



Vegetation changes in the Grote Nete valley (Campine region, Belgium) during the Boreal: a response to the 9.3 ka event?

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Abstract

Environmental changes have had an enormous impact on prehistoric hunter-gatherers as they affect the biotic landscape and availability of resources such as freshwater, edible plants, game and fish. To assess whether various innovations that took place in hunter-gatherer communities during the Boreal may be attributed to changes in the vegetation, a high-resolution pollen and macrofossil analysis of a well-AMS-dated Early Holocene peat record from the Grote Nete valley in the Belgian Campine was carried out. Shifts in the pollen assemblages indicate a change from a birch-pine woodland in the late Preboreal to pine-dominated forests in the Boreal. After the initial expansion of hazel, followed by oak and elm from the early Boreal onward, a prominent and abrupt reduction of the pollen concentration, by up to 95% over several spectra, is observed during the second half of the Boreal. This sharp decline affects all taxa and coincides with a decrease in pollen percentages of thermophilous trees and an increase of the cold-tolerant pine. This shift in pollen concentration and vegetation composition likely reflects a climatic cooling at 9.3 ka which is evident in the stable oxygen isotopic record of the Greenland ice cores. On the one hand, the vegetation dynamics are discussed in the light of the Boreal vegetation history in general and this temporary cooling more specifically. On the other hand, we discuss how these changes may have affected past hunter-gatherer communities.

Keywords 9.3 ka event · Boreal · Hunter-gatherers · Campine · Pollen · Peat

Introduction

From an archaeological point of view, the Early Holocene and particularly the Boreal (ca. 10,600–8,600 cal BP) is an extremely important period, especially for the regions along the southern North Sea basin (Rhine-Meuse-Scheldt area). Here, the Boreal, and more specifically its final stage corresponds to the middle Mesolithic, dated between ca. 9,525–9,210 and ca. 8,450–8,225 cal BP (Crombé 2019). During this period major changes occurred in the archaeological record. Radical transformations in the lithic technology are characterised by the development of new hunting gear (Gendel 1984; Crombé and Vandendriessche 2020) and increased use and circulation of exotic raw materials, such as Wommersom quartzite (Perdaen et al. 2009; Crombé 2018). In parallel, site-density decreased considerably on a regional level, possibly indicating a change in mobility and/or demography of contemporaneous hunter-gatherer groups (Crombé et al. 2011; Van Maldegem et al. 2021). Finally, burial practices were possibly also affected, as cremation

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of the deceased became a new practice besides traditional inhumation (Toussaint et al. 2009).

It is generally assumed that most of these transformations were adaptations to a changing climate and environment during the Early Holocene. During this period several meltwater events caused abrupt climate events as recorded in the Greenland Ice sheet (Rasmussen et al. 2007), which may have resulted locally in socio-economic inequality and territoriality under conditions of socio-ecological stress (Crombé 2019; Schulting et al. 2022). Based on a critical assessment and modelling of radiocarbon dates from archaeological contexts along the southern North Sea basin (Robinson et al. 2013; Crombé 2018, 2019), it has been suggested that some of the cultural changes were triggered by the 9.3 ka cooling event that occurred during the late Boreal. In particular, the shift from backed to invasively retouched stone arrowheads, named microliths, appears to fit particularly well with the timing of this climatic event. It is assumed that the 1 to 2 °C decrease in temperature during this event (Marshall et al. 2007; Lang et al. 2010) may have affected natural resources, such as wild plants, game species and drinking water, forcing contemporaneous hunter-gatherer-fishers to adapt their lifeways and to defend their territorial borders more intensively by means of symbolic tools (theory of social-boundary defence). The latter is linked to resource stress and competition resulting from the reduced availability of natural resources, eventually enhanced by population influx from the adjacent drowning North Sea basin (Crombé 2019).

Unfortunately, the lack of high-resolution palaeoecological data covering the Boreal, required for reconstructions of past vegetation on a decadal-to-centennial scale, hinders a detailed assessment of this climate-environment-human response model. This is partly due to the scarcity of organic archives dating to the Boreal within the southern North Sea basin (Crombé 2018), whereas Preboreal and Atlantic records are more abundant. In addition the available archives are often relatively compacted and frequently contain hiatuses, which impede high-resolution vegetation reconstructions during the full extent of the Boreal including the 9.3 ka event. Although the climatic cooling 9.3 ka ago is well documented in stable oxygen isotope records of the Greenland ice cores (Rasmussen et al. 2007, 2014) and is discerned in lacustrine sediments in Europe as well (von Grafenstein et al. 1999; Marshall et al. 2007; Lang et al. 2010), the vegetation response to this short-lived climatic reversal attributed to a partial shutdown of the North Atlantic thermohaline circulation (Marshall et al. 2007; Fleitmann et al. 2008) remains unclear in the southern North Sea area.

Recently, a ca. 0.5 m long peat sequence was discovered in the Nete basin, southeast of Antwerp (Ryssaert et al. 2017). A preliminary palynological study combined with radiocarbon dating of the base and top of the peat indicated a Boreal age. Hence, a high-resolution multiproxy study of

the peat sequence in core BG4 was conducted to assess vegetation changes during the Boreal with special emphasis on the 9.3 ka event.

Materials and methods

Site location

The peat was sampled after an augering campaign along a 30-km transect in the valley of the Grote Nete river. Core BG4 was taken on the right bank of the river (N 51° 7' 30.2", E 4° 43' 10.2") southwest of the municipality of Herenthout (Province of Antwerp, Belgium) (Fig. 1). The Grote Nete river is one of the main rivers in the Nete basin. Herenthout is located in the Campine region, which consists of sandy soils in a landscape with rivers and river dunes.

Lithology

The top of the peat in core BG4 was found at a depth of 4.53 m above National Ordnance Level (NOL, Tweede Algemene Waterpassing), approximately 1.30 m below the surface. Below the peat an organic clay layer was deposited (56–64.5 cm from the top of the sampled sequence; 4.01–4.08 m above NOL; Fig. 2). The peat is approximately 45 cm thick and is more compact and layered in the lowermost 28.5 cm (27.5–56 cm; 4.08–4.365 m above NOL). The top of the peat is less compact, more homogeneous and contains more visible macroremains and wood (11–27.5 cm; 4.365–4.53 m above NOL). Superimposed on the peat a grey clay layer was found (0–11 cm; 4.53–4.64 m above NOL).

Sampling strategy

The peat, including the top of the underlying clay and the base of the superimposed clay was extracted using an auger. The sequence was subsequently wrapped in black plastic foil and was stored in a coring liner before sampling. The peat layer was sampled in the laboratory by dividing the sequence in 1 cm increments using round copper slicing discs, allowing continuous sampling. All samples were stored in labelled plastic bags under cool conditions at 4 °C. For microfossil analysis the compact peat (lower peat section) was subsampled at 3 cm intervals (10 samples), whereas the less compact peat (upper peat section) was subsampled at 1 cm intervals (8 samples). In addition, one microfossil sample was taken from the organic clay below. For macrofossil analysis the peat was analysed at 1 to 3 cm intervals (13 and 6 samples from the lower and upper section, respectively). Two additional samples were taken from the underlying clay. For loss-on-ignition analysis samples were taken at 1 cm intervals allowing continuous sampling, except for the depths that

Fig. 1 Left: Location of the studied borehole plotted on the Digital Elevation Model Flanders version 2 (background: Agentschap Informatie Vlaanderen 2014). Right: Location of the study area in the valley of the Grote Nete in the southern Campine region of Belgium (background: Antrop et al. 2002)

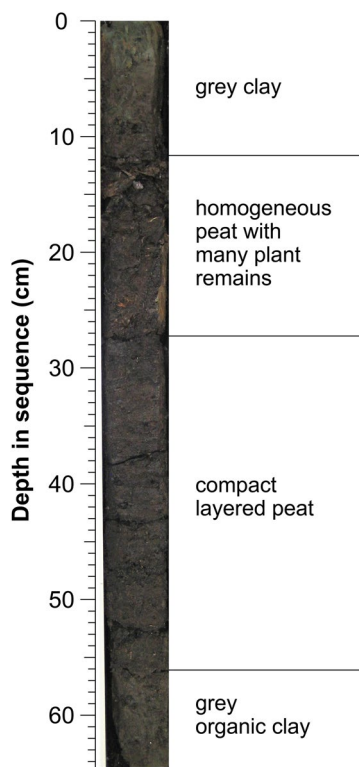
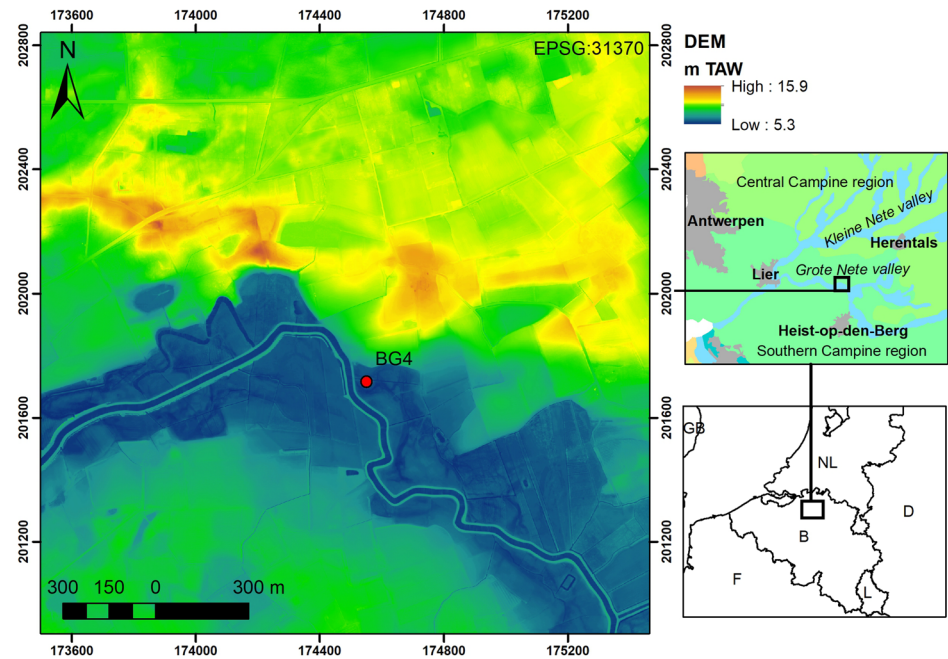


Fig. 2 Lithology of the sampled sequence of core BG4 taken in the Grote Nete valley

were sampled for the preliminary dating study (17–19.5 cm and 53.5–56 cm) and depths where no material was left after sampling for pollen and macrofossil analyses.

Microfossil analysis

In total 19 pollen samples were analysed. The pollen samples were processed according to the preparation technique described by Fægri and Iversen (1989). A heavy liquid separation using sodium polywolframate was performed after the acetolysis step. *Lycopodium* spores were added as a marker to calculate pollen concentrations. The residues containing microfossils were mounted onto microscope slides using glycerine jelly and were subsequently sealed. Palynological remains were analysed using a compound microscope (Olympus BX41, with a maximum magnification of $\times 1,000$, with the possibility of using phase contrast). Pollen and spores were identified using Moore et al. (1991), Beug (2004), the North European Pollen Flora volumes I–IX (Punt et al. 1976–2009) and the reference collection at BIAx. Non-pollen palynomorphs (NPPs) were identified based on the classification of van Geel and colleagues (Miola 2012). Nomenclature of the microfossils follows this identification literature. Ecological preferences were assessed using Weeda et al. (1985–1994), van der Meijden (2005) and Van Landuyt et al. (2006). A minimum of 600 pollen grains and spores, excluding those of aquatic plants, were counted. The pollen sum consisted of pollen and spores from plants of regional origin (trees and shrubs of dry soils, herbaceous forest plants, upland herbs, heather and grassland plants). In an environment where peat is formed, bog, marsh and aquatic plants as well as riparian plants, including trees and shrubs that grow on relatively wet soils may be regarded as local vegetation, which is confirmed by the macrobotanical analysis. As pollen and spores of this local vegetation are

likely overrepresented, they were not included in the pollen sum. Hence, percentages of all pollen, spores and NPPs were calculated based on the upland pollen sum.

Macrofossil analysis

21 samples were investigated for the presence of botanical and zoological macroremains. All macrofossil samples were sieved using an 80 µm mesh sieve. Macroremains were manually picked under a stereo microscope (Leica MZ 7.5 with a maximum magnification of ×50) using a fine forceps. If needed, a compound microscope (Olympus BX41, with a maximum magnification of ×1,000) was used to discern cell patterns. Plant macrofossil abundances were scored in absolute quantities, whereas non-botanical macrofossils were assigned to abundance classes (+/++/+++). Botanical macroremains were identified using Berggren (1969, 1981), Anderberg (1994) and Cappers et al. (2006), as well as the reference collection at BIAx. Non-botanical macroremains were identified using Mauquoy and van Geel (2007).

Loss-on-ignition analysis

Loss-on-ignition analysis (LOI) was carried out on 37 samples following Heiri et al. (2001) to assess the organic and mineral content of the sequence by combusting dried samples at 550 °C for 4 h.

Diagrams

The microfossil and macrofossil assemblages are displayed in diagrams which have been constructed using TILIA. Curves were sorted based on their (weighted average) abundance. As for the microfossil diagrams curves have been exaggerated ×10 (grey envelope). For reasons of readability, pollen or spore types with single occurrences were omitted from the diagrams. Also pollen or spore curves with a maximum total abundance of <1% or a maximum total concentration of <4,500 grains/ml were excluded in the microfossil percentage and concentration diagrams, respectively, unless the taxon is specifically mentioned in the text. Local taxa were not included in the calculation of arboreal pollen (AP)/non-arboreal pollen (NAP) ratios. Zones were assigned subjectively based on shifts in the pollen assemblages. Zone boundaries were always placed in between two adjacent samples.

Radiocarbon dating

Macrofossils of terrestrial plants suitable for AMS radiocarbon dating were selected in 17 samples. Two samples were dated by the Poznan Radiocarbon Laboratory, Poland, as

part of the preliminary assessment of the age of the peat. All other samples were dated by the Royal Institute for Cultural Heritage in Brussels, Belgium. Radiocarbon dates were calibrated using OxCal 4.4 (Bronk Ramsey 2021) applying the IntCal20 calibration curve (Reimer et al. 2020).

Results and interpretation

Age-depth model

The results of the AMS ¹⁴C dates are displayed in Table 1. Although the overview indicates that all dates yield Early Holocene ages, there are some doubtful reversals or potential outliers. The selection of riparian species such as *Menyanthes trifoliata* seeds may lead to an overestimation of the age due to the fact that *Menyanthes* is able to take up old carbon through its root system, particularly when growing on a calcareous substratum (Hoek et al. 1999). A priori rejection of these samples has been considered, but in most of these cases *Menyanthes* is only a small fraction of the selected macrofossils, while the substratum in the area is also not calcareous. Oxcal 4.4 outlier analysis (Bronk Ramsey 2009, 2021) provides information on *a posteriori* outliers after running a general P_{sequence} model with specified outlier parameters with a 5% threshold. A P_{sequence} model allows for variable accumulation rates, and calculated a best age for each individual cm of the sequence (Fig. 3). This results in the (partial) rejection of the following dates for the final age model: RICH-26710 (97%), RICH-26213 (97%), RICH-26212 (97%) and RICH-23374 (52%).

Loss-on-ignition

The organic matter and mineral content of the sequence is plotted in Fig. 4. The organic matter content increases from the base of the examined part of the organic clay that was deposited before peat formation (from 5 to 21%). In the top of the clay the amount of organic matter remains relatively stable (14–18%). There is a distinct increase in the organic matter content in the peat when compared to the clay. An overall increasing trend is discerned with the highest organic matter content in the top of the peat where wood and macroremains were clearly visible (65%).

Vegetation reconstruction

The pollen percentage and concentration diagrams (Figs. 5 and 6) as well as macrofossil abundance diagrams (Fig. 7) are subdivided into four local pollen assemblage zones (LPAZ): Nete 1–4.

Table 1 Radiocarbon dates core BG4

Lab. code	Profile depth (cm)	Weight (mg)	¹⁴ C age (BP)	Cal. age, 2σ-range (cal BP)	Dated material
Poz-79059	17–19.5	8	8,120±50	9,274–8,811	<i>Lycopus europaeus</i> 1×, <i>Betula</i> (non-nana) fruit 1×, <i>Oenanthe aquatica</i> 1×, cf. <i>Quercus</i> leaf frg +, cf. <i>Quercus</i> bud scale +, <i>Salix calyptra</i> 1×, <i>Carex</i> cf. <i>paniculata</i> 1×
RICH-26210	17–19.5	18	8,099±33	9,193–8,811	<i>Salix</i> twig 4×
RICH-23371	19.5–22	14	8,021±47	9,020–8,651	<i>Betula</i> cf. <i>pubescens</i> fruit 4×, <i>Betula</i> bud scale +, deciduous tree leaf frg.+ deciduous tree bud +, <i>Salix calyptra</i> 2×, <i>Menyanthes trifoliata</i> 1×, <i>Oenanthe aquatica</i> 3×, <i>Lycopus europaeus</i> 3×, <i>Carex elata</i> 5×
RICH-23373	23–25	17	8,310±42	9,440–9,142	<i>Lycopus europaeus</i> 4×, <i>B. pubescens</i> fruit 2×, <i>Betula</i> leaf frg+, <i>Betula</i> bud scale +, <i>C. elata</i> 3×, <i>M. trifoliata</i> 2×, <i>Carex rostrata</i> 1×, <i>Salix calyptra</i> 2×, <i>Mentha</i> cf. <i>aquatica</i> 1×
RICH-26211	25–26	8	8,177±32	9,270–9,015	cf. <i>Quercus</i> bud scale 3×, cf. <i>Quercus</i> leaf frg +, <i>L. europaeus</i> 3×, <i>Cyperaceae</i> leaf frg +, <i>B. pubescens</i> fruit 1×
RICH-23374	27.5–31	15	8,473±46*	9,540–9,425*	<i>L. europaeus</i> 9×, <i>Oe. aquatica</i> 5×, <i>B. pubescens</i> fruit 4×, <i>Betula</i> bud scale +, <i>Betula</i> leaf frg +, <i>C. elata</i> 2×, deciduous tree bud 1×, <i>Lysimachia vulgaris</i> 1×, <i>Mentha</i> cf. <i>aquatica</i> 1×, <i>M. trifoliata</i> 1×
RICH-26704	31–33	3	8,179±38	9,273–9,014	<i>L. europaeus</i> 10×, <i>Mentha</i> cf. <i>aquatica</i> 2×, <i>L. vulgaris</i> 2×, <i>Oe. aquatica</i> 7×, <i>Berula erecta</i> 1×, <i>Betula</i> (non-nana) catkin scale 1×, <i>Alisma</i> fruit 1×, <i>Betula</i> cf. <i>pendula</i> fruit 1×
RICH-26706	31–33	4	8,168±40	9,270–9,010	<i>Quercus</i> bud scale +, <i>Quercus</i> leaf frg.+
RICH-26703	34–35	3	8,592±56	9,690–9,480	<i>C. elata</i> 2×, <i>Cladium mariscus</i> 1×, <i>C. paniculata</i> 1×, <i>Eleocharis palustris/uniglumis</i> 2×, <i>B. cf. pendula</i> fruit 3×, <i>Galium palustre</i> 1×, <i>L. europaeus</i> 3×
RICH-26709	34–35	3	8,424±34	9,530–9,322	<i>Quercus</i> bud scale +
RICH-26212	36–37	16	8,160±33*	9,265–9,009*	<i>L. europaeus</i> 4×, <i>Quercus</i> bud scale 1×, <i>Betula/Quercus</i> leaf frg 1×, <i>C. elata</i> 2×, <i>Mentha</i> cf. <i>aquatica</i> 2×, <i>Salix</i> twig 4×
RICH-26213	43–44	10	8,276±33*	9,419–9,130*	<i>Galium palustre</i> 1×, deciduous tree bud 2×, <i>Betula/Quercus</i> leaf frg +, <i>Pinus sylvestris</i> bud scale 1×, <i>C. rostrata</i> 1×, <i>C. pseudocyperus</i> 1×, <i>C. elata</i> 1×, <i>L. vulgaris</i> 2×, <i>Quercus</i> bud scale 1×, <i>Frangula alnus</i> 1×, <i>B. cf. pubescens</i> fruit 1×, <i>B. pubescens</i> fruit 1×, <i>Potentilla</i> 1×, <i>Mentha</i> cf. <i>aquatica</i> 1×
RICH-26705	45–46	3	8,789±3	10,117–9,606	<i>C. elata</i> 1×, <i>Oe. aquatica</i> 1×, <i>P. sylvestris</i> bud scale 2×, <i>M. trifoliata</i> 2×, <i>L. europaeus</i> 2×, <i>B. cf. pendula</i> fruit 3×, <i>C. pseudocyperus</i> 2×, <i>C. riparia</i> 1×, <i>G. palustre</i> 2×, <i>C. paniculata</i> 1×
RICH-26710	45–46	6	8,336±35*	9,467–9,150*	<i>Quercus</i> bud scale +, <i>Quercus</i> leaf frg. +
RICH-23372	51–53.5	23	8,779±45	10,117–9,555	<i>C. rostrata</i> 5×, <i>B. pubescens</i> fruit 4×, <i>Betula</i> leaf frg +, <i>Mentha</i> cf. <i>aquatica</i> 2×, <i>C. elata</i> 2×, <i>Rumex hydrolapathum</i> 2×, <i>Oe. aquatica</i> 3×, <i>Salix calyptra</i> 3×, <i>M. trifoliata</i> 2×, <i>Cornus sanguinea</i> fruit stone 1×
Poz-79063	53.5–56	14	9,010±50	10,249–9,916	<i>M. trifoliata</i> 3×, <i>Cladium mariscus</i> 1×, <i>Betula</i> (non-nana) fruit 4×, <i>C. pseudocyperus</i> 2×, <i>Salix calyptra</i> 2×, <i>Cicuta virosa</i> 1×, <i>C. rostrata</i> 3×, <i>Schoenoplectus lacustris</i> 1×, <i>Rumex hydrolapathum</i> 1×, <i>Eleocharis palustris/uniglumis</i> 1×, <i>Ranunculus flammula</i> 1×; cf. <i>Quercus</i> bud scale +
RICH-26214	58–59	12	9,221±37	10,499–10,253	<i>Salix calyptra</i> 1×, <i>Quercus</i> bud scale 4×, <i>C. pseudocyperus</i> 1×, <i>B. pubescens</i> fruit 1×, <i>Salix</i> twig 2×

Ages have been calibrated using OxCal 4.4 (IntCal20, 95.4% probability)

+ = <10, frg = fragment, * = outlier

Fig. 3 Age model of the studied peat sequence in core BG4 taken in the Grote Nete valley. The 9.3 ka event following Rasmussen et al. (2014) is likely positioned between 27 and 30 cm

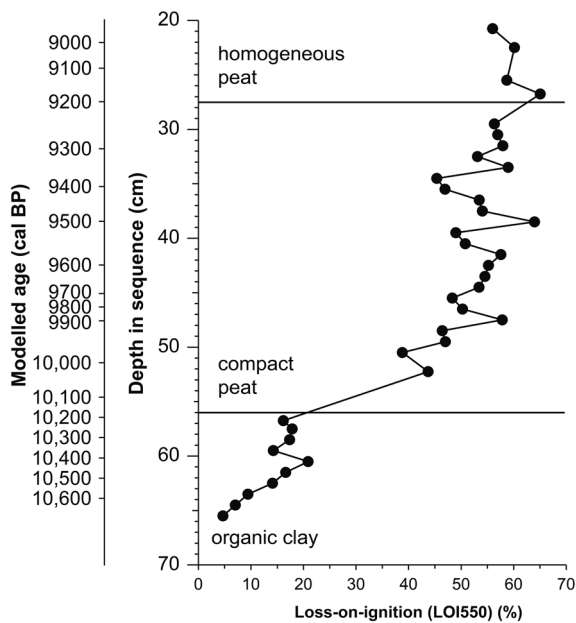
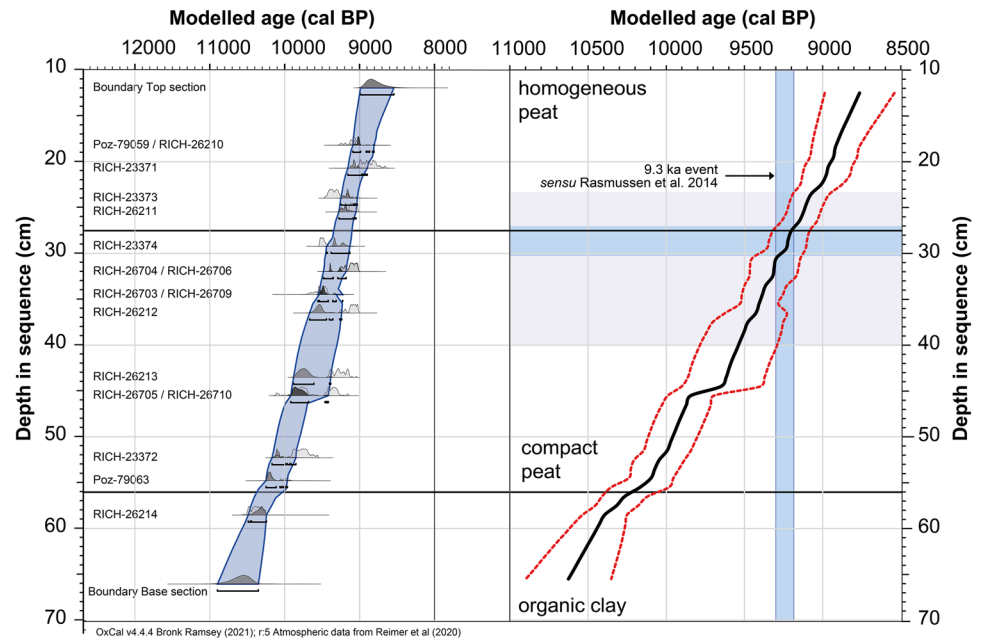


Fig. 4 Loss-on-ignition at 550 °C (LOI550) of core BG4 taken in the Grote Nete valley. LOI550 equals the organic matter content, whereas the remainder of the sample represents the mineral fraction

LPAZ Nete-1 (58.5–63 cm)

Both a high pollen percentage (43%) and concentration (145,000 grains/ml) of *Betula* (birch) characterise LPAZ Nete-1, which covers the organic clay layer below the peat. Also *Pinus* (pine) and Poaceae (grass family) pollen is abundant (22% and 18%, respectively), as well as pollen of *Artemisia* (mugwort; 3%). This likely reflects rather open

birch-pine woodlands in the region. Based on the AMS ^{14}C dates (Table 1), this LPAZ dates to the Late Preboreal. Its composition resembles that of regionally defined biozones 4c and 5 (Hoek 1997) as biozone 4c shows expansion of pine forests at the expense of birch woodland during the early late Preboreal followed by zone 5 during which pine forests expanded further. Fruits and bud scales of amongst others *B. pubescens* (downy birch) as well as calyptra and twigs of *Salix* (willow) in the clay layer suggests tree birches and willow were locally present. Cyperaceae (sedge family) such as *Carex pseudocyperus* (cyperus sedge) and *Schoenoplectus lacustris* (common club-rush) were also constituents of the local peat-forming vegetation as well as aquatic taxa such as *Nuphar lutea* (yellow water-lily), *Nymphaea alba* (white water-lily), *Potamogeton* sp. (pondweed) and *Myriophyllum spicatum* (spiked water milfoil). Algae of the Volvocaceae family (HdV-128 A and -B; Jouffroy-Bapicot 2010) also indicate wet conditions.

LPAZ Nete-2 (29–58.5 cm)

A sharp decrease in *Betula* pollen percentages marks the transition from LPAZ Nete-1 to Nete-2. The zone boundary coincides with the start of peat formation, which dates to the early Boreal (Table 1). *Betula* pollen percentages remain relatively low throughout LPAZ Nete-2 suggesting the reduction of birch woodland from the start of the Boreal onward. However, fruits, catkin scales, bud scales and leaf fragments indicate (tree) birches remained locally present during peat formation. Although no macroremains in the peat could be assigned to *Betula nana* (dwarf birch), its local presence in the Grote Nete valley as a relict during

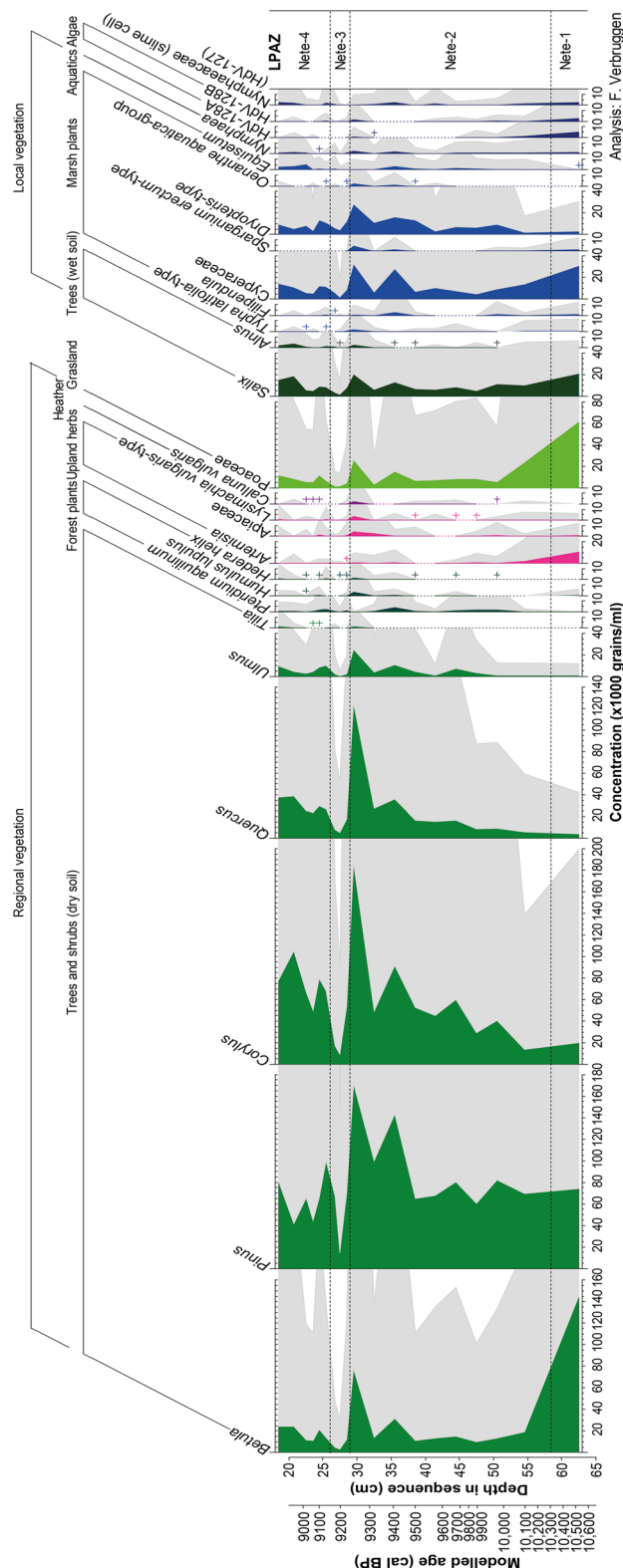


Fig. 6 Microfossil concentration diagram of core BG4 taken in the Grote Nete valley. The concentrations are expressed as 1,000 grains per millilitre (ml)

the early Boreal has been previously shown (Gelorini et al. 2007). *Pinus* and *Corylus* (hazel) co-dominate LPAZ Nete-2, confirming the expansion of pine forests with hazel growing along the forest edges and in the understorey where sufficient light penetrated. The pollen concentrations of *Corylus* increase during this LPAZ and the percentage curve reaches its rational limit at around 51 cm in the sequence, reflecting the regional expansion of hazel. Both pollen percentages and concentrations of *Quercus* (oak) and *Ulmus* (elm) increase from the base of the peat upward showing their regional colonisation. Bud scales and leaf fragments confirm the local presence of oak in the valley from a depth of 46 cm upward. Macroremains of *Cornus sanguinea* (dogwood), *Crataegus monogyna* (hawthorn) and *Frangula alnus* (alder buckthorn) indicate their local occurrence on moist soils in the developing pine-hazel forests in the area. Ferns such as *Pteridium aquilinum* (bracken) and those producing *Dryopteris*-type spores appeared along the forest edges and in open areas during the expansion of these forests. The local peat-forming vegetation was diverse and consisted of *Frangula alnus*, various species of Cyperaceae such as *Carex pseudocyperus*, *C. rostrata* (bottle sedge), *C. elata* (tufted sedge), *C. paniculata* (greater tussock sedge), *Eleocharis* sp. (spike-rush), as well as marsh plants such as *Equisetum* sp. (horsetail), *Lycopus europaeus* (gipsywort), *Mentha* cf. *aquatica* (water mint), *Menyanthes trifoliata* (bogbean) and *Oenanthe aquatica* (fine-leaved water dropwort). *Carex elata* and *C. paniculata* are typical tussock-forming species that are tolerant of fluctuating water levels (Weeda et al. 1994). The aquatic flora consisted of *Nymphaea alba*, *Potamogeton*, *Nuphar* and *Ceratophyllum demersum* (rigid hornwort).

Especially during the upper half of this LPAZ pollen concentrations increase. This is most pronounced in *Pinus*, *Corylus* and *Quercus* and to a minor extent in *Betula*, *Ulmus* and *Salix* (Fig. 6). Also herbaceous plants such as grasses, sedges and ferns display higher concentrations in the second half of this LPAZ. A maximum in pollen concentrations of most taxa characterizes the top of LPAZ Nete-2. This peak coincides with a decrease in pollen percentages of *Pinus* and a maximum in pollen percentages of *Quercus*, *Ulmus* and the first occurrence of *Tilia* (lime). This likely reflects the colonisation of these thermophilous deciduous taxa in the area at the expense of pine. This succession in natural vegetation is frequently observed in Early Holocene pollen records in this region (e.g. Verbruggen et al. 2019).

LPAZ Nete-3 (26–29 cm)

Shortly before the lithological change from compact and layered peat to a more homogeneous organic peat, a sharp decline in pollen concentrations is observed in all taxa reaching a minimum exactly at the lithological boundary at a depth of 27–28 cm. Simultaneously with the abrupt decline

A dense forest cover is supported by increased pollen accumulation of typical forest herbs including climbing vines such as *Hedera helix* (ivy) and *Humulus lupulus* (hop) and the epiphytic hemiparasite *Viscum album* (mistletoe) towards the top of LPAZ Nete-2. Both *Hedera helix* and *Viscum album* are considered climate indicators (Zagwijn 1994). *Hedera helix* is sensitive to winter frost and only tolerates mild winters (mean January temperature > -2 °C), whereas *Viscum album* requires warm summers (mean July temperature > 15.5 °C) (Iversen 1944). Additionally, post-depositional processes resulting in a relatively more compact upper part of the lower peat section may account for the high pollen concentrations seen towards the top of LPAZ Nete-2. A groundwater lowering may cause a compaction of peat, or even result in a hiatus. It is generally assumed that in temperate climate zones large stands of pine can withdraw large quantities of water from the subsoil as evergreen trees such as pine require sufficient water throughout the year to maintain their leaf foliage. The year-round presence of these needles implies continued evapotranspiration, which may result in periods of drought in areas with extensive pine cover such as the sandy soils of the Campine region during the Boreal. The age-depth model does not show clear indications for a hiatus, although at 45 cm there seems to be a sudden shift in the model. Remarkably, this coincides with the double dates that show a considerable difference in outcome. Assessing the LOI data and lithology, there are no clues for a disturbance. Superimposed on this, climatic factors may have played a role in the hydrology of the study area affecting peat compaction during and after accumulation.

After the initial development of mixed deciduous forests at the expense of pine cover, a sudden decrease in various thermophilous trees such as oak and elm, followed by hazel is observed (LPAZ Nete-3) coinciding with a renewed spread of pine and a prominent sharp decline in pollen concentrations of most taxa. This abrupt reduction of up to 95% of the pollen concentrations, observed in multiple pollen spectra, may indicate a decrease in pollen productivity. This could imply a strong decline in vegetation cover. However, there is no evidence for a reduction in forest cover in general as grasses, *Artemisia* and other heliophilous taxa do not increase during LPAZ Nete-3. On the other hand *Pteridium aquilinum*, an indicator of forest openings due to a disturbance (e.g. fire, anthropogenic clearing or climatic change) (den Ouden 2000) does display a minor peak at the onset of LPAZ Nete-3 suggesting forests had locally opened to some extent (Figs. 5 and 8). Unfavourable environmental conditions such as a cooling during spring and summer when most plants flower may have caused a reduction in pollen production in most plants for several decades. For instance hazel requires stable weather conditions as described by Tallantire (2002), including a minimum temperature of c. 14–16 °C at some time during the period (January) February–April for

successful pollen release, and sufficiently high mean temperatures between July and September for nut production and maturation as well as the formation of the following year's catkins. Early frosts and winter temperatures below ca. -15 °C as well as drought and heavy rains may result in a less successful reproduction. Additionally, increased peat accumulation rates or a temporary influx of pollen-poor sediments (e.g. sand) may also have resulted in relatively lower pollen concentrations. Yet, there is no indication for increased accumulation rates during LPAZ Nete-3 in the age-depth model, nor is there evidence for an increased influx of coarse-grained sediments in the loss-on-ignition record (Fig. 4). Nonetheless, there is a change visible in lithology during LPAZ Nete-3 (at 27 cm) as a homogeneous peat rich in macroremains formed on top of the compact and layered peat that initially accumulated in the valley (see Fig. 2).

Following the sudden drop in pollen concentrations, the gradual succession from pine-hazel forests towards mixed deciduous forests in the region proceeded with the expansion of hazel, oak and elm (LPAZ Nete-4) after the initial start in the second half of LPAZ Nete-2 and the temporary increase in pine cover during LPAZ Nete-3. All thermophilous taxa that were adversely affected during the LPAZ Nete-3 eventually appear to recover.

Interestingly the local vegetation remains relatively stable throughout the period of peat formation as pollen and macrofossil assemblages of wetland taxa show only minor variations towards temporary less abundant (semi-) aquatic taxa in LPAZ Nete-3. Ferns, sedges, horsetails and willow were important constituents of the local wetland vegetation in the Grote Nete valley throughout the Boreal.

A response to the 9.3 ka event?

The anomaly observed in the pollen record during LPAZ Nete-3 (26–29 cm in the sequence) suggests a temporary interruption in the regional vegetation succession from a pine-hazel woodland towards mixed deciduous forests in the region (e.g. Verbruggen et al. 2019), characterised by an expansion of cold-tolerant pines. The AMS ^{14}C dates at the base and above this level suggest an age between 9,270 and 9,015 and 9,540–9,425 cal BP (Table 1) and the age model suggests the position of 9.3 ka between 27 and 30 cm (Fig. 3). Hence, it is possible that this temporary shift in regional vegetation is indeed a response to the climatic cooling at 9.3 ka BP, which is clearly recorded in the stable oxygen isotope records from the Greenland ice cores, but so far has been recognised in few palaeoecological studies in northwestern Europe. Similar responses where cold-tolerant taxa briefly expanded and the presence of thermophilous taxa simultaneously decreased around 9.3 ka BP have sparsely been recorded in other parts of northwestern

Europe, such as Cooney Lough in western Ireland (Ghilardi and O’Connell 2013). In two low alpine lakes in central Norway the pollen records show minor fluctuations around 9.3 ka BP (Paus et al. 2019). A palynological study of deposits in an abandoned channel of the Vlootbeek in Posterholt (The Netherlands), 90 km east of our study site, also shows a clear decline in pollen percentages of hazel, oak and elm coinciding with a sharp increase in pine pollen during the Boreal (Bakels 2017). Similarly, a pollen diagram from Berlare in the Scheldt valley, ca. 60 km west of the studied site, displays an abrupt decrease of hazel and an increase of pine shortly after $8,730 \pm 70$ uncal BP (Verbruggen 1971; Crombé 2018). Yet this vegetational shift remained undiscussed and, therefore, was not linked to the 9.3 ka event. The pollen records of Cooney Lough, Posterholt, Berlare and the Grote Nete valley bear remarkable similarities during the Boreal, indicating the vegetational shifts are not a local phenomenon, but are indeed a response to a climatic anomaly that affected northwestern Europe at least partly.

There are several explanations as to why this event is often unnoticed or absent in pollen records. The overall duration of the 9.3 ka event varies from 40 to more than 100 years, depending on the data set and criteria to define onset and end (Rasmussen et al. 2007, 2014). Therefore, only high-resolution studies will potentially register shifts in vegetation and even then they may be smoothed out as samples usually comprise one or several decades. Furthermore, hiatuses are frequent in Boreal peat records from the sandy areas of Belgium and the Netherlands, e.g. at Oud-Turnhout-De Liereman (Verbruggen et al. 2019), Mildert-Tungelroyse Beekvallei (Woelders et al. 2016), Zutphen (Bos et al. 2006) and Berlare-Donk (Verbruggen 1971). Finally, local environmental conditions vary through space, which may result in an enhanced sensitivity of the vegetation to climatic anomalies in certain regions, whereas in other areas the vegetation may be little affected. It is very well possible that the coversand region of Belgium, with ample suitable habitats for both pines and deciduous trees is relatively prone to climatic changes. Nonetheless, peat records in such sandy areas are rare (Verbruggen et al. 2019), which may also contribute to the lack of sites recording a vegetation response to the 9.3 ka event.

The vegetation response to the well-studied climatic cooling at 8.2 ka BP is more frequently recorded (and noticed) in pollen and macrofossil records in Europe (e.g. Giesecke et al. 2011 and references therein; Ghilardi and O’Connell 2013), although the vegetation is affected differently in various regions due to different hydrological responses to the changes in ocean circulation patterns. Past lake level reconstructions, as well as pollen and speleothem records point to drier climate conditions in northern and southern Europe, whereas mid-Europe, including the Alps, is characterised by wetter conditions (see Tinner and Lotter 2001;

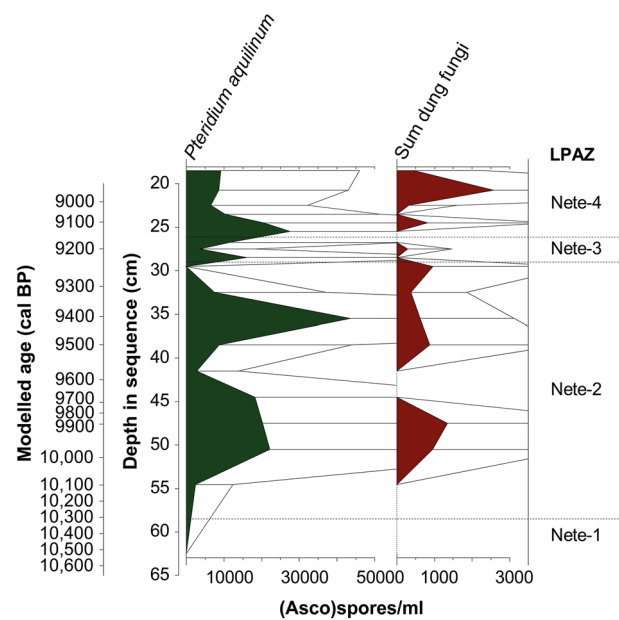


Fig. 8 Concentrations of *Pteridium aquilinum* spores and the sum of ascospores of coprophilous (dung) fungi throughout core BG4 taken in the Grote Nete valley. The depth bars represent an exaggeration of $\times 5$

Magny et al. 2003). Whether the hydrological responses at the 9.3 ka and 8.2 ka BP events were similar remains uncertain. Fully aquatic and wetland taxa are less abundant in the two macrofossil spectra within LPAZ Nete-3, which may suggest drier environmental conditions locally in the valley. It should be noted that *Lycopodium europaeus*, which is the most abundant macrofossil during LPAZ Nete-3 is a species that can quickly colonise recently dried up river banks (Weeda et al. 1988), which may be in agreement with drier conditions. However, it should be noted that only minor changes occur in the pollen percentages of the local vegetation during this LPAZ.

Implications for human occupation

The changes in both pollen percentages and concentrations are pronounced in the late Boreal pollen record of the Grote Nete valley and translate to considerable changes in the regional vegetation around 9.3 ka BP. It is assumed that these affected the food sources of hunter-gatherers that frequented the valley. Obviously, the decrease of both hazel and oak during LPAZ Nete-3 will have resulted in less available hazelnuts and acorns, some of the main food resources in Mesolithic Europe. Hazelnuts, which are mainly a source of fat and protein were used throughout the entire Mesolithic period, whereas roasted acorns, which would have been added to the Mesolithic diet from the early Boreal onwards, provided Mesolithic hunter-gatherers mostly with

carbohydrates (Kubiak-Martens 1999, 2019a). Moreover, hazel and oak are also important firewood species (Bishop et al. 2015) and provide raw materials for tool production such as arrow shafts and basketry.

Various authors (e.g. Kubiak-Martens 1999, 2016; Bishop et al. 2013, 2022) have convincingly shown that Mesolithic man ate more than just hazelnuts and acorns, which are often found and easily recognised during archaeological research. The Mesolithic diet was much more diverse and also consisted of seeds, fruits, berries and greens. However, the use of such food is often hard to prove from an archaeobotanical perspective, especially when organic material is not or poorly preserved. When fire is involved in food preparation and/or cooking it is more likely that the remains get charred and, hence, preserved. Furthermore, a variety of plants and their green parts would have been eaten raw. Recently with the deployment of scanning electron microscope (SEM) techniques the presence of charred underground storage organs (archaeological parenchyma) such as starchy roots, tubers, rhizomes and bulbs was successfully demonstrated in archaeological deposits (e.g. Kubiak-Martens 1999, 2016; Kubiak-Martens et al. 2015). Starchy underground organs usually need to be processed. Cooking increases their nutritional value and digestibility and sometimes is required to transform the root foods into an edible form. These starchy root foods likely contributed substantially to the Mesolithic diet. It seems that early and middle Mesolithic hunter-gatherers were particularly attracted to marsh plants as sources of starchy foods. The underground storage organs of the sedge family (Cyperaceae) plants seem to be of special value to these groups. This was well documented at two recently excavated sites in the Netherlands, Soest Staringlaan and Kampen Reevediep, both occupied from the Preboreal through the Boreal (main occupation phase) up to the early Atlantic (Kubiak-Martens 2019a, b). The underground parts of marsh plants might have been of great value particularly in winter and spring, when they carry their highest concentrations of starch, and when other plant foods (such as hazelnuts and acorns, but also greens, fruits and berries) were scarce. The most striking feature of the archaeobotanical assemblages in Soest Staringlaan was the relatively low frequency of charred hazelnut shells, especially during the middle Mesolithic (late Boreal) occupation phase (Kubiak-Martens 2019a). Although no pollen record was available for the pre-Atlantic period in Soest, this may be due to the fact that hazel occurred only sporadically in the landscape and/or this represents years of poor hazelnut harvest. Hazelnuts would have been then used as an addition to other plant foods, for example, starchy root foods.

In the pollen and macrofossil record of the Grote Nete valley several taxa occur whose remains have previously been identified as a food source for Mesolithic man (Kubiak-Martens 2016). They include marsh plants such as

Schoenoplectus lacustris, *Typha latifolia* (bulrush, edible parts: rhizomes), various *Carex* species (edible stem base) and *Equisetum* (tubers), as well as upland herbs like *Polygonum* (knotgrass), *Rumex* (dock) (both rhizomes and greens) and *Urtica dioica* (nettle, greens), aquatic plants *Nymphaea* and *Nuphar* (seeds and rhizomes) and forest inhabitants *Crataegus monogyna* (fruits), *Cornus sanguinea* (berries), *Viburnum opulus* (Guelder rose, berries) and *Sambucus nigra* (elder, berries). During LPAZ Nete-3 many of these edible plants were available including *Corylus*, *Quercus*, *Viburnum opulus*, *Rumex*, *Equisetum*, *Nuphar* and *Nymphaea*, even though it is uncertain what the yield of the nut, fruit, seed and berry harvest was around 9.3 ka BP since pollen productivity probably decreased drastically.

Yet another plant food, which would have been well known to Mesolithic hunter-gatherers, and used in addition to hazelnuts, acorns and root foods, particularly during the Boreal, are pine seeds. The large quantities of charred pine cone scales found at various Mesolithic sites in the Netherlands (e.g. Soest Staringlaan and Kampen Reevediep), often in features dated to the early and/or middle Mesolithic, are interpreted as either the remains of pine cones that were collected for fuel and/or kindling, or for their edible, starch- and fat-rich seeds, or possibly both (Kubiak-Martens 2019a, b).

Not only man, but probably also game was affected by the changing environment. Many wild animals such as wild boar depend on the availability of nuts and acorns, which likely decreased substantially around 9.3 ka BP. In the palynological record the abundance of dung fungi remains may be indicative of the local presence of animals (van Geel et al. 2003). Also in the Boreal peat ascospores of dung fungi are present, i.e. mainly *Cercophora*-type (HdV-112) but also *Sordaria*-type (HdV-55B), *Arnium*-type (HdV-261) and *Apiosordaria verruculosa*-type (HdV-169). Interestingly, during LPAZ Nete-2 the concentration curve of ascospores of dung fungi appears to correlate with the spore concentration curve of *Pteridium aquilinum*, indicating increased animal abundances during periods of forest openings or disturbances (Fig. 8). However, coprophilous fungi are less abundant during the increase in *Pteridium aquilinum* spores at the onset of LPAZ Nete-3. This suggests a reduced presence of animals in the Grote Nete valley and surroundings during the suggested climatic cooling at 9.3 ka BP. This may be attributed to a decreased availability of food resources or fresh water, or a combination of both. The percentages of dung fungi increase towards the upper part of LPAZ Nete-4, as hazel and pine and other thermophilous trees re-expanded, suggesting the effects of the climate perturbation were only temporary.

Hence it remains questionable whether this short-term climatic and vegetation event was the only trigger responsible for the numerous fundamental changes in human behaviour and material culture during the late Boreal (see

Introduction). Rather it seems that this event was the ultimate tipping point in the context of long-term climatic and environmental changes that characterise the Boreal. In particular the gradual but continuous drowning of the North Sea basin most likely played a major role in these cultural changes (Crombé 2019). This process probably induced the movement of people and animals originally occupying the North Sea basin towards higher inland ground, which was already inhabited by other groups of hunter-gatherers. This might have led to resource competition amongst different groups, a process which was strengthened by the vegetation changes in response to the 9.3 ka event discussed in this paper. In addition decreasing water availability might have had an important impact as well.

Conclusion

A multi-proxy palaeoecological study including pollen and macrofossil analyses and loss-on-ignition on a well-dated peat sequence from the Grote Nete valley has shown the vegetation dynamics during the Boreal in the Belgian Campine area. The pollen assemblages indicate a natural vegetation succession from open birch-pine woodlands during the late Preboreal to a landscape dominated by pine during the early Boreal. Soon after the expansion of pine various thermophilous taxa spread in the region. First hazel expanded and became co-dominant colonising the edges and open areas in the pine woodlands, followed by oak and elm. However, a clear interruption in the late Boreal vegetation succession is discerned where the cold-tolerant pine re-expands at the expense of thermophilous taxa. Simultaneously a sharp decline in overall pollen concentrations characterises the transition from relatively compact and layered peat to more homogeneous peat. It is argued that a climatic perturbation caused unfavourable conditions for pollen production and that a temporary cooling resulted in a short-lived reversal in vegetation succession. AMS ^{14}C dates confirm that this anomaly likely corresponds to the 9.3 ka event, a cooling triggered by a meltwater pulse into the North Atlantic, weakening thermohaline circulation patterns during the Boreal. As this cooling led to major changes in the regional vegetation, albeit temporary, it likely affected both food and freshwater resources of hunter-gatherer groups in the area.

Only a few sites in northwestern Europe have recorded a change in vegetation composition and pollen production around 9.3 ka BP. The short duration (40–100 years) of the event in combination with low sampling resolutions may account for this. Additionally hiatuses, which frequently occur in Boreal archives likely as the result of a large year-round groundwater uptake by massive pine stands, may preclude the detection of this climatic anomaly. Finally, sensitivity to the environmental change may differ in various

regions. High-resolution multi-proxy studies at sensitive sites, such as river valleys in sandy regions, allow the assessment of vegetational responses to even small-scale climatic anomalies that otherwise may have remained unnoticed.

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Data availability Data resulting from this study are available upon contact with corresponding author. The microfossil data will be deposited at the European Pollen Database (EPD) upon publication.

References

- Agentschap Informatie Vlaanderen (2014) Digitaal Hoogtemodel Vlaanderen II, DSM, raster, 1 m, Geopunt (www.geopunt.be)
- Anderberg A-L (1994) Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 4: Resedaceae-Umbelliferae. Swedish Museum of Natural History, Stockholm
- Antrop M, Van Eetvelde V, Janssens J, Martens I, Van Damme S (2002) Traditionele landschappen van het Vlaamse Gewest. Ghent University, Department of Geography, Ghent
- Bakels C (2017) Posterholt, a Late Pleistocene—Holocene record of the vegetation history in and around the valley of the Vlootbeek, a tributary of the river Meuse (southeastern Netherlands). *Neth J Geosci* 96:175–182
- Berggren G (1969) Atlas of seeds and small fruits of Northwest-European plant species: with morphological descriptions. Part 2: Cyperaceae. Swedish Natural Science Research Council, Stockholm
- Berggren G (1981) Atlas of seeds and small fruits of Northwest-European plant species: with morphological descriptions. Part 3: Salicaceae-Cruciferae. Swed Nat Sci Res Council, Stockholm. Berlings, Arlöv
- Beug H-J (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil, München
- Bishop RR, Church MJ, Rowley-Conwy PA (2013) Seeds, fruits and nuts in the Scottish Mesolithic. *Proc Soc Antiq Scot* 143:9–71
- Bishop RR, Church MJ, Rowley-Conwy PA (2015) Firewood, food and human niche construction: the potential role of Mesolithic hunter-gatherers in actively structuring Scotland's Woodlands. *Quat Sci Rev* 108:51–75
- Bishop RR, Kubiak-Martens L, Warren GM, Church MJ (2022) Getting to the root of the problem: new evidence for the use of plant root foods in Mesolithic hunter-gatherer subsistence in Europe. *Veget Hist Archaeobot*. <https://doi.org/10.1007/s00334-022-00882-1>
- Bos JAA, van Geel B, Groenewoudt BJ, Lauwerier RCGM (2006) Early Holocene environmental change, the presence and disappearance of early Mesolithic habitation near Zutphen (The Netherlands). *Veget Hist Archaeobot* 15:17–43
- Bronk Ramsey C (2009) Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* 51:1,023–1,045
- Bronk Ramsey C (2021) OxCal 4.4. Oxford
- Cappers RTJ, Bekker RM, Jans JEA (2006) Digitale zadenatlas van Nederland. Groningen Archaeological Studies 4. Barkhuis, Eelde
- Crombé P (2018) Abrupt cooling events during the Early Holocene and their potential impact on the environment and human behaviour along the southern North Sea basin (NW Europe). *J Quat Sci* 33:353–367

- Crombé P (2019) Mesolithic projectile variability along the southern North Sea basin (NW Europe): Hunter-gatherer responses to repeated climate change at the beginning of the Holocene. *PLoS ONE* 14:e0219094. <https://doi.org/10.1371/journal.pone.0219094>
- Crombé P, Vandendriessche H (2020) “Les pointes à retouches couvertes”: a first inter- and intraregional assessment of their typological variability in the Rhine-Meuse-Scheldt region. *Bull Soc Archéol Champenoise* 113:123–135
- Crombé P, Sergant J, Robinson E, De Reu J (2011) Hunter-gatherer responses to environmental change during the Pleistocene-Holocene transition in the southern North Sea basin: Final Palaeolithic-Final Mesolithic land use in northwest Belgium. *J Anthropol Archaeol* 30:454–471
- den Ouden J (2000) The role of bracken (*Pteridium aquilinum*) in forest dynamics. PhD thesis, Wageningen University, Wageningen
- Fægri K, Iversen J (1989) In: Fægri K, Kaland KE, Krzywinski K (eds) *Textbook of pollen analysis*, 4th edn. Wiley, Chichester
- Fleitmann D, Mudelsee M, Burns SJ, Bradley RS, Kramers J, Matter A (2008) Evidence for a widespread climatic anomaly at around 9.2 ka before present. *Paleoceanogr* 23:PA1102. <https://doi.org/10.1029/2007PA001519>
- Gelorini V, Meerschaert L, Boudin M, Van Strydonck M, Thoen E, Crombé P (2007) Vroeg- en middenholocene vegetatie-ontwikkeling en preboreale klimatologische oscillatie in de vallei van de Grote Nete (Hechtel-Eksel, Limburg). *Notae Praehistoricae* 27:5–17
- Gendel P (1984) Mesolithic social territories in Northwestern Europe, vol 218. *British Archaeological Reports*, Oxford
- Ghilardi B, O’Connell M (2013) Early Holocene vegetation and climate dynamics with particular reference to the 8.2 ka event: pollen and macrofossil evidence from a small lake in western Ireland. *Veget Hist Archaeobot* 22:99–114
- Giesecke T, Bennett KD, Birks HJB et al (2011) The pace of Holocene vegetation change—testing for synchronous developments. *Quat Sci Rev* 30:2,805–2,814
- Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J Paleolimnol* 25:101–110
- Hoek WZ (1997) Palaeogeography of Lateglacial vegetations. Aspects of Lateglacial and Early Holocene vegetation, abiotic landscape, and climate in the Netherlands. *Netherlands Geographical Studies* 230. Koninklijk Nederlands Aardrijkskundig Genootschap, Utrecht
- Hoek WZ, Bohncke SJP, Ganssen GM, Meijer T (1999) Lateglacial environmental changes recorded in calcareous gyttja deposits at Gulickshof, southern Netherlands. *Boreas* 28:416–432
- Iversen J (1944) *Viscum*, *Hedera* and *Ilex* as climate indicators. *Geol Fören Förhandl* 66:463–483
- Jouffroy-Bapicot I (2010) Évolution de la végétation du massif du Morvan (Bourgogne - France) depuis la dernière glaciation à partir de l’analyse pollinique. Variations climatiques et impact des activités anthropiques. PhD thesis, Université de Franche-Comté, Besançon
- Kubiak-Martens L (1999) The plant food component of the diet at the late Mesolithic (Ertebølle) settlement at Tybrind Vig, Denmark. *Veget Hist Archaeobot* 8:117–127
- Kubiak-Martens L (2016) Scanning electron microscopy and starchy food in Mesolithic Europe: the importance of roots and tubers in Mesolithic diet. In: Hardy K, Kubiak-Martens L (eds) *Wild harvest: plants in the hominin and pre-agrarian human worlds*. Oxbow Books, Oxford, pp 113–133
- Kubiak-Martens L (2019a) Archeobotanisch onderzoek. In: Woltinge I, Opbroek M, Tebbens LA, Devriendt I, Drenth E (eds) *Mesolithisch verblijf en maretakspitsen aan de Staringlaan te Soest. De opgraving van een mesolithische ‘persistent place’*. BAAC report A-15.0124. BAAC BV, ‘s-Hertogenbosch, pp 582–603
- Kubiak-Martens L (2019b) Parenchym als zetmeelbron. In: Geerts RCA, Müller A, Niekus MJLT, Vermue F (eds) *Mesolithische kampen onder de oever van het Reevediep*. ADC monography 26. ADC ArcheoProjecten BV, Amersfoort, pp 193–210
- Kubiak-Martens L, Verbruggen F, Kooistra LI (2015) Archaeobotany: landscape reconstruction and plant food subsistence economy on a meso and microscale. In: Moree JM, Sier MM (eds) *Twenty metres deep! The Mesolithic period at the Yangtze Harbour site—Rotterdam Maasvlakte, The Netherlands*. Early Holocene landscape development and habitation (Part 1). BOORrapporten 566. BOOR, Rotterdam, pp 223–286
- Lang B, Bedford A, Brooks SJ, Jones RT, Richardson N, Birks HJB, Marshall JD (2010) Early-Holocene temperature variability inferred from chironomid assemblages at Hawes Water, northwest England. *Holocene* 20:943–954
- Magny M, Bégeot C, Guiot J, Peyron O (2003) Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. *Quat Sci Rev* 22:1,589–1,596
- Marshall JD, Lang B, Crowley SF et al (2007) Terrestrial impact of abrupt changes in the North Atlantic thermohaline circulation: early Holocene, UK. *Geology* 35:639–642
- Mauquoy D, van Geel B (2007) Plant macrofossil methods and studies: Mire and Peat Macros. *Encycl Quat Sci* 1–4:2,315–2,336
- Miola A (2012) Tools for Non-Pollen Palynomorphs (NPPs) analysis: a list of Quaternary NPP types and reference literature in English language (1972–2011). *Rev Palaeobot Palynol* 186:142–161
- Moore PD, Webb JA, Collinson ME (1991) *Pollen analysis*, 2nd edn. Blackwell, Oxford
- Paus A, Hafliðason H, Routh J, Naafs BDA, Thoen MW (2019) Environmental responses to the 9.7 and 8.2 cold events at two ecotonal sites in the Dovre mountains, mid-Norway. *Quat Sci Rev* 205:45–61
- Perdaen Y, Crombé P, Sergant J (2009) The use of quartzite as a chrono-cultural marker in the Mesolithic cultures of the Low Countries. In: Sternke F, Eigeland L, Costa L-J (eds) *Non-flint raw material use in prehistory. Old Prejudices and new direction, Proceedings of the XVth Congress of the “Union International de Sciences Pré- et Protohistoriques”*, Lisbon, 2006. BAR International Series 1939. Archaeopress, Oxford, pp 217–224
- Punt W et al (1976–2009) *The Northwest European Pollen Flora*, vol I (1976), vol II (1980), vol III (1981), vol IV (1984), vol V (1988), vol VI (1991), vol VII (1995), vol (1976–2009) VIII (2003), vol IX (2009). Elsevier, Amsterdam
- Rasmussen SO, Vinther BM, Clausen HB, Andersen KK (2007) Early Holocene climate oscillations recorded in three Greenland ice cores. *Quat Sci Rev* 26:1,907–1,914
- Rasmussen SO, Bigler M, Blockley SP et al (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat Sci Rev* 106:14–28
- Reimer PJ, Austin WEN, Bard E et al (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62:725–757
- Robinson E, van Strydonck M, Gelorini V, Crombé P (2013) Radiocarbon chronology and the correlation of hunter-gatherer socio-cultural change with abrupt palaeoclimate change: the Middle Mesolithic in the Rhine-Meuse-Scheldt area of northwest Europe. *J Archaeol Sci* 40:755–763
- Ryssaert C, Exaltus R, Orbons J, Verbruggen F (2017) Archeologisch vooronderzoek cluster Vallei van de Grote Nete: Landschappelijk booronderzoek – Veldkartering - Archeologische boringen. Odin, Deinze
- Schulting RJ, Mannermaa K, Tarasov PE et al (2022) Radiocarbon dating from Yuzhniy Oleniy Ostrov cemetery reveals complex

- human responses to socio-ecological stress during the 8.2 ka cooling event. *Nat Ecol Evol* 6:155–162
- Tallantire PA (2002) The early-Holocene spread of hazel (*Corylus avellana* L.) in Europe north and west of the Alps: an ecological hypothesis. *Holocene* 12:81–96
- Tinner W, Lotter AF (2001) Central European vegetation response to abrupt climate change at 8.2 ka. *Geology* 29:551–554
- Toussaint M, Brou L, Le Brun-Ricalens F, Spier F (2009) The Mesolithic site of Heffingen-Loschbour (Grand Duchy of Luxembourg). A yet undescribed human cremation possibly from the Rhine-Meuse-Schelde culture: anthropological, radiometric, and archaeological implications. In: Crombé P, van Strydonck M, Sergant J, Boudin M, Bats M (eds) *Chronology and Evolution Within the Mesolithic of North-West Europe. Proceedings of an International Meeting*, Brussels, May 30–June 1, 2007. Cambridge Scholars Publishing, Newcastle-upon-Tyne, pp 245–267
- Van der Meijden R (2005) *Heukels' Flora van Nederland*. Wolters-Noordhoff, Groningen
- Van Geel B, Buurman J, Brinkkemper O, Schelvis J, Aptroot A, van Reenen G, Hakbijl T (2003) Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *J Archaeol Sci* 30:873–883
- Van Landuyt W, Hoste I, Vanhecke L, Vercruyssen W, Van den Bremt P, De Beer D (2006) *Atlas van de flora van Vlaanderen en het Brussels Gewest. Instituut voor Natuur- en Bosonderzoek*, Brussels
- Van Maldegem E, Vandendriessche H, Verhegge J et al (2021) Population collapse or human resilience in response to the 9.3 and 8.2 ka cooling events: a multi-proxy analysis of Mesolithic occupation in the Scheldt basin (Belgium). *J Anthropol Archaeol* 64:101348
- Verbruggen C (1971) *Postglaciale landschapsgeschiedenis van Zandig Vlaanderen*. PhD thesis, Ghent University, Ghent
- Verbruggen F, Bourgeois I, Cruz F, Boudin M, Crombé P (2019) Holocene vegetation dynamics in the Campine coversand area (Liereman, N Belgium) in relation to its human occupation. *Rev Palaeobot Palynol* 260:27–37
- Von Grafenstein U, Erlenkeuser H, Brauer A, Jouzel J, Johnsen SJ (1999) A mid-European decadal isotope-climate record from 15,500 to 5000 years BP. *Science* 284:1,654–1,657
- Weeda et al (1985–1994) *Nederlandse Oecologische Flora, wilde planten en hun relaties*, vol 1 (1985), vol 2 (1987), vol 3 (1988), vol 4 (1991), vol 5 (1994). IVN, Amsterdam
- Woelders L, Bos JAA, de Kort J-W, Hoek WZ (2016) Early Holocene environmental change and the presence of Mesolithic people in the Tungelroyse Beek valley near Mildert, the Netherlands. *Veget Hist Archaeobot* 25:177–189
- Zagwijn WH (1994) Reconstruction of climate change during the Holocene in western and central Europe based on pollen records of indicator species. *Veget Hist Archaeobot* 3:65–88

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