

1 **The resilience of postglacial hunter-gatherers to abrupt climate change**

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1 Abstract

2

3 **Understanding the resilience of early societies to climate change is an essential part of**
4 **exploring the environmental sensitivity of human populations. There is significant**
5 **interest in the role of abrupt climate events as a driver of early Holocene human**
6 **activity, but there are very few well-dated records directly compared to local climate**
7 **archives. Here we present evidence from the internationally important Mesolithic site of**
8 **Star Carr showing occupation during the early Holocene, which is directly compared to**
9 **a high-resolution palaeoclimate record from neighbouring lake beds. We show that once**
10 **established there was intensive human activity at the site for several hundred years**
11 **when the community was subject to multiple, severe, abrupt climate events that**
12 **impacted air temperatures, the landscape and ecosystem of the region. However, these**
13 **new results show that occupation and activity at the site persisted regardless of the**
14 **environmental stresses experienced by this society. The Star Carr population displayed**
15 **a high-level of resilience to climate change, suggesting that postglacial populations were**
16 **not necessarily held hostage to the flickering switch of climate change. Instead we show**
17 **that local, intrinsic changes in the wetland environment were more significant in**
18 **determining human activity than the large-scale abrupt Early Holocene climate events.**

19

20

21 The response of prehistoric societies to abrupt climate change is fundamental to our
22 understanding of the resilience of early populations to environmental drivers^{1,2,3,4,5,6,7,8,9,10}.
23 Rapid changes in temperature and precipitation, and their concomitant impact on landscape
24 and ecosystems, have been argued to lead to adaptations within early societies or, in extreme
25 cases, the abandonment of a region^{7,8}.

26

27 In this respect the early part of the Holocene was a key time interval. This period was
28 characterized by numerous Abrupt Climatic Events (ACEs, defined here as centennial-scale
29 abrupt climatic oscillations), triggered by ice-ocean interaction during the final wastage of
30 northern hemisphere ice sheets^{11,12}, and was critical to the postglacial recolonization of
31 northern Europe. Of these ACEs, the impact of the 8.2 ka event has been most frequently
32 discussed^{2,3,6,7,8,9,10} because the evidence indicates that northwestern Europe was widely
33 populated by this time. Whilst some studies have argued that hunter-gatherer communities
34 showed resilience to the 8.2 ka event^{1,5,9}, other work suggests these societies were highly
35 susceptible to rapid climate forcing^{7,8,10}. In particular it has been argued that this climatic
36 event may have caused a crash in Mesolithic populations in Northern Britain^{7,8} and it has also
37 been linked with changes in the Irish Mesolithic¹⁰. Consequently, sensitivity of these hunter-
38 gatherer societies to environmental change and their resilience to ACEs continues to be
39 debated.

40

41 Other ACEs are known from the early Holocene (e.g. the pre-Boreal oscillation, 11.1 and 9.3
42 ka events), but there are comparatively few well-dated archaeological sites of this time
43 period. The impact on populations of these ACEs is therefore poorly understood. These
44 societies did not simply occupy northwest Europe but were the earliest populations to attempt

1 to recolonise this region after the last glacial, against a backdrop of some of the most extreme
2 ACEs known from the Holocene. Whether these populations were resilient to such events or
3 were susceptible to the environmental changes that they triggered is crucial to understanding
4 patterns of recolonisation in Europe at this time.

5
6 Resolving the effects of ACEs on early Holocene communities is problematic for two
7 reasons. The first relates to problems of producing high-resolution chronologies for
8 archaeological sites that can be directly compared with climatic events that may last only 100
9 years¹³. The second is that most archaeological studies directly compare human activity to
10 either local environmental archives (i.e. pollen), which may not conclusively record climatic
11 change, or the Greenland ice cores. With respect to the former, it has been argued that some
12 episodes of tree population decline in Britain during the early Holocene relate to
13 anthropogenic burning rather than climatic cooling¹⁴. Additionally, whilst the Greenland ice
14 cores contain clear expressions of ACEs¹⁵, this assumes that the climate forcing that triggers
15 an effect recorded in Greenland also forces significant changes in climates and different
16 environments of NW Europe. Studies of single sites with high-precision chronologies for
17 human activity that are directly compared to detailed palaeoclimate records from the same
18 location are extremely rare and yet it is this approach that is essential for investigating the
19 effects of ACEs on early societies.

20
21 This study adopts such an approach in order to examine the resilience of early populations to
22 ACEs. It is based on a detailed re-investigations of the early Holocene site of Star Carr; an
23 internationally-renowned Early Mesolithic site where a large assemblage of material culture
24 and faunal remains has been recovered from a stratified sequence of wetland deposits
25 accumulating at the edge of an extensive former lake basin (Palaeolake Flixton) in the Vale
26 of Pickering^{16,17,18,19,20,21,22} (Figure 1). This site has produced one of the largest Mesolithic
27 organic assemblages in Europe, the oldest evidence of carpentry in Europe in the form of
28 large wooden platforms, rare artefacts such as red deer antler headdresses/masks²³ (Figure 2),
29 and the earliest evidence for built structures in Britain¹⁸. Our analysis integrates this record
30 through a high-resolution archaeological chronology coupled with a multi-proxy
31 palaeoclimate record.

32 33 **Results – Re-investigation of the Palaeolake Flixton archaeology and landscape**

34 35 *Archaeological evidence*

36 The Bayesian age model for occupation at Star Carr (Methods) and a summary of the site
37 chronology are presented in Figures 3 and 4. The highest posterity density intervals for key
38 parameters are given in Supplementary Table 2.

39
40 The archaeological record includes the construction of ‘house’ structures, timber
41 platforms/trackways, economic activity, and more ritualized practices of deposition
42 (Supplementary Figure 1). Evidence of this kind is extremely rare within the record for
43 Northern Europe at this time and the site is unique within a British context. Some of the
44 earliest activity consists of humanly-modified woodworking debris within a natural lake edge

1 accumulation of brushwood (Supplementary Figure 2). Broadly contemporary with this is the
2 detrital wood scatter; a large, sub-linear arrangement of worked wood, laid down to stabilize
3 the soft basal deposits (Supplementary Figure 3). Within this, animal bone and a range of
4 artefacts were deposited. Occupation of the dryland also occurred at this time, represented by
5 a circular structure (central dryland structure); the earliest known ‘house’ structure in the
6 British Isles. In the following centuries a series of large timber platforms were laid down
7 within the lake-edge wetlands (Supplementary Figures 2 and 4) and large quantities of faunal
8 remains, antler headdresses/masks, and organic and stone artefacts were deposited into the
9 lake edge, whilst further structures were constructed on the dryland (Supplementary Figure
10 1). Occupation then became more episodic, with activity focusing on the edges of the
11 wetlands. These changes in human activity occurred against the progressive evolution of the
12 lake edge setting with a species-rich reedswamp environment forming in standing water
13 gradually becoming shallower and boggy before being succeeded by more terrestrial fen and
14 carr (Supplementary Figure 7).

15

16 *Palaeoclimates of the Palaeolake Flixton*

17 The deepest parts of the Palaeolake basin contains sediments spanning the period from the
18 late Dimlington stadial to the final transition of wetland from an open water body to peatland,
19 early in the Holocene²¹. To assess the interval represented by human occupation in the region,
20 a composite palaeoenvironmental record was constructed by combining data from two cores
21 that contained the best record of the Younger Dryas (Core C) and the earliest Holocene (Core
22 B)²¹. The age model was based on tephrochronology, radiocarbon dating and was integrated
23 with archaeological chronology (Methods and Supplementary sections 6 and 7).

24

25 The palaeoclimate record contains evidence for two ACEs in the early Holocene (ACE 1 =
26 the older, and ACE 2 = the younger). These are defined by a) cooling recorded in both
27 chironomid-inferred temperature reconstructions (C-IT) and $\delta^{18}\text{O}$ values, b) a centennial-
28 scale duration and c) a response in the local environment recorded in the vegetation
29 assemblage (Supplementary data 4 & 5; Supplementary Figures 6-12). As such they exhibit
30 all of the features of early Holocene climate oscillations as expressed in the British
31 record^{12,26,27}. ACE 1 is most strongly seen in the $\delta^{18}\text{O}$ signal (decline by $\sim 4\%$) along with a
32 1.5°C decline in C-IT summer temperatures. ACE 2 is clearly expressed in both the $\delta^{18}\text{O}$
33 signal (decline by $\sim 1.5\%$) and the C-IT record (decline by $\sim 1.5^\circ\text{C}$). Although the C-IT shifts
34 associated with ACE 1 and 2 are only just greater than the resolution of the technique, they
35 are considered valid as they occur in association with well-defined isotopic shifts
36 (Supplementary Figures 4 and 6). ACE 1 is coincident with the 11.4 ka event recorded in the
37 Greenland ice cores²⁸, whilst ACE 2 is coincident with an event at 11.1 ka recorded in
38 NGRIP (but not in GRIP or GISP). The magnitude of the $\delta^{18}\text{O}$ shifts associated with ACE 1
39 and 2 are also similar to those recorded in Greenland for the 11.4 ka, 9.3 ka and 8.2 ka events,
40 which all see shifts of ~ 1.5 to 2% ²⁸ (Figure 4 and 5). In Greenland this magnitude of isotopic
41 shift equates to a decadal average temperature decline of $\sim 3.3^\circ\text{C}$ for the latter event²⁹.

42

43 Our isotope-based estimates of temperature change for ACE 1 and 2 of $\sim 10^\circ\text{C}$ and 4°C
44 respectively (Supplementary section 7) are greater than those estimated from the Greenland

1 record. This is consistent with the widely acknowledged observation that temperature
2 changes of the same magnitude are more muted in carbonate isotopic records than those of
3 the ice cores³⁰. They are also greater than the C-IT reconstructions which reflects CI-T's
4 providing mean summer temperature estimates, whilst $\delta^{18}\text{O}$ are closer to mean annual
5 temperatures³¹. This implies that the ACE 1 and 2 temperature shifts were characterised by
6 cooling in both summer and mean annual temperatures. Furthermore, the climatic cooling
7 seen in ACE 1 and 2 can be considered of comparable or greater magnitude than that
8 associated with the 8.2 ka event (Figure 4 and 6). They are also associated with low
9 percentages of *Betula*, which in the case of ACE 2 leads to a pause in the early Holocene
10 *Betula* rise, coupled with increases in open ground taxa and/or indicators of landscape
11 instability³⁰ (Figure 5). All of this suggest that the ACE's are significant and extreme cooling
12 events, with perhaps the greatest impact on winter temperatures.

13

14 **Discussion – The nature of hunter-gatherer adaptation during the early Holocene at** 15 **Star Carr**

16 Star Carr represents some of the earliest evidence for postglacial re-occupation of the British
17 Isles and highlights the rapidity with which humans returned to the region after the onset of
18 the current interglacial. Despite an ostensibly temperate interglacial landscape, the
19 environment that these hunter-gatherer communities occupied was dominated by climatic
20 instability as ACEs changed both the climate and the environment of the region for many
21 generations. These ACEs caused cooling of several degrees for >100 years and caused a
22 pause in the development of a woodland environment.

23

24 The existence of human communities in a climatically unstable time interval invites two
25 questions. Firstly, did abrupt cooling events result in the region being abandoned by these
26 communities? Secondly, if these communities were resilient enough to persevere in a region
27 despite sudden cooling, did the activities and operation of these societies change or adapt?
28 These questions can be addressed by comparing the abrupt climatic events and the detail of
29 the Star Carr archaeological record. The first event, ACE 1, occurs close to the transition to
30 Holocene conditions and is only associated with the first, limited occupation of the site; the
31 brushwood, which is largely naturally occurring - having washed in or fallen from trees - with
32 some inclusions of worked wood demonstrating small-scale human activity in the area
33 (Figure 3). This suggests that initial climate instability represented in Palaeolake Flixton
34 palaeoenvironmental data may have delayed more intensive occupation of the site but this
35 cannot currently be proven. The 4°C annual cooling of ACE2, implied from isotopic
36 analysis, is as extreme as other events in the early Holocene²⁶ (Figure 6). ACE 2 is expressed
37 clearly in core B, and when combined with C-IT and pollen analyses, show that cooling
38 temperatures also coincide with an increase in shrub and herb taxa and a delay in the
39 transition into a tree-dominated landscape (Figure 5). Comparison between the timing and
40 structure of ACE 2 and the chronology of human activity allows us to make three important
41 observations in relation to the above questions.

42

43 Firstly, there is no hiatus in occupation during the climatic cooling of ACE 2 (Figure 4). The
44 evidence for this primarily comes from the detrital wood scatter, a large accumulation of

1 wood, about half of which is made up of wood-working debris (Supplementary Figure 6).
2 Within the wood scatter animal bones have also been deposited. One of the earliest deposits
3 is an elk cranium which was placed there at the start of the detrital wood sequence. This has
4 clear parallels with deposition of bundles of elk bones into a kettle hole at Lundy Mose; the
5 earliest Mesolithic date in Denmark³². At Star Carr, the detrital wood scatter continued to
6 accumulate for several centuries, with animal remains, barbed points, antler
7 headdresses/masks and utilised flint blades deposited. Of these, the most remarkable is the
8 partially articulated remains of at least two red deer and two antler headdresses/masks which
9 were deposited around an opening in the wood scatter. These activities are also consistent
10 with the early phases of dryland structure construction (Figure 4).

11
12 The second point is that ACE 2 triggers no change or adaptation in human activity. Whilst it
13 is impossible to be certain whether the earliest occupation at Star Carr pre-dated the onset of
14 ACE 2, our chronologies indicate that there is a 65% probability that this was the case. The
15 accumulation of brushwood (and its associated artefacts) and the detrital wood scatter both
16 probably continued beyond ACE 2 (97% and 77% probability respectively). After ACE 2 the
17 population of Star Carr continued to stabilise the lake edge using worked wood, as evidenced
18 by the three wooden platforms (Supplementary Figure 4 and 6). These are composed of larger
19 pieces of wood and with more structure (thus termed 'platforms') than the detrital wood
20 scatter. However, the construction of these platforms is coincidental with the shift in local
21 environment to a shallower and more extensive reed swamp allied to the expansion of tree
22 pollen in the palaeoenvironmental records, rather than any ACE. The construction of more
23 substantial wooden structures, thus, appears to result from a desire to maintain access to the
24 lake, due to local lake-level changes, and enabled by the availability of a greater number of
25 large trees. Despite these changes, the communities continued to deposit faunal remains and
26 artefacts into the lake edge. This is particularly evident in Clark's area, dating to after ACE 2
27 (Figure 4), where large quantities of faunal remains, headdresses/masks and barbed points
28 have been excavated.

29
30 Finally, the abandonment of platform construction and a shift to more sporadic activity across
31 the site is coincident with the transition from the reed swamp environment to a fen carr
32 setting. Therefore, the wetland environment resources that were provided by that ecosystem
33 and the main focus of human activity were lost, leading to the abandonment of the site
34 (Figure 4; Supplementary data 3, Supplementary Figure 5). Therefore, it is important to
35 highlight that whilst the populations at Star Carr were resilient to abrupt cooling events, the
36 major changes in activity at the site are coincident with intrinsic changes in local
37 environmental ecological conditions and not to external climate drivers.

38
39 The populations whose presence is recorded in the Palaeolake Flixton region were some of
40 the earliest postglacial re-colonizers of Northwest Europe¹⁹. Therefore, it may be logical to
41 assume that such societies would be highly susceptible to ACEs, given some arguments for
42 the impact of the 8.2 ka event on hunter-gatherer populations^{7,8}. However, this study
43 highlights that there is far greater complexity to the story. The slightly more significant
44 cooling of ACE 1 may be a limiting factor in the onset of the more intensive occupation of

1 Star Carr, while not causing complete lack of activity of the region. ACE 2 by contrast does
2 not appear to lead to any substantial impact on lifeways. It is possible that once established,
3 the Star Carr community were buffered from the cooling effects of ACE 2 by continued
4 access to a range of resources, such as red deer, which are unlikely to have been adversely
5 affected by the changes in climate and environment recorded here.

7 **Implications**

8
9 Star Carr is almost uniquely positioned to contribute to the debates surrounding the role of
10 abrupt climate change in the development and activity of early Holocene populations. Many
11 studies have considered the role of the 8.2 ka event on Mesolithic communities of northern
12 Europe. Whilst occupation at Star Carr occurred several millennia prior to this well-defined
13 event it is important to highlight that the magnitude of the ACEs recorded in the isotopic and
14 chironomid records at Star Carr are as large as, and in most cases larger than, those associated
15 with the 8.2 ka event in other British lake sequences. Furthermore, the length of time that
16 ACE 1 and 2 persisted for, *ca* 100 years, also makes them of comparable duration to the 8.2
17 ka event. The Star Carr community were clearly able to cope with this level of abrupt climate
18 change, as not only did they continue to occupy the region despite the occurrence of ACE 2
19 but their activities, lake-edge occupation and platform construction/usage, continued with
20 negligible evidence for climatically-induced change. Whilst much debate focusses on
21 whether ACEs in the early Holocene of Northwest Europe caused large-scale population
22 crashes, this study shows that when a high-precision archaeological chronology can be
23 directly compared with a local climate record, hunter-gatherer populations can show a high
24 degree of resilience to abrupt climate forcing. Thus when considering the impact of unstable
25 early Holocene climates on hunter-gatherer populations in northwest Europe, the evidence
26 from Star Carr indicates continuity and resilience throughout at least one ACE event.

27
28 Whilst the Star Carr dataset indicates a population with high resilience to an 8.2 ka-like ACE
29 it is probable that the magnitude and duration of the climatic event are only two of a number
30 of factors that dictate whether societies respond to climate forcing. Both ACE 1 and 2 occur
31 in the very earliest Holocene and impacted upon a society living in a relatively open
32 landscape. Whilst this study demonstrates that vegetation does respond to ACEs, the overall
33 characteristics of the landscape, a mosaic of open grassland with areas of shrub and
34 woodland, is maintained throughout. The 8.2 ka event occurs after closed woodland has
35 established itself across much of the British Isles and may lead to opening up of woodland
36 alongside a reduction in thermophilous taxa³³. Therefore, it is possible that the 8.2 ka event
37 may have had a different impact on the nature of resources, and by extension postglacial
38 societies, than earlier ACEs did. It is important to state, therefore, that the resilience of early
39 populations may change through time both in relation to the impact of ACEs on particular
40 ecological/landscape characteristics (and concomitant effect on resources) and the forms of
41 activity and practices of the early societies involved. The adoption of the site-specific
42 approach presented here, has allowed the specific human/climate interaction Holocene to be
43 investigated. It is important for future research on this topic that more high resolution site-
44 based studies are added to the record of hunter-gatherer archaeology to refine the evidence

1 from broader regional studies. This is particularly relevant as the pattern of human/climate
2 interaction that is seen at one site, may not be replicated at others. The ability to examine
3 many individual sites across a region with similar levels of resolution is necessary to test for
4 differences between communities and ecological settings, and avoid missing important detail
5 that allow us to understand the drivers behind both resilience and susceptibility to climate
6 change.

7 8 **Methods**

9 **A. Methods employed on site at Star Carr**

10 **A1. Archaeological excavations**

11 Each excavation context was given a unique number. Detailed sediment descriptions were
12 undertaken of all contexts encountered, and logged on a pro forma context record sheet.
13 Mineral sediments were described by principal grain size (gravel, coarse sand, fine sand, silt
14 and clay, or combinations thereof), sorting (well sorted to poorly sorted) and inclusions
15 (material forming less than 10% of the deposit), following the Museum of London
16 Archaeology Service (MoLAS) handbook. From 2010 the recording of the wetland deposits
17 followed a simplified, longhand version of the Troels-Smith method³⁴. All cut features were
18 recorded in plan, half sectioned, and the section hand drawn at an appropriate scale. Plans
19 were drawn in relation to planning points that were recorded three dimensionally using the
20 total station. Likewise, all section datum points were recorded using the total station.
21 Registers for contexts, drawings, samples, photographs, levels and recorded finds were kept
22 on recording sheets. All records were entered into excel spreadsheets during each season and
23 checked in post-excavation.

24 25 **A2. Macrofossil analysis**

26 Macrofossil analysis was undertaken on samples from three locations across the site in order
27 to establish the character of the local environment and the wetland context within which
28 human activity took place. In each case contiguous sequences of samples (25-50mm thick)
29 were taken through the complete sequence of detrital muds and peat at the lake edge,
30 spanning the entire stratigraphic range of the archaeological material. These were subsampled
31 (50 ml), and disaggregated by boiling in 10% sodium hydroxide. The material was then
32 washed through sieves (2 mm-125 microns) and examined under a Nikon SMZ45T stereo
33 microscope at x10 – x40 magnification. Material from the 2 mm-250 micron sieves that could
34 be identified to a taxonomic level (typically seeds, fruits, nuts/nutlets, oospores, and catkin
35 bud scales) were counted, with the exception of moss stems and water-lily seed fragments
36 (see below). The results were quantified and displayed using the C2 software³⁵. Small
37 fragments of water-lily seed, indeterminate aquatic plant tissue, fern sporangia and any highly
38 fragmented but identifiable plant macrofossils, were quantified on a scale of relative
39 abundance (0=absent, 1=sparse, 2=present, 3=abundant).

40

1 Wood identifications were carried out by taking thin sections from the radial, transverse and
2 transversal planes using a sharp razor blade, which were mounted on slides and examined
3 under x10-x30 magnification.

4

5 **B. The lacustrine record**

6 **B1. Core profiles**

7 The stratigraphy of the climatic events that occurred after the Last Glacial Maximum was
8 reconstructed through a detailed survey of the deposits of Palaeolake Flixton²¹ The core
9 stratigraphies were analysed for carbon content and CI-T, oxygen and carbon isotopes,
10 tephrochronology, pollen, and radiocarbon dating across the whole profiles of cores B and
11 C²¹ (see Supplementary information). High-resolution analyses then focussed on the early
12 Holocene and late Loch Lomond stadial sections. The age model of this record is constrained
13 by six radiocarbon ages, the presence of the Vedde Ash (at 523-522cm below surface in core
14 C) and correlation of four key biostratigraphic markers within previously well dated Star Carr
15 records (Supplementary Table 1). This model is defined by the OxCal CQL2 code,
16 `star_carr_climate_B_C_to_Vedde_final.oxcal`²; and summarised in supplementary Figures
17 13-15; and Supplementary Tables 2-4. The Younger Dryas/Holocene transition history
18 recorded in this sequence is broadly synchronous with the Greenland ice cores.

19 **B2. Pollen**

20 1cc pollen samples were extracted at 8cm resolution between 509-333cm and 4cm between
21 301-205cm in core B; and 12cm between 525-381cm and 4cm between 381-281cm in core C,
22 down to the Vedde Ash²¹ following standard procedures, including treatment with HCL,
23 acetolysis and Hydrofluoric Acid. Residues were mounted in Glycerine Jelly without
24 staining. A minimum count of 300 total land pollen (TLP) grains was obtained for all levels
25 using an Olympus CX41 binocular microscope (400x), aided by reference collections³⁶. All
26 land pollen, aquatic pollen and pteridophyte spores are presented as percentages of TLP.
27 Pollen diagrams were constructed using C2³⁵ with diagram zonation, using untransformed
28 TLP pollen data cut off at 2%, assisted by CONISS³⁷. All micro-charcoal greater than 5µm
29 was also counted.

30 **B3. Chironomids**

31 Chironomid larvae head capsules from the 3rd and 4th instars (developmental stages) are
32 typically preserved as fossils, are extracted and typically identified to genus or species
33 morphotype. They are excellent indicators of temperature as this influences their emergence,
34 flight, swarming, maturing of eggs and sexual activity. Samples for chironomids (~2 cm³ wet
35 weight) were disaggregated in 10% KOH and sieved to <90 µm, whilst retaining all head
36 capsules. Head capsules were picked and mounted on microscope slides in Hydro-Matrix,
37 and identified under x400 magnification. Subfossil chironomid taxonomy is based on Brooks
38 et al.³⁸. 122 chironomid samples were analysed from cores B and C covering the Early
39 Holocene and Loch Lomond stadial transition. Data were analysed using a transfer functions
40 for summer temperatures developed from Norwegian lakes³⁹.

1 **B4. Isotopes**

2 $\delta^{18}\text{O}$ of lacustrine carbonate is primarily controlled by the temperature at which carbonate
3 mineralisation occurs and the $\delta^{18}\text{O}$ value of the lake water. The latter is determined by the
4 $\delta^{18}\text{O}$ of rainfall, which is controlled by ~ air temperature, rainfall amount, seasonality and
5 distance from the moisture source⁴⁰. Stable carbon isotopic ratios ($\delta^{13}\text{C}$) are determined by ~
6 the amount of organic input and productivity in a lake, and, at this site, in-wash of
7 minerogenic carbonate from the surrounding chalk. The latter is an indicator of a detrital
8 component and we have excluded any paired isotope samples with a $\delta^{13}\text{C}$ value above 2, as
9 this is close to the bedrock value. 200 isotope samples were taken from the Star Carr core B
10 over between 2-5 m depth; approximately 20-23 m OD, with the Early Holocene (2-3 m)
11 analysed in greatest detail. 26 samples were taken from core C 2.83-4 m depth in core (c. 21
12 to 19.83 m OD). Carbonates were sampled at 10 mm, disaggregated in sodium
13 hexametaphosphate and sieved over a 63 micron mesh with the > 63 micron fraction used for
14 further analyses. Samples were treated with hydrogen peroxide, weighed in a microbalance
15 and isotopes measured on the liberated fraction of CO_2 after reaction with phosphoric acid at
16 90°C , and are reported with reference to VPDB standard.

17 **B5. Sampling for Radiocarbon Dating**

18 1 cm wide sections were contiguously cut from the core B, then sub-sampled by taking 2.5cm
19 x 2.5cm x 1cm thick blocks from the central part of the disc. The outer edges of each
20 subsample were cleaned and stored at 4°C prior to sieving.

21
22 Samples were sieved over a 200 micron mesh and macrofossil material was cold-stored in
23 glass vials with acidified water. Terrestrial macrofossil remains were picked using a low
24 powered binocular microscope (10-40x magnification) and identified using reference
25 collections and manuals⁴¹.

26
27 To avoid possible hard-water error from a site on a carbonate bedrock, sampling was
28 restricted to what were thought to be terrestrial plant macrofossils. Where possible,
29 macrofossils of leaves, fruit, bud and catkin scales from *Betula* sp. and *Populus* sp. were
30 selected. These were sparse, thus, *Carex* sp. seeds were also isolated. In some cases, small
31 fragments of what were thought to be sedge remains had to be bulked together to provide
32 sufficient material. Given some enriched $\delta^{13}\text{C}$ values (SI), unidentifiable remains of
33 freshwater plants appear to have been incorporated in some samples. Where individual
34 centimetres could not provide sufficient material for dating, macrofossils from adjacent slices
35 were amalgamated. Samples were then analysed at the University of Oxford Radiocarbon
36 Accelerator Unit.

37 **C. Radiocarbon dating, Bayesian chronological modelling**

38

39 **C1. The archaeological and palaeoenvironmental model**

40 200 radiocarbon measurements are available from archaeological and lake-edge
41 environmental deposits²⁵. A complex Bayesian chronological model has been constructed to
42 estimate the dates of different aspects of human activity at Star Carr and the contemporary

1 local environment at the lake-edge. The dating evidence and chronological model is fully
2 defined by the OxCal CQL2 code files provided here (the principal part of the model is
3 defined by “star_carr_combined_all_v3.oxcal”, with additional parameters calculated by
4 “star_carr_combined_all_v3_additional.oxcal”). The basic principle behind this model is that
5 relationships between radiocarbon dates associated with human activity and radiocarbon
6 dates associated with environmental sequences and events are implemented together, and
7 then cross reference is made to these constrained distributions in considering the chronologies
8 of the human activity and lake edge environment respectively. For example, the dates on
9 artefacts from the detrital wood scatter from Trench 34 were recovered from fine detrital mud
10 that must post-date the start of organic sedimentation in the adjacent environmental profile
11 3178. This date estimate also, however, provides information on when environmental Zone 1
12 began in a specific part of the lake edge. The parameter *onset organics 3178* therefore cross-
13 refers to both the archaeological and environmental parts of the model and is constrained by
14 relationships of both types.

15 **C2. Radiocarbon dating**

16 Establishing a robust chronology for the climate record in the vicinity of Star Carr has been
17 challenging because of the poor preservation of macrofossils from terrestrial plants within the
18 studied sediments. This constrained both the number of samples that could be dated, and the
19 character of the material that was isolated for dating. This analysis covers the early Holocene
20 part of core B (above 298–300cm) and the upper part of core C (above 522–3cm, the depth
21 marking the Vedde ash²¹). Six radiocarbon measurements on waterlogged plant macrofossils
22 were obtained on the upper part of core B by the Oxford Radiocarbon Accelerator Unit in
23 2015. All samples were pretreated using acid-base-acid, graphitised and dated by AMS⁴² and
24 they are reported in Supplementary section 7.

25
26 The model for the chronology of the lacustrine sediments is based on two inter-linked age-
27 depth models for the upper parts of cores B and C. Both are poisson process depositional
28 models⁴³ implemented using a variable rigidity parameter and the general outlier model
29 proposed in⁴⁴. Dates have been interpolated every centimetre. The age model of this record is
30 constrained by six radiocarbon ages, the presence of the Vedde Ash (at 523-522cm below
31 surface in core C) and correlation of four key biostratigraphic markers within previously well
32 dated Star Carr records (Supplementary data 6; Supplementary Tables 3 and 4,
33 Supplementary Figure 14). This model is defined by the OxCal CQL2 code, provided as
34 supplementary information (Supplementary Figures 13-15; Supplementary Tables 2-4; data
35 file star_carr_climate_B_C_to_Vedde_final.oxcal²⁴). The Younger Dryas/Holocene transition
36 history recorded in this sequence is broadly synchronous with the Greenland ice cores.

37 Core B has six radiocarbon ages from five depths in the core. Mixed-source calibration (see
38 above) has been used for the lowest three measurements, including the two from replicate
39 macrofossil samples at a depth of 285cm. Each result at this level has first been calibrated
40 using the specific calibration curve derived from the mixing model, and then the calibrated
41 dates combined to provide an estimate for the date of sediment deposition at this depth

1 (*Rumex_peak*). The upper three measurements have been calibrated using a fully terrestrial
2 calibration curve⁴⁵.

3 Core C contains the Vedde Ash at a depth of 522–3cm. We recalculated the combined age-
4 depth model which includes the integrated age of this tephra⁴⁶ at a resolution of 1 year to
5 ensure compatibility with the archaeological and lake-edge palaeoenvironmental model
6 (Bronk_Ramsey_tephra_model.oxcal), and imported the resultant posterior distribution for
7 the Vedde ash as a prior distribution at the relevant depth in Core C. A potential change in
8 deposition rate was modelled at the transition from clay to marl.

9 The two age-depth models for Cores B and C were then inter-related using a series of
10 biostratigraphic tie points (Supplementary Figure 14), and Core B was similarly related to
11 lake-edge monolith M1 from the archaeological investigations, that is built into the overall
12 age model for Star Carr archaeology^{25,47}. Appropriate correlation points were determined by
13 observations of similar trends in each of the pollen diagrams. Pollen taxa that relate to very
14 local influence were not selected, and neither were taxa that were found in very low
15 abundance, thus ensuring that the correlation is as robust as possible.

16

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18

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11

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22

23 **Author Contributions**

24 S.B., I.C., I.M., P.Lan., A.P. designed and directed the climate and environmental analysis.
25 S.B. and A.M. analysed tephra, I.C. directed carbon and oxygen isotope analyses, these were
26 conducted by L.D., C.D., R.K., I.M. and A.A. analysed pollen data, A.P., S.B., I.M., A.A.,
27 A.M., I.C. and P.L. analysed lake topography and sediments, B.T. analysed macrofossil data
28 from the site, M.B. and M.T. analysed the archaeological wood and platforms. P. Lan and
29 C.L. analysed chironomid samples, R.S. carried out the radiocarbon dating, A.B. carried out
30 the Bayesian modelling, with assistance from I.M., S.B., A.P., A.A., C.C., B.T. P.L. and
31 N.M. N.B. carried out the source proportion mixing model. N.M., B.T., C.C. designed and
32 directed the archaeological excavation. NM was granted funding. S.B., I.C., A.B., P. Lan. and
33 NM led the writing of the paper and all authors contributed to the writing, discussed the
34 results and commented on the manuscript.

35

36 **Competing Financial Interests Statement**

37 The authors declare no competing financial interests.

38

39 **Data Availability Statement**

40 All relevant data supporting figures in the text is available in the main Supplementary
41 Information PDF with the exception of the full OxCal codes, which have been uploaded as
42 separate SI files and can be used to reconstruct the site age models. The specific OxCal codes
43 for each element are highlighted in Supplementary Information section 7.

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Figure Legends

Figure 1: The context for the site: (a) Greenland ice core record of the Last Glacial to interglacial Transition, highlighting abrupt events and the timeline for archaeological occupation events; maps showing the position of Star Carr with relevance to; B) Location of the site in its European context, B1 location within North East England, B2 Sites around Palaeolake Flixton; C) borehole survey results for the Star Carr area of Palaeolake Flixton and; D) stratigraphic logs and CaCO₃ results.

Figure 2: An antler headdress/mask from Star Carr. This was found in 2015 within Clark's area (Photo: Neil Gevaux).

Figure 3: Probability distributions of key parameters of archaeological activities at Star Carr. *OxA-3349* is the start of burning 1, *OxA-33662* is the dated timber from the eastern platform, *SUERC-59177* is the bark mat, and *OxA-25240* is the bow, derived from the model defined exactly by the OxCal⁴⁸ CQL2 code files provided in supplementary information (*star_carr_combined_all_v3.oxcal* and *star_carr_combined_all_v3_additional.oxcal*) all on the IntCal13 timescale⁴³.

Figure 4: The main elements of the occupation of Star Carr against key palaeoenvironmental indicators for Palaeolake Flixton: Pollen for cores B and C, carbon and oxygen isotopes for cores B and C and Chironomid-Inferred temperatures for cores B and C, all plotted against the chronologies provided by the Bayesian age model (see Supplementary data).

Figure 5: Summary pollen and isotopic results for core B against depth: showing the local ecological impact of the ACE 2 event, in particular the pause in the Early Holocene *Betula* rise and total land pollen, and the peak in *Salix* and *Juniperus*.

- 1 **Figure 6: The structure of the climatic shifts for ACE 2 in comparison with other data:**
- 2 detailing the $\delta^{18}\text{O}$ and C-IT against the same data for best record for the UK expression of the
- 3 8.2 ka BP event in Northern England, from Hawes Water ($\delta^{18}\text{O}^{26}$; C-IT⁴⁹), Northeast
- 4 England. All records have been chronologically centred on the coldest point of each profile.







