JOURNAL OF QUATERNARY SCIENCE (2024) **39**(7) 987–1010 ISSN 0267-8179. DOI: 10.1002/jqs.3641

JQS Journal of Quaternary Science QRA Quaternary Research Association

Advancing chronologies for Last Interglacial sequences

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Received 19 February 2024; Revised 24 May 2024; Accepted 31 May 2024

ABSTRACT: Studies of the Last Interglacial (ca. 129 to 116 ka BP) provide an opportunity to study the impact of high-latitude warm temperatures on the Earth system. To build an accurate spatio-temporal picture of climate and environmental variability during the Last Interglacial, building robust chronologies, through which the patchwork of terrestrial, marine, and ice core archives can be correlated, is paramount. In this review, we briefly evaluate the most common approaches used to date climate and environmental archives from the Last Interglacial, as well as the chronostratigraphic tools available for direct correlation between sequences, with a focus on terrestrial archives. We then present a case study on the use of pollen biostratigraphy for correlating sequences in NW Europe, highlighting its strength as a local correlation tool, and the challenges this approach presents in comparing sequences to global records of climate and environmental change. A move towards consistently dated sequences will improve our understanding of environmental responses to Last Interglacial climate variability across different elements of the global climate system and the rates at which different elements of the climate system respond to changes in global temperatures. © 2024 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: chronology; climate; Eemian; Last Interglacial; palynology

Introduction

During the Last Interglacial period, high-latitude regions experienced temperatures warmer than those of the present day (Capron et al., 2014). Detailed studies of the Last Interglacial palaeoarchives can provide important information on the nature, magnitude and rate of the environmental response to climate change. As such, the Last Interglacial can be used to test climate and ice-sheet models, capturing changes in the Earth's climate and ice-sheet processes not recorded in observational records (DeConto and Pollard, 2016; Edwards et al., 2019; Gilford et al., 2020). Due to differing orbital configurations, the amount, distribution and timing of heightened solar insolation at the Earth's surface differ between the Last Interglacial and the current Holocene interglacial (Laskar et al., 2004); therefore, the Last Interglacial interval is far from a perfect analogue for ongoing climate change (Yin and Berger, 2015). Studying the Last Interglacial does, however, allow us to assess the impact that increased high-latitude temperatures can have on climate-sensitive components of the Earth system, including ecosystems, ice sheets and sea level.

Archives that span from the Last Interglacial to the present are limited, meaning that high-resolution studies of Last Interglacial climate and environmental change rely on a patchwork of stratigraphically disparate deposits (Fig. 1). Therefore, to build a comprehensive picture of Earth system responses during the Last Interglacial, it is paramount to have accurately date and correlate sequences to allow response times and leads and lags in the Earth system to be resolved. Across the Last Glacial and Holocene periods, a focus on robust chronologies, primarily through radiocarbon dating, annually laminated lake and ice-core records and tephrostratigraphies, has yielded valuable insights into leads and lags in the global climate system, as well as the interactions between, and environmental responses to, different climate forcing mechanisms (Lane et al., 2013; Brauer et al., 2014). The construction of robust chronologies for Last Interglacial sequences is, however, far more challenging as the time period sits beyond the upper limit of radiocarbon dating and calibration (ca. 55 ka BP; Reimer et al., 2020).

Sediments of the Last Interglacial age have been recognised and studied in NW Europe for decades (Fig. 1), typically in greater detail than in any other region, making it one of the richest archives of shifting climate and environment across the period (Turner, 2000). However, many of these archives have only been dated through means of lithostratigraphical and biostratigraphical correlation. The timing of the Last Interglacial was unlikely to have been synchronous between, or even within, regions. As a result, terrestrially, sediments are often assigned to a regional stratotype. The Last Interglacial is termed the Eemian in NW Europe (Zagwijn, 1961; Cleveringa et al., 2000) and the Ipswichian in the British Isles (West, 1957). Elsewhere, the Last Interglacial is known by local names such as the Luhe or Ribains (France; Reille et al., 1998; De Beaulieu et al., 2001), the Riß-Würm interglacial (Alps; Wegmüller, 1992) and the Mikulinian (Poland and Russia; Mamakowa, 1989; Ikonen and Ekman, 2001). Importantly, the timing and duration of the Last Interglacial vary between regions.

Typically, the Eemian, as defined palynologically by the occurrence of temperate taxa (e.g., *Quercus*), is correlated to marine isotope stage (MIS) 5e (ca. 123 ka; Lisiecki and Raymo, 2005) in the marine oxygen isotope stratigraphy (Shackleton, 1969). Climate changes were likely time-transgressive during the Last Interglacial. For example, in sediments from the Iberian Margin, there is a 6000-year delay between the onset of MIS 5e (132 ka), defined by changing oxygen isotope concentrations, and the onset of terrestrial thermophilous vegetation (126 ka), marking the onset of the

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Eemian as defined palynologically (Tzedakis et al., 2018). Local factors such as ocean currents, shifting atmospheric jets and regional sea level and water table changes can add further complexity as proxies rarely record a direct response to climate warming. For example, in the lowland coastal regions and glacial basins of the Netherlands, which preserve many of the terrestrial Eemian deposits, the complex interplay of proglacial, fluvial, marine and solid Earth responses can overprint proxy records (Turner, 2000; Roebroeks et al., 2021). Perhaps most famously, the marine inundation of the Amersfoort basin led to the deposition of a sand layer that does not contain pollen (see Kasse et al., 2022 and references therein). Similarly, marine sequences, such as those from the Western Mediterranean, record not only rising sea surface temperatures during the Last Interglacial but also a complex interplay between tropical and polar climate systems following deglaciation (Martrat et al., 2014).

Given the role subsequent proglacial and periglacial processes played in shaping the landscapes of NW Europe, many sedimentary sequences that would have contained sediments of the Last Interglacial age have been eroded. Last Interglacial age sequences survive in some areas due to preservation within local topographic features, or due to their location beyond the margins of subsequent ice advance. In NW Germany, for example, sediments of Last Interglacial age are found in a number of small (<110 m wide) basins formed in the dead-ice terrain of the preceding glacial period, regionally termed the Saalian complex (which typically correlates to MIS 6; Kukla et al., 2002). In the Netherlands, the deep glacial basins that formed during the Saalian, such as those at Amsterdam and Amersfoort, preserve Eemian sequences (the latter being the Eemian terrestrial type site; Cleveringa et al., 2000). However, many terrestrial sedimentary sequences are discontinuous across the Last Interglacial with breaks in the record due to local marine transgression, their topographic position at the margin of an ice-pushed ridge and/or changing hydrodynamic conditions (Cleveringa et al., 2000; Van Leeuwen et al., 2000).

In the British Isles, the Ipswichian stratigraphy is largely made up of fluvial deposits, such as abandoned channel fills and overbank sequences (Gibbard and Lewin, 2002; Briant et al., 2012; Gibbard et al., 2021). Given the tendency of riparian wetlands to accumulate and preserve fossil-rich sediments, they contain an array of palaeoenvironmental indicators, such as pollen, molluscs and mammalian fauna (Langford et al., 2017). The dynamic nature of fluvial environments means that these sequences are invariably short-lived, containing stratigraphically isolated snapshots of Last Interglacial climate and environment. Thus far, no Ipswichian sites have been identified that contain a full Last Interglacial sequence (Candy et al., 2016). Given the patchwork nature of the Ipswichian sedimentary records in the UK, compared to the Eemian records in continental NW Europe, building chronologies is challenging. In particular, it is challenging to correlate to wider regional chronologies, although this is an important step to integrate the British and continental stratigraphies.

Integrating records of palaeoclimate and palaeoenvironment at an intraregional scale and in a wide range of Quaternary sequences, all with differing approaches to dating and chronology building, is a complex task, especially in marine and terrestrial sequences that fall outside of the radiocarbon dating timeframe. Furthermore, the various dating approaches, ranging from layer-counting methods to radiometric approaches, come with very different inherent uncertainties. In this study, we briefly review the most commonly used approaches for dating Last Interglacial records, illustrated by selected examples. Our focus is primarily terrestrial, however, we do not focus on the dating of environmental reconstructions that utilise faunal assemblages from cave and open-air sequences and archaeological sites. We then present a case study using a range of pollen datasets from NW Europe to interrogate the robustness of commonly applied pollen biostratigraphy as a means of correlating records. We highlight the difficulty of making robust intraregional linkages using pollen biostratigraphy as well as the dangers of assuming temporally synchronous vegetation responses. We finish by outlining best practices in developing age models for the Last Interglacial that are reproducible and can be updated as new approaches to dating Last Interglacial sequences are developed.

Dating Last Interglacial environmental archives

Unlike the current Holocene interglacial, Last Interglacial records of climate and environmental change cannot be dated using radiocarbon. Regardless, there are many chronostratigraphic tools that can be utilised to date Last Interglacial records, all with their specific advantages and constraints. Here, we overview the key approaches that can be applied to date Last Interglacial archives. We subdivide these approaches into three main categories: incremental dating (e.g., varve counting), absolute dating (e.g., trapped charge) and relative dating (e.g., pollen biostratigraphy). Although our focus here is on the Last Interglacial, the same dating methods, with all the associated limitations and uncertainties, can be applied to sediments that span the last glacial cycle, particularly those which predate the upper limit of radiocarbon measurement and calibration, and many can be applied across earlier Quaternary interglacials.

Incremental dating

In some Last Interglacial archives, annual layer counting can be used to produce precise chronologies. In lacustrine sequences, varves (annual layers) can be produced by changing lake conditions driven by prevailing seasonal climates, which result in cyclic variations in sediment deposition (Kitagawa, 2012). Crucially, sedimentary laminations within a lake are not always related to annual variability, and demonstrating a link between the changes seen in sediment composition and annual cyclicity is fundamental when using varves (Brauer et al., 2014). For sediment varve chronologies to act as independent absolute dating tools, seasonal layer formation must continue up to the present day, thereby establishing a starting point for the chronology at the time of core retrieval (Brauer et al., 2014). Non-continuous varve chronologies are, instead, 'floating' chronologies that require anchoring to absolute chronologies using absolutely dated markers, such as tephra layers (Beckett et al., 2023).

Limited European Last Interglacial sequences have established varve chronologies; however, lake sediments from Bispingen (Germany; Müller, 1974) and Lago Grande di Monticchio (Italy; Brauer et al., 2007) both contain annual laminations across the Last Interglacial period. The Bispingen varve chronology of Müller (1974) provided a key regional stratotype, which has been used for decades to determine the duration of the Eemian to ca. 11 kyr based on the presence of arboreal pollen, varve counts and derived sedimentation rates (see Pollen biostratigraphy). Revised varve counts, however, estimate the duration of the Eemian as ca. 15 kyr (Lauterbach et al., 2024). The updated Bispingen chronology of Lauterbach et al. (2024), developed through microscopic varve counting of multiple cores, suggests that earlier work from the site underestimated the duration of the Eemian as their investigation relied upon an incomplete sediment core. Such findings

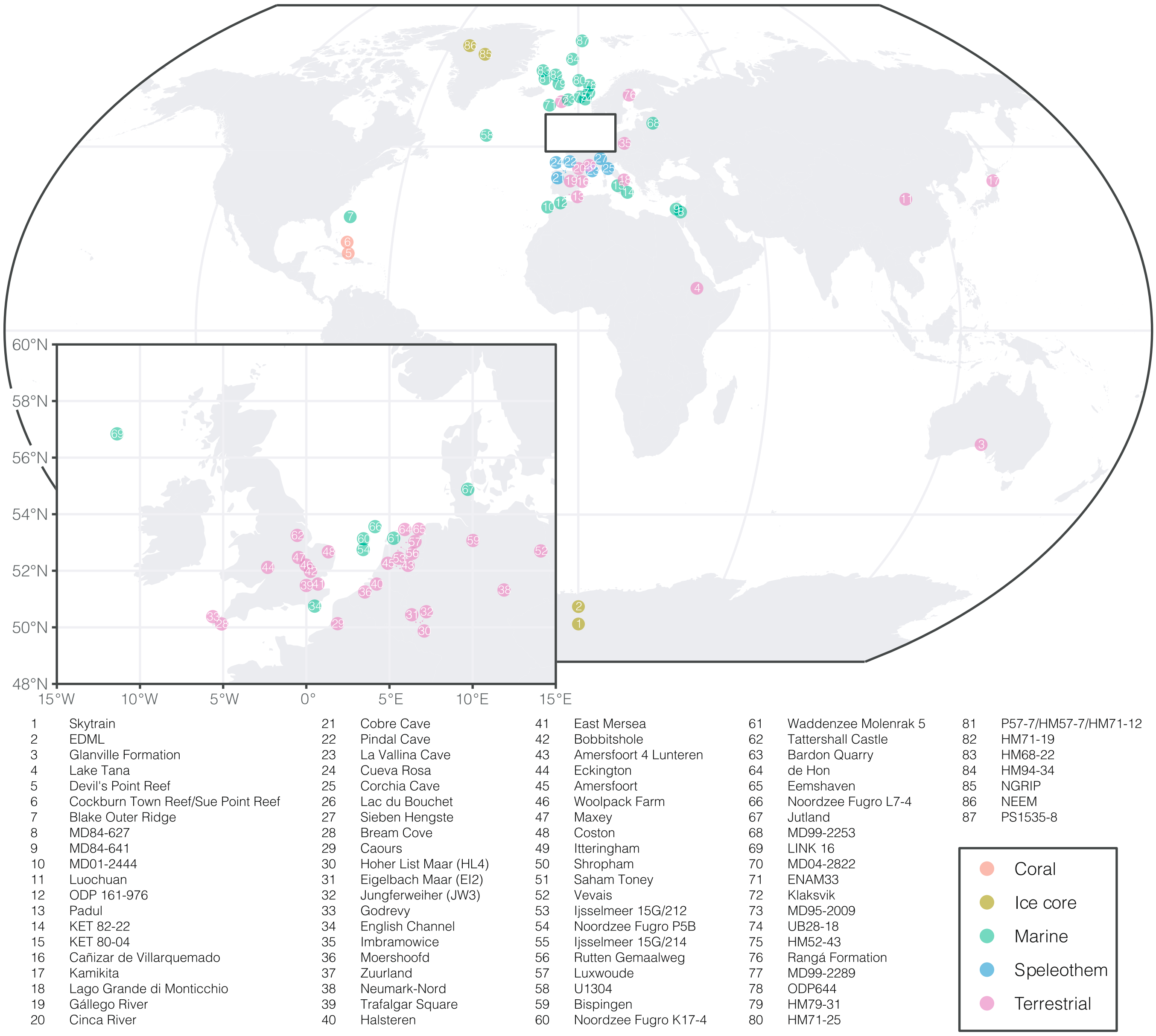

Figure 1. Map showing the locations of key sites mentioned in the text, with inset map showing sites within the case study region. [Color figure can be viewed at http://wileyonlinelibrary.com]

demonstrate the importance of, where possible, testing and ultimately verifying varve-derived durations using independent chronological techniques.

In karstic environments, speleothem sequences, including flowstones, can also contain annual banding. Annually laminated stalagmites are often identified within cave systems where there is strong seasonality in the regional climate (Baker et al., 2008). In stalagmites where annual banding is not visible or is unclear, trace element laminae series can potentially be counted (Fairchild et al., 2001). Very few annually banded records exist that span the Last Interglacial, with most laminated for only part of the sequence or period (Batchelor et al., 2024). As with varved lake sequences, a speleothem that contains annual banding from the Last Interglacial through to the present is unlikely. Therefore, annually laminated speleothems do not provide a calendar age but rather a duration, requiring anchoring through another method, such as U/Th dating (see U/Th methods), to provide an absolute age constraint. For example, a key record of Last Interglacial climate, the North Iberian Speleothem Archive, uses annual layer counting to supplement, and enhance the precision of, an absolute U/Th chronology (Stoll et al., 2022).

In ice cores, similar incremental dating techniques are also applied. Annual signals preserved in ice core records, such as isotopic fluctuations related to seasonal climate variability, can be used to build a chronology (North Greenland Ice Core Project members, 2004). Such chronologies have been vital in improving our understanding of the timing and character of sub-millennial scale climate change across the last glacial cycle (Cheng et al., 2020; Corrick et al., 2020). Layer counting is not possible in all ice core sequences as varying accumulation rates and thinning due to ice flow can limit the identification of annual signals. For example, the EPICA (European Project for Ice Coring in Antarctica) ice core from the Antarctic plateau provides a 800 ka record (Lambert et al., 2008) that includes the Last Interglacial; however, identifying annual banding is not feasible in the central part of the Antarctic ice sheet as annual ice accumulation cycles are largely indistinguishable (Ekaykin et al., 2002; Parrenin et al., 2007). By contrast, the rapidly accumulating ice preserved in Greenland ice cores, which typically contain annual banding throughout, does not provide a continuous or complete record of the Last Interglacial. The NGRIP (North Greenland Ice Core Project) ice core from 123 to 110 ka is the only continuous Greenlandic record covering this time interval (North Greenland Ice Core Project members, 2004), and misses the early part of the Last Interglacial. The NEEM (North Greenland Eemian Ice Drilling) ice core contains ice dating back to 128.5 ka; however, the record includes regular melt features between 127 and 118.3 ka (NEEM community members, 2013). In West Antarctica, where annual layers can be used to develop age models, ice between 129 and 127 ka is missing, hinting at either a reduction in snow accumulation during this period, the flow of ice from inland over-riding the core site leading to the removal of ice or a possible retreat of the West Antarctic Ice Sheet during the Last Interglacial (Hoffmann et al., 2022). Future ice coring projects may yet find preserved Last Interglacial ice in stratigraphic order and featuring annual banding, which will help to unravel the nature of climate change during interglacial polar warming.

Absolute dating

U/Th methods

The production of ^{230}Th from the Uranium series decay chain is a useful geochronometer in calcite deposits of the Last Interglacial age such as corals and speleothems. U/Th dating of Last Interglacial fossil corals provided the first absolute age constraints on the timing of the Last Interglacial sea-level highstand (Broecker and Thurber, 1965). U/Th ages have been applied to coral sequences globally, advancing our understanding of the timing and magnitude of regional sea-level highstands, and subsequently interglacial ice-mass loss (Dutton et al., 2015; Hibbert et al., 2016).

Advances in mass spectrometry over recent decades have substantially reduced analytical uncertainties in Last Interglacial fossil coral U/Th ages, often to 1000 years (1 kyr) or less (see Chutcharavan and Dutton, 2021 and references therein). Similarly, speleothem sequences dated using U/Th have also provided key insights into the timing of Last Interglacial climate variability. For example, the speleothem record from Corchia Cave (Italy; Tzedakis et al., 2018) spans the Last Interglacial and has a chronology constrained by 87 U/Th ages across four stalagmites with a climatic optimum at ca. 128 ka. Alpine speleothems suggest a thermal optimum occurring around the same time, for example, at Sieben Hengste (Switzerland; Luetscher et al., 2021) where oxygen isotopes suggest a Last Interglacial peak at ca. 128.1 ± 1.2 ka.

A key challenge in U/Th dating sequences of the Last Interglacial age is the presence of detrital material, often containing ^{230}Th, in calcite. Correction for detrital ^{230}Th is a prerequisite when building a chronology in such sequences. Thorium contamination can be determined by measuring ^{232}Th, which, whilst chemically similar to ^{230}Th, is not part of the ^{238}U decay chain. If the ^{232}Th concentration and the initial $^{230}Th/^{232}Th$ are known, the ^{230}Th concentration at formation can be calculated and corrected (see Wendt et al., 2021 and references therein). Such considerations are important as discrepancies have emerged, with the closed-system ages from corals reporting a significantly earlier Last Interglacial sea-level highstand in the Bahamas and Barbados (Chen et al., 1991; Speed and Cheng, 2004) relative to those derived from open-system ages (Thompson and Goldstein, 2005; Thompson et al., 2011). Consequently, recent studies have applied strict geochemical screening criteria to remove data that have been altered through open-system behaviour (Dumitru et al., 2023).

K/Ar methods

The decay of radioactive potassium-40 (^{40}K) to argon-40 (^{40}Ar) can also be used as a geochronometer in Last Interglacial sequences. $^{40}Ar/^{39}Ar$, and to a lesser extent $^{40}K/^{40}Ar$, dating is most widely applied to volcanic rocks or tephra on Last Interglacial timescales. Whilst other materials can be dated, volcanic outgassing provides a release mechanism for excess argon, that is to say argon incorporated into the mineral through processes other than in situ decay (Kelley, 2002). Thus, we can assume that the radiogenic argon present within volcanic deposits has formed within a closed system since the event being dated. The precision of K/Ar dating increases with increased potassium content within the target mineral. Thus, sanidine, anorthoclase feldspars and leucites typically yield the most precise dates (Renne, 2006).

K/Ar dating approaches have been applied to Last Interglacial sediments. For example, in Iceland, Van Vliet-Lanoë et al. (2018) used K/Ar ages to date the Last Interglacial marine transgression. Through K/Ar dating of the underlying glaciovolcanic unit, the marine Rangá Formation is estimated to have an upper age limit of 155–129 ka (Van Vliet-Lanoë et al., 2018). Two other ages from the same unit (using the Ar/Ar method) also yielded similar ages (Flude et al., 2008; Clay et al., 2015).

However, not all volcanic deposits are ideal for potassium series dating approaches. In proximal volcanic environments, the presence of large crystals of sanidine and biotite allows application of a standard analytical approach (Mark et al., 2010). In scenarios where large volumes of volcanic ash are present in distal environments, the Ar/Ar technique can be applied to small shards of well-preserved biotite after a rigorous extraction process (Mark et al., 2014). Typically, tephra units within Last Interglacial sequences, such as lake sequences, consist largely of potassium-bearing glass shards. Although it is possible to date tephra glass shards, ages are often unreliable due to potassium loss through hydration and irradiation during the measurement process, both of which are, in turn, amplified by the high surface area:volume ratio of glass shards (Morgan et al., 2009). Therefore, more typically, tephra glass shards are correlated to a specific eruption through tephrostratigraphic approaches, which is then dated in the proximal stratigraphy (see Tephrochronology).

At present, limited Ar/Ar ages are available for Last Interglacial eruptions. One eruption with potential for a refined date is the 116 000 ± 16 000 ka Dümpelmaar tephra originating from the East Eifel Volcanic Field (Van den Bogaard and Schmincke, 1990). Given the volcanic history of both the French Massif Central and German Eifel, it is likely that further eruptions, not easily identified in the proximal record due to burial by later eruptions, may be identified through the development of new tephrostratigraphic frameworks for this period. Should such eruptions be identified, this should provide a motivation to revisit these volcanic centres for further investigation and dating.

Trapped charge methods

Trapped charge dating, most commonly through luminescence or electron spin resonance (ESR), exploits the build-up of trapped energy within the crystal lattice in naturally occurring minerals such as quartz and feldspar due to the decay of radioactive elements (e.g., potassium) and cosmic rays. The trapped charge, which accumulates when the minerals are buried and can be released and measured by heating the sample or exposure to light of a particular wavelength (see Penkman et al., 2022 and references therein). For example, for fluvial sands or loess sequences rich in quartz or feldspar luminescence is the preferred technique (Roberts, 2008), whereas in fossil biominerals, ESR is typically used (Bahain et al., 2012).

Luminescence dating can be used to date different events; however, in most Quaternary contexts, it is used to calculate when the mineral grains within the sediment, typically quartz and feldspar, were last exposed to daylight. Luminescence dating has been applied to sediments of the Last Interglacial age in aeolian (Zhang et al., 2022), fluvial (Lewis et al., 2009; Sier et al., 2015b), lacustrine (Roberts et al., 2018), coastal (Barnett et al., 2023) and shallow marine (Mellett et al., 2012) contexts. In particular, luminescence dating underpins the chronologies of river terrace sequences in the British Isles, such as the Solent (Briant et al., 2012), providing important absolute age constraints on terrestrial glacial–interglacial cycles.

Some attempts have been made to robustly date the onset, duration and end of the Eemian, as defined palynologically, using luminescence dating. For example, detailed pollen analysis and luminescence approaches have been applied on a sediment section in Vevais (NE Germany; Lüthgens et al., 2011). Pollen analysis from the Vevais section contains the full Eemian vegetation succession as defined in the German pollen zonation scheme (Table 1). Through luminescence dating of quartz and feldspars within lake marls, the onset of the Eemian was dated to 126 ± 16 ka, with the termination and transition to the Weichselian cold stage dated to 108.9 ± 7.8 ka. These ages, whilst absolute, come with large uncertainties that span the duration of MIS 5e and various definitions of the Eemian. Thus, whilst luminescence ages can be used to robustly demonstrate a link between the terrestrial Eemian pollen chronology and MIS 5e, their ability to precisely situate the Eemian on an absolute timescale is limited. More broadly, OSL dating of loess sequences has provided some age constraints on the onset of the Last Interglacial, for example, high-density OSL dating of the Luochuan section (Chinese Loess Plateau, China) yielded an LIG onset of 129 ± 4 ka (Zhang et al., 2022). Whilst an invaluable absolute constraint on the timing of LIG onset, the associated large uncertainty of 8 kyr with the OSL technique (Zhang et al., 2022) hinders precise correlation between records.

Whilst OSL is a vital technique in deriving absolute ages for changes in Last Interglacial sequences, the inherent uncertainties in estimating the dose rate and equivalent dose result in typical luminescence age uncertainties >4% (Wallinga and Cunningham, 2014). Additionally, the impact of only partial bleaching of sediments can present a further challenge (Smedley and Skirrow, 2020), especially given the number of Last Interglacial sequences studied to date in fluvial environments, such as higher-energy, deeper river channels. However, the effects of partial bleaching can be addressed through single-grain analysis techniques (Duller et al., 1999) and the application of statistical age models (see Galbraith and Roberts, 2012 and references therein). Furthermore, saturation of the quartz OSL signal may limit the accuracy of dates from sediments of the Last Interglacial age; depending on the dose rate, saturation of quartz may start between 70 and 150 ka. However, older ages from fluvial sequences have been shown to closely mirror independent U/Th ages (Murray-Wallace et al., 2016), highlighting that in ideal settings OSL can be useful on these timescales.

Infrared stimulated luminescence (IRSL) signal of feldspars saturates at greater doses than quartz, and thus can be applied to dating older samples, particularly where the quartz OSL signal nears saturation (Wallinga and Cunningham, 2014). However, they also present their challenges, such as anomalous fading of individual grains (Spooner, 1994). Buylaert et al. (2011) apply IRSL to coastal marine sands from southern Denmark, where they identify a significant age underestimation (ca. 35%), which they attribute to anomalous fading. IRSL has also been applied to Last Interglacial lake sediment sequences, for example, in Lake Tana in Ethiopia, where in younger sections of the sequence

Table 1. Overview of Eemian pollen zonation schemes for different areas of NW Europe based on abundant and characteristic taxa, adapted from Turner (2000).

		The Netherlands		N Germany
Early-glacial		NAP (Ericales)		NAP (Ericales)
Post-temperate	E6b	*Pinus*	VII	*Pinus*
		Pinus–Betula		
	E6a	*Picea*	VI	*Pinus–Picea–Abies*
		Pinus–Picea–Abies–Alnus		
Late-temperate	E5	*Carpinus*	V	*Carpinus–Picea*
		Pinus–Picea–Carpinus		
Early-temperate	E4b	*Taxus*	IVb	*Corylus–Taxus–Tilia*
		Quercus–Corylus–Ulmus–Fraxinus–Tilia		
	E4a	*Corylus*		
		Corylus–Quercus–Alnus		
	E3b	*Quercus–Corylus–Ulmus–Fraxinus–Tilia*	IVa	*Quercus–Corylus*
		Quercus–Corylus–Ulmus–Fraxinus–Tilia		
	E3a	*Quercus*		
		Quercus–Ulmus–Fraxinus		
	E2b	*Pinus–Quercus*	III	*Pinus–Quercus*
		Pinus–Quercus–Alnus		
	E2a	*Pinus–Ulmus*		
		Pinus–Ulmus		
Pre-temperate	E1	*Betula–Pinus*	II	*Pinus–Betula*
		Pinus–Betula		
			I	*Betula*
Late-glacial	LS		SSC	*Hippophae–Juniperus–NAP*

Abbreviation: NAP, non-arboreal pollen.

IRSL ages closely match radiocarbon-derived ages for sediments (Roberts et al., 2018) and to date Last Interglacial marine terraces in Japan (Ito et al., 2017).

ESR dating has been applied to materials of the Last Interglacial age, for example, the dating of Last Interglacial coral reef terraces (Schielein et al., 2020) and in a range of fluvial and marine environments (Dalton et al., 2022). The technique, whilst a powerful tool in dating fossil biominerals, offers lower analytical precision than radiometric approaches, and standardised analytical procedures have yet to be developed (Duval et al., 2020).

Correlation tools

Correlation tools can be a powerful way of synchronising sedimentary sequences of the Last Interglacial age, particularly in the absence of or challenge posed by the absolute chronological tools summarised earlier. In Europe, biostratigraphy is a widely applied approach to correlating and dating sequences on both orbital and suborbital timescales, based upon the presence and absence of floral and faunal communities due to migration, dispersal, extinction and/or evolution of species. It forms the backbone of much of our understanding of the relative timing of Earth system responses (e.g., ice-sheet and sea-level change; Zagwijn, 1983; Lambeck et al., 2006; Long et al., 2015) during interglacial periods. Biostratigraphy assumes that changes in flora and fauna occur broadly synchronously within regions, assuming a mutual driver, often climatic. If these changes can be supposed synchronous, boundaries between different floral and faunal assemblages will be, within regions, time-parallel (Janssen and Törnqvist, 1991; Turner, 2000). Beyond biostratigraphy, we also highlight developments in amino acid racemisation (AAR) dating over the last decade, particularly in NW Europe, which have made it a powerful correlative tool. Finally, we consider the potential applications of tephra deposits and palaeomagnetic events as isochrons for correlating archives of Last Interglacial climate and environmental response, and the scope these approaches have to test assumptions inherent in biostratigraphical correlation.

Pollen biostratigraphy

Pollen biostratigraphy is the most widely adopted approach when dating terrestrial and coastal marine sites of the Last Interglacial age, particularly in Europe. The popularity of the approach can be attributed to the fact that palynology was the earliest method used to characterise interglacial periods (Zagwijn, 1957; Turner and West, 1968) following the identification of distinct patterns of vegetation succession during the various warm stages of the Pleistocene.

In NW Europe, the Eemian (the Netherlands, Northern Germany) and Ipswichian (British Isles) are defined by a multi-phased forested interval wherein a similar pattern of vegetation succession is identified across multiple well-resolved Last Interglacial pollen sequences (see Phillips, 1974 and references therein; Turner, 2000). Many Eemian and Ipswichian sequences were deposited in low-energy coastal and estuarine settings, and thus they are particularly rich in pollen meaning pollen biostratigraphy can be applied across a large proportion of preserved sediment sequences of the Last Interglacial age (Phillips, 1974). For both the Eemian and Ipswichian, the interglacial arboreal succession is characterised by an initial pre-temperate protocratic phase dominated by *Betula* and *Pinus*, followed by an early-temperate mesocratic phase, with a broader woodland composition incorporating *Quercus* and *Corylus*, and a final oligocratic/telocratic phase characterised by late-temperate taxa including *Picea* and *Carpinus* (Tables 1 and 2).

Table 2. Overview of the Ipswichian pollen zonation scheme based on abundant and characteristic taxa, adapted from Sparks and West (1970).

		British Isles
Early-glacial	e De	High NAP
Post-temperate	Ip IV	*Pinus*
Late-temperate	Ip III	*Carpinus*
Early-temperate	Ip IIb	*Pinus-Acer-Corylus*
	Ip IIa	*Pinus-Quercus*
Pre-temperate	Ip Ib	*Pinus-Betula*
	Ip Ia	*Betula-Pinus*
Late-glacial	l Wo	High NAP

Inter-site comparisons are typically undertaken within regional pollen zones; for example, the Netherlands and Northern Germany each have their pollen zonation schema (Table 1), which allow correlation between sites within those regions. Sites that sit in different regions and therefore have slightly different pollen zone frameworks can be broadly correlated with one another. In the Netherlands, there are six primary Eemian pollen assemblage zones, termed E1–E6 (Zagwijn, 1961), which can be broadly linked to pollen zonation schemes from Northern Germany (Müller, 1974) and the British Isles (West, 1957). Turner (2000), however, argued that these biostratigraphic zones should not be treated indiscriminately as chronostratigraphic units.

Due to the discontinuous patchwork nature of Last Interglacial sites in the British Isles, assigned to the Ipswichian, constructing a robust pollen biostratigrapic framework is challenging. Ipswichian deposits, often associated with dynamic fluvial environments (Preece, 1999), typically span one or two pollen zones, contrasting with the terrestrial Eemian in the Netherlands, where deep glacial basins preserved long records spanning much of the interglacial (Turner, 2000). In the British Isles, there are no sites in which the full Ipswichian interglacial is preserved, as well as there being a preservation bias towards the early and middle parts of the interglacial, represented by pre-temperate (Ip I) and early temperate (Ip II) pollen zones (Jones and Keen, 1993; Coope, 2010). As a result, correlation of the British Ipswichian and continental Eemian pollen zones remains a challenge. The pollen succession of the Ipswichian (Table 2) is characterised by the complete absence of *Abies* and far lower abundances of *Picea*, *Tilia* and *Taxus* than observed in the Netherlands during the Eemian. Interestingly, Eemian pollen assemblages from Denmark are also void of *Abies*, suggesting a northerly limit during the Last Interglacial in the Netherlands and Germany, with populations unable to migrate northwards before the onset of climatic cooling (Phillips, 1974).

Pollen biostratigraphies have also been used to great effect beyond NW Europe. For example, in Poland, a large body of research (>400 sites) into Last Interglacial variability exists following the pollen zonation scheme of Mamakowa (1989) and Kupryjanowicz et al. (2018). The zonation scheme of Mamakowa (1989) has recently been revised by Kupryjanowicz et al. (2018) using Eemian pollen records from the Polish Lowlands, improving the interpretation of vegetation history, climate and hydrological changes. Pollen assemblage zones have also been developed for SE Europe from a long core collected at Lake Ohrid that covers the Last Interglacial, and broader late Quaternary (Sadori et al., 2016; Sinopoli et al., 2018). In this case, a first-order age-depth model has been developed using tephrochronology and orbital forcing tie-points to estimate the duration of the pollen zone assemblages.

Last Interglacial chronologies have, frequently, been constructed using the pollen zones as tie-points. In particular, the presence of varves within the Last Interglacial lake sequence from Bispingen, NW Germany, has facilitated estimates of the duration of each of the Eemian pollen zones (Müller, 1974), which have then been transferred to other sites where they help develop that site's age model. Biostratigraphical approaches are particularly powerful early in the interglacial, where the short duration of the early Eemian pollen zones (e.g., E1 spans 0.1 kyr, E2a spans 0.2 kyr and E2b spans 0.2 kyr) has the potential to constrain centennial-scale rates of change when many Last Interglacial dating tools have multi-millennia uncertainties. The Bispingen chronology is floating (that is to say it is not varved through to the present day); thus, in assigning it to other sites, it is necessary to make a further assumption regarding the timing of the Eemian pollen zones relative to the broader Last Interglacial complex (see Testing and anchoring Eemian pollen chronologies). Recent work by Lauterbach et al. (2024), which showed the chronology of Müller (1974), underestimated the duration of the Eemian by ca. 5000 years (see Incremental dating), also brings into question the use of pollen zones as chronological tie-points. The underestimation of the duration of the Eemian as determined by Müller (1974) has been propagated to numerous other sites, which will now likely require revision of their chronologies in light of the new Bispingen (Lauterbach et al., 2024) age model. Therefore, whilst we continue to see the inherent value in the Eemian pollen zones as a tool for comparing records, they must not be used to build chronologies in isolation, but rather as one weapon in an arsenal of dating approaches.

Whilst the marked uniformity in the sequencing of vegetation succession, particularly across the Netherlands, Northern Germany and Poland during the Last Interglacial allows relatively straightforward correlations through the application of pollen biostratigraphy, it requires the inherent, and perhaps questionable, assumption that these vegetation changes occur synchronously. For pollen zones to work effectively as chronostratigraphic units, ideally species would populate a region synchronously, and for all subsequent species to do so in a uniform sequence. A uniform arrival time for specific taxa to an entire region is unlikely, given the number of site-specific features that govern local ecology. For example, in the latter stages of the Eemian in the Netherlands and Northern Germany, there are notable differences in forest composition between sites, potentially arising from varied soil development related to sediment influxes, climate and underlying geology (Turner, 2000). Furthermore, the conventional understanding of post-glacial vegetation succession assumes that species track their climate niche; however, rates of species migration determined from well-dated Lateglacial and Holocene pollen records do not match model simulations of climate-driven vegetation dynamics (Giesecke et al., 2017). Furthermore, there is debate about the differences in vegetation succession with increasing continentality in the Last Interglacial sequences (see Turner, 2000 and references therein). An important example of this is the pollen record from El Cañizar de Villarquemado sequence (NE Iberia), where Last Interglacial vegetation responses did not reflect the sequential succession seen at the coast where there is a shift from treeless to forest-dominated landscapes at the onset of the Last Interglacial, but rather reflects a mosaic of different communities (steppe, savannah-like and forests), with vegetation changes driven by a complex interplay of ecological factors that drove vegetation change as well as climatic variability (González-Sampériz et al., 2020).

The spatial scale at which regional pollen schemes yield time-parallel levels has long been recognised as an important consideration (Janssen and Törnqvist, 1991). Work on the Holocene has shown pollen zones are of limited extent in time and space (Bennett, 1988). The drivers across the Holocene and the Last Interglacial do, however, differ considerably. Across the Last Interglacial, the development of an open seaway across northern Europe which spanned the present-day English Channel, North and Baltic Seas through to the White Sea, facilitated a mild oceanic climate across the whole region (Turner, 2000). Due to this close connection, it has been assumed climate and environmental changes should occur synchronously across what Turner (2000) terms the North European Plain. Further work is needed, however, to test whether vegetation responses to climate and environmental change across the Last Interglacial were time-parallel and to begin to estimate the uncertainty inherent in their use of alignment tools.

Using pollen biostratigraphy as a means of correlating the Last Interglacial sequences in NW Europe is further hindered by the similarity of the succession of temperate taxa between different interglacials. Historically, the expansion of temperate arboreal taxa during the earlier substages, culminating with the dominance of *Carpinus* in late-temperate pollen assemblages was assumed unique to the Last Interglacial; however, subsequent work has demonstrated earlier interglacials and interstadials also saw the expansion of *Carpinus* (Sparks and West, 1970). One key, and potentially unique, feature of the Eemian and Ipswichian interglacials is the muted expansion of *Fagus* populations. Palynological indicators and settings are often ambiguous in revealing whether an interglacial deposit correlates to the Eemian/Ipswichian or an older counterpart. Continuing advances in AAR methods (Penkman et al., 2013) have shown that a number of British sites previously assumed to date to the Last Interglacial based on Ipswichian pollen stratigraphy (Hollin, 1977) have been shown to date to earlier Quaternary interglacials (Penkman et al., 2013).

Finally, the utility of pollen biostratigraphy is also limited in aligning marine and terrestrial sequences. Whilst the Eemian pollen zones have been identified by Zagwijn (1961) offshore in the North Sea Basin, low pollen concentrations in marine environments, and the over-representation of certain taxa within marine sequences (e.g., *Pinus*; Mudie and McCarthy, 1994), means that taphonomic processes need to be carefully considered when aligning pollen archives. Furthermore, variable inputs into the North Sea region through shifting atmospheric and fluvial regimes may also drive changes in the character of pollen assemblages, adding further ambiguity. Even in complex environments, with changing depositional regimes and sediment sources, pollen biostratigraphy remains a powerful tool for within-region correlation, assuming careful consideration is given to pollen sources and transport pathways. We explore this further in our case study example which interrogates the Eemian pollen zones of the Netherlands and Northern Germany.

Mammalian biostratigraphy

In continental NW Europe, mammal records are subdivided into biozones, forming a biostratigraphical framework that is widely applied as a chronological tool throughout continental NW Europe (Kolfschoten, 2000). Both the Eemian and Ipswichian are largely associated with species thought to have inhabited the forested landscape such as numerous deer species, wild boar (*Sus scrofa*), straight-tusked elephant (*Palaeoloxodon antiquus*) and the forest rhinoceros (*Stephanorhinus kirchbergensis*) (Koenigswald, 2007). In Britain, the Last Interglacial is characterised by the presence of Hippopotamus (*Hippopotamus amphibius*) which has not been identified in interglacial deposits from MIS 7, 9 or 11 (Stuart, 1981). The utility of mammalian assemblages as indicators of relative age for Pleistocene sediments in Britain is well established (Schreve, 2001; Stuart and Lister, 2001), with the Joint Mitnor Cave Mammal Assemblage Zone, named after the Joint Mitnor Cave site in Devon (SW England; Sutcliffe, 1960) assigned to the Last Interglacial (Currant and Jacobi, 2011).

Given that mammal faunas are often preserved in karstic caves, particularly in the UK, U-series techniques (see U/Th methods) can be used to date contemporaneous stalagmite and flowstone deposits, facilitating the creation of a chronology for the mammalian assemblages of the British Isles. For example, in Victoria Cave in the Yorkshire Dales (NE England) samples from the Joint Mitnor Cave Mammal Assemblage Zone have been assigned maximum ages in the range of 135 ± 8 to 114 ± 5 ka, based on U-series dates for the enclosing stalagmite deposits (Gascoyne et al., 1981), with more recent ages of a flowstone encasing a narrow-nosed rhinoceros (*Stephanorhinus hemitoechus*) jaw yielding dates of 115.7 ± 2.7 and 111.9 ± 2.4 ka (Gilmour et al., 2007) and a Red Deer (*Cervus elaphus*) antler yielding dates of 116.8 ± 0.8 to 118.3 ± 0.6 ka (Lundberg et al., 2010). These ages suggest stalagmite growth, and thus minimum ages for the fossil jaw and antler, close to the end of MIS 5e (Tzedakis et al., 2018). Similar U-series ages for Last Interglacial fauna have also been derived from speleothem deposits from Kirkdale Cave (121 ± 4 ka; McFarlane and Ford, 1998), in a comparable manner a MIS 5e age for fauna preserved in a beach deposit is inferred from an overlying OSL age at Sewerby cliff (Bateman and Catt, 1996), in North and East Yorkshire, respectively. In a select few archives where the differing preservation requirements of the two proxies are met, the identification of both mammal fossils and pollen has allowed the two biostratigraphical frameworks to be reconciled. In Britain, at Trafalgar Square (London, SE England), Franks (1960) found Ipswichian pollen assemblages alongside a mammal assemblage which includes the hippopotamus. Similarly, at Swanton Morley (SE England) *H. amphibius* is identified in sediments assigned to Ipswichian pollen zone Ip III (Coxon et al., 1980). Similarly, at sites such as Neumark-Nord, a characteristic Eemian fauna including aurochs (*Bos primigenius*) and horses (*Equus* sp.), is preserved alongside the Eemian pollen zones (Britton et al., 2019; Sier et al., 2015b).

Small vertebrate remains can also often be found within fine-grained deposits. The water vole lineage in particular provides an evolutionary trend which can be used biostratigraphically, sometimes referred to as the 'Vole Clock' (see Martin, 2014 and references therein). Water vole remains are common in deposits of the Late Pleistocene age, and their morphology can be used to provide relative constraints on the age of sedimentary deposits. Changes in the tooth morphology of *Arvicola* spp., and an increase in enamel thickness on the trailing edges of the lower molars relative to the leading edge, have been used for biostratigraphical analysis (see Schreve, 2001 and references therein). In particular, the Schmelzband-Differenzierungs-Quotient of Heinrich (1982), based on the trailing edge thickness from established points on the molar and the thickness of the leading edge, has been widely applied in Britain to provide an independent chronology for many Quaternary localities (Schreve, 2001; Roe et al., 2009). Dental changes throughout the Pleistocene have, however, been shown to have a complex, mosaic expression (Martin, 2014; Maul et al., 2014), and should not be used as a sole means of correlating sequences.

Molluscan biostratigraphy

The abundance of molluscs in fluvial and marine settings across the globe makes them useful markers in Quaternary biostratigraphy, with the regional presence and absence of some species tied to particular glacial and/or interglacial periods. The absence of the bivalve *Corbicula* is a particularly useful biostratigraphic marker in assigning sediments to the Last Interglacial. Ergo, the presence of *Corbicula* suggests that sediments date to MIS 11, 9 or 7 (Meijer and Preece, 2000), a chronological framework supported by aminostratigraphy (Penkman et al., 2013). Similarly, molluscan assemblages of Ipswichian/Eemian age typically contain the Mediterranean freshwater species *Belgrandia marginata* (Coope, 2010). However, *B. marginata* is also associated with interglacial deposits from MIS 9 (Keen et al., 1999; Roe et al., 2009), so cannot be used in isolation as a biostratigraphic tie-point.

Importantly, recent work from the Netherlands casts doubt on some traditional biostratigraphic correlations. The molluscan assemblage from Luxwoude in the northern Netherlands (often termed Lusitanian-type fauna) contains several species, including *Bittium* sp., *Acanthocardia paucicostata* and *Polititapes senescens*, that are typically associated with the Eemian interglacial (Wesselingh et al., 2012). The lithostratigraphic context of the Luxwoude deposits, below sediments of MIS 6 age, suggests that the sequence is equivalent to MIS 11, or potentially older (Wesselingh et al., 2023). As such, *Bittium*-dominated assemblages can no longer be attributed to the Eemian using molluscan biostratigraphy alone (Wesselingh et al., 2023).

Amino acid dating

AAR dating estimates the degree of degradation in intracrystalline biomineral proteins, allowing the determination of relative age. As AAR requires calibration to deposits of a known age, we include it here as a correlation technique as opposed to an absolute dating technique. In some regions, where a chronological framework has not been developed for the rate of protein degradation, the AAR dating approach is often conducted alongside a secondary chronological tool. AAR dating has been particularly used in understanding the age of coastal deposits, where shell carbonate is most likely to be present. For example, AAR has used in conjunction with U/Th ages to date the timing of the Last Interglacial sea-level highstand recorded by the Glanville Formation in Australia (Murray-Wallace et al., 2016). AAR dating has also been used to correlate sediments associated with the Last Interglacial marine transgression around the southern part of the North Sea basin (Meijer and Cleveringa, 2009), and in the UK a vertically well-constrained sea-level index point for MIS 5e has been established based upon AAR dating of a salt marsh sequence at Tattershall Castle in Lincolnshire (Holyoak and Preece, 1985; Penkman et al., 2013; Cohen et al., 2022). A wealth of AAR ages (>600), alongside limiting ^{14}C and U-series ages, highlights the presence of an extensive coastal sedimentary aminozone preserved both offshore and onshore Delaware and Maryland, eastern USA, which most likely formed during MIS 5 (Wehmiller et al., 2021). However, the spread of results, in part due to the wide range of material used for dating and the large sample size and area, makes it hard to pinpoint deposition to a particular substage.

Over recent decades, refinements in sample preparation protocols, particularly the isolation of the intracrystalline fraction of amino acids that degrade within a closed system with limited mineral diagenesis, have improved the resolution of the technique considerably (Sykes et al., 1995; Penkman et al., 2011). In Britain, these developments in AAR dating approaches have been tested against the framework of the Thames river terraces (Penkman et al., 2013). As a result, the technique has played an important role in redefining the stratigraphy and chronology of the Pleistocene, facilitating accurate integration of the terrestrial record with the marine oxygen isotope stratigraphy (Penkman et al., 2011). Whilst the potential resolution of the technique depends on the temperature history of the sample, in optimal settings such as the interglacial fluvial sequences of the British Isles, it has been suggested that closed-system AAR ages can be resolved to the level of marine isotope substages (Westaway, 2009; Sier et al., 2011) and is therefore a promising tool for resolving Last Interglacial chronologies.

Tephrochronology

Tephra studies, which use volcanic deposits to make direct stratigraphic correlations between records, have great potential to correlate and provide chronological constraint in sediment archives of the Last Interglacial age. In particular, the identification of cryptotephra (non-visible volcanic ash deposits) in ice core and sediment sequences (see Davies, 2015 and references therein) has expanded the potential of tephra layers to link ice core, marine and terrestrial Last Interglacial sequences across hemispheric scales (Van Der Bilt et al., 2017). Tephra deposits of the Last Interglacial age have been identified in the Greenland ice cores (Davies et al., 2014) and North Atlantic marine deposits (Sjwøholm et al., 1991; Wastegård and Rasmussen, 2001; Brendryen et al., 2010; Abbott et al., 2013; Fig. 2). The Last Interglacial tephra framework for the North Atlantic consists of multiple isochrons with well-characterised major element geochemistries, many of which have been identified in more than one site (Fig. 2; Table S1). Relatively little work has been undertaken terrestrially, except the Klaksvík lake sequence from the Faroe Islands (Wastegard et al., 2005); however, the number of widely dispersed tephra layers found throughout the North Atlantic suggests that there is great potential to construct tephrostratigraphies for Last Interglacial terrestrial sequences within NW Europe.

Away from the North Atlantic, the Dümpelmaar tephra also provides opportunities for correlation. The Dümpelmaar tephra has formed an important tie-point across multiple terrestrial sediment cores collected through the ELSA Project (Eifel Laminated Sediment Archive) and has a $^{40}Ar/^{39}Ar$ radiometric age of 116 000 ± 16 000 (Van den Bogaard and Schmincke, 1990). Given the wide dispersal of the Laacher See tephra, another Eifel tephra that forms a vital isochron in the synchronisation of proxy archives throughout Germany, France and even northern Italy during the Younger Dryas, the Dümpelmaar isochron has similar potential to be used as an anchor point within Last Interglacial chronologies.

Further afield, widespread Last Interglacial tephra deposits have been identified in marine and terrestrial archives from the Mediterranean (Paterne et al., 2008). However, at present, no Last Interglacial-aged Mediterranean tephra deposits have yet been identified beyond the Mediterranean region, Holocene cryptotephra deposits identified in Wales (Jones et al., 2020)

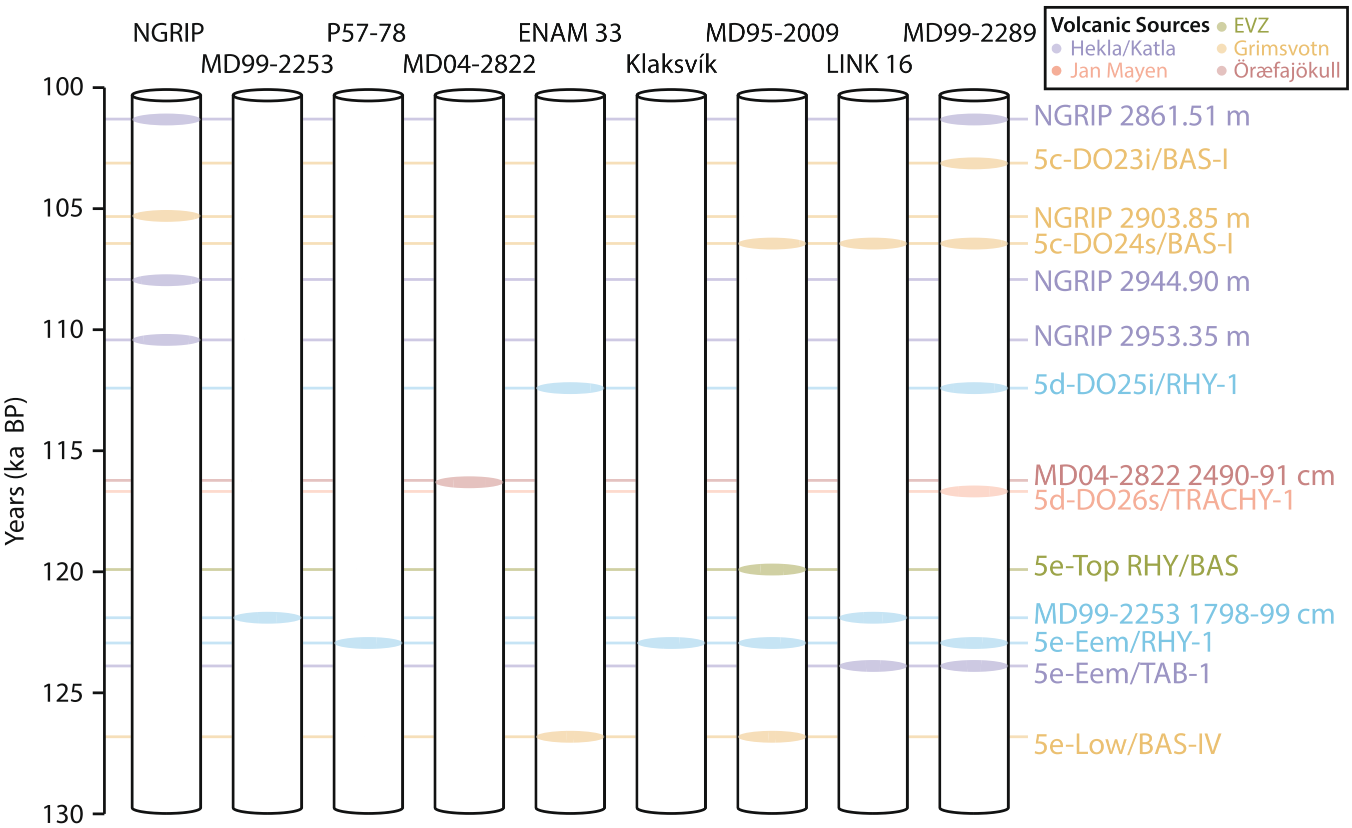

Figure 2. Simplified summary diagram of key tephra horizons within the North Atlantic tephrostratigraphic framework spanning 130–100 ka. Archives included here include ice cores from Greenland (NGRIP; Davies et al., 2014), marine sediment cores North Atlantic (MD99-2253, Davies et al., 2014; P57-7, Sjwøholm et al., 1991; MD04-2822, Abbott et al., 2013; ENAM-33, Wastegård and Rasmussen, 2001), terrestrial sediment cores from the Faroe Islands (Klaksvik, Wastegard et al., 2005) and marine sediment cores from the Norwegian Seas (MD95-2009, Sjwøholm et al., 1991; LINK 16, Abbott et al., 2013; MD99-2289, Brendryen et al., 2010). For a more complete overview, the reader is referred to Table S1. [Color figure can be viewed at http://wileyonlinelibrary.com]

and Germany (Lane et al., 2015) have been correlated with eruptions of the Italian volcano Campi Flegrei. Thus, assuming similar tropospheric wind patterns between the Last Interglacial and the Holocene, future identification of Last Interglacial Mediterranean tephra isochrons (Wulf et al., 2012) in more distal environments may also enhance the dating and correlation of Last Interglacial sequences between regions.

Direct correlation between the terrestrial and deep-marine realm through tephra linkages will provide an unambiguous anchor point through which the Eemian pollen biostratigraphy can be fixed against the marine oxygen isotope stratigraphy. Ideally, such work would be undertaken on a varved sequence, such as the Bispingen palaeolake, where a robust independent chronology (albeit without absolute age control) will allow the development of an Eemian tephra stratotype.

Palaeomagnetism

Secular variability in the Earth's magnetic field has also been used to Last Interglacial sequences, as sediment sequences can record both directional and relative changes in the intensity of the geomagnetic field (Channell et al., 2009). Assuming that these changes are globally synchronous, this variability can be used as a chronostratigraphic tie-point (Stoner and St-Onge, 2007). During the Last Interglacial, the most notable palaeomagnetic variations are the ca. 120 ka Blake Event and the ca. 100 ka Post-Blake excursion (Thouveny et al., 1990).

Multiple studies have utilised the presence of the Blake Event as a means of dating Last Interglacial sequences (Abrahamsen, 1995; Sier et al., 2011, 2015b; Valero-Garcés et al., 2019). Sier et al. (2015b) identified the Blake Event in sediments from Rutten (the Netherlands) that span Eemian pollen zones E1–E5. In this work, Sier et al. (2015b) proposed a later onset of 121 ka for the pollen zones of the Netherlands, based on the correlation of the Blake Event with the chronology of Osete et al. (2012), the end of zone E5 correlates to the end of MIS 5e, and zone E6 is associated with the start of MIS 5d, ca. 114 ka. Luminescence ages broadly support this interpretation; however, these ages come with large associated uncertainties, and the absolute timing of the Blake Event is poorly resolved (Fig. 3). Such an interpretation is controversial as it would require the onset of temperate conditions in NW Europe over 5000 years later than the onset of interglacial conditions in southwestern Europe at ca. 129 ka (Tzedakis et al., 2018).

Due to uncertainty as to the chronological constraints on the Blake Event, however, its utility as a tie-point remains under question. The type locality for the Blake Event is the Blake/Bahama Outer Ridge (Smith and Foster, 1969), where it was dated by (Wollin et al., 1971) to ca. 115 ka BP (MIS 5e to 5d transition). Subsequently, evidence of the Blake Event has been identified in a range of archives globally (Fig. 3 and references within the caption). Largely, sediment studies suggest that the Blake Event occurs within the Last Interglacial; however, there is a large spread of potential ages; in some cases, the Blake Event has been identified in MIS 5d (Tric et al., 1991) or even towards the end of MIS 6 (Nowaczyk and Frederichs, 1999). Likewise, the estimated duration of the Blake Event ranges from 1000 to 8000 years (Tucholka et al., 1987; Nowaczyk and Baumann, 1992). A recent, higher resolution study from the type-site suggests that the Blake Event encompasses a sequence of events, including the Post-Blake excursion, in line with earlier detailed studies of

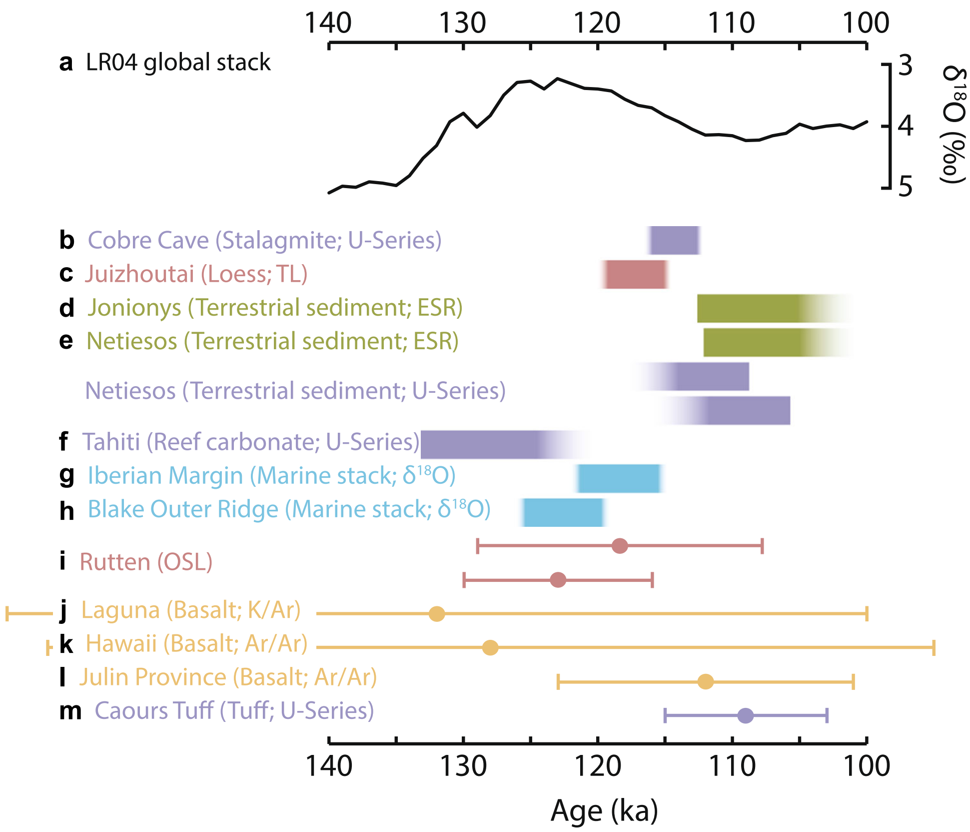

Figure 3. Timings of the Blake event relative to (a) the LR04 benthic stack determined through palaeomagnetic studies in multiple Quaternary archives, including (b) Cobre Cave (Osete et al., 2012), (c) Juizhoutai (Fang et al., 1997), (d) Jonionys (Gaigalas and Hütt, 1996), (e) Netiesos (Gaigalas et al., 2005), (f) Tahiti (Iryu et al., 2010), (g) Iberian Margin (Carcaillet et al., 2004), (h) Blake Outer Ridge (Lund, 2022), (i) Rutten (Sier et al., 2015b), (j) Laguna (Champion et al., 1988), (k) Hawaii (Holt et al., 1996), (l) Julin Province (Zhu et al., 2000) and (m) Caours (Sier et al., 2015a). [Color figure can be viewed at http://wileyonlinelibrary.com]

palaeomagnetic variability (Nowaczyk and Baumann, 1992; Thouveny et al., 2004).

One age constraint often applied is the identification of two palaeomagnetically reversed intervals in a precisely dated Spanish speleothem at 116.5 ± 0.7 and 112.0 ± 1.9 ka (Osete et al., 2012). Given the crucial role that soils play in modulating signals recorded in karstic sequences and the poorly defined magnetisation components within weakly magnetised carbonates (Channell et al., 2020), future work observing the same changes at the same time in other records would be vital to confirm a link between observed magnetic variability and a specific geomagnetic event. Other absolute ages for the Blake event, determined through radiometric dating of lava flows with reversed polarity, suggest a duration from ca. 130 to ca. 120 ka, but all these eruption ages have large associated uncertainties, >50 kyr in the case of the Laguna Basalt (Fig. 3).

The timing inconsistencies presented across these multiple datasets demonstrate an incomplete understanding of changes in the geomagnetic field across the Last Interglacial. A key complexity is that, generally, magnetic excursions are associated with changes in the relative strength of the non-dipole and dipole field, and the field structure is likely to have been complex and not globally homogeneous (Bol'shakov, 2007). Furthermore, disentangling a complex, multiphased geomagnetic signal from local factors of physical or magnetic disturbance in sedimentary sequences is, at present, challenging (Lund, 2022). Given the poorly resolved pattern of magnetic field variability and the limited robust and reproduced constraints on the age and duration of the Blake Event, further work is required before it can be used as a reliable isochron in the dating of Last Interglacial-age sediments.

Cosmogenic radionuclides

Global synchroneity in the atmospheric production of cosmogenic radionuclides, due to changes in solar radiation and the Earth's geomagnetic field, can be used to align marine and terrestrial records. Although limited cosmogenic radionuclide studies span the Last Interglacial, high-resolution analysis of ^{10}Be in terrestrial and ice core sequences contains considerable scope to improve the correlation of records throughout the period. Such techniques have been applied across the last glacial cycle, where the correlation of ice records from Greenland and Antarctica has been refined by synchronising variability in ^{10}Be (Raisbeck et al., 2007). Similarly, variability in the ^{10}Be production rate, which is globally homogeneous, has been used to synchronise a sediment core from the Black Sea to the Greenland ice cores, facilitating detailed interrogation of the propagation of climate signals downstream from the North Atlantic (Czymzik et al., 2020).

High-resolution palaeointensity records can also be aligned with changes in the abundance of cosmogenic nuclides, given that they are both driven by changes in the Earth's geomagnetic fields. For example, detailed palaeointensity reconstructions from the Black Sea (Nowaczyk et al., 2013) contain many of the oscillations recorded by the ^{10}Be-flux in Greenland ice cores (Muscheler et al., 2005) and δ^{14}C record from Lake Suigetsu (Bronk Ramsey et al., 2012). Future studies that develop and synchronise proxies for changes in the Earth's geomagnetic field, such as ^{10}Be, across the Last Interglacial have the potential to advance our understanding of the global leads and lags in Earth system responses, important for understanding which climatic systems are altered under warmer-than-present high-latitude temperatures.

Summary

As we have summarised, a range of techniques have been applied to construct chronologies for the Last Interglacial sequences to better understand the temporal and spatial variability in climate, environment and Earth system responses. Given the limitations associated with and assumptions required in the application of dating approaches outlined here, the strongest chronologies are developed when techniques are used in combination rather than in isolation. The application of multiple chronological techniques to a single site also promotes critical evaluation of the different dating methods, improving our understanding of the uncertainties inherent within our chronological frameworks. Indeed, there is a great deal of information to be gleaned through reconciling seemingly disparate ages, demonstrated perhaps most clearly through how revolutions in AAR dating have driven a re-evaluation of interstadial pollen assemblages of the British Isles (Penkman et al., 2011). There is, however, more work to be done, and a considerable amount of effort is required to refine the Last Interglacial chronologies to allow robust global-scale correlations between records. We explore this through a case study of the Last Interglacial pollen biostratigraphy in the Netherlands and Northern Germany.

Case study: interrogating the Eemian pollen zones of the Netherlands and Northern Germany

Our understanding of the timing of climate and environmental change during the Last Interglacial has been greatly advanced through the application of the methods outlined above, but in particular through the study of sequences from NW Europe, particularly the Netherlands and Northern Germany. For example, the analysis of sequences from NW Europe was amongst the first to identify a Last Interglacial sea-level highstand (Hollin, 1977; Zagwijn, 1983) and provided the first estimates of the duration of the interglacial (Müller, 1974). These insights were largely facilitated by chronologies developed using the Eemian pollen zonation scheme (Zagwijn, 1961), which has formed the backbone for much of the dating and correlation of sequences from NW Europe. As a result, the spatial coverage of pollen data from Eemian sequences, particularly in the Netherlands and Northern Germany, is far greater than many other regions.

Pollen biostratigraphical approaches to dating do, however, have large associated uncertainties. Rather than discounting pollen records as a source of chronostratigraphic information, here we provide an overview of publicly available Eemian pollen data. We highlight, in particular, the consistency in patterns of temperate forest development across sites in different depositional environments, which suggest that biostratigraphic correlation approaches are not greatly hindered by site-specific ecological contexts. We then go on to assess the future work needed to better inform the application of pollen biostratigraphy, primarily by anchoring existing varve stratigraphy, and also the correlation methods that can help identify leads and lags in vegetation response between sites. Much has been done comparing pollen archives from northern Europe to those from south of the Alps (Tzedakis, 2003); here we focus on records from NW Europe to avoid problems of large temporal lags due to the role of cold-stage climate refugia.

Revisiting the Eemian pollen biostratigraphy

To review the current understanding of Eemian pollen biostratigraphy, we combine records available within the

Neotoma database (Williams et al., 2018) with a review of the published literature to directly compare pollen records of the Last Interglacial age from NW Europe. We focus on sites with well-resolved pollen sequences, with >10 samples containing interglacial pollen assemblages. Firstly, we plot all records within the Neotoma database that have been assigned a Last Interglacial age within the database and all sites where the metadata contained the keywords 'Eemian' (Fig. 4). We note that not all of these sequences have independent chronological control to support their assignment to the Last Interglacial; some have been correlated on the basis of pollen stratigraphy alone, and therefore caution is advised in their interpretation. The Neotoma database does not contain information regarding the assignment of Eemian pollen zones to the pollen data. Through a review of the literature, we collate the depths of the pollen zones from their original publications and assign this information to sites with publicly available data in the Neotoma Database. We utilise 17 records for which the complete pollen dataset is publicly accessible in the Neotoma database (Williams et al., 2018) and for which pollen zones have been assigned: one from Bispingen (Germany), one from the North Sea and the remainder ($n = 15$) from the Netherlands (Table S2). Part of this geographical bias is due to the availability of digitised pollen data from Dutch sites (de Wolf et al., 2023); however, the presence of deep Saalian basins located in the Netherlands provides long and continuous Last Interglacial pollen records (Fig. 4). A sufficient sample resolution is necessary for features of the Eemian pollen zonation schema, such as the pronounced *Carpinus* peak associated with zone E5 (Table 1) to be detected, and assignments of samples to individual zones are less robust where sample resolution is insufficient. As a result, we have selected only sites where at least three consecutive primary pollen zones are identified (e.g., E1–E3),

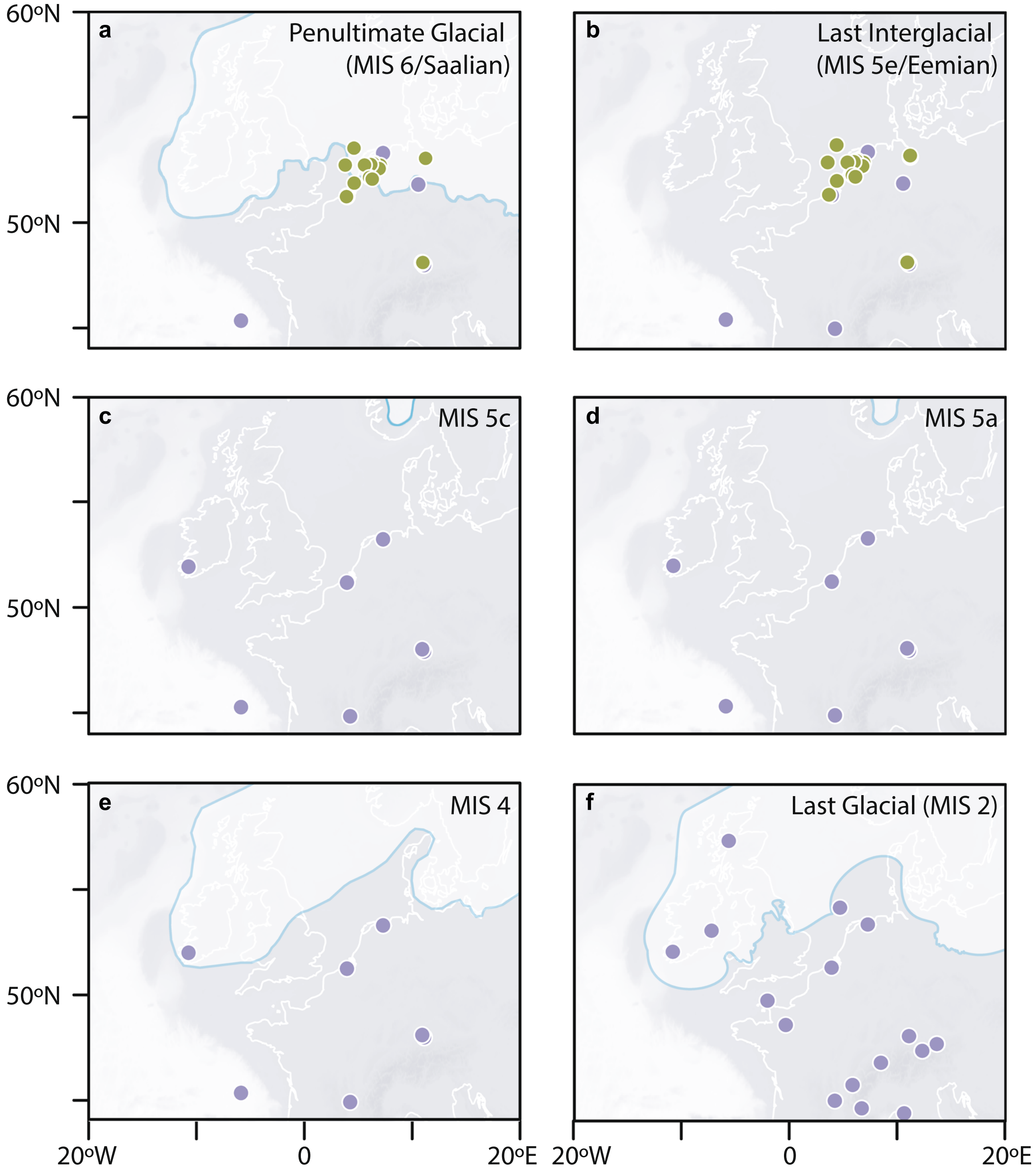

Figure 4. Maps showing the distribution of pollen records in the *Neotoma* database with chronologies that span (purple dots) or site descriptions that reference (green dots) the following marine/terrestrial stages: (a) MIS 6/Saalian/Wolstonian, (b) MIS 5e/Eemian/Ipswichian, (c) MIS 5c, (d) MIS 5a, (e) MIS 4 and (f) MIS 2 alongside the ice margins of Batchelor et al. (2019). [Color figure can be viewed at http://wileyonlinelibrary.com]

and where for each pollen zone at least two samples have been assigned to that zone. All the R scripts used in this analysis are available at https://github.com/amy-mcg/McGuire_LIG.

The consistency of the arboreal pollen signal between sites, long discussed in the literature (Turner, 2000), is very clearly expressed in the data (Fig. 5). Some taxa are, however, more consistent than others in their abundances between pollen zones across a range of sites. For example, there is a distinctive and well-constrained reduction in *Ulmus* pollen across the pollen zones, which is broadly consistent across all sites (Fig. 5). Some taxa, which are distinctive of a particular pollen zone, have clear patterns of expansion and contraction, for example, *Corylus* and *Carpinus* show clear expansions in pollen zones E4 and E5, respectively. The broad spread in *Carpinus* abundance within the E5 subzone is likely linked to the local availability of circum-neutral to slightly acidic soils, which are thought to have facilitated *Carpinus* expansion during the Eemian (Turner, 2002). Patterns of *Quercus* expansions are less consistent, with a broad spread in pollen percentage abundances across the E3 and E4 zones; however, a contraction of *Quercus* in the latter Eemian pollen zones is clearer. As with *Carpinus*, patterns of more variable expansions in *Quercus* taxa may relate to the underlying soils, which may have been less favourable in some regions.

Whilst soil conditions may drive the inter-site variability in the relative abundance of *Quercus* and *Carpinus* pollen, the marked decline of *Ulmus*, *Corylus* and *Quercus*, to be replaced by *Carpinus* in the E5 pollen zone, is a noted feature across Eemian records. Field et al. (1994) assumed this rapid decline is a vegetation response to a major climatic change, based on their reconstructions of mean annual temperature using modern analogues, and Zagwijn (1996) suggested it may serve as a horizon to facilitate intraregional correlation of pollen schema. Improved chronologies, or multi-proxy studies, may allow the attribution of this pollen change to a specific climatic amelioration. Finally, the limited expansion of *Abies* has long been a characteristic used to delineate the Eemian interglacial from earlier Quaternary interglacials (Phillips, 1974); however, as shown here, in many sites assigned to the Eemian, there is a notable expansion of *Abies* towards the end of the interglacial, particularly in the E5 and E6 pollen zones. Likewise, the expansion of *Picea* follows a similar trend, expanding across many sites in the E5 and E6 pollen zones, dominating in a limited number of samples, but in many contributing, in a small way, to the overall assemblage.

One key challenge in correlating pollen records is the importance of site-specific characteristics to the pollen assemblage due to the different taphonomic processes that govern the accumulation of pollen grains in depositional environments. For example, in marine contexts, taxa with buoyant pollen grains, such as *Pinus*, may be over-represented (Mudie and McCarthy, 1994). In contrast, in lake and coastal environments, the presence of proximal wetlands may lead to an over-representation of wetland taxa. Through a study of modern pollen distributions, Chmura et al. (1999) demonstrate that, whilst the taphonomic processes which drive pollen assemblages in coastal environments are complex, the representation of upland pollen taxa within assemblages is sufficiently consistent, away from the channel margins and ditches, to allow the application of biostratigraphical approaches.

Interestingly, when individual pollen samples are plotted against their principal components (Fig. 6), the same pollen zones in different sites are statistically similar, regardless of the specific contexts of the sites. The first two principal components, PC1 and PC2, account for 48.8% and 29.6% of the variance, respectively. These results hint at the potential for robust statistical linkages between the same pollen zones across different sites. In particular, pollen zones E4 and E5 show substantial clustering, potentially related to the fact that both are characterised by the presence of taxa not typically present in other pollen zones. Interestingly, the site that seems to contain the most deviation from the clusters across E4 and E5 is Amersfoort; however, this may be related to the marine transgression recorded at the site in sediments assigned to pollen zone E5 (Zagwijn, 1983; Cleveringa et al., 2000), or the collation of multiple cores from different sedimentary contexts within the basin as part of this analysis.

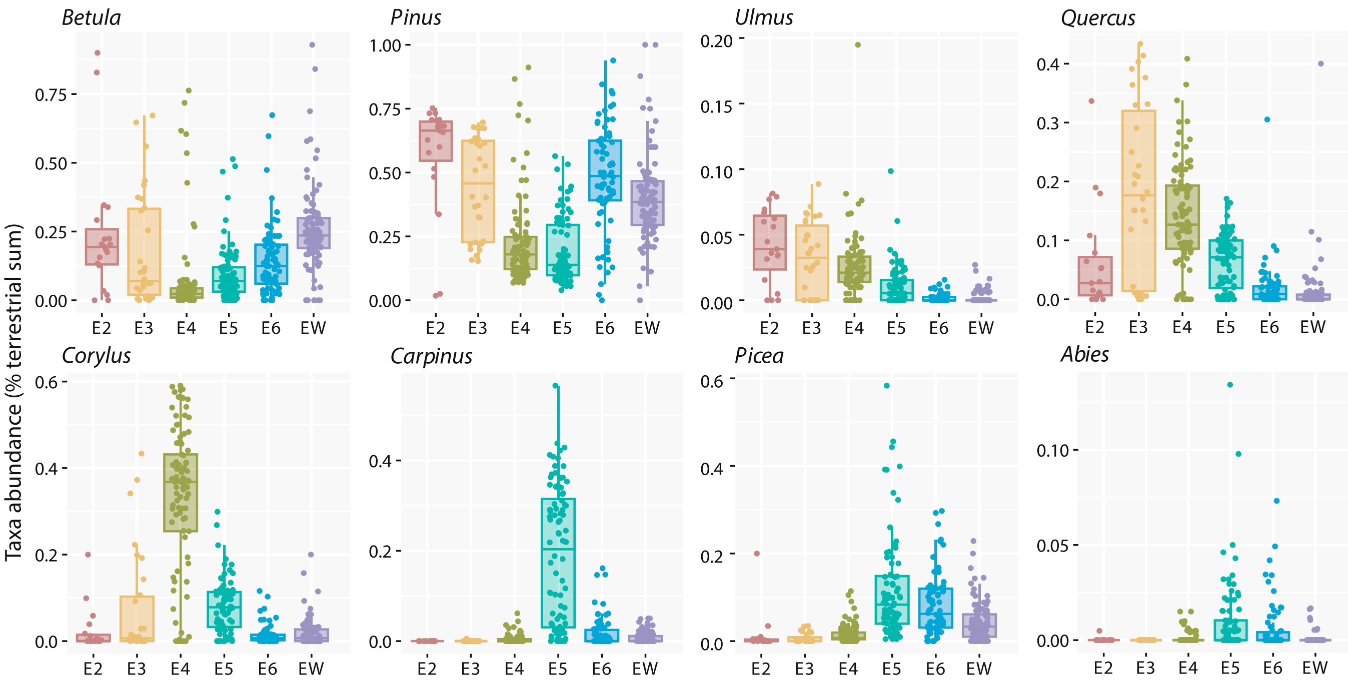

Figure 5. Box plots of pollen percentage abundances from the *Neotoma* database for individual taxa associated with Eemian forest expansion in NW Europe, grouped by the pollen zones (as per the original publication; see Supplementary Materials for full details). Given the limited data availability for E1, this substage is excluded. [Color figure can be viewed at http://wileyonlinelibrary.com]

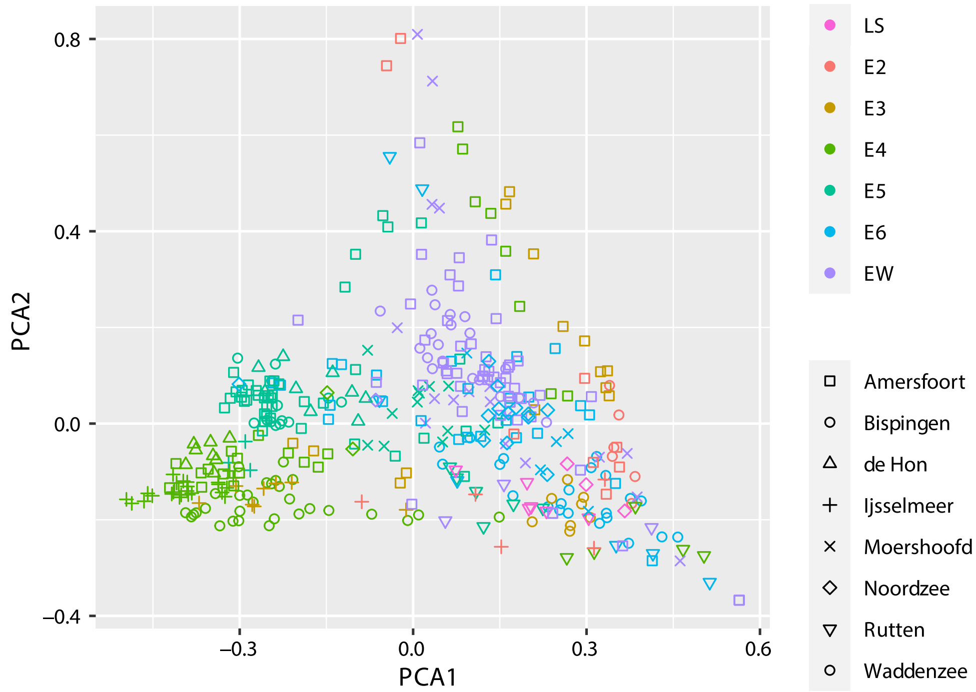

Figure 6. Principal component analysis of pollen data from selected NW European Last Interglacial sites (indicated by the shape of icon) included in the *Neotoma* database, grouped by the pollen zones (indicated by colour) as per the original publication; see Supplementary Materials for full details. [Color figure can be viewed at http://wileyonlinelibrary.com]

Given that a geographically limited range of sites (Fig. 4) are represented in our compilation at present, the addition of British and additional German sites to the dataset is necessary for this type of study to advance the application of pollen zone biostratigraphy across the Last Interglacial. With this in mind, we would like to highlight, and set as a benchmark, the work of de Wolf et al. (2023) in making over 600 fossil pollen and spore datasets from the Netherlands (spanning multiple Dutch research institutes) publicly available in the Neotoma database. Such initiatives will prove hugely important if we are to better understand vegetation dynamics across the Last Interglacial and other temperate stages within the Quaternary record.

Testing and anchoring Eemian pollen chronologies

The challenges associated with dating some Last Interglacial sedimentary sequences (e.g., lack of appropriate material for dating) mean that some sites will invariably rely on biostratigraphic correlation between pollen zones. As demonstrated, pollen biostratigraphy is a useful tool in aligning terrestrial sedimentary sequences of the Last Interglacial age, given the close replication of the pollen signals between sites. Three main challenges must be overcome before biostratigraphic data from the Eemian pollen zones can be incorporated robustly into models of the Last Interglacial age, which we outline here.

Firstly, studies that test the potential leads and lags in vegetation migration both locally and regionally in Europe during the Last Interglacial are needed, as done for the Holocene (Giesecke et al., 2017; Huntley, 1990), to test the uncertainties inherent within biostratigraphic correlation across the Last Interglacial. The challenge here is avoiding circular arguments whereby chronologies which are dependent on biostratigraphic approaches are used to test biostratigraphic approaches. Thus, it is paramount that biostratigraphic correlations are tested using independent dating methods. One possible approach to testing the synchroneity of local vegetation changes across the Last Interglacial could be through the alignment of records on the basis of tephrostratigraphy (McGuire et al., 2024), which would facilitate the evaluation of potential spatial and temporal offsets in vegetation succession across the Eemian.

Secondly, we need to ensure there is a detailed consideration of how the resolution of the pollen records being compared (often controlled by both sedimentation rate and sampling density) impacts the determination of pollen assemblage zones. Given that correlations are usually based on the transitions between different pollen zones, the resolution of the pollen record will impact where in the age-depth model that transition is placed (e.g., 1-cm sampling interval versus a sample every 50 cm). Whilst such uncertainties may be unavoidable due to resource-intensive nature of pollen analysis, transparency in the limitations of the chronological approach is necessary (e.g., terrestrial pollen sums are often higher in more recent work than in the earlier, pioneering, work that much of the correlation is based upon). There is the potential to develop statistical approaches that allow for the uncertainty inherent in the incorporation of time-synchronous horizons between records to be robustly quantified, allowing for both depth and age uncertainty in age-depth models.

The final, and perhaps most important, advance in the application of Eemian pollen biostratigraphy in NW Europe as a dating technique requires the testing and anchoring of the underpinning Bispingen varve chronology. As discussed, almost all chronologies that incorporate the Eemian pollen zones (Zagwijn, 1983; Lambeck et al., 2006) rely heavily upon the pollen zone durations based upon the varve chronology from Bispingen (Germany; Müller, 1974), as these timings are often used to constrain the sequencing of Earth system responses within NW Europe (Cohen et al., 2022). Recent work by Lauterbach et al. (2024) has substantially revised the Bispingen chronology, extending the duration of pollen zone E3 by ca. 3 kyr, and the overall duration of the Eemian by ca. 4 kyr. These new findings highlight the need to test Last Interglacial chronologies through the application of multiple dating approaches, and the need for constant critical evaluation of the chronologies used for correlation. Another key advance that is fundamental if we are to produce meaningful chronologies using the Eemian pollen zones is the anchoring of the currently 'floating' Bispingen varve chronology, which inhibits the construction of absolute chronologies for correlation beyond NW Europe.

Multiple attempts have been made to anchor the Eemian pollen biostratigraphy to allow correlation with global Last Interglacial records, all of which have limitations. Early work attempted to date the Eemian through to the marine oxygen isotope stratigraphy, resulting in the onset of the Eemian being placed at the onset of the substage of MIS 5e rather than MIS 5 more broadly (Shackleton, 1969). MIS 5e is dated to 128 ± 2 ka through astronomical tuning of the marine isotopic record (Imbrie et al., 1984). The synchronous onset and end of the Eemian and MIS 5e assumed by Shackleton (1969) are supported by the Imbrie et al. (1984) 12 kyr duration of MIS 5e, which closely aligned with the 11 kyr duration of the Eemian sequence based upon the Bispingen varve chronology. In the Netherlands, Zagwijn (1983) correlated the regional sea-level highstand, and thus the E5 pollen zone, to 'a round figure of 120 000 years' in accordance with deep sea records. Subsequent work tested this assumed synchroneity between the marine isotopic record and terrestrial interglacial pollen assemblages and found that it did not hold (Sánchez Goñi et al., 1999). Instead, in the Iberian Margin sequence, the Eemian (as palynologically defined) spans from the lightest isotopic values of MIS 5e (ca. 126 ka) to the heavier isotopic values towards the MIS 5e/5d transition (Sánchez Goñi et al., 1999). Thus, the base of the Eemian sits above the base of MIS 5 and ends during MIS 5d (Shackleton et al., 2003). Thus, a limited understanding of the relationship between the Eemian as defined palynologically in NW Europe and the changes recorded in the deep sea record limit the utility of this approach. One approach to dating and anchoring the Bispingen varve chronology to an absolute timescale may be through the application of tephrochronology. The identification of the Last Interglacial tephra in North Atlantic marine cores (Abbott et al., 2014) means that should the same tephra layers be identified within Bispingen, a direct correlation between the Bispingen record and the deep sea marine oxygen isotope chronology will be possible. Moreover, should a tephra deposit associated with an eruption of known age be identified in Bispingen, for example, the radiometrically dated Dümpelmaar Tephra (116 ± 16 ka; Van den Bogaard and Schmincke, 1990), that age can be incorporated into the Bispingen age-depth model.

The presence of abrupt changes in the oxygen isotope record of well-resolved and well-dated Greenland ice cores means that a North Atlantic 'event stratigraphy' could be used to align regional records of climate and environmental change. For example, the NGRIP ice core records the termination of the Last Interglacial with glacial inception at 118 ka (North Greenland Ice Core Project members, 2004). In the NEEM record, the Eemian sequence is argued to span from 128.5 to 114 ka, with the occurrence of surface melt from 128.5 to 126.7 ka (NEEM community members, 2013). Event stratigraphies have been utilised extensively across the last glacial cycle (Björck et al., 1998) to standardise terminology, and as a starting point for correlations across the Last Glacial–Interglacial transition. Alignment to ice core chronologies as a starting point is, however, more challenging across the Last Interglacial than across the last glacial to interglacial transition, as the Last Interglacial sits beyond annual layers in the Greenland ice cores. Thus, the LIG age model for both NGRIP and NEEM is based on the global $\delta ccc^{18}Oatm$ and CH_4 records from the Antarctic EDML ice cores (Capron et al., 2010). The EDML/NorthGRIP common ice timescale of Capron et al. (2014) has a total uncertainty based on two primary sources of uncertainty: the uncertainty in the Δage in the two cores (that is to say the offset between the ice age and the gas age) and the uncertainty inherent in the tie-points between the two different gas records. However, whilst the resultant uncertainties are high by ice core chronology standards (>1000 years) they are far lower than the age uncertainties associated with other dating approaches, and therefore alignment to the ice core chronology may refine chronologies, particularly where abrupt changes (e.g., Dansgaard–Oeshger warmings 24 and 25; Capron et al., 2010) are detected. Such an approach has already been utilised by Sirocko et al. (2004), who synthesised multiple sedimentological proxies across a range of laminated lake sediments from Southern Germany to identify a late Eemian aridity pulse, which they attributed to a close teleconnection between climate in NW Europe and MIS 5d glacial inception in Greenland. The aridity pulse is concomitant with the end of the Eemian, as palynologically defined by the replacement of forests with open vegetation (Menke and Tynni, 1984; Table 1), and thus they assign a 118 ka age for the end of the Eemian in the Eifel region of Germany. Going forward, it is important to test the validity of these correlations using additional chronological control. If we are to settle debates about the timing of the onset or duration of the Eemian, independent, site-specific chronologies are necessary, as assumptions of synchronous Last Interglacial climatic variability in the North Atlantic realm have frequently been questioned by high-resolution, well-dated proxy studies across the last glacial to interglacial transition (Lane et al., 2013; Muschitiello and Wohlfarth, 2015).

The importance of producing absolutely dated Last Interglacial chronologies

Testing temporal asynchroneities in climate and environmental change across the Last Interglacial

A large body of earlier work (Tzedakis, 2003) sought to develop explanations as to why the duration of the Eemian, as defined palynologically in the varved Bispingen record (11 kyr; Müller, 1974) was 7 kyr shorter than recorded in Iberian Margin sediments (19 kyr; Tzedakis et al., 2018). A similar paradox persists regarding the duration of interglacial conditions during MIS 11 (ca. 426 to 396 ka) where varve records from Northern Europe suggest a duration of ca. 15–16 kyr, around half of the 32 ka duration of the corresponding interglacial substage, MIS 11c (Candy et al., 2024). Given the recent revisions to the Bispingen varve chronology, which proposes the duration of the Eemian in NW Europe as ca. 15 kyr, the latitudinal offset in the duration of the Last Interglacial between Southern and Northern Europe is greatly reduced and now sits at around 2.5–3 kyr (Lauterbach et al., 2024). There remains, however, a difference in the duration of the Last Interglacial between higher and lower latitudes which needs to be resolved, and which would greatly benefit from improved Last Interglacial chronologies.

Typically, it has been assumed that the offset in the timing of *the start* of the Last Interglacial forest expansion was minimal between southern and northern Europe (Tzedakis, 2003), as seen at the onset of the Holocene (Engels et al., 2022); however, such hypotheses have yet to be robustly tested due to a lack of absolutely and precisely dated records. Interestingly, a rapid increase in temperate forest cover in the Bay of Biscay pollen record, ca. 130 ka, occurs in concert with a peak in runoff from the southern Greenland ice sheet (Sanchez Goni et al., 2012), suggesting a close connection between forest cover and ice sheet geometry.

If the onset of the Last Interglacial was synchronous across NW and SW Europe, it is possible that at *the end* of the Last Interglacial, there was a 2.5–3 kyr offset in the timing of vegetation response. To understand this potential offset in the timing of vegetation change, it is important to understand the different limiting factors which would have driven the decline in temperate taxa at the end of the interglacial. At more northerly latitudes, the shortening of the growing season and reduced summer temperatures are likely to have led to the decline of temperate taxa (Tzedakis, 2003). During the Last Interglacial, June insolation at 65°N drops below Holocene minima (ca. 120 ka; Fig. 7). The dramatic reduction in surface temperatures, which would likely result from this decline in summer insolation, is a likely driver of the transition from interglacial warm-temperate pollen to the cold-stage pollen of NW Europe during early stages of the subsequent (Weichselian) glaciation. In contrast, in SW Europe, moisture availability is likely the major driver of forest development (Sánchez Goñi et al., 1999). Terrestrially, higher water levels at the Padul wetland (SW Iberia) during the early Last Interglacial relative to the Holocene were likely the result of increased autumn–winter precipitation (Camuera et al., 2019) associated with high summer and low winter insolation. Towards the end of the Last Interglacial, summer insolation increases (Berger, 1978) are refelected in vegetation assemblages in some records, for example a peak in *Abies* ca. 116–113 ka in El Cañizar de Villarquemado (González-Sampériz et al., 2020). Ecosystem composition in SW Europe is, therefore, not linked simply to temperature, as is often assumed in records from NW Europe, but rather to precipitation. As such, the timing of interglacial forest expansion in SW Europe is not simply a product of Last Interglacial temperature increases, but rather a complex interplay between changing insolation, ice-sheet geometry and atmospheric and ocean circulation.

The relationship between orbital geometry and the duration of interglacial conditions is a complex one, as evidenced when comparing the Last Interglacial with the Holocene (Fig. 7). For example, during the Last Interglacial thermophilous woodland reaches its maximum extent, as recorded in Iberian Margin pollen records, before the peak in June insolation at 65°N

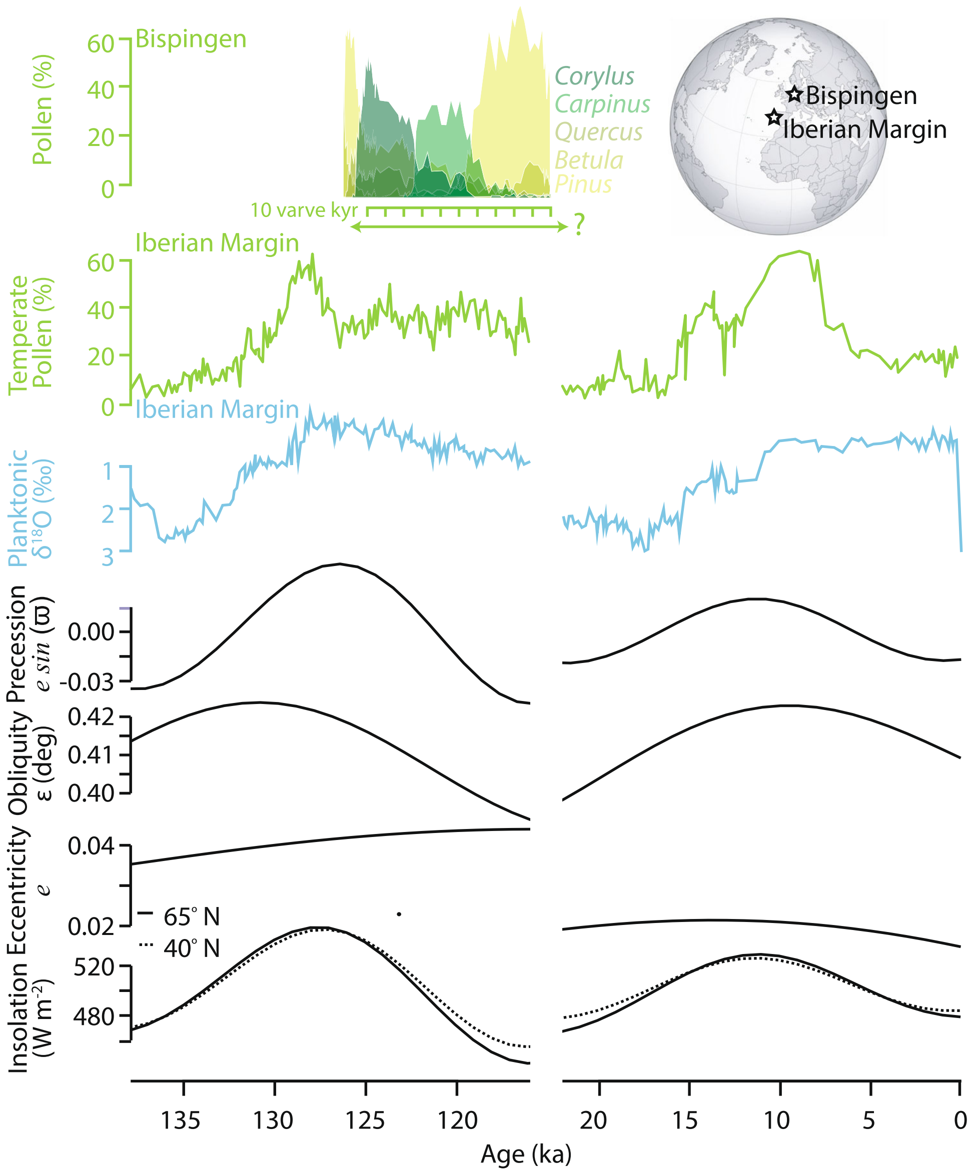

Figure 7. Comparison of Last Interglacial and Holocene records, including (a) the Bispingen pollen record (Müller, 1974); (b) Last Interglacial (MD01-2444; Tzedakis et al., 2018) and (c) Holocene (SHAK06-5K; Cutmore et al., 2022) temperate tree pollen records and (d) Last Interglacial (MD01-2444; Tzedakis et al., 2018) and (e) Holocene (SHAK06-5K; Ausín et al., 2019) planktonic $\delta^{18}O$ from the Iberian Margin cores; plotted against orbital parameters calculated after Berger and Loutre (1991) using the *Palinsol* R package (Crucifix, 2016), including (f) precession, (g) obliquity, (h) eccentricity and (i) June insolation at 65°N and 40°N. [Color figure can be viewed at http://wileyonlinelibrary.com]

(Tzedakis et al., 2018). It should, however, be noted that the chronologies for the Iberian Margin marine sequences across the Last Interglacial aligning its temperate tree pollen curve to the oxygen isotope record from Corchia Cave speleothems (Tzedakis et al., 2018); therefore, robust assessment of chronological uncertainties across this period is not possible. In contrast, over the Holocene thermophilous woodland reaches its maximum extent ca. 2 ka after the insolation maxima (Cutmore et al., 2022). Cutmore et al. (2022) suggest this intra–interglacial difference results from the evolution of northern hemisphere ice sheets, argued to have a dominant influence over regional temperatures due to the southward deflection of the westerly jet (Harrison et al., 1992; Cutmore et al., 2022; Fletcher et al., 2013). At present, given that many Northern European palaeo-climate and vegetation records only have floating chronologies, it is not possible to draw inferences about the relative timing of the Last Interglacial onset relative to the Holocene, and therefore climatic drivers, and future work should seek to facilitate detailed comparisons between the regions.

The integration of records from NW and SW Europe, only possible through precise and accurate geochronological frameworks, is paramount to test whether there is a latitudinal difference in the duration of the Last Interglacial. Whether these improved chronologies will arrive through developments in correlative approaches or absolute dating techniques remains to be answered. The potential for such studies to unpick the complex interplay and lead, lags and responses between vegetation, temperature, ice sheet volume, oceanic circulation and changes in orbital configuration, is demonstrated. Ultimately, whilst biostratigraphy can be used with confidence to determine relative ages within a sequence, the development of vital regional- and global-scale correlations will require a robust means of anchoring Northern European varve chronologies to an absolute timescale.

The way ahead

As we have reviewed, numerous techniques exist for dating the Last Interglacial sequences. Incorporating these varied approaches into one single, site-specific chronology to facilitate correlations between regional and global records of climate and environmental change is a vital stage in facilitating inter-archive comparison and identifying forcings, drivers and responses in the Earth's climate system. Here, we consider the advances which would help in constructing better chronologies for the Last Interglacial, and other Quaternary interglacials beyond the upper age limit of radiocarbon dating, before outlining a best practice for constructing better age-depth models. Our suggestions draw, in large part, from the successful protocols set out by the INTIMATE climate network for constructing chronologies for the Last Glacial–Interglacial transition (Lowe et al., 2008; Blockley et al., 2012; Rasmussen et al., 2014).

Primarily, we argue that reliance on a single dating technique can result in errors, and thus, wherever possible, multiple chronological approaches should be applied to test and refine existing age models. Much as the need for multi-proxy approaches when reconstructing palaeo-environmental change, robust chronologies developed through the integration of multiple techniques, should always be the aim. Challenges, however, can arise when developing age-depth models with different inherent calibration, instrumental and statistical uncertainties. Perhaps one of the best examples of an integrated Last Interglacial terrestrial chronology is that of Lago Grande di Monticchio, Italy, for which both a varve chronology (Martin-Puertas et al., 2014) and a tephra record (Wulf et al., 2012) have been developed. Subsequently, Bayesian age-depth modelling approaches have been applied to integrate the varve and tephra records to minimise the absolute age uncertainty (Martin-Puertas et al., 2019). Integrative approaches will be vital if the floating Eemian varve chronologies of Bispingen and other North European sites are to be anchored to an absolute timescale, which will facilitate interrogation of the relative timing of climate, sea-level and vegetation changes during the Last Interglacial.

We are aware, however, that most sequences from which one may wish to reconstruct environmental changes do not contain annual laminations, and that if we are to get a full picture of the spatial variability in Earth system responses to the Last Interglacial climate change, it will involve correlating less precisely dated sequences. The first step is to confirm correlation to the Last Interglacial, as opposed to an earlier interglacial, by using AAR or luminescence approaches. Subsequently, other dating approaches (e.g., palaeomagnetism and tephrochronology) can refine the chronologies, allowing for more precise correlations between records. Bayesian age-depth modelling approaches are still applicable in reconciling these approaches, even in the absence of radiocarbon dating, for example, as applied in the El Cañizar de Villarquemado record (Valero-Garcés et al., 2019).

The challenges associated with dating some Last Interglacial sedimentary sequences (e.g., lack of appropriate material for dating) mean that some sites will invariably rely on biostratigraphic correlation, for example, between pollen zones. As argued through our case study, a number of challenges must be overcome before biostratigraphic data can be incorporated robustly into the Last Interglacial age models. Primarily, for accurate assessment of chronological uncertainties, biostratigraphic dating approaches will require an evaluation of the potential leads and lags in vegetation migration both locally and regionally, and a detailed consideration of how the resolution of vegetation reconstructions (controlled by both sedimentation rate and sampling density) impacts the determination of pollen assemblage zones. Although neither challenge is insurmountable, both are necessary to quantify the uncertainty inherent in biostratigraphic alignment.

A key challenge for those attempting to construct chronologies for Last Interglacial sequences is that the dating methods outlined herein have, largely, been undertaken by researchers with different backgrounds and research interests (e.g., geochemistry versus palaeo sea level). Consequently, different communities have adopted differing approaches to reporting results and dealing with uncertainties, hindering direct comparison of the resulting chronologies. Across all dating approaches, age uncertainties should be accurately conveyed and how they were calculated explained. Any assumptions that have been made in the calculation of an absolute age should be made clear, to allow the work to be reproduced reliably. There has been significant progress made via the Last Interglacial palaeo sea-level community (Rovere et al., 2023) to develop standardised approaches and databases for reporting U/Th dates from Last Interglacial sequences (Hibbert et al., 2016; Chutcharavan and Dutton, 2021), a framework that could be adapted and applied to other techniques. Finally, following the guidance of Brauer et al. (2014), we highlight that the development of a robust geochronological model should be considered at the onset of research, rather than as an afterthought. Good chronologies are the result of selecting the most suitable dating methods for a sequence, and integrating multiple approaches provides opportunities for chronologies to be tested and, if necessary, re-evaluated.

Summary and future developments

There are many questions that remain regarding the spatial and temporal variability in regional responses to Last Interglacial climate warming (Capron et al., 2019). Such questions can only be answered by building accurate, and as far as possible, independent chronologies.

Due to reliance on a limited number of independently dated archives we are still uncertain if a true difference in the timing and duration of the Eemian, as defined palynologically, exists between Northern and Southern Europe. The newly revised Bispingen chronology (Lauterbach et al., 2024) demonstrates the value of re-evaluating existing age models, as it has reduced estimates of the offset in the duration of the Eemian with the duration of the Last Interglacial as observed in a range of proxies across Southern Europe, significantly. Furthermore, the timing and rates of sea-level change, particularly in the high and mid-latitudes, are still poorly constrained (Barnett et al., 2023). Sea-level reconstructions from NW Europe, currently primarily dated through pollen biostratigraphy, have huge potential to resolve the timing of ice sheet retreat during the Last Interglacial (Dutton et al., 2015) should their chronologies be substantially revised, and temporal uncertainties better quantified.

Refinements in dating techniques which can provide absolute age control in difficult-to-date sedimentary sequences, such as AAR and trapped charge dating techniques, have continued at pace over recent decades (Penkman et al., 2013). There is considerable scope for further advances in these fields going forward, for example, AAR dating of mammalian tooth enamel (Dickinson et al., 2019). The opportunities presented for these techniques to test and improve our existing chronologies and to construct chronologies for new sites without relying on the alignment of proxy records are considerable.

If we are to comprehensively interrogate the assumed synchroneities that underpin existing NW European Eemian pollen biostratigraphies, improvements in data accessibility are vital. Here, we bring together all the publicly available pollen data; however, pollen data from published work for many European sites, particularly those on the British Isles, are unavailable beyond stratigraphic diagrams within publications. For quantitative inter-site comparison, count data that can be harmonised and taxonomically standardised are required. Wherever possible, we advocate the original pollen counts, where they exist, to be made publicly available, following the work of de Wolf et al. (2023) in the Netherlands.

Large spatial and temporal gaps in data coverage inhibit more detailed study of vegetation responses to warmer-than-present climates. The investigation of new sites, particularly in the British Isles where few continuous sequences of the Last Interglacial age have currently been identified, and/or reanalysis of previously studied sites, employing high-resolution pollen analysis, has huge potential to yield further insights. Any such work, however, should be supported by rigorous application of the dating techniques outlined in this article and not rely on pollen biostratigraphy alone.

Finally, it seems clear that tephrochronology has, thus far, been an under-utilised tool in anchoring the floating chronologies for key Last Interglacial sites such as Bispingen. Tephra isochrons will also be of considerable value for correlating sequences, allowing for an interrogation of asynchroneities in vegetation responses, and thus the utility of the Eemian and Ipswichian pollen chronologies. In cases where good radiometric ages exist for a particular eruptive event, tephra isochrons can also be incorporated when constructing age-depth models. In doing so, we may be able to better constrain the sequencing of climate and environmental responses to Last Interglacial change, providing important insights into the response of the Earth system to warm high-latitude temperatures.

Acknowledgements. This article forms a contribution to the RISeR project, which has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 80228), supporting AMM and NLMB. We thank the JQS editor, Neil Roberts, for inviting this review, and to Simon Blockley and an anonymous reviewer for their thoughtful feedback, which has greatly improved this manuscipt. We also thank Freek Busschers, Víctor Cartelle, Kim Cohen, Timme Donders, Stefan Lauterbach, Megan Edwards, Kirsty Penkman, Graham Rush, Chronis Tzedakis, Rachael Smedley, Frank Wesselingh and Lucy Wheeler for extensive discussion on this topic, and Bob Jamieson for proof reading.

Data availability statement

The data that support the findings of this study are openly available at https://github.com/amy-mcg/McGuire_LIG.

Supporting information

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

Supplementary Information

Supplementary Information

Abbreviations. AAR, amino acid racemisation; ESR, electron spin resonance; IRSL, infrared stimulated luminescence; LIG, Last Interglacial; MIS, marine isotope stage; OSL, optically stimulated luminescence.

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