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Palaeoecological signals for Mesolithic land use in a Central European landscape?

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ABSTRACT: During the Early Holocene, climate was the major factor causing fires, but whether during the Mesolithic (~11.5–7.4 cal ka BP) people co-shaped their environment by means of fire remains of debate. Few studies have tackled this question by linking high-resolution multi-proxy palaeoecological studies from near Mesolithic occupation sites. An Early Holocene sediment record from the Ammer Valley palaeo-wetland in south-west Germany was studied using pollen, micro- and macrocharcoal, and plant macroremains. Archaeological evidence from Early and Late Mesolithic sites of Rottenburg-Siebenlinden allowed us to link this palaeoecological record with Mesolithic land use in the same catchment. Between 11.6 and 10.6 cal kaBP,intensive wildfires reinforced the persistence of open and pioneer vegetation. A transition from a river-dominated landscape towards a wetland with open stagnant waters at 10.6–9.5 cal kaBPmade the region attractive to hunter-gatherers, providing various plant resources (incl. hazel). From 10.1 cal kaBPonwards, Mesolithic communities may have shaped their environment by using fire as a tool to expand open areas, which were important for the implementation of their subsistence strategies. After 9.5 cal kaBP, human control over fires cannot be excluded as Mesolithic occupation phases chronologically coincide with frequent low-intensity fires and vegetation disturbance.

KEYWORDS: macrocharcoal; Mesolithic; palaeofire; palynology; south-western Germany

Introduction

The human contribution to land cover changes in the late Quaternary has been attracting worldwide attention for decades. It remains unclear what processes enabled human communities to start interacting with their environment and whether the expansion of farming and clearance of forests are related to the use of fire (e.g. Marlon et al., 2012; Scherjon et al., 2015). Fire in general is an important agent for the natural disturbance of landscapes as it influences the structure and composition of the local vegetation. It introduces nutrient-rich particles into the soil and atmosphere, which are important agents for the carbon and nitrogen global cycles (Feurdean et al., 2018; Florescu et al., 2019; Lasslop et al., 2019).

During the Lateglacial/Early Holocene transition, a changing climate has been put forward as the major control on biomass burning through wildfires (Archibald et al., 2009; Daniau et al., 2010; Marlon et al., 2013). However, the extent to which human communities of the Mesolithic period (~11.5–7.4 cal kaBP; all ages are reported as calibrated years before present) co-shaped their environment using fire remains of debate. For a long time, Mesolithic hunter-gatherers were understood as mobile groups who had a minor impact to their environment – an interpretation that has been challenged beginning in the late 1960s (Simmons, 1969; Smith, 1970; Woodburn, 1980; Price, 1987). Many studies have proposed that Mesolithic peoples actively managed wild resources for their subsistence, in which fire might have been a significant tool (Simmons and Innes, 1987; Harris, 1989; Zvelebil, 1994; Scherjon et al., 2015; Dietze et al., 2018). Thus, manipulations of vegetation, aimed at increasing available food resources including by attracting animals for hunting, could have resulted in alterations in woodland dynamics as early as the Mesolithic period (Zvelebil, 1994; Simmons, 1996; Bos and Urz, 2003; Kuneš et al., 2008; Bishop et al., 2015). So far, very few multi-proxy palaeoecological records from the immediate neighbourhood of Mesolithic sites have been evaluated in terms of anthropogenic fire use in the landscape, but carrying out such studies would have immense potential to provide a better understanding of natural or human-driven palaeo-fires in the Early Holocene.

Numerous Mesolithic sites can be found near (palaeo)-wetlands as such habitats provide favourable conditions for human settlement and subsistence activities (Kind, 1997; Gonzalez et al., 2009). Shallow water levels, characterized by tufa sedimentation, make wetland resources even more accessible (Limondin-Lozouet et al., 2010; Dabkowski, 2020). Wetland sediments also provided material suitable for building hearths for roasting hazelnuts (Holst, 2010), which played an important role in Mesolithic subsistence strategies across

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Europe (Warren et al., 2014; Divišová and Šída, 2015). Besides the ecological benefits of wetlands to Mesolithic hunter-gatherers, the low-energy, water-driven accumulation of tufa allows *in situ* fossilization of organic remains of natural and anthropogenic origin, including burned materials (Capezzuoli et al., 2014; Dabkowski, 2014; Heidgen et al., 2020).

Here we present a multi-proxy palaeo-environmental reconstruction for a time span between 11.6 and 7.8 cal kaBPbased on palynological (including non-pollen palynomorphs, NPPs), macro-botanical and macro-charcoal investigations of a sediment core from the tufa-dominated palaeo-Ammer wetland (mire) (Fig. 1). The results of this study are cross-compared and evaluated with respect to the archaeological investigations carried out on the nearby Mesolithic settlements of Rottenburg-Siebenlinden. Although more than 750 Mesolithic sites are documented in south-western Germany, only a few such as Jägerhaus Cave (Taute, 1973/74), Burghöhle Dietfurt (Gietz, 2001) or Felsställe (Kind, 1987) provide well-stratified Mesolithic remains due to their location in caves and rock shelters. Most of the evidence from hunter-gatherer occupation phases are, however, known from surface finds that lack precise or any stratigraphic context (Schmidt, 1913; Peters, 1934; Taute, 1973/74; Jochim, 1998; Kind, 2003). The settlement of Rottenburg-Siebenlinden is an exception, as an open-air site, where well-stratified cultural deposits have been excavated over an area covering ~580 m^2 (Kind, 2009). Bones, burned stone fragments and hearths were found together with traces of gathering and the processing of wild plant resources including hazelnuts (Kieselbach et al., 2000; Kind, 2010). Considering the cultural-rich deposits from Rottenburg-Siebenlinden, the multi-proxy palaeoecological study from the Ammer palaeo-wetland provides a unique opportunity to shed light on the prevailing Holocene fire regimes, vegetation changes and their relationship to Mesolithic land use.

Setting

Geographical and climatic setting of the study region

The research was conducted on an 8-m-long sediment core (X039B) obtained from a former wetland (48°31′44.11″N, 08°57′47.73″E) near two areas of prehistoric occupation (Fig. 1). Area 1 is in the Ammer River Valley near the village of Ammerbuch-Pfäffingen, <1 km from X039, where several Early Neolithic settlements of the Linearbandkeramik (LBK) period have been excavated (Krauß et al., 2020). Area 2 include the sites of Rottenburg-Siebenlinden (Kind, 2003) in the town of Rottenburg a. N, adjacent to the Neckar River and located ~6 km from the X039. The study area is situated in the foothills of the Swabian Jura plateau with a hilly landscape on Triassic ground, affected by diverse land use activities. The humid-temperate climate of the region reaches its highest temperatures in June to August (mean 21–24 °C), whereas its lowest temperatures are usually recorded during December to February (mean – 1–0 °C) (meteoblue.com). Precipitation fluctuates around 80 mm per month. The SW-facing slopes of the Schönbuch nature reserve delimiting the northern part of the study area have a distinct microclimate with unusually high temperatures. High evaporation rates in combination with clayey soils of low effective field capacity allow a thermophilus and drought-adapted vegetation to thrive. Those soils are developed on the Triassic Gipskeuper Formation, which dominates the slopes of the Schönbuch and much of the upper Ammer valley (Reuter, 1927).

The archaeological record of the study region

Archaeological excavations at the nearby Mesolithic sites of Rottenburg-Siebenlinden (Fig. 1) were conducted by the Baden-Württemberg State Office for Cultural Heritage between 1990

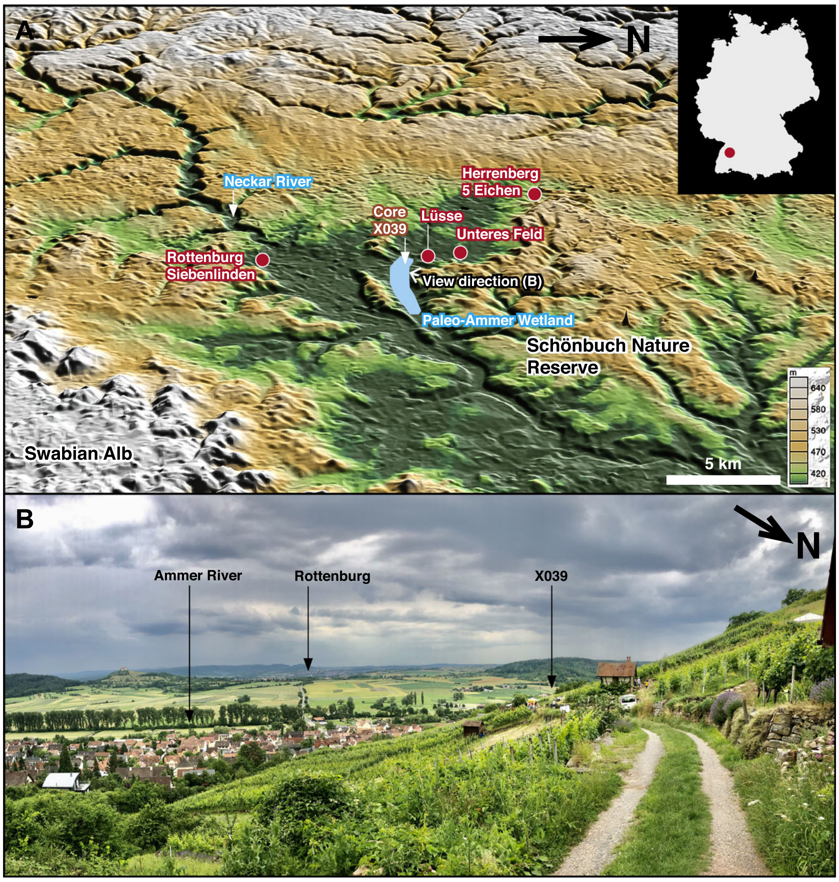

Figure 1. (A) Map of the Ammer River Valley with areas mentioned in the text. (B) Photo taken from the landscape over the Ammer River Valley. [Color figure can be viewed at wileyonlinelibrary.com].

and 2004. Between 1990 and 1995, scatterings of Siebenlinden 1–3 were excavated, and extended to Siebenlinden 4 and 5 between 2001 and 2004, with an area of ~580 m^2 in total (Kind, 2010). The chronology is based on 54 radiocarbon dates from Rottenburg-Siebenlinden Sites 3–5 (Ro-Si 3–5), obtained from charcoal and bone material (Beutelspacher and Kind, 2004; Kind, 2010; Kind et al., 2012) and have been three-dimensionally recorded during excavation. From these 54 radiocarbon dates, only 35 (bones $n = 19$ and charcoals $n = 16$) were considered reliable and calibrated with CalPal (see Table 2) (Weninger, 2007).

The oldest Mesolithic occupation is consistently placed within the older Boreal covering the period 10.1–9.9 cal kaBP (8.1–7.9k cal ABC) (Kind, 2001, 2003, 2010; Kind et al., 2012). Furthermore, in Horizon IV (H-IV) not only were lithic artefacts, bones and burned stone fragments found but also hammer stones and stone slabs used for cooking or roasting. Although no artefacts of bone and antler were discovered, their manufacture on-site is indicated by production waste. Horizon III (H-III) shows settlement activities at 9.4–8.7 cal kaBP (7.4–6.7k cal ABC). Here, concentrations of lithic artefacts, bones and burned stone fragments were discovered. An amphibolite flake from a polished adze proves the early appearance of ground stone tools. The uppermost occupation layer, Horizon II (H-II), documented human activities between 8.4 and 7.8 cal kaBP(6.4–5.8k cal ABC).

In all horizons the intensive use of fire is documented by a total of 34 fireplaces. In Horizon III ground level hearths are just as common as fire pits. They often contain stone constructions. In one pit of the early Mesolithic Horizon IV, hundreds of burned hazelnuts have been discovered (Kind et al., 2012). Interpreting this as an accident during roasting, the total amount of hazelnuts should have been significantly higher, around 11 000 nuts (Kind, 2010). This quantity corresponds to about 10 kg, which has a nutritional value of over 60 000 kcal (Holst, 2010). Evidence for domestic dogs (*Canis familiaris*) as well as water birds is found in Horizons III and II, while red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*) and wild boar (*Sus scrofa*) dominate the animal remains, being the three most important Mesolithic species of southern Germany (Kind, 2003, 2010).

Recent archaeological excavations at Ammerbuch-Pfäffingen, 'Lüsse' in the Ammer River valley revealed a radiocarbon age of 11.46–11.19 cal kaBP(Poz-120560) from an indeterminable tooth of a herbivore (Table 1). Although this archaeological site is known for its Neolithic occupation history (Krauß et al., 2020), human activities here seem to reach further into the Mesolithic period. Since the date turned out to be surprisingly old and given the possibility of a reservoir effect, an aliquot of collagen to $\delta^{13}C$ and δ ^{15}N analysis was performed. The sample remeasured was even older, 11.74–11.28 cal kaBP(Poz-121661). Remarkably, the dated material came from the easternmost outskirts of the Neolithic settlement that is closest to the Ammer mire. It is possible that this was already an area of Mesolithic human activities, and the tooth represents a relocated piece from a nearby Mesolithic feature destroyed by later occupation. The Neolithic settlement begins around 7.5 cal kaBP,which is why any connection between the dated Mesolithic sample and the LBK occupation can be ruled out. However, the new results support previous hypotheses that Mesolithic groups were active also in the Ammer River valley. These hypotheses are based on isolated finds along the southern slopes of the Schönbuch Nature Reserve and the open-air site 'Fünf Eichen' at Schlossberg north-east of Herrenberg, where campsites were repeatedly visited by Mesolithic hunter groups, especially during the early Mesolithic (Müller-Beck, 1981). Recent palaeohydrological studies estimated the spatial extent of the Ammer mire (Heidgen et al., 2020; Martin et al., 2020), opening perspectives for systematic search for Mesolithic sites near its shore in the future.

Materials and methods

Lithology and chronology of core X039

Two parallel cores, X039A (14 m) and X039B (16 m), were obtained through drilling in 2018, 2 m in each run, with 82% recovery (Heidgen et al., 2020). The upper 8 m of core X039B is considered here. Lithology and drilling details have been described in Heidgen et al. (2020) (Fig. 2). The age model of X039B is based on 12 accelartor mass spectrometry (AMS) ^{14}C dates including four AMS ^{14}C ages from a preliminary study (Heidgen et al., 2020). Dateable material consists either of terrestrial plant macrofossils or charcoal fragments (Table 2). The plant materials were identified using a stereomicroscope (10–70×), identification literature and reference collection (Grosse-Brauckmann, 1972; Grosse-Brauckmann and Streitz, 1992; Mauquoy and Van Geel, 2007; Jäger, 2016). AMS ^{14}C dating was conducted at the Curt-Engelhorn-Zentrum für Archäometrie, Mannheim, Germany, applying the ABA-method (acid/base/acid) for pre-treatment with HCl, NaOH and HCl and measuring with the MICADAS AMS system. The AMS ^{14}C ages determined were standardized to $\delta^{13}C = -25‰$ (Stuiver and Polach, 1977) and calibrated with the IntCal20 curve. An age–depth model was calculated applying rBacon Software (Blaauw and Christen, 2011) (Fig. 2). We used six boundaries; no hiatus was noted. All ages in this paper are reported as calendar years before present.

Pollen, NPPs, spores and microcharcoal analysis

To receive a higher resolution, the previously studied core X039B (Heidgen et al., 2020) was re-sampled between 7.6 and 2.8 m and 28 additional samples were obtained. Pollen, spores, NPPs and microcharcoal extraction was performed at the Laboratory for Archaeobotany at the Baden-Württemberg State Office for Cultural Heritage, Germany, following standard procedures (Faegri and Iversen, 1989), including acetolysis (Erdtman, 1934). Glycerine and Histolaque LMR were used for mounting (Heidgen et al., 2020). One *Lycopodium* spore tablet (Batch number: 050220211) was added to each sample for calculation of the microfossil concentration. An Olympus BX50 microscope with magnification of 400×, 600× and 1000× was used for identification and counting between 150 and 500 pollen grains per sample. Pollen and spore taxonomy follows Beug (1961, 2004), Moore et al. (1991) and Reille (1992, Photo atlas). NPPs and microcharcoals were counted on the same pollen slides. NPPs were mainly identified following Van Geel et al. (1980, 1986, 1989, 2003). The software TAXUS (www.schnelke.de/taxus.htm) was applied for counting, while TILIA (Grimm, 1992a,b) was used for visualization and biostratigraphical zonation, applying stratigraphically constrained cluster analysis (CONISS). NPP zonation was defined by concentration value changes for the most abundant taxa. Poaceae was excluded from the pollen sum as the *Phragmites* rhizomes occur in the sedimentological record at the same levels with most of the Poaceae peaks. The following pollen types were used to create a sum of anthropogenic indicators based on Behre (1981) and Kuneš et al. (2008): *Calluna vulgaris*, *Cannabis*/*Humulus*-type, *Viscum album*, Brassicaceae, *Campanula*, *Chenopodiaceae*, *Cirsium*, *Crepis*-type, *Epilobium*, *Daucus*-type, Papaveraceae, *Plantago*

Table 1. List of ^{14}C-AMS results of Siebenlinden and Lüsse

			Age (cal ABC)			Age (cal ABP)					
Laboratory-code	Site	Horizon	From	To	%	From	To	%	Material	Technocomplex	Citation
ETH-26381	Ro-Si 3–5	II	5668	5476	95.4	7617	7425	95.4	Bone	Late Mesolithic	Kind et al. (2012)
ETH-12777	Ro-Si 3–5	II	5966	5571	95.4	7915	7520	95.4	Bone	Late Mesolithic	Kind (2003); Kind et al. (2012)
ETH-26380	Ro-Si 3–5	II	5967	5641	95.4	7916	7590	95.4	Bone	Late Mesolithic	Kind et al. (2012)
ETH-14244	Ro-Si 3–5	II	6222	5901	95.4	8171	7850	95.4	Bone	Late Mesolithic	Kind (2003); Kind et al. (2012)
ETH-32102	Ro-Si 3–5	II	6349	5989	95.4	8298	7938	95.4	Bone	Late Mesolithic	Kind et al. (2012)
ETH-33046	Ro-Si 3–5	II	6399	6067	95.4	8348	8016	95.4	Charcoal	Late Mesolithic	Kind et al. (2012)
ETH-32101	Ro-Si 3–5	II	6394	6073	95.4	8343	8022	95.4	Bone	Late Mesolithic	Kind et al. (2012)
GrA-40163	Ro-Si 3–5	II	6475	6266	95.4	8424	8215	95.4	Bone	Late Mesolithic	Kind et al. (2012)
ETH-27068	Ro-Si 3–5	II	6650	6251	95.4	8599	8200	95.4	Charcoal	Late Mesolithic	Kind et al. (2012)
ETH-33039	Ro-Si 3–5	II	7023	6444	95.4	8972	8393	95.4	Charcoal	Late Mesolithic	Kind et al. (2012)
ETH-32109	Ro-Si 3–5	IIIu	7042	6535	95.4	8991	8484	95.4	Bone	Beu C	Kind et al. (2012)
ETH-33049	Ro-Si 3–5	IIIu	7174	6641	95.4	9123	8590	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-14247	Ro-Si 3–5	IIIu	7067	6656	95.4	9016	8605	95.4	Charcoal	Beu C	Kind (2003); Kind et al. (2012)
ETH-14245	Ro-Si 3–5	IIIu	7136	6655	95.4	9085	8604	95.4	Bone	Beu C	Kind (2003); Kind et al. (2012)
ETH-33050	Ro-Si 3–5	IIIu	7175	6654	95.4	9130	8598	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-32108	Ro-Si 3–5	IIIu	7303	6648	95.4	9552	8597	95.4	Bone	Beu C	Kind et al. (2012)
ETH-33052	Ro-Si 3–5	IIIu	7329	6702	95.4	9278	8651	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-31237	Ro-Si 3–5	IIIu	7450	6841	95.4	9399	8790	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-31238	Ro-Si 3–5	IIIu	7451	7040	95.4	9400	8989	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-31244	Ro-Si 3–5	IIIu	7455	7057	95.4	9404	9006	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-31245	Ro-Si 3–5	IIIu	7461	7067	95.4	9410	9016	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-31239	Ro-Si 3–5	IIIu	7464	7070	95.4	9413	9019	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-32110	Ro-Si 3–5	IIIu	7471	7070	95.4	9420	9019	95.4	Bone	Beu C	Kind et al. (2012)
ETH-26385	Ro-Si 3–5	IIIu	7475	7076	95.4	9424	9025	95.4	Bone	Beu C	Kind et al. (2012)
ETH-33051	Ro-Si 3–5	IIIu	7523	7077	95.4	9472	9026	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-31243	Ro-Si 3–5	IIIu	7523	7086	95.4	9472	9035	95.4	Charcoal	Beu C	Kind et al. (2012)
ETH-32105	Ro-Si 3–5	IIIu	7536	7082	95.4	9485	9031	95.4	Bone	Beu C	Kind et al. (2012)
ETH-32097	Ro-Si 3–5	IIIu	7581	7191	95.4	9530	9140	95.4	Bone	Beu C	Kind et al. (2012)
ETH-31236	Ro-Si 3–5	IIIo	7454	7056	95.4	9403	9005	95.4	Charcoal		Kind et al. (2012)
ETH-14248	Ro-Si 3–5	IV	8459	7580	95.4	10 108	9529	95.4	Bone	Beu B	Kind (2003); Kind et al. (2012)
ETH-14246	Ro-Si 3–5	IV	8166	7585	95.4	10 115	9534	95.4	Bone	Beu B	Kind (2003); Kind et al. (2012)
ETH-32111	Ro-Si 3–5	IV	8167	7591	95.4	10 116	9540	95.4	Bone	Beu B	Kind et al. (2012)
ETH-33045	Ro-Si 3–5	IV	8173	7584	95.4	10 122	9533	95.4	Charcoal	Beu B	Kind et al. (2012)
ETH-26386	Ro-Si 3–5	IV	8248	7747	95.4	10 197	9696	95.4	Bone	Beu B	Kind et al. (2012)
ETH-26387	Ro-Si 3–5	IV	8290	7826	95.4	10 239	9775	95.4	Bone	Beu B	Kind et al. (2012)
Poz-120560	Lüsse	N.A	9513	9243	95.4	11 462	11 192	95.4	Animal bone	N.A	N.A
Poz-121661	Lüsse	N.A	9795	9331	95.4	11 744	11 280	95.4	Animal bone	N.A	N.A

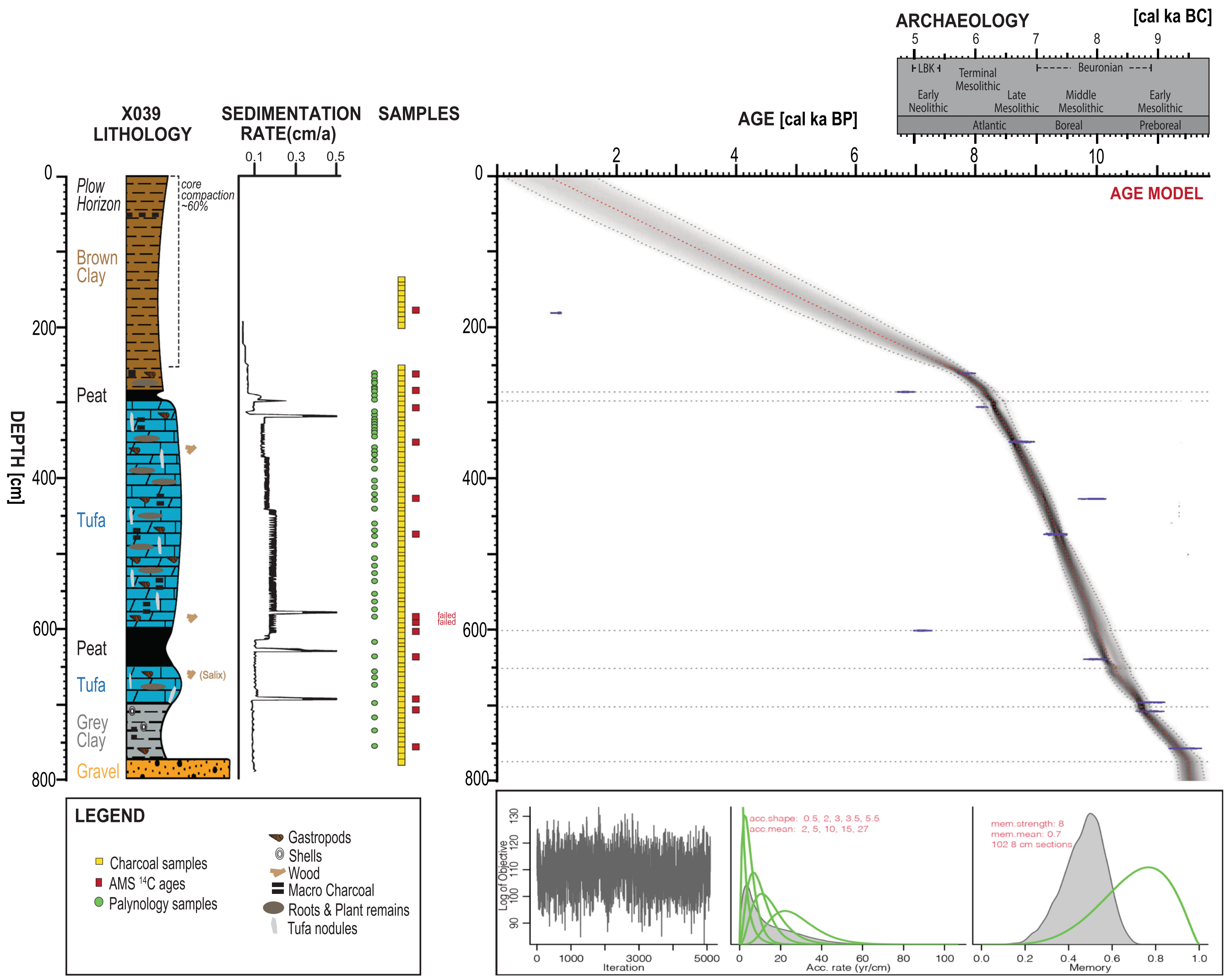

Figure 2. Lithology and age–depth model of X039B drill core sediments. [Color figure can be viewed at wileyonlinelibrary.com].

major-type, *Ranunculus acris*-type and *Rumex acetosella*. According to Kuneš et al. (2008), the most important taxa for detecting Mesolithic land use are *Calluna vulgaris*, *Ranunculus acris*-type, *Cannabis*/*Humulus*-type and *Corylus avellana* and therefore particluar attention was paid to those. Changes in sedimentation rates were considered as an factor influencing microcharcoal and pollen concentrations.

Micro- and macrocharcoal analysis

Microscopic charcoal analysis was performed on pollen slides without extra preparation. Microcharcoal was identified as opaque, planar, angular black fragments with a length size >10 µm (Clark, 1982; Patterson et al., 1987; Whitlock and Larsen, 2002). The macroscopic charcoal record summarizes all charcoal particles larger than 100 µm (Mooney and Tinner, 2011). A continuous sampling resolution of 1 cm summed to a total of 559 samples was applied for macrocharcoal analysis. Results are presented as concentrations values per 1 cm^3 of sediment. From 29 levels with significant charcoal abundances, identifiable macrocharcoal was selected for morphotype identification. The classification of macrocharcoal morphotypes follows Mustaphi and Pisaric (2014) with a focus on five main types according to our study area – grasses, herbs, wood, deciduous leaves and indeterminate. Macroscopic charcoal preparation followed the protocol by Rhodes (1998). Samples were submerged in 12% NaOCl for 48 h at room temperature for bleaching and then gently sieved through a 100-µm mesh with the residue on the mesh being transferred to a Petri dish. A high-resolution Leica Z16 Apo stereoscope with an attached MicroPublisher 5.0 RTV camera (2560 × 1920-pixel resolution) and the software Image-Pro Plus 7 (www.mediacy.com/imageproplus) was used for macrocharcoal selection and identification. Counting of macrocharcoal particles was performed by the software ImageJ (imagej.nih.gov/ij/) on sample images obtained via an EOS 200D camera (Objektiv: 0570C005AA EF 50 mm, focal length: F1. 8 STM focus) with resolution of 24.2 pixels. Following Higuera et al. (2010), charcoal accumulation rate, fire frequency, fire return interval (FRI) and peak magnitude were calculated via the CharAnalysis software version 0.9 (Higuera et al., 2009; code.google.com/p/charanalysis/. last accessed 30 October 2020) and visualized by MATLAB software version 9.9 (R2020b). Charcoal accumulation rate (cm^{-2} a^{-1}) represents the deposited charcoal in the sediment with time, indicating fire events. The fire frequency represents the numbers of fire events within a defined area and time, and FRI is an indicator of time between fire events. The peak magnitude estimates the fire magnitude or area burned and the significance of the fire event (total area burned). The smoothed series from the palaeo-fire R package (Ali et al., 2012; Blarquez et al., 2013, 2014; Kelly et al., 2013) were used to visualize past regional fire frequency. Data for the burned biomass curve for the Atlantic Region (Feurdean et al., 2020)

Table 2. AMS ^{14}C chronology of core X039

Laboratory code	Sample name	Core depth (cm)	Material	Unit	Age ($^{14}C_{BP}$)	Error (a)	$\delta^{13}C$ AMS (‰)	C (%)	Calendar age −2σ (cal aBC)	Calendar age −2σ (cal aBP)
MAMS-44671	X039B/C14-7	180–181	Charcoal	Brown clay	1012	26	−32.1	36.1	979–1145	926–954
MAMS-42988	X039B/C14-1	260–261	Charcoal	Base brown clay	7032	48	−43.9	53.1	6010–5804	7820–7924
MAMS-46307	1	285–286	Charcoal	Silty clay peat	5973	36	−27.20	49.1	4957–4744	6693–6703
MAMS-46308	2b	305–306	Seed	Tufa top	7296	31	−26.30	50.3	6225–6077	8027–8172
MAMS-44672	X039B/C14-6	351–352	Charcoal	Tufa middle	7882	35	−30.70	56.1	7017–6639	8629–8751
MAMS-42990	X039B/C14-2	426–427	Charcoal	Tufa middle	8879	33	−22.8	61.7	8227–7849	9940–10 125
MAMS-46309	X039B/3A	473–474	Charcoal	Tufa lower part	8368	35	−28.70	60.3	7523–7351	9301–9473
MAMS-46310	X039B/4A	591–592	Charcoal	Tufa lower part				Dating failed		
MAMS-42989	X039B/C14-3	586–587	Charcoal	Tufa lower part				Dating failed		
MAMS-46314	X039B/8	606–607	Plant fragment	Silty clay peat upper part	6186	29	−33.6	50.6	5220–5043	6993–7168
MAMS-46311	X039B/5B	638–639	Seed	Silty clay pea lower part	8943	43	−32.4	53.7	8264–7967	9917–10 114
MAMS-46312	X039B/6	695–696	Charcoal	Tufa lower part	9613	34	−28.3	66.5	9213–8830	10 780–11 163
MAMS-46313	X039B/7A	707–708	Fruit	Massive clay	9575	34	−33.1	50.2	9147–8799	10 749–11 097
MAMS-42991	X039B/C14-5	756–757	Wood	Gravel–grey clay transition	10 027	35	−20.7	37.9	9764–9381	11 396–11 687

were plotted using RStudio software (www.rstudio.com/). All data were compared to the Global palaeo-fire database (www.paleofire.org/index.php). To explore if the local palaeo-fire, expressed by the macrocharcoal influxes preceding the increased abundance of main vegetation components such as pine, birch, hazel and grasses, a Granger causality test (as provided by the EViews software) was performed on the macrocharcoal influx values towards pollen influx of *Pinus, Betula*, *Corylus* and Poaceae. Granger causality is a means to investigate intertemporal 'causal' patterns between two time series. It does not provide insights into the true causal relationship between two variables, but it is used to evaluate the intertemporal flow of effects between two variables X and Y. Y is said to 'Granger-cause' X if information about the history of Y improves the capacity to predict the behaviour of X, above what can be achieved when only information regarding the history of X is used for this purpose (Hamilton, 1994).

Results

Sedimentology

The 8-m-long core X039B is represented by gravel from 800 to 774 cm, which abruptly turns into grey clay between 774 and 650 cm that is low in organics except at its base (Fig. 2). The dominant facies of the core are two tufa horizons, one at 707–650 cm and a second at 580–297 cm consisting of carbonate precipitates with high organic content dominated by macro-remains of *Phragmites*, Cyperaceae-rhizomes, macrocharcoal, gastropods, molluscs as well as sporadic moss layers. The two horizons are separated by silty–sandy peat layers at 650–600 and 297–285 cm. The upper thin peat layer marks the transition into loamy brown clay that dominates the upper part of the core (285–0 cm). Due to 60% core compaction during drilling of the clay horizon between 250 and 0 cm, we refrained from carrying out detailed analyses on this section.

Chronostratigraphy

Despite the variable lithology, no considerable hiatuses have been identified in the analysed section. Of 14 AMS ^{14}C samples, two dating attempts failed (Table 2). Another four AMS ^{14}C results showed ages too young or too old compared to the adjacent samples and were considered as outliers (Fig. 2). MAMS-46314, a dated plant fragment from the lower peat at 606–607 cm, shows an age that is too young. This result is probably due to drill hole breakouts, contaminating the top of the during the different runs. Dated charcoal (MAMS-42990) from the main tufa horizon at 351–352 cm, in contrast, yielded ages that are too old compared to the lower and upper dated material. The charcoal may have been transported into the wetland system by erosion from older strata in the catchment. Charcoal from 285 to 286 cm (MAMS-46307) and 180–181 cm (MAMS-44671) also show ages taht are too young, probably due to compaction that occurred during the drilling process. The age model suggests that the gravel layer has been deposited during the Younger Dryas (YD, 12.8–11.6 cal kaBP) cold stage, terminated by the abrupt onset of clay deposits by 11.4 cal kaBP.The lower tufa was deposited between 10.8 and 10.3 cal kaBP, followed by peat formation between 10.3 and 10 cal kaBP.The following main tufa horizon was deposited between 10 and 8.2 cal kaBP, which transformed into peat by 8.1 cal kaBP.

Pollen and NPP results

The pollen sum varies between 150 and 500 grains per sample. Successive changes in vegetation between 11.4 and 7.8 cal kaBPcan be summarized within three local pollen assemblage zones (LPAZ-AM1, LPAZ-AM2, LPAZ-AM3) and subzones divisions for LPAZ-AM2 and for LPAZ-AM3 (Figs. 3 and 4).

LPAZ-AM1 (*Pinus*), 11.6–10.6 cal kaBP(760–675 cm), is dominated by pine (*Pinus*, ~90%), followed by birch (*Betula*, >10%) and hazelnut (*Corylus avellana* ~8%). The non-arboreal-pollen (NAP) fraction is dominated by grasses (Poaceae), *Artemisia* and Asteroideae. Wetland taxa are dominated by Cyperaceae and fern spores such as *Polypodium vulgare*. NPPs of shallow open water are represented by Type 179e and *Spirogyra* (Type 130, 131, 132). Coprophilous NPPs such as *Coniochaeta* (Type 172), *Chaeotomium* (Type 7a) and Sordariaceous NPPs indicate the presence of herbivores in the area (Van Geel et al., 2003; Graf and Chmura, 2006; Marinova and Atanassova, 2006; Van Geel and Aptroot, 2006; Ekblom and Gillson, 2010). NPPs typical of fire events such as *Neurospora*-Type 55c and *Gelasinospora*-Type 1 occur here. Plant macroremains of *Eupatorium cannabinum* and *Schoenoplectus* cf. *lacustris* were found at 10.8 cal kaBP(700–690 cm).

LPAZ-AM2 (*Pinus–Corylus–Quercus*), 10.6–9.5 cal kaBP (675–490 cm), is divided into two subzones: LPAZ-AM2-2 and LPAZ-AM2-1. LPAZ-AM2-1, 10.6–10.1 cal kaBP (675–610 cm), is dominated by pine (*Pinus*, ~80%), but deciduous vegetation gains in importance, with hazelnut (*Corylus avellana*, 30%), oak (*Quercus,* up to 20%), elm (*Ulmus*, ~10%), lime (*Tilia*, ~8%) and birch (*Betula*, ~5%). Notable NAPs include *Artemisia*, Chenopodiaceae, Asteroideae and *Galium*-type. The local wetland vegetation is composed of *Urtica* and *Filipendula*. Wetland taxa include Cyperaceae, *Cladium mariscus*, *Sparganium*-type, *Typha latifolia*-type and *Polypodium vulgare*. LPAZ-AM2-2, 10.1–9.5 cal kaBP(610–490 cm), is also dominated by pine (*Pinus*, ~70%), but hazelnut abundance increases conspicuously (*Corylus avellana*, 60%), whereas oak (*Quercus*, 10%) and lime (*Tilia*, ~5%) decrease. Elm (*Ulmus*, ~10%) and birch (*Betula*, ~5%) abundances remain unchanged. NAP vegetation includes *Artemisia*, *Crepis*-type and Asteroideae. Local wetland taxa again include *Urtica* and *Filipendula*, while open water is characterized by Cyperaceae, *Cladium mariscus*, *Typha latifolia*-type, *Sparganium*-type*, Potamongeton*, and as single presence at 9.6 cal kaBP(514 cm) of *Nuphar lutea* and *Nymphaea alba*. In LPAZ-AM2 peaks of coprophilous indicators such as *Coniochaeta* (Type 172) at 10.4 cal kaBP(658 cm), *Chaetomium* (Type 7a) and Sordariaceous at 9.9 cal kaBP (569 cm) occur and a single *Sporormiella* spore was found at 10 cal kaBP(587 cm). NPPs indicative of fire are absent. Shallow open-water NPPs such as Type 179e and *Spirogyra* (Type 130, 131, 132) are continuously present. Plant macro remains of *Eupatorium cannabinum* occur at ~10.3 cal kaBP (642 cm), ~9.5 cal kaBP(495 cm), ~9.4 cal kaBP(476 cm) and *Cladium mariscus* at ~10.2 cal kaBP(627 cm).

LPAZ-AM3 (*Pinus–Corylus–Quercus–Ulmus–Tilia*), 9.5–7.8 cal kaBP(490–290 cm), is divided into three subzones: the lower subzone LPAZ AM3-1 is dominated by pine (*Pinus*, up to 60%), while hazelnut (*Corylus avellana*, up to 50%), oak (*Quercus*, 30%) and elm (*Ulmus*, 25%) increase gradually. NAP reaches up to 20%, mostly consisting of *Artemisia* and Chenopodiaceae. LPAZ-AM3-2 (*Pinus–Corylus–Quercus–Ulmus–Tilia*), 8.7–8.1 cal kaBP (340–290 cm), is characterized by a rapid decrease of *Pinus* to 40% along with the pioneer taxon *Corylus avellana* to 45%. The mixed deciduous oak forests expand gradually to reach their maximum in the last sub-zone LPAZ-AM3-3, 8.1–7.8 cal kaBP

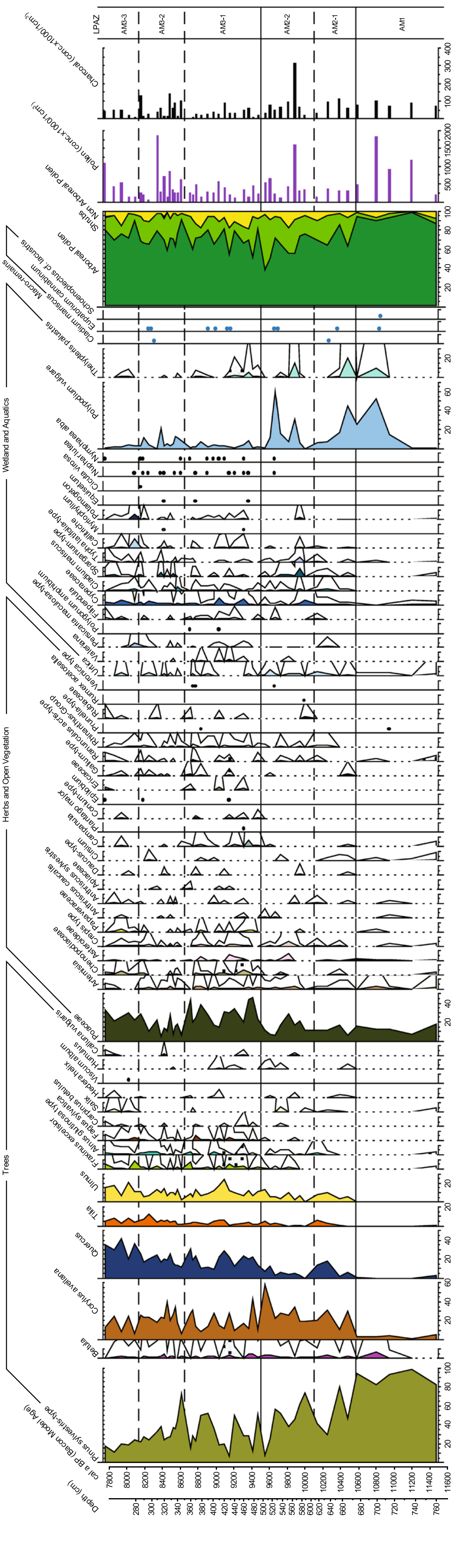

Figure 3. Percentage pollen diagram for selected pollen types and charcoal concentration observed in core X039B (dots indicate minor abundances, exaggeration curves are ×10). [Color figure can be viewed at wileyonlinelibrary.com].

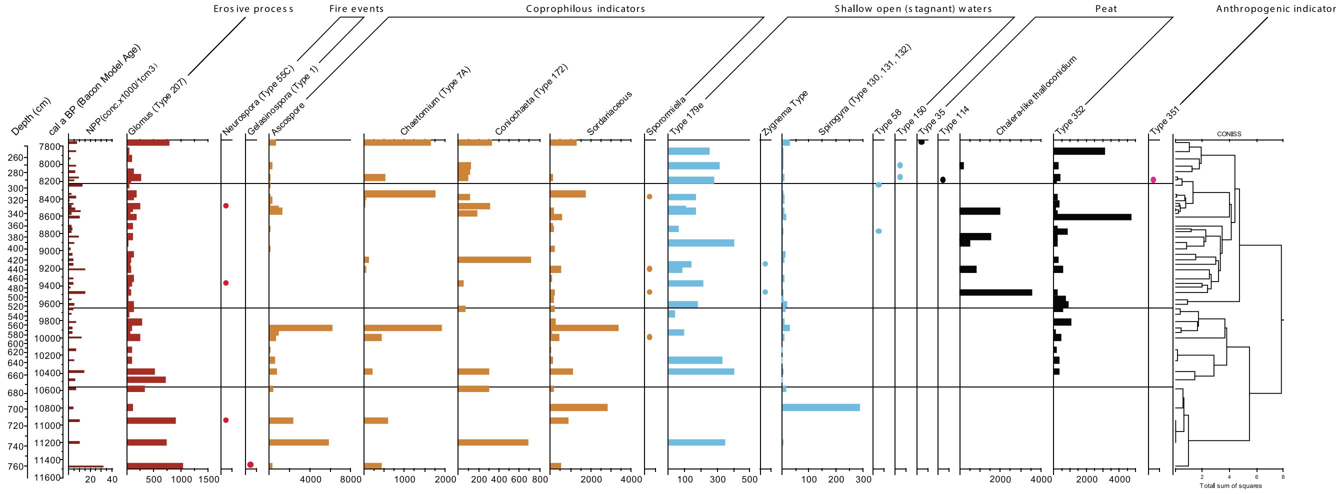

Figure 4. Concentration of main NPPs observed in core X039B. [Color figure can be viewed at wileyonlinelibrary.com]

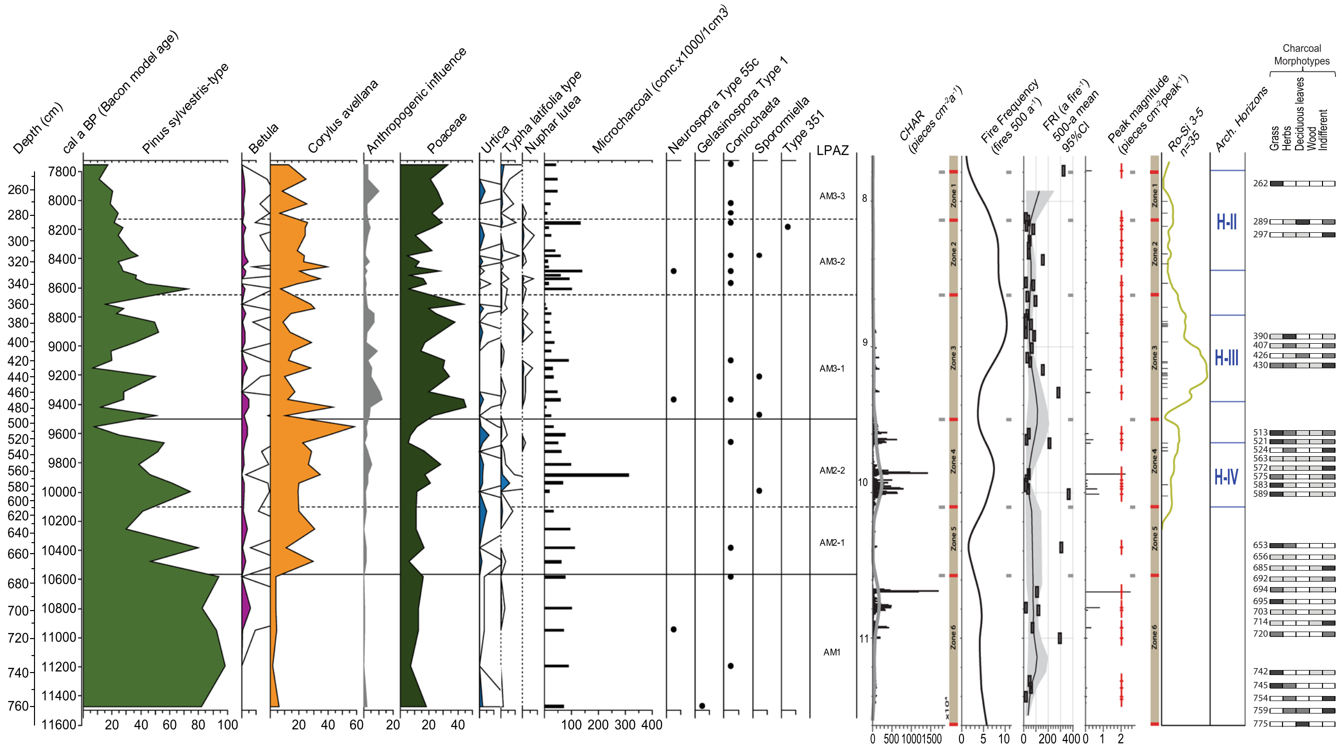

Figure 5. Reconstruction of vegetation, palaeo-fire events and human impact including macrocharcoal morphotypes from X039B. CHAR, charcoal accumulation rate (pieces cm^{-2} a^{-1}); peak magnitude of fire episodes over time (pieces cm^{-2} per peak), the crosses indicating significant fire events; fire return intervals (FRIs) over time, shaded area showing the 95% confidence interval and grey squares indicate a fire episode; fire frequency expressed as number of fires per 500 years; Ro-Si 3–5, Rottenburg-Siebenlinden ^{14}C dating and macrocharcoals morphotypes represented as: black = dominating, dark grey = ca. 50%, light grey = single finds and white = absent.

(340–290 cm). NAP is dominated by *Artemisia*, Chenopodiaceae and Asteraceae. The local vegetation, which includes *Cladium mariscus*, Cyperaceae and *Sparganium*, suggests the presence of shallow wetlands. Open water is indicated by obligatory aquatics, such as *Potamogeton*, *Nuphar lutea* and *Nymphaea alba*, which decrease in the uppermost section (LPAZ AM3-3) and are replaced by wet meadow vegetation such as *Urtica*, *Filipendula*, Cyperaceae and *Callitriche*. NPPs at LPAZ-AM3 include coprophilous indicators, dominated by *Coniochaeta* (Type 172) with peaks at 8.3 cal kaBP(304 cm) and 7.8 cal kaBP(263 cm) and Sordariaceous NPPs being continuously abundant, whereas *Sporormiella* appears as a single find at 9.5, 9.2 and 8.4 cal kaBP(495, 438 and 318 cm, respectively). Shallow open-water NPP indicators are diverse with a strong and continuous presence of Type 179e, and a weak but continuous presence of *Spirogyra* (Type 130, 131, 132). Type 58 and Type 150 appear only as single finds. Type 351, indicative of anthropogenic activities, is recorded at the levels corresponding to ~8.2 cal kaBP(292 cm). An NPP indicator of fire events is represented by *Neurospora*-Type 55c. Plant macroremains include *Eupatorium cannabinum* at ~9.3, ~9.2, ~9 cal kaBP, ~8.9 and ~8.2 cal kaBP(457, 438, 405, 390, 292 cm, respectively) and *Cladium mariscus* at ~8.3 cal kaBP(304 cm).

Local and regional palaeo-fire record

The results of macrocharcoal analysis were evaluated within the pollen assemblage zones to correlate fire events and vegetation change in the Ammer River valley. Within LPAZ-AM1

Figure 6. Selected macrocharcoal morphotypes identified in core X039B. (1) Herbal; (2a,b) grasses (Poaceae); (3) moss; (4) wood; (5a,b) *Eupatorium cannabinum*; (6a) indifferent, (b) indifferent-glassy; (7) deciduous leaves. Scale bar: 1000 μm.

(11.6–10.6 cal kaBP), macrocharcoal accumulation rates increase gradually from 11 cal kaBPonwards and reach maximum values at ca. 10.7 cal kaBP(Fig. 5). Fire frequency is low to moderate in comparison to the rest of the record. The FRI is also moderate, as well as the time return interval between the peak magnitude. At ~ 10.5 cal kaBP, peak magnitude reaches its maximum for this zone. The identified charcoal morphotypes suggest that in this period predominantly grasses and herbs burned (Fig. 6). Within LPAZ-AM2 (10.6–9.5 cal kaBP), curves of both macrocharcoal accumulation rates and fire frequency show similar fluctuation patterns. According to the identified charcoal morphotypes, grasses and herbs burned predominantly. Within LPAZ-AM3 (9.5–7.8 cal kaBP), macrocharcoal accumulation rates decrease strongly. The FRIs are short, and consequently fire frequency is high and its trend was maintaining. The time between peaks increases and the peak magnitude decreases from moderate to low. Morphotypes indicate that deciduous leaves, grasses and herbs dominate the burned material. Time series analyses of macrocharcoal influxes towards those of *Pinus, Betula*, *Corylus* and Poaceae (ESM 1) suggest that local palaeo-fire events, as reflected by macrocharcoals, cause increases in hazel at a very high level of significance.

Discussion

Ammer River valley vegetation versus European climate

The beginning of the Holocene at 11.6–10.6 cal kaBP(Period 1) is generally marked by an increase in precipitation and temperatures in the North Atlantic (Fig. 7) (Alley *et al.*, 2004; Andersen, 2004) and Western–Central Europe (Mauri et al., 2015; Breitenbach et al., 2019). Isopollen maps show that shrub and herbaceous vegetation was replaced by open woodland dominated by *Pinus* and *Betula* (e.g. Huntley and Birks, 1983; Rösch, 1993; Lang, 1994; Smettan, 2002; Theuerkauf et al., 2014). The early Holocene in the Ammer River Valley also experienced such an amelioration trend, as indicated by the dominance of *Pinus* with minor abundances of *Betula* and *Corylus*. Favoured by the establishment of a subcontinental climate at 11.5 cal kaBP, *Pinus* could have entered rapidly into the open birch woodlands of the previous cold and dryer period at the Ammer River Valley. The post-glacial Ammer River Valley, consisting of vast riverbeds as indicated by gravel at the base of the investigated core and comprehensive mapping of the area (Martin et al., 2020),

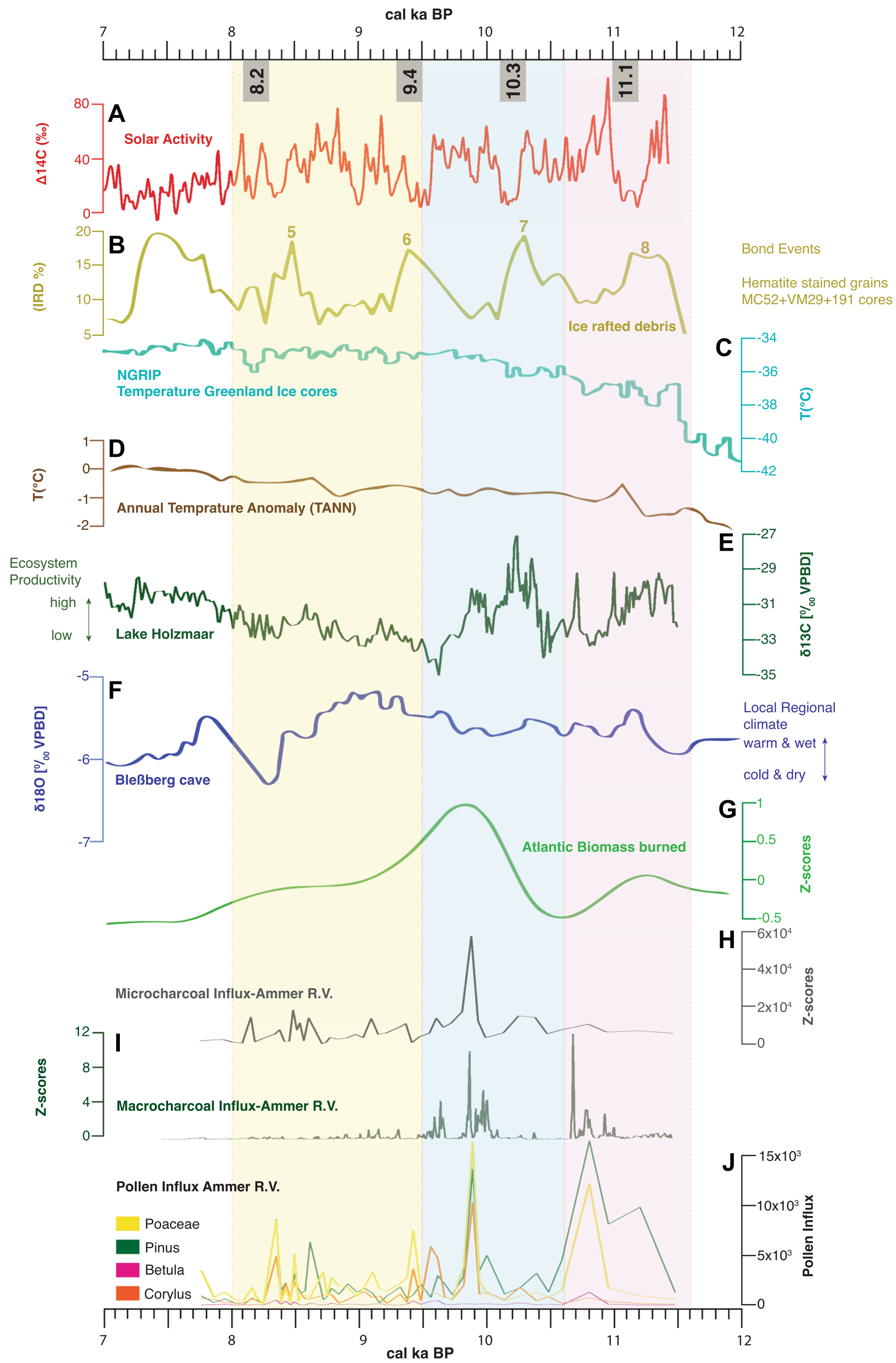

Figure 7. Holocene records in comparison with the Ammer River Valley. (A) Holocene solar activity (Solanki et al., 2004). (B) Holocene Bond events 5–8 derived from Bond et al. (1997, 2001) and ice-rafted debris (IRD) record based on haematite-stained grains of cores MC52 and VM29-191 from the subpolar North Atlantic (Bond *et al.*, 2001). (C) NGRIP $\delta^{18}O$ Greenland Ice Core (Andersen et al., 2004). (D) Mean annual temperature (TANN) from Europe during the Holocene (Davis et al., 2003). (E) Lake Holzmaar $\delta^{13}C$ values (Lücke et al., 2003). (F) Bleßberg Cave $\delta^{18}O$ (Breitenbach et al., 2019). (G) Atlantic Ecoregion Biomass Burned (Feurdean et al., 2020). (H) Microcharcoal influx from the Ammer River Valley. (I) Macrocharcoal influx transformed (*Z*-scores) from the Ammer River Valley. (J) Pollen accumulation rate (PAR) from the Ammer River Valley. Vertical shaded grey bars show rapid climate change events. Vertical shaded pink bar: Period 1 (11.6–10.6 cal kaBP), blue bar: Period 2 (10.6–9.5 cal kaBP) and yellow bar: Period 3 (9.5–8.0 cal kaBP). [Color figure can be viewed at wileyonlinelibrary.com].

would have offered suitable habitat for pine, which with its shallow roots can grow well on sandy soils (Theuerkauf et al., 2014). The strong dominance of *Pinus*, followed by peaks in *Betula* and *Artemisia*, at ~11 cal kaBPcoincides (within the error bounds) with drier climatic conditions in Western Germany, as indicated by decreasing $\delta^{13}C$ values in the sediments of Lake Holzmaar (Eifel, Germany) (Lücke et al., 2003). In contrast, an abrupt increase in temperatures and precipitation in Western–Central Europe is suggested by Davis et al. (2003) and from Bleßberg cave in Eastern Germany (Breitenbach et al., 2019). During the same period, an increase in ice rafted debris (IRD) probably associated with a reduction in solar activity caused a sudden change in the North Atlantic thermohaline circulation (Bond et al., 1997; Alley, 2004; Heiri et al., 2004; Solanki et al., 2004; Alley and Ágústsdóttir, 2005; Seppä et al., 2009; Blockley et al., 2012) possibly causing centennial-scale cooling in the local climate. At the end of this period, the ecosystem around the Ammer River Valley underwent major changes related to extensive reorganization of the landscape from a river-dominated (gravel and clay deposition) to a wetland area. When the onset of tufa deposition at 10.85 cal kaBP(707 cm), the influx of pine and grass pollen reached their highest values. However, the peaks in pollen influx can be explained by local abrupt changes in the palaeo-wetland, such as fast deposition and lower water energy associated with the start of tufa formation (Bertini et al., 2014; Ricci et al., 2015) and therefore are not considered as significant.

During the later stages of the Early Holocene, 10.6–9.5 cal kaBP(Period 2), temperatures recorded in the polar regions of the Northern Hemisphere gradually increased with flattening of the warming trend towards its end (Fig. 7) (Andersen et al., 2004), whereas temperature anomalies in Western–Central Europe remain relatively stable (Davis et al., 2003; Breitenbach et al., 2019). Pollen records from Central and Northwestern Europe point to a rise in summer temperatures and to milder winters (Atkinson et al., 1987; Davis et al., 2003; Mauri et al., 2015). The vegetation record of the Ammer River Valley is marked by an abrupt change expressed in a strong reduction of pine and a steady spread of broadleaf vegetation. The substantial local environmental change related to the formation of the wetland in the valley resulted in a reduction of sandy substrates on which *Pinus* was growing. The wetland therefore favoured additional wetness and more shade-tolerant *Corylus*. Thus, the enlarged wetland area created favourable conditions for the growth of hazels, as visible in the pollen record.

The decrease in pine and birch pollen accumulation rates (Fig. 7) dated to ca. 10.6 cal kaBPis most probably related to a temperature increase recorded by NGRIP. The increasing temperatures led to better climatic and edaphic conditions, thus allowing the open pine–birch woodland to be replaced by mesophilous trees, which subsequently expanded in the study area.

The centennial-scale return to drier and colder conditions at 10.3 kaBPresulting from alterations in the North Atlantic thermohaline circulation following increased iceberg discharge during lower solar activity (Björck et al., 2001; Florescu et al., 2019) is not clearly detectable in the palaeoecological record of the Ammer River Valley due to its low resolution in this section. At 9.96 cal kaBP(580 cm), another peak of high pollen and microcharcoal concentrations led back to a short rise in the sedimentation rate (Fig. 2) and thus not significant, i.e. not related to actual vegetation or palaeo-fire change.

Period 3 (9.5–7.8 cal kaBP) falls into a period of stable climate recorded in the northern polar regions (Fig. 7) (Andersen et al., 2004) and a warming but fluctuating climate in Europe (Davis et al., 2003). At the start of the period, the vegetation in the Ammer River Valley was probably still dominated by open woodland, which was followed by an increase of mixed oak forests, while pines and hazelnuts were still present, as generally seen in south-western Germany (Smettan, 2002). The widely recognized climate excursion towards drier and windier conditions at ~8.2 cal kaBPin the Northern Hemisphere (Seppä and Birks, 2001; Florescu et al., 2019) coincides with a transition from tufa to peat formation at 8.34 cal kaBP(310 cm) in the Ammer River Valley record. This change indicates the decrease of carbonate deposition (leaching) in shallow underground water (Grube and Usinger, 2017). A hiatus in the Bleßberg cave record suggests a complete absence of drip water possibly resulting from prolonged drought or permafrost conditions with temperatures lower than −6 °C (Fig. 7C) (Breitenbach et al., 2019). The Ammer River Valley pollen influx of Poaceae, *Pinus* and *Corylus* decreases at the onset of the 8.2 cal kaBPevent (Fig. 7D), as with the relative abundances of the most deciduous tree taxa such as *Quercus*, *Ulmus* and *Tilia* (Fig. 3). Soon after the 8.2 cal kaBPevent, hazel, which is tolerant to seasonal drought, cold winters and relatively cool summers (Theuerkauf et al, 2014), recovers within a shorter period compared to all other broadleaved taxa (Huntley, 1993). At ~8.1 cal kaBP, the mire of the Ammer River Valley gradually transforms back to a floodplain until the end of the pollen record at 7.8 cal kaBP.The record indicates that mixed oak forests are the dominant vegetation in the Ammer River Valley, although hazel remains an important component of the vegetation, distributed most probably along the alluvial plain.

Ammer Valley palaeo-fire record

The sum of the macro- and microcharcoal influx record reflects the general trend of biomass burning across Europe during the Holocene (Fig. 7E; Feurdean et al., 2020). The general increasing trend at the start of the Holocene at 11.6 cal kaBPhas been related to the rapidly changing climate resulting in a widespread reorganization of ecosystems as a consequence of deglaciation (Tinner and Lotter, 2001; Alley and Ágústsdóttir, 2005; Marlon et al., 2013).

During Period 1 (11.6–10.6 cal kaBP), the macrocharcoal record of the Ammer Valley follows the general trend of intensified fire events in Europe, but with an offset of <300 years (Fig. 7F). This offset could be an artefact of dating uncertainties in the lower part of the core. Based on macrocharcoal identifications, the main burned biomass comprise grasses (Fig. 5), which is typical for wildfires in an open vegetation. Such a picture is known for the first two millennia of the Early Holocene in Central Europe, where climate had a rather continental character with typically drier seasons (Theuerkauf et al., 2014).

During Period 2 (10.6–9.5 cal kaBP), local fire events (indicated by the macrocharcoal influx) are less intense and less frequent between 10.6 and 10.1 cal kaBPbut increased abruptly at 10.1 cal kaBPand remained relatively high until 9.5 cal kaBP.The microcharcoal influx shows a similar trend, with a short period of intensified influx between 10.4 and 10.2 cal kaBPrelated to an interruption of the generally warm and humid climate because of changes in the North Atlantic thermohaline circulation (Björck et al., 2001; Florescu et al., 2019). Macrocharcoal morphotypes were dominated by grass and herbs (Fig. 6), but deciduous leaves and wood are also constantly present in small quantities, indicating the development of at least some woodland component (*Corylus*) in the mire. Together with the regional palaeo-fire record reflected by the microcharcoal influx, fire events in the Ammer River Valley correlate with the overall trend for biomass burning in the ecoregion (Feurdean et al., 2020) explained by increased fuel availability (Fig. 7). The intense palaeo-fire phase from 10.1 to 9.5 cal kaBPis well in line with strong fluctuations in the *Corylus* pollen influx suggest that hazel was affected by these local fires at the onset of this period. As a fire-enhanced shrub (Tinner et al., 2000), it recovers well and rapidly, which is indicated by consecutive high pollen influx rates implying increasing abundance. This relationship between local fire and hazel was also confirmed for the whole sequence by time series analyses (ESM 1). This statistical analysis shows that macrocharcoal peaks, i.e. local palaeo-fires, cause the increase of *Corylus* at a very high level of significance. Thus, local fires created additional favourable conditions for the distribution of hazel stands so that after the local decline of pine and birch woodland after 10.6 cal kaBP, the spread of open hazel woodland in the floodplain was supported additionally by the palaeo-fire regime.

During Period 3 (9.5–7.8 cal kaBP), the macrocharcoal record is characterized by only small peaks with a decreasing trend towards the end of this period, high fire frequency and short FRIs until 8 cal kaBP.This indicates the continuous role of fires in shaping the landscape. Macrocharcoal morphotypes were dominated by grass, herbs, deciduous leaves and small quantities of wood. Thus, the mire vegetation was dominated by grasses (*Phragmites*) and herbs (including *Eupatorium cannabinum*) (Fig. 6), but the surrounding deciduous woodland was also affected by fire events. This woodland consisted mostly of hazel, as the probably dominant tree in the valley. In contrast to the macrocharcoal record, the microcharcoal influx indicates strongly fluctuating regional fire activities during Period 3 with enhanced fluctuations between 8.5 and 8.1 cal kaBP.This period of enhanced regional fires falls into one embracing the 8.2 cal kaBPclimatic cold event, which led to a return to cold and dry conditions with deceased fuel moisture indicated by the Bleßberg Cave record (Breitenbach et al., 2019). Worldwide, this climate event is discussed to have occurred over several hundreds of years, starting at 8.6 cal kaBP(Walker and Salt, 2012).

Possible Mesolithic land use patterns

Several Mesolithic sites are known from the Ammer River Valley, the most prominent being Rottenburg-Siebenlinden (Fig. 1), located in a landscape characterized by several ecozones and dominated by a riverine wetland. The dryer, continental climate of the early Holocene, especially from 11 to 9.5 cal kaBP, when vegetation was more open, may have favoured natural fires resulting from lightning in open spaces. The changes that such wildfires brought about, which include persistent forest openings or increased pioneer wetland vegetation, were attractive to the Mesolithic communities. The presence of young, fresh undergrowth vegetation provided edible plants and fruit- and nut-bearing shrubs (e.g. wild apple, hazel, blackberry and elder), but also various herbaceous plants (e.g. nettle, rush) which could have been used to produce basketry and nets (Crombé, 2019; Crombé and Langohr, 2020). Moreover, it has been suggested that fire was an important element of Mesolithic land use strategies as the landscapes it impacted yielded more and better food resources for people and game (e.g. Zvelebil, 1994; Kubiak-Martens, 1999; Bishop et al., 2015). As the hunting of animals, both vertebrates and invertebrates, was an important component of Mesolithic subsistence (Ptáková et al., 2021), it is possible that people used fire to manipulate the vegetation structure towards increased open areas (Bos et al., 2006; Bishop et al., 2015). The presence of charred epidermis parts of *Phragmites* or grasses in the macrocharcoal record of the Ammer River Valley could, for example, indicate the clearing of reed swamps in the area through fires. Furthermore, the abundance of *Urtica, Typha* and most of the taxa considered as anthropogenic indicators during the Mesolithic (see Kuneš et al., 2008) reflect nitrogen-rich habitats and semi-aquatic vegetation that could have been favoured by such local fires. The presence of coprophilous fungi (Fig. 4.), by contrast, suggest that those habitats were regularly visited by herbivores, including those attractive for hunting game.

Remarkably, pollen indicators of nutrient-rich habitats and macrocharcoal morphotypes implying locally burned wetland vegetation overlap with the occupation periods at Rottenburg-Siebenlinden, especially at Horizons H-IV (10.1–9.9 cal kaBP) and H-III (9.4–8.7 cal kaBP) (Fig. 5). Here, the earliest Mesolithic occupation represented by H-IV coincides with a major increase in intensity and frequency of local palaeo-fire activity in the Ammer River Valley. As a result, human agency cannot be completely ruled out. This is the period with highest values of *Corylus* pollen, suggesting the high abundance of hazelnuts in the landscape. The Early Holocene spread of *Corylus* is widely debated to be favoured by human activities (Huntley, 1993; Tallantire, 2002; Bos and Urz, 2003; Kalis et al., 2003; Kuneš et al., 2008). Hazelnuts formed an essential part in Mesolithic nutrition (Holst, 2010; Crombé et al., 2013) and the large amount of hazelnuts found in a fire pit in H-IV (Kind, 2003) suggest its systematic processing for consumption. Although it is difficult to disentangle natural versus human-driven fires, it is clear that the Mesolithic population in the region benefited from the favourable conditions created by such fire events.

For the period coinciding with H-III (9.4–8.7 cal kaBP) and H-II (8.4–7.8 cal kaBP) at Rottenburg-Siebenlinden, fire intensity (magnitude of events) is lower, but they occur at a more frequent rate. Such a pattern could correspond to controlled, less intense fires caused by humans (Archibald et al., 2009). Another argument for a possible human influence on the local fire regime during this time is that the increasingly dominating deciduous forest vegetation is known to be less prone to natural wildfires. These periods also coincide largely with the development of aquatic environments such as slow flowing open waters, marshes and reed swamps in the area surrounding the studied core. Such environments are especially attractive for hunter-gatherers and were probably regularly visited by them as they provide a stability of the available natural resources (Fig. 5). This could also explain why the Mesolithic occupation of H-II (8.4–7.8 cal kaBP) persisted even during the climatic deterioration related to the 8.2 cal kaBPevent (Kind, 2003), as also observed elsewhere (Blockley et al., 2018).

Conclusions

This study achieved detailed reconstruction of Early Holocene palaeo-fire activities and vegetation changes occurring in the Ammer River Valley, south-western Germany, in relation to environmental change and possible human agency. The reconstruction is based on pollen, NPPs as well as micro- and macrocharcoal from a drill core situated at a few kilometres from the well-stratified multi-phase Mesolithic site Rottenburg-Siebenlinden, located on the Neckar River. Our results suggest that during the Early Holocene (between 10.1 and 9.8 cal kaBP), naturally caused fires favoured forest and wetland openings. These openings were associated with young edible undergrowth attractive for grazing animals, as well as pioneer vegetation including the nutrient-rich hazel, all preconditions for Mesolithic occupation in the study region. The hunter-gatherers probably enlarged the open areas using fire. This is indicated by an increase in local palaeo-fire activities in the Ammer River Valley that coincide with the oldest occupation Horizon H-IV (10.1–9.9 cal kaBP) at the archaeological site Rottenburg-Siebenlinden. Here, evidence of large-scale hazel processing confirms the importance of expanding hazel woodland in the region. After 9.5 cal kaBP, charcoal and pollen analysis of the Ammer River Valley show that low-intensity, frequent local fires were probably controlled by Mesolithic hunter-gatherers, who used fire as part of their subsistence practices. This is suggested by an increase of habitats enriched in hunting and gathering resources in the wetlands after 9.5 cal kaBP.Moreover, periods of more frequent fires coincide roughly with periods of human occupation at H-III (9.4–8.7 cal kaBP) and H-II (8.4–7.8 cal kaBP) at Rottenburg-Siebenlinden. Our results demonstrate that the study region provided a favourable natural environment for early Holocene hunter-gatherers. Further research is needed to better understand Mesolithic land use strategies and settlement activities in the region.

Supporting information

Additional supporting information can be found in the online version of this article. This article includes online-only Supplemental Data.

Appendix S1. Results of time series analysis.

Table S1. Raw data for time series analysis.

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