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13,000-year-old fen mosses from Paderborn, eastern Westphalia, reveal a rich fen habitat that is since long lost

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Abstract
During an archaeological rescue excavation in the old town centre of Schloß Neuhaus, a district of the city of Paderborn in eastern North Rhine-Westphalia, Germany, large masses of mosses from the Allerød oscillation (c. 13,900 to 12,900 cal. BP) were encountered. In the ten studied samples, the two mosses *Sarmentypnum tundrae* and *Scorpidium scorpioides* dominated, whereas small amounts of *Calliergon giganteum* and *Drepanocladus trifarius* were found. All four species are typical of rich fens, and all four have nowadays either vanished from Germany (*Sarmentypnum tundrae*) or became rare and Red-Listed in the country. Together with earlier finds in North Rhine-Westphalia and surrounding regions, the Paderborn finds show that rich fens were likely widespread during the Allerød oscillation and during the time periods before and after. It seems likely that a combination of a changing climate (*Sarmentypnum tundrae*), natural succession and, especially during the last centuries, agricultural management have contributed to the loss or near-loss of these species from North Rhine-Westphalia.

Keywords: Allerød oscillation, archaeobotany, *Drepanocladus trifarius*, endangered rich-fen mosses, *Sarmentypnum tundrae*

Kurzfassung
Bei einer archäologischen Rettungsgrabung im alten Stadtkern von Schloß Neuhaus, einem Stadtteil von Paderborn im östlichen Nordrhein-Westfalen, Deutschland, wurden große Mengen von Moosen aus dem Alleröd-Interstadial (ca. 13.900 bis 12.900 cal. BP) gefunden. In den zehn untersuchten Proben dominierten die beiden Moose *Sarmentypnum tundrae* und *Scorpidium scorpioides*, während geringe Mengen von *Calliergon giganteum* und *Drepanocladus trifarius* gefunden wurden. Alle vier Arten sind typisch für artenreiche Niedermoore, und alle vier sind heute entweder aus Deutschland verschwunden (*Sarmentypnum tundrae*) oder selten geworden und stehen hierzulande auf der Roten Liste. Zusammen mit früheren Funden in Nordrhein-Westfalen und den umliegenden Regionen zeigen die Paderborner Funde, dass reiche Niedermoore während des Alleröd-Interstadials und in den Zeiträumen davor und danach wahrscheinlich weit verbreitet waren. Eine Kombination von Klimaschwankungen (*Sarmentypnum tundrae*), natürlicher Sukzession und, insbesondere in den letzten Jahrhunderten, landwirtschaftlicher Bewirtschaftung hat wahrscheinlich zum Verlust oder Beinahe-Verlust dieser Arten in Nordrhein-Westfalen beigetragen.

Schlagwörter: Alleröd-Interstadial, Archäobotanik, *Drepanocladus trifarius*, gefährdete Niedermoormoose, *Sarmentypnum tundrae*

Introduction

In March 2021, several subfossil tree trunks or logs have been found during an archaeological rescue excavation in the old town centre of Schloß Neuhaus, a district of the city of Paderborn in eastern North Rhine-Westphalia, Germany. More than 14 logs have been recovered that are up to 8 m long and 30 cm in diameter. Together with the logs, more than one thousand pine cones have been encountered. The cones were all identified as Scots Pine (*Pinus sylvestris* L.) and consequently, it is most likely that the logs also belong to that species – an identification of the wood at the Laboratory of Dendroarchaeology of the University Cologne, Cologne, Germany, confirmed the identification.

The logs were found below a layer of sand from the latest period (Younger Dryas) of the Weichselian glaciation and may thus be assigned to the Allerød oscillation. The Allerød oscillation was a warm and moist global interstadial that occurred c. 13,900 to 12,900 cal. BP, nearly at the end of the Last Glacial Period.

On the outer surface of some of the logs, a thick and rich layer of well-preserved mosses was associated. Mosses are frequently found in late- to postglacial subfossil deposits and often provide valuable evidence for paleoenvironmental reconstruction (e.g., Behre et al. 2005; Biewer & Poschlod 1995; Stojakowits et al. 2020). The good preservation status of the mosses allowed reliable identifications of most of the fragments and based on this, we get valuable insights into how fens looked in the Paderborn area during the Allerød.

Materials and methods

An archaeological rescue excavation was carried out at a construction site in Neuhäuser Kirchstraße, Schloß Neuhaus (Fig. 1), when archaeological objects were found during the construction work for a new vicarage ("Pfarrhaus"). Along with these objects, a layer yielding thick pine logs (Fig. 2A, B) and several hundreds of pine cones was discovered at a depth of c. 3.30 m below ground level. Some of the logs were covered by cushions of mosses (Fig. 2C), of which several bulk samples were taken and brought to the LWL-Museum of Natural History, Münster, Germany. Ten wet samples were sent to Lars Hedenäs at the Swedish Museum of Natural History, Stockholm, Sweden, for identification.

The samples were placed in water and mosses were separated from other organic and inorganic material. Most samples were rich in material, and between c. 100–>300 fragments were studied in most samples (Table 1). The samples were studied under a dissecting microscope, and when required, also under a compound light microscope. The material, or in the case of the larger samples, large subsets of the studied material, were placed in glass vials with a few drops of thymol added for preservation. These samples are stored in the palaeobotanical collection of the LWL-Museum of Natural History, Münster, Germany, and are available under accession numbers WMNM P88091–P88100.

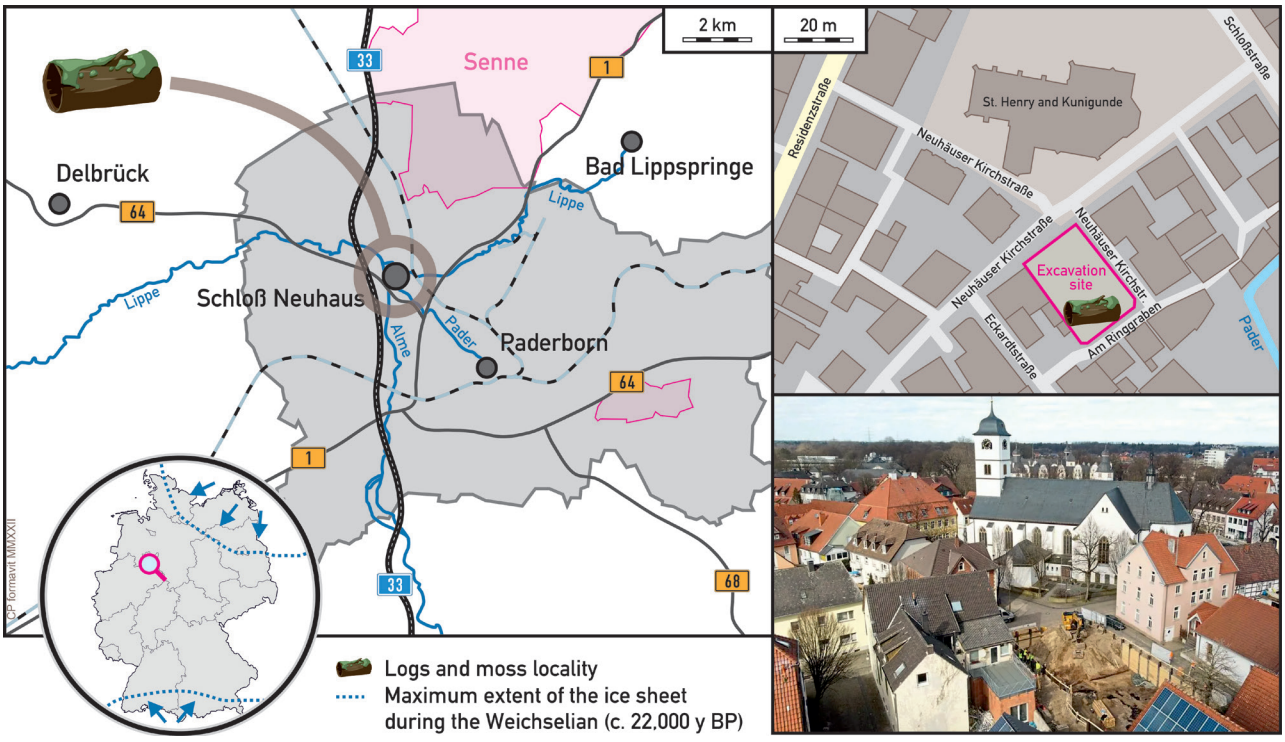

Fig. 1: Maps showing the location and situation of the excavation site in Paderborn-Schloß Neuhaus, and the maximum extent of the Weichselian Ice Sheet in Germany. Maps: LWL-Museum of Natural History/Pott; photo: LWL-Archaeology of Westphalia/EggensteinExca/Beverungen.

Fig. 2: Excavation site in Paderborn-Schloß Neuhaus. **A** Overview of the entire site with the locality of the moss findings analysed in this study (arrowhead). **B** One of the logs of Scots Pine (*Pinus sylvestris*). **C** Moss cushion on one of the logs. Photos: LWL-Archaeology of Westphalia/EggensteinExca/Beverungen and LWL-Museum of Natural History/Schöllmann/Ali.

Geological situation

The Cretaceous bedrock, represented by lower Santonian clay marls at a depth of about 15 m, is in the area commonly overlain by up to 13-m-thick Weichselian low terraces of the Alme, Lippe and Pader rivers (Fig. 1). The low terraces generally consist of grey to white, sandy to silty gravel and fine- to medium sands. They encompass the Allerød stratum, which includes a 10-cm-thick humic layer at about 270 cm below ground level, and the sandy strata of the Younger Dryas at the top (c. 70 cm).

The overlying yellowish to brownish/grey to yellow-grey layers of argillaceous, silty to sandy haugh (floodplain deposits) show locally restricted intercalations of argillaceous, silty sand and thin layers of gravel and whitish-grey argillaceous fine sand from the Holocene (c. 80 cm), topped by a c. 20-cm-thick layer of aeolian sand (see Skupin 1982). The youngest strata are interpreted as a bioturbated soil zone (c. 30 cm) overlain by garden soil (c. 50 cm) below the A horizon (15 cm). The layer yielding the logs, cones and mosses was assigned to the Allerød oscillation period, based on the overlying sand layer representing low terraces from the latest period (Younger Dryas) of the Weichselian glaciation (pers. comm. A. Deppe, A. Lenz, GD NRW, Krefeld, February/March 2022).

Most late-glacial sediments in the outcrop area were obviously aeolian sands blown into the late-glacial floodplain. In contrast to the geological map of the area (Geological Map of North Rhine-Westphalia 1:25,000, sheet 4218 Paderborn; Skupin 1982), no cover of the sequence by Holocene argillaceous floodplain deposits was found in the area of the outcrop. The geological situation is interpreted as a small-scale, island-like aggregation of aeolian sands accumulating on a kind of

sandbank at the confluence of the Alme, Lippe and Pader rivers (pers. comm. A. Lenz, GD NRW, Krefeld, February 2022). It is consequently very likely that the pine logs and cones accumulated in or along a former oxbow lake, or within the floodplains of the Pader River, and were later overgrown by mosses.

The outcrop locality is in the centre of the estuary formed by the Pader River at it's confluence with the Alme and Lippe rivers. The Pader River is here split into several arms that flow into the Alme and Lippe rivers to the west and east, respectively. The outcrop locality (<20 m from a current arm of the Pader River; Fig. 1) is consequently positioned in a lowland setting that was part of the alluvial plain of the adjacent rivers, and was flooded regularly at least during late-winter rises of the rivers' water level through snow melting. Such river valleys, oxbow lakes or floodplains that successively became transformed into fens were quite important habitats for minerotrophic mosses (cf., Gałka et al. 2020).

Results

Five moss species occurred in the ten studied samples, with *Scorpidium scorpioides* (Hedw.) Limpr. and *Sarmentypnum tundrae* (Arnell) Hedenäs (Fig. 3) by far the most common ones (Table 1). *Scorpidium scorpioides* was the only species in four samples and dominated in another two samples, whereas *Sarmentypnum tundrae* was most common in four samples. Two of the samples in which *Sarmentypnum tundrae* dominated were also the only ones that included significant amounts of vascular plant remains. *Drepanocladus trifarius* (F.Weber & D.Mohr) Broth. ex Paris (Fig. 4) occurred, with few shoots, in three of the samples, and one or two fragments of cf. *Campylium stellatum* (Hedw.) Lange & C.E.O.Jensen and *Calliergon giganteum* (Schimp.) Kindb., respectively, were found in sample 7 (Table 1). Vascular plant remains, mainly in the form of epidermal fragments, were present in samples 2 and 9 (Table 1).

Discussion

The found mosses nowadays typically grow in wet, mineral-rich to moderately mineral-rich fens, with *Calliergon giganteum* and especially *Sarmentypnum tundrae* indicating a slight nutrient enrichment (Hedenäs 2003). The relative abundance of *Sarmentypnum tundrae* in the two samples with vascular plant remains may reflect a higher level of available nutrients in these (Kooijman & Hedenäs 2009).

In Europe, *Calliergon giganteum*, *Drepanocladus trifarius* and *Scorpidium scorpioides* are currently frequent to very abundant in the north and partly at

Tab. 1: Moss remains present in ten samples from Allerød strata that were temporarily exposed at Schloß Neuhaus, Paderborn. The material or, in the case of the larger samples, subsets, is stored at LWL-Museum of Natural History, Münster, under accession numbers WMNM P88091–P88100.

Sample no.	Sample type	Studied fragments	Moss species (% of sample)
1 (P88091)	Moss mixed with little sand (mainly moss)	>200	Scorpidium scorpioides (100%)
2 (P88092)	Moss mixed with sand	c. 300	Scorpidium scorpioides (100%; 1 male bud)
3 (P88093)	Moss mixed with sand	>200	Scorpidium scorpioides (100%)
4 (P88094)	Moss mixed with vascular plant remains	c. 300	Sarmentypnum tundrae (75%) Scorpidium scorpioides (25%) Drepanocladus trifarius (8 shoots)
5 (P88095)	Organic material with some sand; sparse moss[A]	c. 100	Sarmentypnum tundrae (60%) Scorpidium scorpioides (40%)
6A (P88096)	Pure moss	c. 200	Sarmentypnum tundrae (85%) Scorpidium scorpioides (15%) Drepanocladus trifarius (2 shoots)
6B (P88096)	Sand and organic material intermixed; little moss	few	Sarmentypnum tundrae (few) Scorpidium scorpioides (few)
7 (P88097)	Clay with layers of organic material; little moss[A, B]	c. 100	Scorpidium scorpioides (80%) Sarmentypnum tundrae (20%) Calliergon giganteum (1 shoot/branch, 1 leaf) cf. Campylium stellatum (1 tiny, etiolated shoot)
8 (P88098)	Clay with layers of organic material; little moss[B]	c. 100	Scorpidium scorpioides (80%) Sarmentypnum tundrae (20%) Calliergon giganteum (2 shoots/branches)
9 (P88099)	Peaty soil with moss or vascular plant remains	c. 200	Sarmentypnum tundrae (65%) Scorpidium scorpioides (35%) Drepanocladus trifarius (1 shoot)
10 (P88100)	Jar with moss in water	--	Scorpidium scorpioides (100%)

[A] One piece of charcoal

[B] Obviously allochtonous since most fragments, like other plant remains, were torn or present only as leaves or small shoot / branch pieces

higher elevations in Central Europe, for example in portions of the Alps. In Germany, they are rare and currently occur mainly in the Pre-Alps, in Brandenburg and Mecklenburg-Vorpommern (Meinunger and Schröder 2007), that is the German regions where significant areas of fens remain (Trepel et al. 2017).

For *Calliergon giganteum* and *Scorpidium scorpioides*, historical finds are known from the Paderborn area (Koppe 1949) and the species occur at few (*Scorpidium scorpioides*) or scattered localities also outside the three mentioned regions. For the rarest of the three species, *Drepanocladus trifarius*, a single find from 1866 exists from the Paderborn area (Düll et al. 1996; Koppe 1949; Meinunger & Schröder 2007). Even during historical times, this species was almost completely absent from other regions than the Pre-Alps and the north-eastern portions of Germany, and today it occurs almost exclusively in the Pre-Alps.

All three species have significantly decreased in frequency in Germany and continue to do so, and they are currently classified as endangered (EN; "Stark gefährdet") (Caspari et al. 2018). The situation is similar in other portions of Central Europe (e.g., Hájková et al. 2018). Because the single shoot of cf. *Campylium stellatum* could not with certainty be referred to this species, it is not discussed further here.

Late-glacial or Holocene fossil *Calliergon giganteum*, *Drepanocladus trifarius* and *Scorpidium scorpioides* were found at several localities in Germany and surrounding European countries (Biewer & Poschlod 1995; Hájková et al. 2018; Janssens 1977). In the regions relatively close to the present locality, late-glacial or Holocene finds are known, for example, of *Calliergon giganteum* near Bremerhaven (NW Germany) from Holocene deposits (Van Odgaard 1988), of *Drepanocladus trifarius* in Warmings Mose north of Copenhagen (Denmark) from 10,000–6,000-year-old sediments and from Belgian late-glacial sediments (Janssens 1977; Van Odgaard 1988), and of *Scorpidium scorpioides* near Enschede (E Netherlands) from 12,200-year-old sediments and Belgian late-glacial sediments (Janssens 1977; Wiegers & Van Geel 1983). Because these three species still occur at suitable sites in lowland Germany, their disappearance from the Paderborn area is unlikely a direct result of the Holocene warming climate.

The fourth species that was confidently identified from the present site, *Sarmentypnum tundrae*, occurs in central and northern Fennoscandia, Iceland, Russia, Estonia and Latvia (and the Arctic) (Hedenäs 2003). In addition, one extant locality was recently found in the French Alps (Bonte and Boudier 2014). Today, *Sarmentypnum tundrae* does not occur in Germany, but subfossil finds are known from the Brørup interstadial (c. 100,000 years BP) at Oerel, between Bremen and Hamburg (Behre et al. 2005), and from the end of the Weichselian Late-Glacial from the Lautermoor, south of Mannheim (Hölzer & Hölzer 1994). *Sarmentypnum tundrae* currently occurs only in the north of Europe, from shortly south of the northern boreal zone and northwards (and in the French Alps at almost 2,200 m a.s.l.). It therefore makes sense to assume that this species gradually disappeared from Germany when the climate became warmer, irrespective of other changes in the habitat.

Fig. 3: *Sarmentypnum tundrae* from Paderborn sample no. 9 (WMNM P88099; Table 1). **A** Leaf. **B** Leaf decurrencies. Scale bars: 500 µm (A), 100 µm (B)

Considering the several late-glacial and Holocene fossil finds of all four species at some or several localities in the wider region, the here reported finds are probably representative of fens in the Paderborn area during the Allerød oscillation and during the colder Younger Dryas period. This suggests that mineral-rich fens were then widespread here. When the climate gradually became warmer during the late Holocene, birch and pine started to invade the fens, and these

Fig. 4: *Drepanocladus trifarius* from Paderborn sample no. 4 (WMNM P88094; Table 1). **A** Shoot. **B** Leaves. Scale bars: 3 mm (A), 500 µm (B)

were later followed by alder (Averdieck et al. 1990). Towards the end of the Holocene climatic optimum (c. 9,000 to 5,000 cal. BP) bogs started to develop, and the mineral-rich fen habitats gradually disappeared (Averdieck et al. 1990).

It seems likely that a large proportion of the suitable fen habitats disappeared due to the general changes in climate and accompanying or successional changes in vegetation during the first half of the Holocene. However, there still existed several suitable sites until historical times, based on known finds of the three species that still occur in Germany (Meinunger & Schröder 2007). We also know from surveys of peat soil and historical maps that originally Germany had between 1,400,000 and 1,800,000 ha of mires, and that probably >5% of its surface was covered by mires (Trepel et al. 2017). The distribution was uneven and in, for example, Mecklenburg-Vorpommern and Brandenburg, 10% of the surface was covered by mires. Currently, only 25,000 ha of mires, or 2% of the original surface, remain in Germany due to human management of the land (Trepel et al. 2017). This drastic general decrease in mire surface is probably the main reason why many fen species are now endangered in Germany and why the three species with extant German localities no longer occur in the Paderborn area.

An early human impact on the disappearance of suitable fen habitats is less likely because no settlement activities can be proven by pollen analysis prior to the Neolithic in the Westphalian area (Kramm 2017). Following improved peat-cutting and agricultural technologies during the 19th and 20th centuries, large scale transformation of fens and bogs occurred (Trepel et al. 2017). Because the human impact was low until the last few centuries, many fens suitable for the species found here likely disappeared due to natural succession rather than human actions.

Conclusions

Four typical rich-fen mosses were found in an Allerød deposit during an excavation in Paderborn, *Calliergon giganteum*, *Drepanocladus trifarius*, *Sarmentypnum tundrae*, and *Scorpidium scorpioides*. Together with finds reported in the literature, these finds show that rich fens were likely once widespread in North Rhine-Westphalia and surrounding regions. As habitat conditions changed, whether natural climate- or succession-related, or human-induced, the rich fen species disappeared (*Drepanocladus trifarius*, *Sarmentypnum tundrae*) or became very rare. This study adds to the evidence that the history of European biota was strongly dynamic and that many species that are today rare or absent in large areas of lowland Europe were once much more widespread.

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