*Betula*–*Filipendula*
Characterised by *Betula*. Low frequencies of *Juniperus* and *Salix* occur. Cyperaceae frequencies fall sharply whilst Poaceae is also reduced. *Filipendula* rises to peak percentages. *Thalictrum*, *M. alterniflorum* and *Equisetum* are all increased. *Pediastrum* rises to a high peak, whilst *Botryococcus* algae occur. Microcharcoal falls to low values before being no longer recorded.		
302.5–272.5	PAB-f	*Corylus*–*Ulmus*–*Quercus*
Characterised by *Corylus*, with lesser frequencies of *Ulmus* and *Quercus*. *Betula* frequencies are very low and *Juniperus* is no longer recorded. No other taxa are significant, including previously common aquatic taxa such as *Pediastrum*. Microcharcoal is absent.		
272.5–177.5	PAB-g	*Alnus*–*Quercus*–*Corylus*–*Ulmus*
Characterised by *Alnus* and *Quercus*, with high frequencies of *Corylus* and lesser values for *Ulmus*. *Pinus* briefly expands at the start of the zone. *Tilia* and *Betula* are present in very low frequencies. Other taxa are not significant, although Poaceae occurs at high frequencies in one level. Microcharcoal is absent.		
177.5–130	PAB-h	*Alnus*–Cyperaceae
Characterised by *Alnus*, which reaches over 90 % of total land pollen in some levels. All other tree and shrub types are much reduced. *Ulmus* in particular falls sharply at the zone g/h boundary. *Fraxinus* occurs sporadically. Cyperaceae is increased and Poaceae and *Typha angustifolia* percentages rise sharply at the end of the zone. Grains of *Plantago lanceolata* are sporadically present. Microcharcoal is absent.		

relatively poor conditions of preservation, in addition to periods of reduced vegetation cover. The remains have been subjectively grouped into four assemblage zones PABm1–PABm4, based on variations in the macrofossil diagram (Fig. 4), and described in Table 2. The pollen assemblage zones of Table 3 are added to Figure 4, for comparison.

The occurrence of Characeae spp. oosporangia in PABm1 indicates that the clay in the lower half of the core was deposited in a calcareous waterbody (Moore, 1986). The chironomids, ostracods and Bryozoan statoblasts at PAB (Table 2) also indicate the presence of clear, standing freshwater. The Poaceae caryopsis may be from a semi-aquatic grass growing around the water's edge. The low number and diversity of plant remains in this zone may indicate that there was limited vegetation cover at this time due to cold climatic conditions, or that the waterbody was deep, with its margins some distance from the sample site. Characeae has been identified as an important pioneering taxon in Lateglacial aquatic systems, particularly as it is a source of carbonate (Jones et al., 2002), and its macrofossils have been recorded in many other calcareous Lateglacial sequences in the region, such as at Neasham Fen in the Tees valley (Blackburn, 1952) not far to the north of PAB, at Turker Beck (Young et al., 2021) to the south, as well as further afield, as at Beanrig Moss (Webb and Moore, 1982) in southeast Scotland.

The diversity and number of aquatic plant remains increase in PABm2 which might result from shallowing of the waterbody or a change in trophic status. *Myriophyllum spicatum* indicates eutrophic to mesotrophic water up to 2 m deep (Haslam et al., 1975). *Ceratophyllum demersum* usually reproduces by vegetative fragmentation and will only produce fruits occasionally and in calm water (Preston et al., 2002), so the occurrence of the fruits of this species in PABm2 confirms that the water was still rather than flowing. Fruits and bracts of *Betula pendula*/*pubescens*, probably *pubescens* given the edaphic conditions of the site (Atkinson 1992), indicate that birch trees were growing nearby. This suggests mean July temperatures of > 10 °C (Birks, 2003). *Sphagnum*, sedges and ferns are common in the cores as macro- and microfossils, and would have grown in marshy areas around the waterbody.

The plant-macrofossil assemblage in PABm3 indicates that a few *Alnus glutinosa* trees were growing locally. The low number of plant macrofossils in this zone prevents a definitive interpretation of the local vegetation, but the presence of *Sphagnum* spp., *Potamogeton* spp., *Carex* spp., *Juncus* spp. and Cladocera remains may indicate open fen vegetation with pools of water. The occurrence of numerous wood fragments and an *Alnus glutinosa* fruit in PABm4 suggests that an alder carr had become established at the site. *Lycopus europaeus*, *Phragmites australis*, *Carex* spp. and Pteridophyta would have grown in the wet understorey.

Although the core contains a low number and diversity of plant macrofossils, the limited assemblage suggests that the clays of the lower sediments were deposited in a still, clear calcareous lake and that the overlying peats record a hydroseral succession through fen to carr vegetation, which was probably alder-dominated. This succession would have been facilitated by improving climatic conditions that resulted in a greatly increased vegetation cover and gradual infilling of the basin.

4.3. Palynology

The results of pollen analysis at PAB are presented in Figure 5, which shows tree and shrub percentages, and in Figure 6, which shows herb, aquatic, spore and freshwater algal percentages. Microcharcoal frequencies are shown on both diagrams. Pollen was present and well preserved in most of the levels analysed, with only a few in which pollen was too badly preserved for a count to be made.

The pollen stratigraphy at PAB has been subjectively divided into eight pollen assemblage zones (PAZs) based on major changes in the percentages of the components of the land-pollen sum, mainly those of trees and shrubs but also using non-arboreal pollen taxa where appropriate. The PAZs are described in Table 3. By analogy with dated pollen sequences from nearby sites (Innes, 1999, 2002) such as Mill House and The Flasks (Innes et al., 2009, 2021), Killerby Quarry (Hudson et al., 2023), Seamer Carrs (Jones, 1976) and Snape Mires (Bridgland et al., 2011), and in the wider Yorkshire region generally, as in the Vale of Pickering (Day, 1996), at Routh Quarry (Gearey, 2008) and Gransmoor (Walker et al., 1993), it is clear that the lowest four pollen zones, PAB-a to PAB-d, are of Lateglacial age, with their vegetation and thus pollen record determined by the major climatic fluctuations of that interval. The substantial *Betula* and *Juniperus* values of PAB-a, with some *Salix*, reflect some open shrub woodland of Interstadial age, but they are insufficient to indicate any great local density.

The summary pollen group diagram (Fig. 8), with herbaceous plants at around 60 % of total pollen, shows that there must have been considerable areas of open sedge fen and short-turf grassland, with abundant Cyperaceae (Fig. 6). These would have been in marshy areas by the lake, where *Equisetum*, *Filipendula* (if *F. ulmaria*) and *Thalictrum* would have grown. On its drier, calcareous catchment slopes would have grown a diverse herb community that consistently included *Thalictrum*, *Helianthemum*, *Sedum* and Filipendula (if *F. vulgaris*). *Filipendula's* continuous high frequency curve indicates the warm and humid conditions of the middle of the Lateglacial Interstadial, as it is intolerant of low summer temperatures (Karlsen et al., 2005). It can be very common within both the marsh and wet-meadow tall-herb communities and the calcareous soils (Edwards and Whittington, 1997) at PAB would have favoured it. Increased *Pediastrum* frequencies at this time could suggest warmer conditions (Sarmaja-Korjonen et al., 2006), but as *Pediastrum* persists in variable but substantial values throughout the climate fluctuations of the Lateglacial, it is likely that the lake's trophic conditions was also an important factor (Nielsen and Sørensen, 1992). Weckström et al. (2010) have shown that low nutrient concentrations result in low *Pediastrum* abundances. Pre-Quaternary spores are very common throughout the Lateglacial at PAB, indicating consistent inwash of nutrient-rich material from the catchment's poorly vegetated and unstable calcareous soils and supporting *Pediastrum*. The lake would have contained shallow eutrophic water for the whole of this period (Jankovská and Komárek, 2000), encouraging *Pediastrum* to bloom, although with little macrophyte growth as shown by the lack of macrofossils in the Lateglacial sediment (Fig. 4), whilst the catchment supported very open herbaceous vegetation.

The rise in *Juniperus* at the expense of *Betula* and *Salix* in zone PAB-b, the disappearance of cold-intolerant plants like *Filipendula* and *Equisetum* and the reduction in *Pediastrum* suggest a climatic deterioration during which birch trees were replaced by juniper bushes, juniper being more cold-tolerant than tree birch (Atkinson, 1992; Thomas et al., 2007a). There is no great increase in herbaceous pollen concentrations or percentages (Figs. 7 and 8) but, although the severity of the decline is difficult to determine, it had appreciable effects on the composition of the tree and shrub vegetation. The concentration data (Fig. 7) shows the great abundance of *Juniperus* in this zone relative to all other taxa, and it probably dominated the local vegetation around the site. Huntley and Birks (1983) regarded frequencies greater than 5 % as indicating strong local presence, so the very high concentrations and frequencies of Figures 7 and 8 must represent almost complete local dominance of the vegetation. The sedimentation regime in the lake changed at this time, with PAB-b coinciding with lithostratigraphical unit 7, which is entirely clastic, in contrast to the slightly organic deposits above and below it; this reflects inwashing of clays under colder climatic conditions at this time, supported by the major presence of pre-Quaternary spores in these levels.

Zone PAB-c sees an increase in the representation of tree and shrub taxa, which indicates a return to warmer temperatures, although not as warm as in the early Interstadial (Brooks and Birks, 2000). This is supported by the start of low but consistent curves for *Corylus*-type (highly unlikely to be *Myrica* in this Lateglacial calcareous context) and *Empetrum* curves (Brown, 1971), as there was some diversification in the tree/shrub assemblage, although *Empetrum* would not have been favoured by the calcareous nature of the catchment soils (Bell and Tallis, 1973). The substantial *Pinus* curve might represent growth on the morainic soils of the interfluve but is more likely to represent a component of long-distance transport. Although *Betula* recovers during this zone, it is apparent that the environs of the lake remained mostly unwooded, with shrubby heathland cover and with herbaceous pollen rising to 80 % of total land pollen (Fig. 8). Whilst mainly caused by an increase in Cyperaceae percentages, presumably from an expanded sedge fen around the lake, there is also a much more diverse tall-herb and weed assemblage (Fig. 6) that includes both marshland taxa like *Mentha*-type and *Filipendula*, but also more dry-grassland types like *Plantago lanceolata* and *Helianthemum* in a rich meadow flora, and some ruderal taxa including *Artemisia*. These open-ground taxa would have benefited from any disturbance in the catchment that is reflected in the consistent microcharcoal presence. Peaks of *Myriophyllum* spp. indicate some colonisation of the lake by aquatic plants and increased bio-productivity. The concentration values shown in Figure 7 are very low indeed for all taxa so, unless sedimentation was very rapid, vegetation cover of all kinds near the site must have been very light.

Zone PAB-d must correspond to the severe cold episode of the Loch Lomond Stadial, as sedimentation at the time was entirely clastic (unit 4) and both tree and shrub pollen fall to very low values, with much of this contributed by probable long-distance *Pinus* input, although there are still consistently low values for *Betula* and *Juniperus*. Sporadic low *Juniperus* might well have been a member of the local tundra flora, as Blackburn (1952) found juniper macrofossils within Stadial moss layers at Neasham Fen in the Tees valley. Low frequencies of the thermophilous *Corylus*-type are recorded, although these are unlikely in this very cold phase, and might well be reworked from earlier, warmer phases, including the Interstadial. Reworking of sediment did occur at PAB, as reworked pre-Quaternary spores occur in all of the four Lateglacial zones, as at several sites of this period, *e.g.*, Gransmoor (Walker et al., 1993) and Mill House (Bridgland et al., 2011), with these attesting to the unstable catchment slopes and sparse vegetation; notably, they are particularly common in the very cold zone PAB-d with its unstable soils. Herbaceous pollen consistently accounts for 90 % of total land pollen and is almost entirely contributed by Cyperaceae and Poaceae, with aquatics and tall herbs now absent and even ruderal, cold-tolerant types like *Artemisia* hardly present. Sedge-tundra conditions seem likely. Two levels, at 405 and 415 cm, had insufficient pollen to count. Total pollen concentrations remain very low indeed and the catchment must have contained bare, unstable soils supporting very sparse vegetation.

Major changes in the site's vegetational history occur in zone PAB-e, as *Betula* frequencies rise sharply to account for almost 60 % of total land pollen (Fig. 5), clearly recording very rapid expansion of birch woodland. *Salix* also increases as a result of woodland expansion, although *Juniperus* fails to rise from its low frequencies of the cold Lateglacial stadial, perhaps being shaded out by the proliferation of birch trees. *Filipendula* values are consistently almost 10 % of total land pollen, with *Rumex* and *Thalictrum* as the other prominent herb taxa. The sediments in the lake became much more organic in unit 3, reflecting its greater biological productivity, shown by greatly increased *Pediastrum* and *Botryococcus* algal percentages and peaks for aquatic herbs *Myriophyllum alterniflorum* and *Typha angustifolia*. That the Poaceae curve declines only slowly is explained by the presence of *Phragmites* macrofossils in the sediment, as reedswamp vegetation began to colonise the middle of the lake, with most of the grass pollen probably derived from this taxon. PAB-e must represent the first phase of the Holocene, when abrupt amelioration of climate (Atkinson et al., 1987; Coope et al., 1998; Dansgaard et al., 1989) allowed the rapid expansion of birch woodland and its suppression of most ground flora. Reworked pre-Quaternary spores no longer occur, as catchment soils became stable.

Zone PAB-f sees the replacement of *Betula* by *Corylus*-type, which rises to almost 70 % of total land pollen, quickly followed by *Ulmus* and *Quercus* as postglacial mixed broadleaf woodland developed. At this time (unit 2) the sediment type changes from organic silt to peat and pollen representation of aquatic taxa like *Pediastrum* declines sharply. This marks the change at the sampling site from open water to more terrestrial reedswamp/carr deposition at the lake edge, caused by the gradual infilling of the lake, with wood fragments present in the peat.

The dryland closed-canopy deciduous forest was maintained until the start of zone PAB-g when alder entered the local vegetation and quickly became an important component of the woodland, probably occurring in wetter carr areas around the lake. In mid-zone *Tilia* joined the local woodland, which must have been quite dense as *Corylus*-type percentages fall, shaded out by the forest canopy, which also effectively filtered out airborne *Pinus* pollen. Herb pollen becomes virtually absent in this zone except for one level with abundant Poaceae pollen, perhaps representative of another inwash episode.

In zone PAB-h *Alnus* frequencies increase to account consistently for >80 % of total land pollen, with *Corylus*-type, *Quercus* and *Ulmus* falling sharply, *Ulmus* to almost zero. These percentage changes are also clearly present in the concentration data (Fig. 7), showing that *Alnus* replaced all the other trees in a real change in local tree populations. This *Ulmus* pollen decline at this level on the diagram occurs a little before the radiocarbon date of 5090 ± 35 ^{14}C BP (5745–5915 cal. BP) and so can be identified as the mid-Holocene *Ulmus* Decline (Parker et al., 2002; Griffiths and Gearey, 2017) that occurs on virtually all pollen diagrams in Britain in the centuries around *c.* 5100 ^{14}C BP, depending upon local factors, primarily altitude. Some diversification of the woodland occurred in PAB-h, with *Fraxinus* appearing, but other than a few *Plantago lanceolata* grains there is no indication of forest opening at this time, with dense alder carr dominating the local vegetation for the rest of the profile.

4.4. Microcharcoal analysis

The analysis of the charcoal content of sediments is an important addition to palynology and provides evidence of burning at and around the site at various spatial scales (Clark, 1988; Clark and Patterson III, 1997). Macroscopic charcoal is often present in lake sediments, acting as a record of local fire within the lake catchment (*e.g.*, Edwards and Whittington, 2000). Microscopic charcoal percentages are a record of fire in the wider landscape, both within and beyond lake catchments, with particles being transported to the site of deposition by wind action in addition to overland flow (Sugita et al., 1997). Microcharcoal occurs throughout the lower part of the studied profile, in zones PAB-a to PAB-d, which correspond to the Lateglacial period, but is absent from the upper part of the core.

Considerable fluctuations occur in the microcharcoal curve, with high peaks in places, whereas in others, such as the first half of PAB-d, numbers fall to very low values. It is clear that burning, to a greater or lesser degree, was taking place in the wider environs of PAB during the Lateglacial, although perhaps not within the lake basin catchment itself, from where it would have been washed into the lake, as macroscopic charcoal was not reported in any of the previous cores from the site, including those from the basin edge (Lillie and Gearey, 1999), nor was any retained in the 180 μm sieves during pollen preparation for this study. The variability in the microcharcoal percentages during this period might be because of real changes in the amount and intensity of burning in the wider vicinity, but this could also be affected by taphonomic changes in the transport of particles to the site because of varying vegetation filtration effects or climatic change impacts to wind or rainfall patterns. Microscopic charcoal particles can also be subject to resuspension and redistribution in lake sediments after initial deposition, processes that need to be considered as part of their interpretation as fire history (Whitlock and Millspaugh, 1996; Edwards and Whittington, 2000). Microcharcoal concentrations mirror the fluctuations in the percentage curve, with low peaks in PAB-a, b and late in zone PAB-d, but are low throughout the microcharcoal record. At PAB, microcharcoal percentages quickly declined after the Lateglacial (Fig. 5), suggesting a significant reduction in burning. Microcharcoal concentrations increase strongly at the start of the Holocene (Fig. 8), but this rise is due to a general great increase in microfossil concentrations, rather than any real increase in fire. Burning then ceased completely, as microcharcoal is absent from the rest of the core, which corresponds to the early and mid-Holocene. Its complete absence is unusual but in early and mid-Holocene pollen records in lowland northern England microcharcoal tends to occur mostly during phases of fire-disturbance near the site and is almost absent during the rest of the record, contrasting with a virtually continuous background microcharcoal presence at upland sites where burning seems to have occurred throughout this period (Innes and Blackford, 2023). The lack of microcharcoal in the Holocene at PAB will result from the lack of fire disturbance during the Mesolithic period around this lowland wetland.

5. Discussion

5.1. Vegetation history

There is only one radiocarbon date (5090 ± 35 ^{14}C BP) at PAB, near to the top of the profile, but the approximate dates of changes in Lateglacial and Holocene pollen assemblages, and therefore vegetation, at this site can be estimated from other radiocarbon-dated pollen diagrams in the region, such as Askham Bog (Gearey and Lillie, 1999) near York in the south and, to the north, Neasham Fen and Mordon Carr (Bartley et al., 1976) and Hartlepool Bay (Innes et al., 2005), all in County Durham. The dates and durations of the climatic oscillations in the Lateglacial at PAB can also be inferred using the modelled Greenland GRIP and NGRIP ages from previous research (Rasmussen et al., 2006; Lowe et al., 2008; Walker et al., 2009, 2012), although some spatial variation in timing around the North Atlantic is to be expected. The modelled ages before present (1950) shown below and on the summary diagram (Fig. 8) are rounded figures derived from Whittington et al. (2015) and provide a good approximation.

5.1.1. The mid-Interstadial (GI-c)

The pollen record at PAB apparently started within the Lateglacial Interstadial, at some date after its beginning (at *c.* 14,640 years ago) and before its end at *c.* 12,850 years ago, its boundary with the Loch Lomond Stadial (Whittington et al., 2015). It is inferred that the record began within the mid-Interstadial temperate phase GI-1c and so after *c.* 13,900 years ago, judging from the fact that only one vegetation reversion, attributable to a cold phase (zone PAB-b), occurs in the pollen stratigraphy before the clear Lateglacial Stadial and subsequent Holocene. This lone Interstadial cold phase must therefore be GI-1b, starting *c.* 13,260 years ago, and so the pollen spectra below it in the profile must represent the temperate mid-Interstadial phase GI-1c. This is defined as a temperate phase between two short-lived colder episodes based on a range of proxy evidence, including chironomid data at Whitrig Bog in south-east Scotland (Brooks et al., 1997; Brooks and Birks, 2000) and isotopic data at Hawes Water in north-west England (Marshall et al., 2002). Despite the temperate climate and the relative length of the mid-Interstadial warm phase, *Betula* percentages are always below 40 % and *Juniperus* and *Salix* frequencies are high, the former matching those of birch, so that woodland must have been very open, perhaps comprising birch copses with much intervening grassland and scrub. That the microcharcoal curve is considerable suggests that fire might have played a role in suppressing birch expansion, at least locally. Unless there is a hiatus in the PAB profile, for which there are no indications in the litho- or pollen-stratigraphy, there is no sign of the earlier climatic phases established within the Lateglacial Interstadial (GI-1d and GI-1e), so deposition at the site, along with its vegetational record, can be assumed to have commenced in GI-1c.

The PAB *Betula* values match those to the north of the region, as at Thorpe Bulmer (Bartley et al., 1976) where *Betula* frequencies are 40 % at most, and at Cranberry Bog (Turner and Kershaw, 1973) where birch percentages are always less than 20 % of total land pollen. Sites near to PAB, such as Mill House at Snape Mires (Innes et al., 2009), Killerby (Hudson et al., 2023) and Seamer Carrs (Jones, 1976) are similar in having *Betula* percentages below 40 % and therefore very open woodland. This contrasts with the south of the region, such as Tadcaster (Bartley, 1962) where Interstadial *Betula* frequencies exceed 50 % and *Juniperus* values are very low, and Bingley Bog (Keen et al., 1988), where *Betula* frequencies are very high, as at Dishforth Bog (Giles, 1992), and at Gransmoor (Walker et al., 1993) and Routh Quarry in East Yorkshire (Gearey, 2008). Mild rather than warm temperatures at this point in the Interstadial might have been close to the thermal threshold for tree *Betula* and so it might have been sensitive to slightly colder conditions in the north of the region, and therefore suppressed (Walker et al., 2003).

5.1.2. The late Interstadial cold phase (GI-1b)

In pollen zone PAB-b the progression towards full *Betula* woodland cover is seen to have been interrupted by a sudden reversion in vegetation development, as *Betula* frequencies fall sharply to low values and are replaced mainly by greatly increased *Juniperus* percentages at *c.* 13,260 years ago. Microcharcoal frequencies are little changed, so that this change to more open, lower-stature vegetation reflects the effects of a cold-climate episode rather than burning. This is supported in the lithostratigraphy by the switch to clastic sedimentation and by a major reduction in the thermophile *Filipendula*, as well as *Pediastrum* algae (Jankovská and Komárek, 2000), the decline of which suggests the lake became colder and less productive. Although also influenced by other factors, *Pediastrum* frequencies are a sensitive indicator of Lateglacial temperature fluctuations (Sarmaja-Korjonen et al., 2006; Turner et al., 2014). Given the pollen stratigraphical position of this phase as the last cold event before the clear, severely cold episode of the Lateglacial (Loch Lomond) stadial, zone PAB-b must correlate with the late Interstadial cold event GI-1b (*cf.*, Gerzensee oscillation) which began at *c.* 13,300 years ago in the ice-core record and lasted for about two centuries (Lowe et al., 2008; Walker et al., 2009, 2012). According to chironomid data from southern Scotland (Brooks and Birks, 2000), this oscillation included a temperature drop of about 2 °C from the late Interstadial mean, although the severity of the cooling varied spatially (Brooks and Langdon, 2014; Candy et al., 2016). This late Interstadial cold phase is recorded in various types of proxy record all around the northern Atlantic (Levesque et al., 1993), for example by Andresen et al. (2000), Birks and Ammann (2000), Yu and Eicher (2001), Marshall et al. (2002) and Whittington et al. (2015), although perhaps less strongly in western Europe (Bos et al., 2017; Paus et al. 2023). However, some sites in Britain show this oscillation clearly, such as Hawes Water (Marshall et al., 2002), Gransmoor (Walker et al., 1993), Whitrig Bog (Brooks et al., 1997; Mayle et al., 1997; Brooks and Birks, 2000) and Llanilid (Walker and Harkness, 1990; Walker et al., 2003). It is also clearly revealed at sites near to PAB with sufficiently sensitive pollen sampling intervals, including Thorpe Bulmer (Bartley et al., 1976), Neasham Fen (Blackburn, 1952), Dishforth Bog (Giles, 1992), Mill House (Innes et al., 2009) and Seamer Carrs (Jones, 1976), as well as at Star Carr in North Yorkshire (Day, 1996).

At many of these sites that reveal the GI-1b cold oscillation, pollen data show the replacement of open *Betula* woodland by a significant increase in open ground herbs, as slopes became destabilised by a reduction in vegetation cover, followed by a return to birch woodland *via* a scrub juniper phase. This is not the case at PAB, where the major reduction in *Betula* woodland cover allowed *Juniperus* to expand immediately and form scrub, with no increase in herb pollen; frequencies of the latter are actually depressed (Figs. 6 and 7), implying that the cover of juniper shrubs must have been extensive. The temperature fall during this phase hereabouts might have been only moderate; enough to badly affect *Betula* (Atkinson, 1992) but insufficient to remove the cold-tolerant *Juniperus* (Thomas et al., 2007a), which expanded quickly as a legacy species (Franklin et al., 2000; Morimoto et al. 2013) to occupy the PAB vicinity. Walker and Lowe (2019) at Whitrig Bog, Bedford et al. (2004) at Hawes Water and Lang et al. (2010) at Little Hawes Water found evidence to suggest that phase GI-1b might have been the least severe of the major Interstadial cold phases, at least in this part of Britain, as has also been indicated for Ireland (van Asch et al., 2012). The dominance of *Juniperus* rather than steppe/tundra weeds at PAB might therefore make sense, although it marks out this site as an anomaly among most records of GI-1b.

5.1.3. The Late Interstadial phase (GI-1a)

The latest, and perhaps warmest (Walker et al., 1993), temperate phase of the Lateglacial Interstadial occurred between *c.* 13,050 and *c.* 12,850 years ago (Whittington et al., 2015), with the associated temperature rise allowing the renewed expansion of tree *Betula* in the vicinity of the study site. The presence of thermophilous taxa such as *Corylus*-type and *Filipendula* throughout this phase in the PAB pollen record suggests significant warming. In the nearby region *Corylus*-type pollen is also present at Neasham Fen (Blackburn, 1952) and Romaldkirk (Bellamy et al., 1966), and macrofossils of thermophilous trees occur at Turker Beck (Young et al., 2021). The increase in *Betula* at PAB is limited, however, consistently being around 20 % of total land pollen. Indeed, the high *Juniperus* frequencies, the suite of cold-intolerant tall herbs such as *Helianthemum* and the continued abundance of Cyperaceae and Poaceae indicate that the vegetation around the site remained open, probably as a meadow environment with copses of birch and juniper, and the shrub taxa were not shaded out by *Betula*. The presence of the nitrogen-fixing pioneer shrub *Hippophaë* (Stewart and Pearson, 1967), common in this late stage of the Interstadial (Andrieu et al., 1993; Ammann et al., 2013), indicates that soils would have been improving and more stable, but that progression towards woodland was slow and incomplete. *Hippophaë* is present in late Interstadial deposits at a few sites in the area, such as at Tadcaster (Bartley, 1962) and at Seamer Carrs (Jones, 1976), where it reaches significant values. As this final Interstadial phase lasted just two centuries, perhaps there was insufficient time for *Betula* to recover from the preceding cold phase and progress to a more complete woodland cover at PAB. Sites to the north are similar in having a weak *Betula* expansion with *Juniperus* prominent, as at Cranberry Bog (Turner and Kershaw, 1973) and Thorpe Bulmer (Bartley et al., 1976). In contrast, sites to the south, like Tadcaster, record *Betula* at over 50 % of total land pollen, with much of their herb pollen component coming from wetland taxa. Consequently, they had a denser birch woodland cover, although much less than in the early Holocene; at all sites the early Holocene Preboreal birch expansion greatly exceeds that in the Interstadial. The relative importance of birch and juniper in the final Interstadial and earliest Holocene woodland expansions across a transect between northerly and southerly sites in the region is shown in Table 4. Clearly there was a latitudinal dichotomy in regional woodland composition and density between north and south at these times which, whether caused by climate, soil or migration rate, requires further research.

Table 4

Comparison of main pollen taxa across the Lateglacial–Holocene transition at PAB and sites on a south–north transect in North Yorkshire and County Durham, northeast England: Dishforth Bog (Giles, 1992), Killerby Quarry (Hudson et al., 2023), The Flasks (Innes et al., 2009), Romaldkirk (Bellamy et al., 1966), Thorpe Bulmer (Bartley et al., 1976), and Cranberry Bog (Turner and Kershaw, 1973).

	Cranberry Bog	Thorpe Bulmer	Romaldkirk	PAB	The Flasks	Killerby Quarry	Dishforth Bog
Earliest Holocene	*Juniperus* *Betula*	*Betula* *Juniperus*	*Betula* *Corylus*	*Betula*	*Betula*	*Betula*	*Betula* *Corylus*
Loch Lomond Stadial	Poaceae Cyperaceae	Cyperaceae Poaceae	Poaceae Cyperaceae	Cyperaceae	Cyperaceae	Poaceae Cyperaceae	Cyperaceae
Temperate Interstadial	*Juniperus*	*Juniperus*	*Betula* *Juniperus*	*Betula* *Juniperus*	*Betula*	*Betula*	*Betula*

5.1.4. The Lateglacial (Loch Lomond) Stadial (Younger Dryas) (GS-1)

The severe cold event of the Lateglacial Stadial (GS-1) lasted about a thousand years, between *c.* 12,850 and *c.* 11,700 years ago. The significant reduction in temperature, by several degrees (Walker et al., 1993), and increased aridity (Macpherson, 1980), caused major changes in the vegetation both in the PAB lake catchment and beyond. The dominant Cyperaceae and Poaceae frequencies indicate that very open, cold-tolerant sedge-tundra communities replaced the open park-woodland of the preceding Interstadial, abruptly reversing the slow succession towards woodland cover. The high Cyperaceae pollen values indicate that sedges dominated at least the local vegetation, a conclusion supported by *seda*DNA studies at nearby Killerby (Hudson et al., 2023) where various sedge taxa, with *Phragmites*, dominated the Lateglacial DNA assemblage.

The second half of the stadial was apparently the coldest and most arid (Lowe and Walker, 1986; Lowe et al., 1994, 1995), which could explain the form of the microcharcoal concentration curve in Figure 8, aridity encouraging natural fire. Lake levels at PAB might have fallen, a trend recorded at other sites in northern England (Keen et al., 1984; Candy et al., 2015; Palmer et al., 2015), although the evidence for this at PAB is equivocal. Most regional lake sediment sequences of Stadial age are entirely clastic, *e.g.*, at Kildale (Keen et al., 1984) and Gormire Lake (Blackham et al., 1981). Some are devoid of pollen, as at Mill House and Marfield (Fig. 1), reflecting the virtually devegetated nature of the nearby landscape (Bridgland et al., 2011; Innes et al., 2009, 2021). In contrast, pollen recruitment at PAB continued throughout the Stadial, although the very low pollen concentrations shown in Figures 7 and 8 indicate that the locality was poorly vegetated, only Cyperaceae having a discernable curve. Sedge-tundra was apparently dominant locally, but it seems that a background presence of taller vegetation persisted, perhaps with juniper and even birch scrub locally surviving in sheltered locations as park-tundra, as macrofossil data indicate occurrence elsewhere in the wider region (Hunt et al., 1984). *Juniperus* increased at the end of the Lateglacial Stadial at some sites in the region, as is indicated at Newby Wiske (Bridgland et al., 2011), suggesting local populations from which it could have expanded. The consistent low *Salix* count could refer to *S. herbacea*, whilst some of the *Betula* grains could represent *B. nana*, a dwarf species that would have been more suited to the severe cold climate than tree birch, although the morphology of the studied grains generally does not match that taxon. Whilst *Corylus*-type pollen is consistently recorded in low frequencies during this phase (along with *Hedera*), it is difficult to accept that hazel, bog myrtle or ivy was growing at PAB at this time. *Corylus*-type pollen occurs, however, in Lateglacial Stadial pollen sequences at other sites in the region, including Neasham Fen (Blackburn, 1952), Dishforth Bog (Giles, 1992), Romaldkirk (Bellamy et al., 1966) and Tadcaster (Bartley, 1962), so the presence of hazel must be considered to be indicative of the fact that this species was perhaps lingering from regional Interstadial refugia (Young et al., 2021), unless long-distance transport or reworking is invoked as explanations in all cases. Although reworked pre-Quaternary grains are common, indicating destabilisation and inwash of soil, the latter seems unlikely at PAB as the *Corylus*-type grains were as well preserved as other pollen.

The grassy sedge-tundra nature of the dominant vegetation at PAB resembles that recorded at almost all sites in the region from this time, at locations both to the south and north (Innes, 1999), although with some variations (Table 4). Most sites record a rich suite of open-ground herbs, as, for example at Gransmoor (Walker et al., 1993), where ruderal and tall herb types, in particular *Artemisia*, are well represented from the stadial (*e.g.*, Tipping, 1985; Walker et al., 2003). A steppe/tundra taxon typical of exposed, bare and unstable-ground communities and favoured by aridity, *Artemisia* at high frequencies is a signature of the severe cold and dry conditions of the Lateglacial Stadial in most British pollen diagrams of that period.

In the sites to the south of PAB *Artemisia* values vary but are generally high, as at Newby Wiske (Bridgland et al., 2011), Dishforth Bog (Giles, 1992), Tadcaster (Bartley, 1962) and particularly at Bingley Bog (Keen et al., 1988). In addition, some sites to the north of PAB also have high *Artemisia* curves during GS-1, as at Thorpe Bulmer (Bartley et al., 1976). In contrast, the open-ground herb assemblage at PAB is highly impoverished, with only isolated grains recorded, and *Artemisia* almost absent. This seems anomalous and suggests a continuous Lateglacial Stadial (GS-1) vegetation cover at PAB, comprising grass and sedge tundra, judging from the very high percentages of those taxa, and the absence of the frost-disturbed and bare soils that would have favoured *Artemisia*. Perhaps the PAB basin was a sheltered location within the morainic ridge landscape, allowing low-stature vegetation to persist.

5.1.5. The Earlier Holocene

The start of the Holocene occurred around 11,700 years ago (Walker et al., 2009, 2012) and generally the rise in temperature initiated the immigration and rapid succession through tall herb, heath and shrub communities until *Betula* woodland was established as a temporary climax vegetation cover, although the rate at which seral progression occurred varied from place to place because of local factors. Previous research in northwest Europe (Birks and Birks, 2008) has shown that vegetation recolonisation of morainic deposits, like those at PAB, was often slow after the severe cold conditions of the Lateglacial Stadial, when already poorly developed and unstable, friable soils became further destabilised and eroded by periglacial processes. Expansion of *Betula* woodland in particular was in some places delayed by centuries. This seems not to have been the case at the start of the Holocene (*cf.*, Preboreal) at PAB, as the record here shows *Betula* pollen values rising sharply to high frequencies, implying that birch must have swiftly formed an open woodland, with subsidiary *Salix* and *Juniperus* contributing at much lesser frequencies. Although established quickly, the open nature of the woodland is suggested by the continued presence of successional tall herb associations including *Filipendula*, *Thalictrum* and *Rumex*.

The presence of fruits of *B. pendula* or *B. pubescens* at the start of the Holocene (Fig. 4) shows that tree birches colonised the vicinity of the lake. The elevated trophic status of the water body, caused by increased plant growth both in and around it, is typical of the start of the Holocene at most sites in the region, such as Dishforth Bog (Giles, 1992), and is shown by the greatly enhanced representation of aquatic taxa, particularly *Pediastrum* and *Myriophyllum*, as well as the recovery of plant macrofossils from this stage onwards (Fig. 4). This rapid Holocene spread of *Betula* at PAB is analogous to the records from sites in North Yorkshire, with hardly any increase of *Juniperus* pollen in a transitional shrub and heath phase after the end of the Stadial. It is very different, however, to the situation to the north, such as at Thorpe Bulmer in mid-Durham (Bartley et al., 1976) where a peak of *Juniperus* occurs and the rise of *Betula* to high frequencies is slow, and especially at Cranberry Bog (Turner and Kershaw, 1973) in north Durham, where the beginning of the Holocene is marked by very high and persistent *Juniperus* percentages that indicate major local populations of juniper occurring as a protracted stage in the transition to *Betula* woodland. These contrasts (Table 4) further emphasise the location of PAB and the Swale–Tees interfluve as an important boundary between different vegetation and habitat provinces within northern England.

Sites to the north of Cranberry Bog show the same high juniper phase, as seen at Embleton's Bog and Longlee Moor in Northumberland (Bartley, 1966). As such, it is apparent that the boundary between very rapid and much slower establishment of *Betula* woodland in the early Holocene lies around south Durham and the Tees valley. This variability agrees with the lack of synchrony in the *Juniperus* rise in north Britain, as noted by Tipping (1987). In the Swale–Tees area this variability is clearly apparent. There was an almost immediate expansion of *Betula* at Seamer Carrs, Kildale Hall, The Flasks 69 and Mill House (Jones, 1976, 1977; Innes et al., 2009; Bridgland et al., 2011), presumably from local populations that persisted in the area through the Lateglacial Stadial, as suggested by the persistent low *Betula* pollen frequencies during that very cold period, with *Juniperus* very low or almost absent. At Marfield (Bridgland et al., 2011), however, the earliest Holocene has a significant *Juniperus* peak as *Betula* gradually increases, perhaps because of local factors at this site higher up the Ure valley. At Snape Mires (Bridgland et al., 2011), one site has a significant *Juniperus* presence, whereas in a nearby profile at Snape *Juniperus* is almost absent. The Swale–Tees appears to have been a transitional area for this vegetation change. The rapid *Betula* expansion is clearly seen further south, in lowland Yorkshire, with the establishment of closed birch-woodland at Tadcaster (Bartley, 1962) and Bingley Bog (Keen et al., 1988), both unfortunately undated, to the exclusion of almost all other taxa. This rapid *Betula* expansion in the earliest Holocene at most Tees–Swale sites, as recorded at PAB, is similar to the high rates of birch immigration and *Betula* woodland establishment noted at sites in Yorkshire and in southern Britain, such as Hockham Mere (Bennett and Humphry, 1995), where any transitional herb/heath or *Juniperus* phase was very brief indeed.

The initial Holocene *Betula* pollen maximum at PAB includes a single level in which birch percentages are greatly reduced (Fig. 5) with *Salix* and *Juniperus* percentages also falling and the reappearance of the cold-tolerant heath taxon *Empetrum*. There are sharp peaks of Cyperaceae and Poaceae, and some ruderal weeds are recorded (Fig. 6). This rise of total herb pollen at the expense of total trees and shrubs is clearly shown on the summary diagram (Fig. 8). Pollen concentrations of *Betula* and *Juniperus* are significantly reduced at this level (Fig. 7), whilst those of other taxa such as Cyperaceae are unaffected, indicating real reductions in the populations of these woody taxa. There is a small peak in microcharcoal, so fire could have contributed to the sharp decline in tree and shrub taxa, but this pollen fluctuation is likely to be evidence of a brief cold-climate event, and might well represent the effects of the Preboreal Oscillation (Björck et al., 1997; van der Plicht et al., 2004; Bohncke and Hoek, 2007; Bos et al., 2007) which occurred at about 11,400 cal. BP and lasted a few centuries. It is recorded in many pollen stratigraphies around the North Atlantic (Birks and Ammann, 2000), including northern England (Lang et al., 2010), as well as in isotopic excursion data (Marshall et al., 2007) and ice-core data (Rasmussen et al., 2007; Lowe et al., 2008; Walker et al., 2012).

Inspection of the pollen diagrams in the region of PAB (Fig. 1) reveals some pollen changes that reflect similar Preboreal vegetation recessions indicative of a period of climate deterioration. At Bishop Middleham in south Durham, Bartley et al. (1976) recorded a major fall in *Betula* frequencies, and those of other thermophilous taxa, and a major peak in Cyperaceae percentages, with a rise in ruderal herbs, in mid-Preboreal times. A similar but less pronounced event is recorded in the mid-Preboreal at Thorpe Bulmer (Bartley et al., 1976), where *Betula* falls at one level whilst Poaceae and *Artemisia* rise; modest rises in sedge and grass percentages at Burtree Lane (Bellamy et al., 1966) could represent the same event, unless caused by hydrological change, such as the expansion of local reedswamp communities. Most pollen diagrams from sites south of PAB do not exhibit Preboreal tree recession, although Abrook (2017) has noted such a vegetation reversion in the Vale of Pickering, and so the oscillation might have mainly affected only more northerly parts of the region, as well as sites much further north (Edwards and Whittington, 1997; Whittington et al., 1996), where climate was less congenial and woodland less developed.

Whilst *Corylus*-type pollen was recorded during the Preboreal *Betula* maximum at several regional sites, when the replacement of birch woodland by thick hazel scrub occurred in the centuries before 9000 ^{14}C BP it was very rapid. *Corylus*-type pollen curves rise sharply to high frequencies, for example at Bedale (Gearey and Allison, 2010) and Newby Wiske (Bridgland et al., 2011), where it achieved well over 80 % of total land pollen on favourable calcareous soils. The swift expansion of *Corylus*-type pollen occurs at many other lowland sites across England (Bennett and Humphry, 1995). This hazel expansion is likely to have been driven by warming temperature (Huntley, 1993), although the coincidence of charcoal with the *Corylus*-rise at several sites in the region, including at Snape Mires (Bridgland et al., 2011) and in the Vale of Pickering (Simmons et al., 2022), suggests that the destabilisation of woodland caused by fire in places acted as a triggering force for the increase of hazel. The absence of charcoal (Figs. 5 and 7) shows that this did not happen at PAB.

The expansion of the broadleaf trees *Quercus* and *Ulmus* at the same time as the *Corylus* rise marks the establishment of the mixed oak forest in the area, rather earlier in the tree immigration succession at PAB than at many regional sites such as Dishforth Bog (Giles, 1992), Bingley Bog (Keen et al., 1988) and Cranberry Bog (Turner and Kershaw, 1973), where the entry of oak and elm into the woodland occurs well after the expansion of hazel. A representative age for the expansion of *Quercus* in the south of the region is 8505 $\pm$ 50 ^{14}C BP at Askham Bog (Gearey and Lillie, 1999), in contrast to 8202 $\pm$ 95 ^{14}C BP at Neasham Fen (Bartley et al., 1976). *Ulmus* rises to peak values during the *Corylus*-type maximum at sites significantly to the south, such as at Tadcaster (Bartley, 1962), whereas at sites to the north, in Northumberland, *Quercus* and *Ulmus* do not increase until long after the *Corylus*-type peak, and then only modestly, as seen at Lilburn (Jones et al., 2000). *Tilia*, the final component of the mid-Holocene deciduous forest, has an early date of 6310 $\pm$ 45 ^{14}C BP at Askham Bog in the south, whereas at Mordon Carr in the north it is not recorded until almost 5305 $\pm$ 55 ^{14}C BP, a considerable time-lag. A clear north–south chronological gradient evidently existed regarding the immigration of major tree species into the late boreal mixed forest in northeast England. At PAB the established mixed forest was clearly a closed canopy, as total herb pollen frequencies fall sharply at this time (Fig. 8) and only Cyperaceae and Poaceae show significant pollen concentrations (Fig. 7), presumably derived from wetland taxa.

5.1.6. The mid-Holocene

Walker et al. (2012) recommended that the start of the mid-Holocene (now termed the Northgrippian sub-epoch *sensu* Walker et al., 2018) should be defined by the 8.2k cal. BP cold event, an abrupt, severe climatic deterioration (Alley and Ágústsdóttir, 2005) that lasted at least a century and that is clearly apparent in chironomid, isotopic and ice-core data (Rasmussen et al., 2007; Thomas et al., 2007b; Svensson et al., 2008; Daley et al., 2011), including in northern England (Marshall et al., 2007; Lang et al., 2010). This cold and arid event seems not to have always initiated vegetation change (Whittington et al., 2015), but in places it coincided with a reduction in thermophilous trees (Ghilardi and O'Connell, 2013) and their replacement by cold-tolerant taxa. Other factors such as human activity could have caused such vegetation changes (Edwards et al., 2007), and there is substantial evidence of Mesolithic presence and activity in the region at this time (Spikins, 1999; Laurie, 2003; Vyner, 2003; Waughman, 2017). The absence of microcharcoal and ruderal indicators of disturbance in the Holocene PAB profile, however, indicates that any pollen changes will almost certainly have been due to natural factors related to climate and soils. Greatly increased Poaceae frequencies often coincide with the 8.2-ka cooling, as grassland was encouraged by the cold, arid climate (Head et al., 2007; Wicks and Mithen, 2014). At PAB the single-level peak of Poaceae at 40 % of total land pollen at 250 cm (Fig. 6) is coincident with a small peak in Cyperaceae and falls in the frequencies of thermophilous tree taxa *Quercus*, *Ulmus* and *Corylus*-type (Fig. 5). That identical fluctuations also occur in the pollen concentration data (Fig. 7) indicates that these changes reflect real population changes in the vegetation and a temporary replacement of deciduous woodland by grassland. The particularly thermophilous *Corylus*-type seems to have been the taxon most adversely affected by this cooling event (Figs. 6 and 7). More cold-tolerant trees like *Betula* are not affected, so a brief climate excursion seems very likely to have been the cause. A fall in total pollen concentration (Fig. 8) indicates a less well-vegetated landscape. This brief cold phase could record the 8.2k event, as opposed to any unusual incorporation of grass pollen, such as anther deposition at the core site, and assuming broadly consistent sedimentation rates at PAB, interpolation between the known ages of the start of the Holocene (11,700 cal. BP) and the Elm Decline (*c.* 5800 cal. BP) gives an approximate age for this PAB event as the middle of the ninth millennium BP. This is not inconsistent with the 8.2k event, allowing for any small variations in sedimentation rate in the core.

Although alder was present in the area from the early Lateglacial (Young et al., 2021), the rise in the *Alnus* pollen curve is characteristic of the transition to the mid-Holocene and the full establishment of the lowland postglacial mixed forest. Whilst showing considerable variability in date, probably because of local edaphic factors, the rise of alder generally occurred in the centuries around 8000 cal. BP (Chambers and Elliott, 1989), although much earlier dates have been recorded at Askham Bog (Gearey and Lillie, 1999) and at Mordon Carr (Bartley et al., 1976). The alder rise date of 6962 $\pm$ 90 ^{14}C BP (*c.* 7800 cal. BP) from Neasham Fen (Bartley et al., 1976), a site very close to PAB, is very likely to be a good estimate for that event at PAB, where the alder pollen increase is gradual at first although there is a noticeable rise to about 40 % of total land pollen from the time of the putative 8.2k event. This unstable vegetation phase probably gave the heliophyte alder the opportunity to expand into places that *Corylus*-type, *Ulmus* and *Quercus* had ceased to occupy, particularly in wetter areas. This rise in the *Alnus* pollen curve is moderate and in other places, such as river valleys (Brown, 1988), alder rises sharply to over 80 %. In northeast England, however, the mid-Holocene rise of *Alnus* mostly resembles that at PAB, with nearby Neasham Fen and Hutton Henry (Bartley et al., 1976) and Nosterfield SH1 (Bridgland et al., 2011) yielding similar records, and with few sites showing alder abundance, an example being Shibdon Pond in the Tyne valley (Passmore et al., 1992) where edaphic factors would have been favourable. Again, fire was clearly not a factor in the diversification of the woodland and *Alnus* expansion at PAB, in contrast with other sites in North Yorkshire (Cloutman, 1988; Simmons. et al., 2022), and the brief cold episode would seem likely to have been responsible. The return to warmer climate after the brief cold phase is demonstrated by the start of a consistent *Tilia* curve, as well as the recovery of *Quercus*, *Ulmus* and *Corylus*-type within a stable woodland, as shown by the consistent tree pollen curves and the lack of any significant herb pollen percentages (Fig. 8).

The final mid-Holocene pollen-stratigraphical event at PAB is the *Ulmus* Decline, a ubiquitous feature in pollen records of this period in northern England and more widely, occurring at about 5800 cal. BP (Parker et al., 2002), the *Ulmus* Decline date of 5210 $\pm$ 52 ^{14}C BP at Hartlepool Bay (Innes et al., 2005) being typical and a good local example. At PAB, this event is not only identified by the sharp fall in elm pollen frequencies, but also by the radiocarbon date of 5090 $\pm$ 35 ^{14}C BP (5745–5915 cal. BP) 10 cm above it, which shows that the date of the PAB Elm Decline accords with the typical dates from lowland sites in the region (Griffiths and Gearey, 2017). Regarded as multi-causal, with climate, disease and human activity all likely factors, the structure of the *Ulmus* Decline varies from site to site. At PAB, elm values, both percentage and concentration, fall to almost zero but there are almost no signs of forest clearance and human activity. There is a small increase in *Calluna*, perhaps surprising in this calcareous environment, and the start of a *Fraxinus* curve, ash being favoured on these calcareous soils (Wardle, 1961) and suggesting a more open woodland structure. Total herb pollen percentages rise markedly (Fig. 7) but the increase is in wetland types, mainly Cyperaceae, and only an isolated *Plantago lanceolata* grain well above the *Ulmus* Decline indicates any open-ground habitats. *Alnus* frequencies double to around 80 % of total land pollen at the *Ulmus* Decline. As there are no indicators of disturbance or land use, such as cereal-type grains, *Plantago lanceolata* or other ruderal weeds as is clearly seen in some other regional pollen profiles, such as at Newby Wiske (Bridgland et al., 2011) or Thorpe Bulmer (Bartley et al., 1976), this alder expansion, and probably also the *Ulmus* decline itself, can be attributed to climatic deterioration and increased wetness such as is recorded in bog profiles from this time (Tipping, 1995; Hughes et al., 2000; Cayless and Tipping, 2002). The records point to alder-carr expansion, coincident with the *Ulmus* Decline at many sites in the area, such as Cranberry Bog (Turner and Kershaw, 1973) and The Flasks 69 (Innes et al., 2009), and more regionally in southern Scotland (Cayless and Tipping, 2002).

The absence of pollen evidence of human activity in connection with the *Ulmus* Decline at PAB, both locally and regionally, matches records from other nearby sites, such as Seamer Carrs (Jones, 1976) and Neasham Fen (Bartley et al., 1976) in the Tees valley. This contrasts with most Elm Decline pollen evidence in the south of the area. For example, there is heavy clearance evidence at nearby Newby Wiske (Bridgland et al., 2011) with high frequencies of ruderal weeds including *P. lanceolata*, charcoal and a consistently high cereal-pollen curve, indicative of substantial forest clearance and Neolithic agriculture. Nearby, cereal pollen at the Elm Decline is also recorded at Langland's Farm (Bridgland et al., 2011) and Gormire Lake (Blackham et al., 1981). To the north of PAB, at Cranberry Bog (Turner and Kershaw, 1973) and Shibdon Pond (Passmore et al., 1992), there is some pollen evidence for forest opening, with rising *Calluna* and *Fraxinus*, and *P. lanceolata* occurring, although without cereals recorded. Further north in Northumberland (Davies and Turner, 1979), there is almost no indication of woodland disturbance or Neolithic land use at or after the *Ulmus* Decline. At less distance to the north of PAB in Durham, such as at Bishop Middleham (Bartley et al., 1976) and Hartlepool Bay (Innes et al., 2005), evidence for human activity and forest opening at the *Ulmus* Decline is very muted, as at PAB, whereas sites to the south of PAB in North Yorkshire, particularly at Newby Wiske on its favourable calcareous soils, show much more evidence of early Neolithic land use and woodland disturbance. This is an example of palaeoenvironmental variability on a north–south gradient in northeast England, with PAB in this case part of the more northerly group of sites. Whilst there is archaeological evidence of a considerable early Neolithic cultural presence throughout the North Yorkshire/Durham region (Hey and Frodsham, 2021), in its earliest phase at the time of the Elm Decline Neolithic farming populations might have been low and their environmental impacts slight except at more favourable locations (Edwards, 1993), with climate and generally poor soils making the more northerly parts of the region less suitable for more land use at this time (Innes, 1999).

5.2. Fire history

An important aspect of the palaeoenvironmental record at PAB is the history of fire in the landscape as expressed in the charcoal record. That there is no macrofossil charcoal present in the lithostratigraphies of any of the cores in the lake basin is perhaps surprising when compared to the significant microcharcoal presence. Much of the sediment preserved in the cores is detrital in nature, mostly clastic in the Lateglacial period, then a combination of clastic and organic sediment occurs in the Holocene part of the profiles, and so any burning within the lake catchment might be expected to have provided macroscopic charcoal to be washed into the lake by overland flow as the main transport mechanism, across the unstable soils of the poorly vegetated terrain. The open Lateglacial vegetation suggested by the pollen data (Fig. 6) and the paucity of plant macrofossils (Fig. 4), indicating much bare ground between any isolated birch and juniper bushes that were present, might well be the reason for the local absence of fire, with little fuel to carry flames. Burning beyond the small lake basin however, where vegetation might have been better established, seems to have been almost ubiquitous through Lateglacial times, although variable in scale, with wind-blown microcharcoal continually carried to deposition in the lake, directly or *via* inwash from catchment slopes. The variable but generally very low concentrations of microcharcoal particles (Fig. 8), however, indicate that any burning in the microfossil source area was of low intensity and intermittent. The relatively low values of *Betula* in the pollen catchment area might themselves be a function of the low scale but consistent presence of fire, as fire retards succession and stimulates regeneration communities (Veblen, 1992), reverting vegetation to an earlier seral stage, and this might have been responsible for the local inability to establish birch woodland.

The consistent presence of microcharcoal, often in high values, has been recognised for some time in Lateglacial sediments (Pennington, 1977; Edwards et al., 2000), and is a common feature at Lateglacial sites in the region. Microcharcoal frequencies often peak during the cold and arid phases of the Lateglacial (Lincoln et al., 2020), and this also occurs at PAB in early zone PAB-a, in late zone PAB-b and the later stages of zones PAB-c and PAB-d, the latter being the second half of the Loch Lomond Stadial (GS-1), which had a severely cold and arid climate (Walker et al., 1993; Mayle et al., 1999). Natural ignition sources such as lightning strike might be expected to have been more effective under such arid conditions. The vegetation subject to such burning cannot be identified from the microcharcoal itself, but as both concentration and percentage data (Figs. 5 and 7) suggest that *Juniperus* comprised much of the more local vegetation in the Lateglacial, perhaps juniper bushes, with some *Salix* and *Empetrum* heath, might have been the main vegetation affected. Lincoln et al. (2017a) recorded charred juniper macrofossils at Wykeham Quarry in the Vale of Pickering representing Lateglacial periods of increased fire frequency. Microcharcoal could also have derived from longer-distance transport, perhaps of *Pinus*, and some older microcharcoal would probably have been reworked and introduced to the profile with soils eroded from the catchment under cold Lateglacial conditions, as suggested by the presence throughout the Lateglacial sediments of pre-Quaternary spores.

Continuous Lateglacial microcharcoal frequencies closely analogous to those at PAB have been recorded in the nearby Vale of Mowbray at Mill House and The Flasks, Nosterfield (Innes et al., 2009), at Newby Wiske (Bridgland et al., 2011), and at Killerby Quarry (Hudson et al., 2023), with several sites in the Vale of Pickering, in North Yorkshire, also yielding substantial Lateglacial charcoal records (Day, 1996; Abrook, 2017; Lincoln et al., 2017b; Simmons. et al., 2022). There is substantial archaeological evidence that Palaeolithic humans were present in North Yorkshire during the Lateglacial (Schadla-Hall, 1987; Sheldrick et al., 1997; Laurie, 2003; Conneller, 2007; Lord, 2013), even during the Loch Lomond Stadial (Gale and Hunt, 1985), and at Killerby and the Vale of Pickering microcharcoal and Palaeolithic flints occur together. The consistency and intensity of fire that the microcharcoal record represents, however, make it very unlikely that people were responsible for such significant burning, as neither domestic campfires nor game-driving would produce such a consistent record. Natural factors, particularly climate, must be considered as the primary cause, and as such must have been operative regionally. It is therefore likely that all Lateglacial deposits in the wider region will contain significant levels of microscopic charcoal, although in several earlier studies, such as the important Lateglacial sequence at Thorpe Bulmer in County Durham (Bartley et al., 1976), analysis of this proxy was not undertaken.

5.3. Regional variability

As illustrated in Table 4 and discussed in Sections 5.1.3 and 5.1.5, there was considerable variability along a north–south transect in northeast England in the composition and density of vegetation in the temperate climate phases before and after the severely cold Lateglacial Interstadial GS-1. In the final temperate phase of the Interstadial, GI-1a, sites to the north of the Tees valley had an impoverished woodland assemblage, with *Betula* woodland failing to be established and a more open vegetation with much *Juniperus* and other non-arboreal taxa typical. Sites furthest north on the transect, in north Northumberland (Bartley, 1966) and south-east Scotland (Webb and Moore, 1982), show the effects of this latitudinal influence on climate and vegetation most clearly. In contrast, sites to the south of the Tees valley in North Yorkshire had much higher *Betula* pollen values at this time, indicating the presence of a much better-developed birch woodland, as at Tadcaster (Bartley, 1962) in the Vale of York. In this final Interstadial phase Pepper Arden Bottoms falls into the northern group.

In the first phase of the Holocene, a similar dichotomy is apparent with sites north of the Tees valley initially showing poorly developed *Betula* woodland with a strong *Juniperus* component, as at Cranberry Bog (Turner and Kershaw, 1973), whereas at sites to the south of the Tees in northern North Yorkshire denser birch woodland was swiftly established, for example at The Flasks, Nosterfield and Newby Wiske, and at Marfield where earliest Holocene *Betula* frequencies reach 80 % (Bridgland et al., 2011; Innes et al., 2021). In this initial Holocene at PAB, *Betula* contributes up to 60 % of total land pollen, representing well-developed birch woodland and so similar to the more southerly sites of North Yorkshire. It seems that the Tees valley formed a boundary zone on a north–south environmental gradient during the Lateglacial to Holocene climate transition, with Pepper Arden Bottoms, on the edge of the Tees valley, as a pivotal indicator site, changing between the southern and northern groups of sites depending on changing environmental parameters.

There could be various reasons for the differences in vegetation development between the end-Interstadial temperate phase and the initial warm phase of the Holocene, as recorded at PAB. Temperature gradients are likely to have been most important (Birks and Birks, 2014; Brooks and Langdon, 2014), coupled with precipitation. In northeast England the switch to the early Holocene involved a greater and swifter rise to summer temperatures about 3 °C higher than the temperatures of GI-1a in the Interstadial, based on chironomid data from a site of comparable latitude in northern England (Bedford et al., 2004). This would promote more rapid movement through initial Holocene successional communities to the establishment of closed woodland in the warmer southerly areas, where their temperature tolerances would have allowed birch to out-compete and thus suppress the light-demanding juniper (Rodwell, 1991) in seral change, but less so in the cooler northerly sites (Webb and Moore, 1982), accounting for the spatial difference. Warmer temperatures inhibit *Juniperus* dispersal and seed viability (Gruwez et al., 2014), giving *Betula* a competitive advantage. The relatively lower temperatures of GI-1a would have hampered *Betula* and allowed the more cold-tolerant *Juniperus* (Thomas et al., 2007a) to maintain its local populations at PAB, which were very high in the preceding cooler phase GI-1b, through the inertia of the dominant vegetation, suppressing birch establishment, so placing PAB within the more northerly, and so cooler, vegetation group on the appreciable temperature gradient noted by Birks and Birks (2014) for the late Interstadial in northern England. Migration rates and the location of regional population refugia could also have played a lesser role in the colonisation of sites after climate change, with *Juniperus* rapidly dispersed from local populations by birds (Gruwez et al., 2014) and thus having an advantage over *Betula*. Over the period of the Lateglacial Interstadial, however, tree and shrub taxa would have had time to expand northwards from glacial refugia and become established in local populations near PAB, so that migration rates would not have been critical. Climatic limitation would have been the deciding factor in northeast England in the relative abundance of *Juniperus*, *Betula* and other taxa in the latest Interstadial and earliest Holocene.

6. Conclusions

Assuming there is no hiatus in the profile, for which there is no evidence, sedimentation began in this part of the PAB lake basin in the warm mid-Interstadial of the Lateglacial, during Greenland ice-core phase GI-1c. Although frequencies of *Betula* and *Juniperus* indicate some significant expansion of tree and tall-shrub parkland at this time, high frequencies of Cyperaceae and Poaceae indicate that vegetation around the lake was open and certainly not well wooded. Whilst sedges and grasses might have been mainly contributed by lakeside wetland plants, consistent values for open ground dryland herbs indicate very open vegetation. The late Interstadial colder phase GI-1b followed, with *Juniperus* supplanting *Betula*, before the final phase of the Interstadial, GI-1a, which introduced warmer conditions, with the first presence of thermophilous trees, including *Quercus* and *Corylus*-type, in very low frequencies. *Betula* and *Juniperus* failed to expand significantly, however, and the vegetation remained dominantly open. During the Loch Lomond Stadial, GS-1, vegetation was very open indeed and dominated by sedges and grasses, but surprisingly little *Artemisia*. Microcharcoal is common within the Lateglacial record but is completely absent from all but the earliest Holocene. During the Holocene the successive immigration of thermophilous trees occurred until the mid-Holocene *Ulmus* Decline, which at PAB, from the sedimentary record, was accompanied by very little human activity and forest disturbance.

The poor levels of woodland establishment and maintenance of open vegetation during the Lateglacial section of the PAB record show that the site is similar to other more northerly pollen records from this time in northeast England, in contrast to the more wooded sites of the period to the south in North Yorkshire. This is reflective of the south-to-north gradient in Lateglacial woodland cover in this region, confirming the evidence from sites in the adjacent Vale of Mowbray that shows failure of full woodland development to the north. This north–south dichotomy in northeast England is also present in the early Holocene pollen record at Pepper Arden Bottoms, but in the early Holocene PAB is more similar to sites to the south in being dominated by *Betula* woodland in contrast to the more open vegetation to the north. Future research aiming to investigate this dichotomy further should include the pollen analysis and radiocarbon dating of long peat sequences in southern Northumberland and north Durham, both Lateglacial and Holocene, as evidence from those areas is sparse at present.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pgeola.2024.08.005.

CRediT authorship contribution statement

James B. Innes: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Mairead M. Rutherford:** Methodology, Investigation, Formal analysis, Data curation. **David R. Bridgland:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ben R. Gearey:** Writing – review & editing, Methodology, Investigation. **Malcolm C. Lillie:** Writing – review & editing, Methodology, Investigation. **Wishart A. Mitchell:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Charlotte E. O'Brien:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Richard T. Jones:** Methodology, Investigation, Formal analysis. **Gareth J. Thompson:** Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Research by the Durham University Geography Department was funded by Aggregates Levy Sustainability Fund (ALSF) project 4814, administered by English Heritage, to reconstruct the environmental and human history of the Lower Tees Valley. We are very grateful to the Carstairs Countryside Trust for granting site access to MCL, BRG, RTJ and GJT. MCL and BRG performed the initial work at the site whilst at the Centre for Wetland Archaeology, University of Hull. We are grateful to the English Heritage Radiocarbon Dating team for the radiocarbon date, and to Chris Orton of the Cartography Unit, Geography Department, Durham University for the figures. We are very grateful to two anonymous referees who greatly improved the paper.

References

Abrook, A., 2017. Vegetation changes at palaeolake Flixton during the Late-glacial and early Holocene periods. In: Lincoln, P.C., Eddey, L.J., Matthews, I.P., Palmer, A.P., Bateman, M.D. (Eds.), The Quaternary of the Vale of Pickering: Field Guide. Quaternary Research Association, London, pp. 129–134.

Abrook, A., Matthews, I.P., Candy, I., Palmer, A.P., Francis, A.P., Turner, L., Brooks, S.J., Self, A.E., Milner, A.M., 2020. Complexity and asynchrony of climatic drivers and environmental responses during the last Glacial-Interglacial Transition (LGIT) in northwest Europe. Quaternary Science Reviews 250, 106634.

Alley, R.B., Ágústsdóttir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.

Ammann, B., van Leeuwen, J.F.N., van der Knaap, W.O., Lischke, H., Heiri, O., Tinner, W., 2013. Vegetation responses to rapid warming and to minor climatic fluctuations during the Late-glacial Interstadial (GI-1) at Gerzensee (Switzerland). Palaeogeography, Palaeoclimatology, Palaeoecology 391, 40–59.

Andresen, C.S., Björck, S., Bennike, O., Heinemeier, J., Kromer, B., 2000. What do $\Delta^{14}C$ changes across the Gerzensee oscillation/GI-1b event imply for deglacial oscillations? Journal of Quaternary Science 15, 203–214.

Andrieu, V., Huang, C.C., O'Connell, M., Paus, A., 1993. Lateglacial vegetation and environment in Ireland: first results from four western sites. Quaternary Science Reviews 12, 681–705.

Atkinson, M.D., 1992. *Betula pendula* Roth (*B. verrucosa* Ehrh.) and *B. pubescens* Ehrh. Journal of Ecology 80, 837–870.

Atkinson, T.C., Briffa, K.R., Coope, G.R., 1987. Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains. Nature 325, 587–592.

Bartley, D., 1962. The stratigraphy and pollen analysis of lake deposits near Tadcaster, Yorkshire. New Phytologist 61, 277–287.

Bartley, D., 1966. Pollen analysis of some lake deposits near Bamburgh in Northumberland. New Phytologist 65, 141–156.

Bartley, D., Chambers, C., Hart-Jones, B., 1976. The vegetational history of parts of south and east Durham. New Phytologist 77, 437–488.

Beckett, S.C., 1981. Pollen diagrams from Holderness. New Phytologist 8, 177–198.

Bedford, A., Jones, R.T., Lang, B., Brooks, S., Marshall, J.D., 2004. A Late-glacial chironomid record from Hawes Water, northwest England. Journal of Quaternary Science 19, 281–290.

Beijerinck, W., 1947. Zadenatlas der nederlandsche flora, Ten behoeve van de botanie, palaeontologie, bodemcultuur en warenkennis. Wageningen.

Bell, J.N.B., Tallis, J.H., 1973. Biological flora of the British Isles. *Empetrum nigrum*. Journal of Ecology 61, 289–305.

Bellamy, D.J., Bradshaw, M.E., Millington, M.R., Simmons, I.G., 1966. Two Quaternary deposits in the Tees basin. New Phytologist 65, 429–442.

Bennett, K.D., Humphry, R.W., 1995. Analysis of late-glacial and Holocene rates of vegetational change at two sites in the British Isles. Review of Palaeobotany and Palynology 85, 263–297.

Birks, H.H., 2003. The importance of plant macrofossils in the reconstruction of Late-glacial vegetation and climate: examples from Scotland, western Norway, and Minnesota, USA. Quaternary Science Reviews 22, 453–473.

Birks, H.H., Ammann, B., 2000. Two terrestrial records of rapid climate change during the glacial-Holocene transition (14,000 to 9000 calendar years B.P.) from Europe. Proceedings of the National Academy of Sciences 97, 1390–1394.

Birks, H.H., Birks, H.J.B., 2000. Future uses of pollen analysis must include plant macrofossils. Journal of Biogeography 27, 31–35.

Birks, H.J.B., Birks, H.H., 2008. Biological responses to rapid climate change at the Younger Dryas–Holocene transition at Krakenes, western Norway. The Holocene 18, 19–30.

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.

Björck, S., Rundgren, M., Ingólfsson, Ó., Funder, S., 1997. The Preboreal oscillation around the Nordic Seas; terrestrial and lacustrine responses. Journal of Quaternary Science 12, 455–465.

Björck, S., Walker, M.J.C., Cwynar, L.C., Johnsen, S., Knudsen, K.-L., Lowe, J.J., Wohlfarth, B., INTIMATE members, 1998. An event stratigraphy for the Last Termination in the North Atlantic Region based on the Greenland Ice-Core Record: a proposal by the Intimate Group. Journal of Quaternary Science 13, 283–292.

Blackburn, K., 1952. The dating of a deposit containing an elk skeleton found at Neasham, near Darlington, County Durham. New Phytologist 51, 364–377.

Blackham, A., Davies, C., Flenley, J., 1981. Evidence for late Devensian landslipping and late Flandrian forest regeneration at Gormire Lake, North Yorkshire. In: Neale, J., Flenley, J. (Eds.), The Quaternary in Britain. Pergamon Press, London, pp. 184–193.

Blockley, S.P., Lowe, J.J., Walker, M.J., Asioli, A., Trincardi, F., Coope, G.R., Donahue, R.E., 2004. Bayesian analysis of radiocarbon chronologies: examples from the European Late-glacial. Journal of Quaternary Science 19, 159–175.

Bohncke, S.J.P., Hoek, W.Z., 2007. Multiple oscillations during the Preboreal as recorded in a calcareous gyttja, Kingbeekdal, The Netherlands. Quaternary Science Reviews 26, 1965–1974.

Bos, J.A., van Geel, B., van der Plicht, J., Bohncke, S.J.P., 2007. Preboreal climate oscillations in Europe: wiggle-match dating and synthesis of Dutch high-resolution multi-proxy records. Quaternary Science Reviews 26, 1927–1950.

Bos, J.A., De Smedt, P., Demiddele, H., Hoek, W.Z., Langohr, R., Marcelino, V., Crombe, P., 2017. Multiple oscillations during the Lateglacial as recorded in a multi-proxy, high-resolution record of the Moervaart palaeolake (NW Belgium). Quaternary Science Reviews 162, 26–41.

Bridgland, D.R., Westaway, R., Howard, A.J., Innes, J.B., Long, A.J., Mitchell, W.A., White, M.J., White, T.S., 2010. The role of glacio-isostasy in the formation of post-glacial

river terraces in relation to the MIS 2 ice limit: evidence from northern England. Proceedings of the Geologists' Association 121, 113–127.
Bridgland, D.R., Innes, J.B., Long, A.J., Mitchell, W.A., 2011. Late Quaternary Landscape Evolution of the Swale–Ure Washlands, North Yorkshire. Oxbow Books, Oxford.
Brooks, S.J., Birks, H.J.B., 2000. Chironomid-inferred late-glacial air temperatures at Whitrig Bog, south-east Scotland. Journal of Quaternary Science 15, 759–764.
Brooks, S.J., Langdon, P.G., 2014. Summer temperature gradients in northwest Europe during the Lateglacial to early Holocene transition (15–8 ka BP) inferred from chironomid assemblages. Quaternary International 341, 80–90.
Brooks, S.J., Lowe, J.J., Mayle, F.E., 1997. Chironomid-based Late-glacial climatic reconstruction for southeast Scotland. Journal of Quaternary Science 12, 161–167.
Brown, A.P., 1971. *Empetrum* pollen record as a climatic indicator in Late Weichselian and Early Flandrian of the British Isles. New Phytologist 70, 841–849.
Brown, A.G., 1988. The palaeoecology of *Alnus* (alder) and the postglacial history of floodplain vegetation. Pollen percentage and influx data from the West Midlands, United Kingdom. New Phytologist 110, 425–436.
Candy, I., Farry, A., Darvill, C.M., Palmer, A., Blockley, S.P.E., Matthews, I.P., MacLeod, A., Deeprose, L., Farley, N., Kearney, R., Conneller, C., Taylor, B., Milner, N., 2015. The evolution of Palaeolake Flixton and the environmental context of Star Carr: II. An oxygen and carbon isotopic record of environmental change for the early Holocene. Proceedings of the Geologists' Association 126, 60–71.
Candy, I., Abrook, A., Elliot, F., Lincoln, P., Matthews, I.P., Palmer, A., 2016. Oxygen isotopic evidence for high-magnitude, abrupt climatic events during the Lateglacial Interstadial in north-west Europe: analysis of a lacustrine sequence from the site of Tirinie, Scottish Highlands. Journal of Quaternary Science 31, 607–621.
Cappers, R.T.J., Bekker, R.M., Jans, J.E.A., 2006. Digitale Zadenatlas van Nederland, Groningen.
Cayless, S.M., Tipping, R.M., 2002. Data on mid-Holocene climatic, vegetation and anthropogenic interactions at Stanshiel Rigg, southern Scotland. Vegetation History and Archaeobotany 11, 201–210.
Chambers, F.M., Elliott, L., 1989. Spread and expansion of *Alnus* Mill in the British Isles: timing, agencies and possible vectors. Journal of Biogeography 16, 541–550.
Clark, R.L., 1984. Effects on charcoal of pollen preparation procedures. Pollen et Spores 26, 559–576.
Clark, J.S., 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition and sampling. Quaternary Research 30, 81–91.
Clark, J.S., Patterson III, W.A., 1997. Background and local charcoal in sediments: scales of fire evidence in the paleorecord. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.), Sediment Records of Biomass Burning and Global Change, NATO ASI Series 1: Global Environmental Change, vol. 51. Springer, pp. 23–48.
Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012. Pattern and timing of retreat of the last British–Irish ice sheet. Quaternary Science Reviews 44, 112–146.
Cloutman, E.W., 1988. Palaeoenvironments in the Vale of Pickering. Part 2: environmental history at Seamer Carr. Proceedings of the Prehistoric Society 54, 21–36.
Conneller, C., 2007. Inhabiting new landscapes: settlement and mobility in Britain after the last glacial maximum. Oxford Journal of Archaeology 26, 215–237.
Coope, G.R., Lemdahl, G., Lowe, J.J., Walkling, A., 1998. Temperature gradients in northwestern Europe during the last glacial–interglacial transition (14–9 ^{14}C kyr BP) interpreted from coleopteran assemblages. Journal of Quaternary Science 13, 419–434.
Daley, T.J., Thomas, E.R., Holmes, J.A., Street-Perrott, F.A., Chapman, M.R., Tindall, J.C., Valdes, P.J., Loader, N.J., Marshall, J.D., Wolff, E.W., Hopley, P.J., Atkinson, T., Barber, K.E., Fisher, E.H., Robertson, I., Hughes, P.D.M., Roberts, C.N., 2011. The 8,200 yr BP cold event in stable isotope records from the North Atlantic region. Global and Planetary Change 79, 288–302.
Dansgaard, W., White, J.W.C., Johnsen, S.J., 1989. The abrupt termination of the Younger Dryas climate event. Nature 339, 532–534.
Davies, G., Turner, J., 1979. Pollen diagrams from Northumberland. New Phytologist 82, 783–804.
Davies, B.J., Livingstone, S.J., Roberts, D.H., Evans, D.J.A., Gheorghiu, D.M., Cofaigh, C.Ó., 2019. Dynamic ice stream retreat in the central sector of the last British–Irish Ice Sheet. Quaternary Science Reviews 225, 105989.
Day, S.P., 1996. Devensian Late-Glacial and Early Flandrian environmental history of The Vale of Pickering. Journal of Quaternary Science 11, 9–24.
Edwards, K.J., 1993. Models of forest farming for north-west Europe. In: Chambers, F.M. (Ed.), Climate Change and Human Impact on the Landscape. Chapman and Hall, London, pp. 134–145.
Edwards, K.J., Whittington, G., 1997. A 12000 year record of environmental change in the Lomond Hills, Fife, Scotland: vegetational and climatic variability. Vegetation History and Archaeobotany 6, 133–152.
Edwards, K.J., Whittington, G., 2000. Multiple charcoal profiles in a Scottish lake: taphonomy, fire ecology, human impact and inference. Palaeogeography, Palaeoclimatology, Palaeoecology 164, 67–86.
Edwards, K.J., Whittington, G., Tipping, R.M., 2000. The incidence of microscopic charcoal in late glacial deposits. Palaeogeography, Palaeoclimatology, Palaeoecology 164, 247–262.
Edwards, K.J., Langdon, P.G., Sugden, H., 2007. Separating climatic and possible human impacts in the early Holocene: biotic response around the time of the 8200 cal. yr BP event. Journal of Quaternary Science 22, 77–84.
Evans, D.J.A., Clark, C.D., Mitchell, W.A., 2005. The last British Ice sheet: a review of the evidence utilised in the compilation of the glacial map of Britain. Earth Science Reviews 70, 253–312.
Feurdean, A., Bhagwat, S.A., Willis, K.J., Birks, H.J.B., Lischke, H., Hickler, T., 2013. Tree migration-rates: narrowing the gap between inferred post-glacial rates and projected rates. PlosOne 8, e71797.
Franklin, J.F., Lindenmayer., D.B., MacMahon, J.A., McKee, A., Magnuson, S., Perry, D.A., Waide, R., Foster, D., 2000. Threads of continuity: ecosystem disturbances, biological legacies and ecosystem recovery. Conservation Biology in Practice 1, 8–16.
Frost, D.V., 1998. Geology of the country around Northallerton. Memoir of the Geological Survey. HMSO.
Gale, S.J., Hunt, C.O., 1985. The stratigraphy of Kirkhead cave, an Upper Palaeolithic site in northern England. Proceedings of the Prehistoric Society 51, 283–304.
Gearey, B.R., 2008. Lateglacial vegetation change in East Yorkshire: a radiocarbon dated pollen sequence from Routh Quarry, Beverley. Proceedings of the Yorkshire Geological Society 57, 113–122.
Gearey, B.R., Allison, E., 2010. Palaeoenvironmental evidence from deposits at Bedale, North Yorkshire. Yorkshire Archaeological Journal 82, 1–29.
Gearey, B.R., Lillie, M.C., 1999. Aspects of Holocene vegetational change in the Vale of York: palaeoenvironmental investigations at Askham Bog. In: van de Noort, R., Ellis, S. (Eds.), Wetland Heritage of the Vale of York, Centre for Wetland Archaeology. University of Hull, pp. 109–123.
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, 99–114.
Giesecke, T., Brewer, S., Finsinger, W., Leydet, M., Bradshaw, R.H.W., 2017. Patterns and dynamics of European vegetation change over the last 15,000 years. Journal of Biogeography 44, 1441–1456.
Giles, J.R.A., 1992. Late Devensian and early Flandrian environments at Dishforth Bog, North Yorkshire. Proceedings of the Yorkshire Geological Society 49, 1–10.
Griffiths, S., Gearey, B.R., 2017. The Mesolithic–Neolithic Transition and the chronology of the "Elm Decline": a case study from Yorkshire and Humberside, United Kingdom. Radiocarbon 59, 1321–1345.
Grimm, E.C., 1993. TILIA Software. Illinois State Museum, Chicago.
Grimm, E.C., 2004. TGView v. 2.0.2, Software. Illinois State Museum, Research and Collections Center, Springfield, IL.
Gruwez, R., De Frenne, P., De Schrijver, A., Leroux, O., Vangansbeke, P., Verheyen, K., 2014. Negative effects of temperature and atmospheric depositions on the seed viability of common juniper (*Juniperus communis*). Annals of Botany 113, 489–500.
Haslam, S., Sinker, C., Wolseley, P., 1975. British Water Plants. Field Studies Council Publications, vol. 4, pp. 243–351.
Head, K., Turney, C.S.M., Pilcher, J.R., Palmer, J.G., Baillie, M.G.L., 2007. Problems with identifying the '8200-year cold event' in terrestrial records of the Atlantic seaboard: a case study from Dooagh, Achill Island, Ireland. Journal of Quaternary Science 22, 65–75.
Hey, G., Frodsham, P., 2021. New Light on the Neolithic of Northern England. Oxbow Books, Oxford, UK.
Hoek, W.Z., 2001. Vegetation response to the ~14.7 and ~11.5 ka cal. BP climate transitions: is vegetation lagging climate? Global and Planetary Change 30, 103–115.
Hudson, S.M., Waddington, C., Pears, B., Ellis, N., Parker, L., Hamilton, D., Greve Alsos, I., Hughes, P., Brown, A., 2023. Lateglacial and Early Holocene palaeoenvironmental change and human activity at Killerby Quarry, North Yorkshire, UK. Journal of Quaternary Science 38, 403–422.
Hughes, P.D.M., Mauquoy, D., Barber, K.E., Langdon, P.G., 2000. Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. The Holocene 10, 465–479.
Hunt, C.O., Hall, A.R., Gilbertson, D.D., 1984. The palaeobotany of the Late-Devensian sequence at Skipsea Withow Mere. In: Gilbertson, D.D. (Ed.), Late Quaternary Environments and Man in Holderness, British Archaeological Reports, British Series, vol. 134, pp. 81–108 (Oxford).
Huntley, B., 1993. Rapid early-Holocene migration and high abundance of hazel (*Corylus avellana* L.): alternative hypotheses. In: Chambers, F.M. (Ed.), Climate Change and Human Impact on the Landscape. Chapman and Hall, London, UK, pp. 205–216.
Huntley, B., Birks, H.J.B., 1983. An Atlas of Past and Present Pollen Maps for Europe: 0–13000 Years Ago. Cambridge University Press, Cambridge, UK.
Innes, J.B., 1999. Regional vegetation history. In: Bridgland, D.R., Horton, B.P., Innes, J.B. (Eds.), The Quaternary of North-East England, Field Guide. Quaternary Research Association, London, pp. 21–34.
Innes, J.B., 2002. Introduction to the Late Glacial record of northern England. In: Huddart, D., Glasser, N.F. (Eds.), Quaternary of Northern England, Geological Conservation Review Series, vol. 25. Joint Nature Conservation Committee, pp. 211–220.
Innes, J.B., Blackford, J.J., 2023. Disturbance and succession in early to mid-Holocene northern English forests: palaeoecological evidence for disturbance of woodland ecosystems by Mesolithic hunter–gatherers. Forests 14, 719.
Innes, J.B., Simmons, I.G., 2000. Mid-Holocene charcoal stratigraphy, fire history and palaeoecology at North Gill, North York Moors, UK. Palaeogeography, Palaeoclimatology, Palaeoecology 164, 151–165.
Innes, J.B., Donaldson, M., Tooley, M.J., 2005. The palaeoenvironmental evidence. In: Waughman, M. (Ed.), Archaeology and Environment of Submerged Landscapes in Hartlepool Bay, England, Tees Archaeology Monograph Series, vol. 2, pp. 78–120.
Innes, J.B., Rutherford, M.M., O'Brien, C.E., Bridgland, D.R., Mitchell, W.A., Long, A.J., 2009. Late Devensian environments in the Vale of Mowbray, North Yorkshire, UK: evidence from palynology. Proceedings of the Geologists' Association 120, 199–208.
Innes, J.B., Mitchell, W., O'Brien, C., Roberts, D., Rutherford, M., Bridgland, D., 2021. A detailed record of deglacial and early Post-Glacial fluvial evolution: the River Ure in North Yorkshire, UK. Quaternary 4, 9.
Jankovská, V., Komárek, J., 2000. Indicative value of *Pediastrum* and other coccal green algae in palaeoecology. Folia Geobotanica 35, 59–73.
Jones, R.L., 1976. Late Quaternary vegetational history of the North York Moors IV: Seamer Carrs. Journal of Biogeography 3, 397–406.
Jones, R.L., 1977. Late Devensian deposits from Kildale, north-east Yorkshire. Proceedings of the Yorkshire Geological Society 41, 185–188.

Jones, R.L., Keen, D.H., Robinson, J.E., 2000. Devensian Lateglacial and early Holocene floral and faunal records from NE Northumberland. Proceedings of the Yorkshire Geological Society 53, 97–110.

Jones, R.T., Marshall, J.D., Crowley, S.F., Bedford, A., Richardson, N., Bloemendal, J., Oldfield, F., 2002. A high resolution, multiproxy Late-glacial record of climate change and intrasystem responses in northwest England. Journal of Quaternary Science 17, 329–340.

Karlsen, S.R., Elvebakk, E., Johansen, B., 2005. A vegetation-based method to map climatic variation in the Arctic-Boreal transition area of Finnmark, northeasternmost Norway. Journal of Biogeography 32, 1161–1186.

Katz, N.J., Katz, S.V., Kipiani, M.G., 1965. Atlas and Keys of Fruits and Seeds Occurring in the Quaternary Deposits of the USSR, Moscow.

Keen, D.H., Jones, R.L., Robinson, J.E., 1984. A Late Devensian and early Flandrian fauna and flora from Kildale. north-east Yorkshire. Proceedings of the Yorkshire Geological Society 44, 385–397.

Keen, D.H., Jones, R.L., Evans, R.A., Robinson, J.E., 1988. Faunal and floral assemblages from Bingley Bog, West Yorkshire and their significance for Late Devensian and early Flandrian environmental changes. Proceedings of the Yorkshire Geological Society 47, 125–138.

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.

Laurie, T.C., 2003. Researching the prehistory of Wensleydale, Swaledale and Teesdale. In: Manby, T.G., Moorhouse, S., Ottaway, P. (Eds.), The Archaeology of Yorkshire: An Assessment at the Beginning of the 21st Century; Occasional Paper 3. Yorkshire Archaeological Society, Leeds, UK, pp. 223–253.

Levesque, A.J., Mayle, F.E., Walker, I.R., Cwynar, L.C., 1993. The amphi-Atlantic oscillation: a proposed Late-Glacial climatic event. Quaternary Science Reviews 12, 629–643.

Lillie, M.C., Gearey, B.R., 1999. Further Lithostratigraphical and Biostratigraphical Investigations at Pepper Arden Bottoms, Hambleton District, North Yorkshire. Centre for Wetland Archaeology, University of Hull.

Lincoln, P.C., Matthews, I., Palmer, A., Blockley, S., 2017a. Palaeoenvironmental reconstructions from the northern extension of Wykeham Quarry. In: Lincoln, P.C., et al. (Eds.), The Quaternary of the Vale of Pickering: Field Guide. Quaternary Research Association, London, pp. 92–102.

Lincoln, P.C., Matthews, I., Palmer, A., Blockley, S., 2017b. Palaeoenvironmental reconstructions from the southern extension of Wykeham Quarry. In: Lincoln, P.C., Matthews, I., Palmer, A., Blockley, S., Lincoln, P.C., et al. (Eds.), The Quaternary of the Vale of Pickering: Field Guide. Quaternary Research Association, London, pp. 103–113.

Lincoln, P.C., Matthews, I., Palmer, A., Blockley, S., 2017c. Synthesis of records from Wykeham Quarry. In: Lincoln, P.C., Matthews, I., Palmer, A., Blockley, S., Lincoln, P.C., et al. (Eds.), The Quaternary of the Vale of Pickering: Field Guide. Quaternary Research Association, London, pp. 114–123.

Lincoln, P.C., Matthews, I.P., Palmer, A.P., Blockley, S.P.E., Staff, R.A., Candy, I., 2020. Hydroclimatic changes in the British Isles through the Last-Glacial–Interglacial Transition: multiproxy reconstructions from the Vale of Pickering, NE England. Quaternary Science Reviews 249, 106630.

Lord, T.C., 2013. The chronology of the Later Upper Palaeolithic recolonisation of Yorkshire: new results from AMS radiocarbon dating of objects from caves in the Yorkshire Dales. Prehistoric Yorkshire 50, 14–18.

Lowe, J.J., Walker, M.J.C., 1986. Lateglacial and early Flandrian environmental history of the Isle of Mull, Inner Hebrides, Scotland. Transactions of the Royal Society of Edinburgh: Earth Sciences 77, 1–20.

Lowe, J.J., Ammann, B., Birks, H.H., Björck, S., Coope, G.R., Cwynar, L., de Beaulieu, J.-L., Mott, R.J., Peteet, D.M., Walker, M.J.C., 1994. Climatic changes in areas adjacent to the North Atlantic during the last glacial–interglacial transition (14–9 ka BP): a contribution to IGCP-253. Journal of Quaternary Science 9, 185–198.

Lowe, J.J., Coope, R.G., Lemdahl, G., Walker, M.J.C., 1995. The Younger Dryas climate signal in land records from NW Europe. In: Troelstra, S.R., van Hinte, J.E., Ganssen, G.M. (Eds.), The Younger Dryas. Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam & Oxford, pp. 3–25.

Lowe, J.J., Birks, H.H., Brooks, S.J., Coope, G.R., Harkness, D.D., Mayle, F.E., Sheldrick, C., Turney, C.S.M., Walker, M.J.C., 1999. The chronology of palaeoenvironmental change during the Last Glacial–Holocene transition: towards an event stratigraphy for the British Isles. Journal of the Geological Society, London 156, 397–410.

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z., INTIMATE group, 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, 6–17.

Macpherson, J.B., 1980. Environmental change during the Loch Lomond Stadial: evidence from a site in the upper Spey Valley, Scotland. In: Lowe, J.J., Gray, J.M., Robinson, J.E. (Eds.), Studies in the Lateglacial of North-west Europe. Pergamon, Oxford, pp. 89–102.

Marshall, J.D., Jones, R.T., Crowley, S.F., Oldfield, F., Nash, S., Bedford, A., 2002. A high resolution Late-Glacial isotopic record from Hawes Water, north-west England: climatic oscillations: calibration and comparison of palaeotemperature proxies. Palaeogeography, Palaeoclimatology, Palaeoecology 185, 25–40.

Marshall, J.D., Lang, B., Crowley, S.F., Weedon, G.P., van Calsteren, P., Fisher, E.H., Holme, R., Holmes, J., 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.

Marshall, P., Bayliss, A., Meadows, J., Bronk Ramsey, C., Cook, G., van der Plicht, H., 2011. Appendix I. Radiocarbon dating. In: Bridgland et al. (Eds.), Late Quaternary Landscape Evolution of the Swale–Ure Washlands. Oxbow Books, Oxford, UK.

Matthews, I.P., Abrook, A., Lincoln, P.C., Palmer, A.P., 2017. The last glacial interglacial transition (16–8 ka BP) in north east England. In: Lincoln, P.C., Eddey, L.J., Matthews, I.P., Palmer, A.P., Bateman, M.D. (Eds.), The Quaternary of the Vale of Pickering: Field Guide. Quaternary Research Association, London, pp. 23–31.

Mayle, F.E., Lowe, J.J., Sheldrick, C., 1997. The Late Devensian Lateglacial palaeo-environmental record from Whitrig Bog, SE Scotland. 1. Lithostratigraphy, geochemistry and palaeobotany. Boreas 26, 279–295.

Mayle, F.E., Bell, M., Birks, H.H., Brooks, S.J., Coope, G.R., Lowe, J.J., Sheldrick, C., Shijie, L., Turney, C.S.M., Walker, M.J.C., 1999. Climate variations in Britain during the last glacial–Holocene transition (15.0–11.5 cal. ka BP): comparison with the GRIP ice-core record. Journal of the Geological Society, London 156, 411–423.

Mitchell, W.A., Bridgland, D.R., Innes, J.B., 2010. Late Quaternary evolution of the Tees–Swale interfluve east of the Pennines: the role of glaciation in the development of river systems in northern England. Proceedings of the Geologists' Association 121, 410–422.

Moore, J.A., 1986. Charophytes of Great Britain and Ireland. BSBI Handbook No 5 (London).

Morimoto, M., Morimoto, J., Moriya, Y., Nakamura,, F., 2013. Forest restoration following a windthrow : how legacy retention versus plantation after salvaging alters the trajectory of initial recovery. Landscape and Ecological Engineering 9, 259–270.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell, Oxford.

Nielsen, H., Sørensen, I., 1992. Taxonomy and stratigraphy of late-glacial *Pediastrum* taxa from Lysmosen, Denmark a preliminary study. Review of Palaeobotany and Palynology 74, 55–75.

Palmer, A.P., Matthews, I.P., Candy, I., Blockley, S.P.E., MacLeod, A., Darvill, C.M., Milner, M., Conneller, C., Taylor, B., 2015. The evolution of palaeolake Flixton and the environmental context of Star Carr, NE. Yorkshire: stratigraphy and sedimentology of the Last Glacial–Interglacial Transition (LGIT) lacustrine sequences. Proceedings of the Geologists' Association 126, 50–59.

Paus, A., Brooks, S.J., Haflidason, H., Halvorsen, L.S., 2023. From tundra to tree-birch; late-glacial and early Holocene environment and vegetation oscillations at the ecotonal positioned Bjerkreim, Dalane, SW Norway. Quaternary Science Reviews 320, 108347.

Parker, A.G., Goudie, A.S., Anderson, D.E., Robinson, M.A., Bonsall, C., 2002. A review of the mid-Holocene elm decline in the British Isles. Progress in Physical Geography 26, 1–45.

Passmore, D.G., Macklin, M.G., Stevenson, A.C., O'Brien, C.F., Davis, B.A.S., 1992. A Holocene alluvial sequence in the lower Tyne valley, northern Britain: a record of river response to environmental change. The Holocene 2, 138–147.

Pennington, W., 1977. The Late Devensian flora and vegetation of Britain. Philosophical Transactions of the Royal Society of London B280, 247–270.

Pennington, W., 1986. Lags in adjustment of vegetation to climate caused by the pace of soil development: evidence from Britain. Vegetatio 67, 105–118.

Prentice, I.C., 1986. Vegetation responses to past climatic variation. Vegetatio 67, 131–141.

Preston, C.D., Pearman, D.A., Dines, T.D., 2002. New Atlas of the British and Irish Flora. Oxford University Press, Oxford.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., et al., 2006. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research 111, D06102.

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.

Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., et al., 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.

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., et al., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62, 725–757.

Robinson, D., 1984. The estimation of the charcoal content of sediments. A comparison of methods on peat sections from the Isle of Arran. Circaea 2, 121–128.

Rodwell, J.S., 1991. British Plant Communities. Vol. 1. Woodland and Scrub. Cambridge University Press, Cambridge, UK.

Sarmaja-Korjonen, K., Seppänen, A., Bennike, O., 2006. *Pediastrum* algae from the classic late glacial Bølling Sø site, Denmark: response of aquatic biota to climate change. Review of Palaeobotany and Palynology 138, 95–107.

Schadla-Hall, R.T., 1987. Recent investigations of the early Mesolithic landscape in the Vale of Pickering. In: Rowley-Conwy, P.A., Zvelebil, M., Blankholm, H. (Eds.), Mesolithic Northwest Europe: Recent Trends. University of Sheffield Department of Archaeology and Prehistory, Sheffield, UK, pp. 46–54.

Sheldrick, C., Lowe, J.J., Reynier, M.J., 1997. Palaeolithic barbed point from Gransmoor, East Yorkshire, England. Proceedings of the Prehistoric Society 63, 359–370.

Silvertown, J., 1985. History of a latitudinal diversity gradient: woody plants in Europe 13,000–1000 years BP. Journal of Biogeography 12, 519–525.

Simmons., I.G., Cummins., G.E., Taylor., B., Innes., J.B., 2022. Lateglacial to Mid-Holocene vegetation history in the eastern Vale of Pickering, Northeast Yorkshire, UK: pollen diagrams from Palaeolake Flixton. Quaternary 5, 52.

Spikins, P., 1999. Mesolithic Northern England, environment, population and settlement. BAR British Series 283. Archaeopress, Oxford.

Stace, C., 1997. New Flora of the British Isles. 2nd Edition. Cambridge University Press, Cambridge.

Stewart, W.D.P., Pearson, M.C., 1967. Nodulation and nitrogen-fixation by *Hippophaë rhamnoides* L. in the field. Plant and Soil 26, 348–360.

Stockmarr, J., 1971. Tablets with spores used in pollen analysis. Pollen et Spores 13, 615–621.

Sugita, S., MacDonald, G.M., Larsen, C.P.S., 1997. Reconstruction of fire disturbance and forest succession from fossil pollen in lake sediments: potential and limitations. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.), Sediment Records of Biomass Burning and Global Change, NATO ASI Series, vol. I 51. Springer-Verlag, Berlin, pp. 387–412.
Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Röthlisberger, R., Seierstad, I., Steffensen, J.P., Vinther, B.M., 2008. A 60 000 year Greenland stratigraphic ice core chronology. Climate of the Past 4, 47–57.
Thomas, P.A., El-Barghathi, M., Polwart, A., 2007a. Biological flora of the British Isles: *Juniperus communis* L. Journal of Ecology 95, 1404–1440.
Thomas, E.R., Wolff, E., Mulvaney, R., Steffensen, J.P., Johnson, S.J., Arrowsmith, C., White, J.W.C., Vaughn, B., Popp, T., 2007b. The 8.2 ka BP event from Greenland ice cores. Quaternary Science Reviews 26, 70–81.
Tipping, R.M., 1985. Loch Lomond stadial *Artemisia* pollen assemblages and Loch Lomond Readvance regional firn line altitudes. Quaternary Newsletter 46, 1–11.
Tipping, R.M., 1987. The prospects for establishing synchroneity in the early postglacial pollen peak of *Juniperus* in the British Isles. Boreas 16, 155–163.
Tipping, R.M., 1995. Holocene evolution of a lowland Scottish landscape: Kirkpatrick Fleming I. Peat- and pollen-stratigraphic evidence for raised moss development and climatic change. The Holocene 5, 69–82.
Turner, J., Kershaw, A.P., 1973. A Late- and post-glacial pollen diagram from Cranberry Bog, near Beamish, County Durham. New Phytologist 72, 915–928.
Turner, F., Pott, R., Schwarz, A., Schwalb, A., 2014. Response of *Pediastrum* in German floodplain lakes to Late Glacial climate changes. Journal of Paleolimnology 52, 293–310.
Tzedakis, P.C., Emerson, B.C., Hewitt, G.M., 2013. Cryptic or mystic? Glacial tree refugia in northern Europe. TREE 28, 696–704.
van Asch, N., Lutz, A.F., Duijkers, M.C., Heiri, O., Brooks, S.J., Hoek, W.Z., 2012. Rapid climate change during the Weichselian Late-Glacial in Ireland: chironomid-inferred summer temperatures from Fiddaun, Co. Galway. Palaeogeography, Palaeoclimatology, Palaeoecology 315–316, 1–11.
van der Plicht, J., van Geel, B., Bohncke, S.J.P., Bos, J.A.A., Blaauw, M., Speranza, A.O.M., Muscheler, R., Björck, S., 2004. The Pre-Boreal climate reversal and a subsequent solar-forced climate shift. Journal of Quaternary Science 19, 263–269.
Veblen, T.T., 1992. Regeneration dynamics. In: Glenn-Lewin, D.C., Peet, R.K., Veblen, T.T. (Eds.), Plant Succession Theory and Prediction. Chapman & Hall, London, UK, pp. 152–187.
Vyner, B., 2003. The later Mesolithic. In: Butlin, R. (Ed.), Historical Atlas of North Yorkshire. Westbury, Otley, pp. 30–34.
Walker, M.J.C., 1995. Climatic changes in Europe during the Last Glacial/Interglacial Transition. Quaternary International 28, 63–76.
Walker, M.J.C., Harkness, D.D., 1990. Radiocarbon dating the Devensian Lateglacial in Britain, new evidence from Llanilid, South Wales. Journal of Quaternary Science 5, 135–144.
Walker, M.J.C., Lowe, J., 2019. Lateglacial environmental change in Scotland. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 110, 173–198.
Walker, M.J.C., Coope, G.R., Lowe, J.J., 1993. The Devensian (Weichselian) late-glacial palaeoenvironmental record from Gransmoor, East Yorkshire, England. Quaternary Science Reviews 12, 659–680.
Walker, M.J.C., Bohncke, S.J.P., Coope, G.R., O'Connell, M., Usinger, H., Verbruggen, C., 1994. The Devensian/Weichselian late glacial in northwest Europe (Ireland, Britain, north Belgium, the Netherlands, northwest Germany). Journal of Quaternary Science 9, 109–118.
Walker, M.J.C., Coope, G.R., Sheldrick, C., Turney, C.S.M., Lowe, J.J., Blockley, S.P.E., Harkness, D.D., 2003. Devensian Lateglacial environmental changes in Britain: a multi-proxy environmental record from Llanilid, South Wales, UK. Quaternary Science Reviews 22, 475–520.
Walker, M.J.C., Johnsen, S., Rasmussen, S.O., Popp, T., Steffensen, J.-P., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L.C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D.J., Nakagawa, T., Newnham, R., Schwander, J., 2009. Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. Journal of Quaternary Science 24, 3–17.
Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, L.C., Fisher, D.A., Long, A.J., Lowe, J.J., Newnham, R.M., Rasmussen, S.O., Weiss, H., 2012. Formal subdivision of the Holocene Series/Epoch: a discussion paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). Journal of Quaternary Science 27, 649–659.
Walker, M.J.C., Head, M.J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L., Fisher, D., Gkinis, V., Long, A., Lowe, J., Newnham, R., Rasmussen, S.O., Weiss, H., 2018. Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries. Episodes 41, 213–223.
Wardle, P., 1961. Biological flora of the British Isles: *Fraxinus excelsior*, L. Journal of Ecology 49, 739–751.
Waughman, M., 2017. Hunter–gatherers in an upland landscape: the Mesolithic period in North-East Yorkshire. Yorkshire Archaeological Journal 89, 1–22.
Webb, J.A., Moore, P.D., 1982. The Late Devensian vegetational history of the Whitlaw Mosses, southeast Scotland. New Phytologist 91, 341–398.
Weckström, K., Weckström, J., Yliniemi, L.M., Korhola, A., 2010. The ecology of *Pediastrum* (Chlorophyceae) in subarctic lakes and their potential as paleobioindicators. Journal of Paleolimnology 43, 61–73.
Whitlock, C., Millspaugh, S.H., 1996. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. The Holocene 6, 7–15.
Whittington, G., Fallick, A.E., Edwards, K.J., 1996. Stable oxygen isotope and pollen records from eastern Scotland and a consideration of Late-glacial and early Holocene climate change for Europe. Journal of Quaternary Science 11, 327–340.
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.
Wicks, K., Mithen, S., 2014. The impact of the abrupt 8.2 ka cold event on the Mesolithic population of western Scotland: a Bayesian chronological analysis using 'activity events' as a population proxy. Journal of Archaeological Science 45, 240–269.
Wilson, L.J., Austin, W.E.N., Jansen, E., 2002. The last British Ice Sheet: growth, maximum extent and deglaciation. Polar Research 21, 243–250.
Young, D.S., Green, C.P., Batchelor, C.R., Austin, P., Elias, S.A., Athersuch, J., Lincoln, P., 2021. Macrofossil evidence of alder (*Alnus* sp.) in Britain early in the Late Glacial Interstadial: implications for the northern cryptic refugia debate. Journal of Quaternary Science 36, 40–55.
Yu, Z., Eicher, U., 2001. Three amphi-Atlantic century-scale cold events during the Bølling-Allerød warm period. Géographie Physique et Quaternaire 55, 171–179.